VSB TECHNICAL UNIVERSITY OF OSTRAVA

ELECTRICITY GENERATION AND UTILIZATION

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Textbook

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Content

1. INTRODUCTION

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- describe the energy situation in the Czech Republic
- explain the content of the price of electricity

EXPLANATION

Electricity system (ES) plays a very important role in our modern society and affects virtually everyone on a daily basis. The ES transforms different types of energy into electricity and delivers it to different types of customers. The ES consists of three main parts: generation, transmission and distribution.

The Czech energy sector has undergone significant structural changes in recent years. These have been triggered both by the ongoing liberalisation of the domestic energy sector and by the progressing European integration process on the continent and our membership of the European Union. In addition to domestic development factors, it is increasingly European legislation that is influencing companies' decision-making. Today, no company can be successful and profitable without a comprehensive overview of its immediate and more distant surroundings.

In the Czech Republic, approximately 70-75 TWh of electricity is produced annually. The installed capacity of power plants in the Czech Republic is 22 GW. Fossil fuel thermal power plants and nuclear power plants, which form a decisive part of the EC resource base in the Czech Republic, will continue to play a key role in electricity generation in the Czech Republic in the medium and long term. At the same time, however, coal-fired power plants will mainly catch up in the relatively short term. On the contrary, an increase in installed capacity in renewable energy sources (RES) can be expected, but their share in the total resource base of the Czech Republic is relatively low compared to other EU countries. The share of individual types of power plants in the total electricity production in the Czech Republic is shown in Fig. 1.1.

In view of the projected growth in electricity consumption and stagnation or even decline in electricity production, the Czech Republic faces a real risk of having to import electricity in the future. According to the latest studies, the switch from exports to imports will take place in 2030 (critical scenario), while the reference scenario suggests a shift to 2036 at most. Of course, everything depends on the development of production resources in the Czech Republic.

The development of the energy sector takes place within the framework of the State Energy Concept (SEC), which defines the implementation instruments of the Czech energy policy with a view to 2050. The priorities are independence from foreign sources, security of energy sources and sustainable development. The SEC envisages support for nuclear energy in the future.

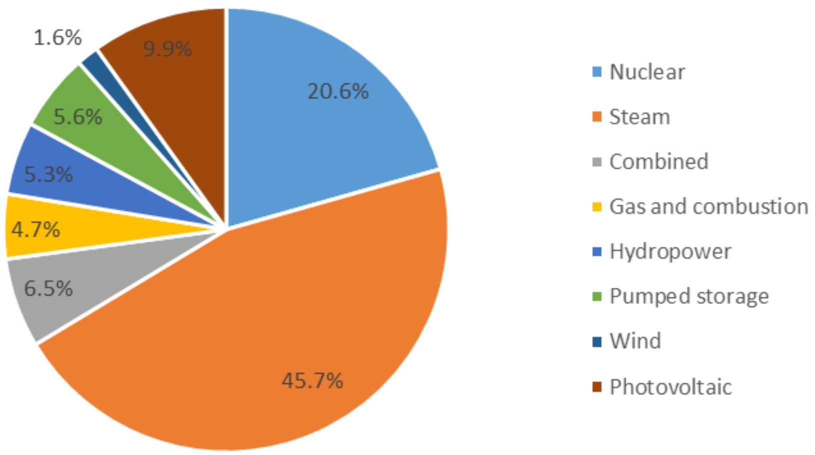

Fig. 1.1 Proportion of each type of power plant in total electricity production

The EC of the Czech Republic, due to its geographical location in the centre of Europe, is intensively connected to the UCTE system and is operated with significant international cooperation. Through seven 400 kV lines and four 220 kV lines it is interconnected with four electricity systems in neighbouring countries (Vattenfall, E.ON, Verbung, SEPS, PSE).

The Czech Republic is one of the few EU Member States that are net exporters of electricity. The Czech Republic is currently a net exporter of approximately 15% of all electricity production. In the long term, most exports have been directed to Germany, followed by Austria and Slovakia.

As a consequence of the EU's intensified fight against global climate change and the promotion of RES, changes in the structure of electricity generation are beginning to take effect, with:

- the decline and closure of coal resources in Central Europe,
- the shutdown of nuclear power plants in Germany,
- the massive development of wind energy in northern and south-western Europe,
- the development of coal-fired power in South-Eastern Europe and,
- the development of natural gas-fired sources as backup sources for RES.

In addition to the more difficult regulation of wind power (WPP) and the instability of supply from them (and the resulting increase in reserve capacity needed), the EU's efforts also include mandatory purchase and integration of RES into the transmission grid. As a result of the change in the service structure induced by RES support, the availability of the current level of capacity for ancillary services can also be expected to decrease.

The promotion of RES in the EU (and especially the RES in Germany) has resulted in increased flows through the Czech Republic, and thus increased demands on the capacity of the long-distance transmission networks, increasing requirements for connection of sources and increased off-take capacities. Transmission and distribution system operators in particular have to cope with these consequences.

❑ EU legislation

The first document of energy legislation was the European Energy Charter, which initiated systematic cooperation in the energy sector between European countries. The provisions adopted concern the protection and promotion of investment, free trade, free energy transit, reduction of the impact of energy on the environment, and a mechanism for resolving disputes between states and investors.

Another document is the White Paper, which aimed to help the associated countries prepare to work within the requirements of the European Union's internal market. It sets out the main measures in the internal market, proposes steps for legislative convergence and describes the necessary administrative and organisational structure.

The relevant Directives of the European Parliament and of the Council of Europe on common rules for the internal market in electricity lay down common rules for the production, transmission and distribution of electricity concerning the organisation and operation of the electricity sector, market access, criteria and procedures for tendering and authorisation procedures, and rules for the operation of networks.

❑ Legislation of the Czech Republic

New legal regulations in a liberalised market environment required the transposition of EU directives into the Czech energy legislation.

The State Energy Concept is defined in the Czech Republic in Section 3 of Act 406/2000 Coll. on Energy Management. It expresses the objectives of the state in energy management in accordance with the principles of sustainable development, ensuring security of energy supply, competitiveness of the economy and social acceptability for the population. It is adopted for a period of 25 years. It is approved by the Government on the proposal of the Ministry of Industry and Trade, most recently in 2015.

Act No. 458/2000 Coll. and later amended Act No. 469/2023 Coll., on the conditions of business and the exercise of state administration in the energy sectors and on amendments to certain acts (Energy Act). It fully implemented into the legal system of the Czech Republic the principles applicable in the EU for the area of business and state administration in the electricity and gas sectors. These include in particular Directive 96/92/EC on common rules for the internal market in electricity, Directive 2004/8/EC on the promotion of combined heat and power based on useful heat demand in the internal energy market, EU Regulation 1228/2003 on conditions for access to the network for cross-border exchanges of electricity and the Energy Charter Agreement and the currently applicable amendments to all these directives and regulations.

The Energy Act regulates the conditions of doing business, the exercise of state administration, regulation, rights and obligations of natural and legal persons, ensures the harmonisation of Czech legislation, introduces a market environment, including the definition of the Energy Regulatory Office (ERO) and the Electricity Market Operator (OTE), with the aim of achieving reliable and quality energy supply at minimum prices for end consumers, regulates the position and competence of the State Energy Inspectorate (SEI), provides for sanctions and creates conditions for environmental protection and the development of the energy sector.

The ERO's remit is to promote competition and protect the interests of consumers in order to meet all reasonable demands for energy supply. In the Czech Republic, the model of regulated access to networks is applied - anyone who meets the conditions set by law has the right to access the networks to carry out the agreed transactions. Prices for the use of the networks are set by the ERO. The ERO also grants licences for electricity generation.

The SEI is an administrative authority subordinate to the MIT of the Czech Republic, which, in addition to controlling compliance with the provisions of the Energy Act, also controls compliance with Act No. 406/2000 Coll., on energy management and compliance with the Act on prices. It imposes fines for breaches of these regulations.

Electricity price structure

The price of electricity consists of an unregulated and a regulated component. The unregulated component is the price of power electricity - around 60 % and is the price at which the electricity produced is sold by generators (power plant operators) and traders. The regulated part includes the following components: Transmission - almost 5% of the cost of transmitting electricity through the high-voltage system, operated in our country by the Czech Transmission Company (ČEPS). Distribution - about 30-40 % of the price is collected by distributors, the distribution companies that bring electricity to consumers. (This is an example of the composition of the price for households. In the case of businesses, the percentages for captive power and distribution are different. Distribution, the "transport" of electricity to businesses, is shorter and therefore the ratio is lower. For large enterprises it can be below 20%, with the share of own power electricity increasing proportionally.) System services - more than 6% are so-called support services, which must be provided by CEPS and producers and which mean quality assurance for consumers, i.e. constant frequency, maintaining backups in case of sudden outages, etc. Renewables support charge - 600 CZK per MWh - we all support renewable electricity generation. Market operator - CZK 4 per MWh, the price includes the cost of running the office that manages the electricity market. Taxes - electricity tax plus VAT 21 %. The rule of thumb is that the more expensive the commodity is, the greater the demand for it - in simplified terms, electricity is more expensive on the market at peak times than off-peak, and more expensive in winter than in summer. There is a system of different tariffs for consumers, which they can set up in agreement with their electricity supplier to best suit their household equipment and the way they work. Both the regulated and unregulated components of the price have changed significantly in 2023 and 2024, with their ratio depending on the tariff chosen and the amount of energy consumed.

Summary of terms 1.1.

Electricity system, energy sources, State Energy Concept, electricity price.

Questions 1.1.

1. What is the annual electricity production in the Czech Republic?
2. What is the installed capacity of CR?
3. What does the price of electricity consist of?

ADDITIONAL RESOURCES 1

[1] ERO - Energy Regulatory Office. Available: https://eru.gov.cz/en

[2] Government Programme Statement. Available: https://vlada.gov.cz/cz/programove-prohlaseni-vlady-193547/

2. THERMAL POWER PLANTS

2.1. The principle of operation of thermal power plants

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- define Rankine - Clausius heat cycle
- describe the function of a thermal power plant

EXPLANATION

Thermal power plants are a large complex of different facilities. The purpose of thermal power plants is to convert the chemical energy bound in the fuel into electricity for distribution to consumers. This conversion is not direct, as it takes place through other forms of energy. In thermal power plants, the chemical energy of the fuel is released as heat, the thermal energy is stored and transferred through a medium, which is usually steam of given parameters, the thermal energy of the carrier medium is converted into mechanical energy and finally the mechanical energy is converted into electrical energy. All these energy conversions are accompanied by losses which affect the overall efficiency of thermal power plants.

It is essential that the electricity generated meets certain quality requirements. These requirements include frequency, compliance with voltage levels, and delivery of the required amount of energy. In order to meet these requirements, the parameters of the generated electricity must be adjusted (transformed). This is also done because the parameters of the generated electricity are not suitable for transmission and do not meet the voltage levels.

Thermal power plants and heating plants always work on the same principle, but differ in the fuel they burn and the way the steam is generated.

Depending on the fuel used, power plants can be divided into coal-fired, using mainly lignite and hard coal, steam-gas-fired, burning natural gas or natural gas, and diesel-fired, burning diesel. Diesel power stations are not power stations in the true sense, but are large diesel generators, usually used as back-up power sources. Solar thermal power plants are less common.

Coal-fired power plants can be pure condensing plants or they can be thermal plants, which is the more common case because thermal plants have higher efficiency. Natural gas-fired power plants are usually steam-gas-fired. All of the power plants mentioned above operate with steam except diesel power plants. Here, no steam is generated.

Principle of function

A typical block arrangement for today's thermal power plants (Fig. 2.1).

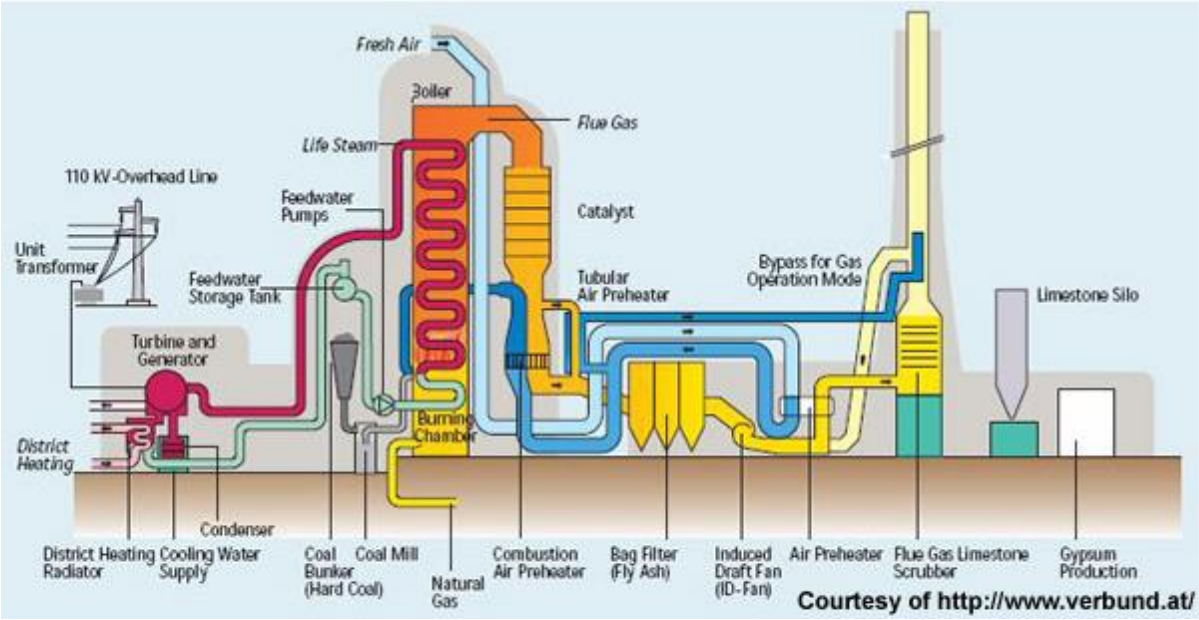

Fig. 2.1 Example of a block layout

One block always contains a boiler, a turbine, an alternator, a block transformer and a tap transformer. These devices characterise a power plant unit. The number of units is determined by the capacity of the units and the installed capacity for which the plant is designed. Each unit also contains auxiliary and service equipment for the operation and protection of the unit and its components.

The basic principle of all thermal power plants is the same. Fuel is fed into the boiler of each unit and burned there. The combustion of the fuel releases heat which is stored in the water flowing through the boiler. The water becomes steam at the required temperature and pressure and is fed to the turbine. The expanding steam turns the turbine, which turns a turboalternator that converts mechanical energy into electrical energy. The turboalternator is followed by a block transformer. This is always step-up, as it is necessary to raise the voltage level from high voltage to very high voltage - usually 400 kV or 110 kV - and to reduce currents from tens of kilo amperes to hundreds of amperes. Such voltages and currents are suitable for transmission.

Some thermal power plants also have the function of thermal power plants, as they supply thermal energy or heat in addition to electricity. This is made possible by the turbines. Part of the steam is diverted from these turbines to a condenser and part of the steam is extracted from the turbine and used as heating steam. The principle of operation described here is typical of power plants using the so-called Rankine - Clausius cycle.

Rankine - Clausius Circulation

It describes the circulation and group states of the feedwater in the thermal circuit of the power plant. It is the most common way of circulating feedwater see. Fig. 2.2 a Fig. 2.3.

1) In the first step, the treated demineralised feed water is pumped by a circulation pump and the water is heated from temperature T1 to temperature T2. Temperature T1 is in the vicinity of 20 °C and normal atmospheric pressure, if the pressure increase caused by the feed pump pumping is neglected, Temperature T2 is in the vicinity of 200 °C and a pressure of about 1.5 MPa. The water is in the liquid state. This heating is done to increase the efficiency of the plant. Feedwater temperatures and pressures vary from plant to plant.

2) Superheated feed water enters the boiler or other steam generator. Here the high pressure water is heated to the saturation point where it starts to boil. In another part of the

boiler, saturated steam is generated and the steam is superheated to the working temperature. The steam is under high pressure and temperature in the boiler. The steam pressures range from 15 - 30 MPa, the temperature between 550 - 700°C. It is necessary that the steam produced does not contain water droplets, i.e. the steam must be dry.

3) The steam from the boiler is led to the turbine where it expands and transfers its thermal and kinetic energy. Large power turbines may be composed of several parts, then they are multi-body turbines or the turbine is only one piece, but the turbine is divided according to the working pressure into a high pressure part, a medium pressure part and a low pressure part. Often, steam heating is used to increase efficiency, where the high pressure section of the turbine is followed by a steam take-off and the steam is fed back into the boiler where it is heated, raising its temperature and fed back into the turbine to the medium pressure section and then to the low pressure section.

4) After passing through the turbine, part of the steam can be used as heating in the case of a heat plant with a take-off turbine, but it is necessary to adjust the temperature and pressure of the steam. The steam that is not used as heating steam or the steam from the non-draw-off turbine is fed into the condenser. Here, the steam changes its state from gaseous to liquid and becomes feed water, which is fed back into the boiler together with demineralised water from the water source to cover the steam losses in the circulation. This completes the whole Rankine - Clausius cycle.

There are many influences on the efficiency of the Rankine - Clausius cycle. The aim is to achieve the highest possible efficiency and is therefore used:

- increasing the steam temperature,
- repeated steam heating,
- regenerative feed water heating,
- increasing the efficiency of individual components of the heat cycle,
- reducing back pressure.

The maximum realistic efficiency of the Rankine - Clausius cycle is limited mainly by the temperature and steam pressure. The steam parameters can only be increased as much as the materials used for the construction of the heat cycle parts allow. Mainly boilers, piping and turbines. These materials must withstand very high pressures and temperatures. For the materials currently used, maximum pressures of up to 30 MPa and temperatures of up to 650°C apply.

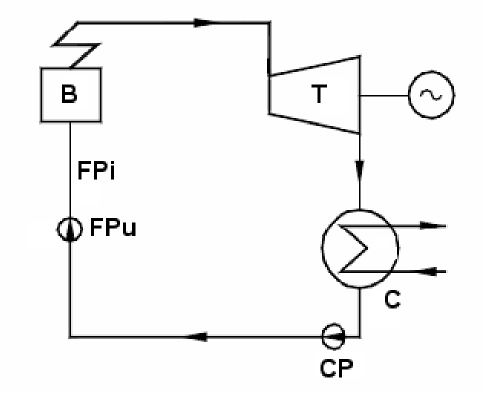

Fig. 2.2 Block diagram of Rankine - Clausius cycle: CP - condenser pump, FPu - feed pump, FPi - feed pipe, K - boiler, T - turbine, ~ - turboalternator, C - condenser

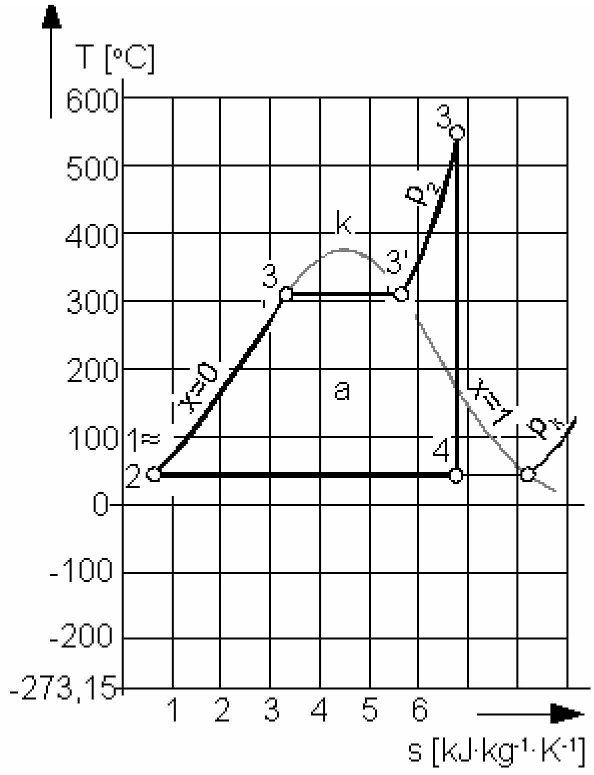

Fig. 2.3 T-s diagram of the Rankine - Clausius cycle [1]

Summary of terms 2.1.

Thermal power plant, Rankine - Clausius heat cycle, thermal power plant, condensing power plant, block arrangement.

Questions 2.1.

4. Describe the Rankine - Clausius heat cycle.
5. What are the working pressures and steam temperatures?
6. How to increase the efficiency of the Rankine - Clausius heat cycle?

2.2. Coal-fired power plants

TIME TO STUDY:

2 hours

TARGET:

After studying this paragraph, you will be able to

- describe the parts of coal-fired power plants and their function

EXPLANATION

Coal-fired thermal power plants are the most common type of thermal power plants. The primary fuel burned is black or brown coal. Some are also capable of burning biomass, coke oven gas and fuel oils. In addition to electricity, they also often supply heat. Due to the long time required to start up, coal-fired power plants operate in all load conditions on the grid. The efficiency of coal-fired power plants is usually up to 35 %.

In 2020, the share of electricity from coal-fired power plants in the Czech Republic will be around 40-50 %. In 2021, for example, coal-fired power plants generated approximately 43 % of all electricity in the Czech Republic. This share has a long-term downward trend due to the gradual closure of older coal-fired power plants and the increasing share of renewable energy sources and nuclear power.

Fuel

Black coal differs from brown coal in age and calorific value. Black coal is geologically older and has a higher calorific value. The calorific value of hard coal is approximately 25 MJ/kg. This value may be lower or higher depending on the quality of the coal. Black coal contains more carbon and less ash and sulphur. The best quality coal is called anthracite, it is the geologically oldest coal with the highest calorific value. Black coal was mined in underground mines, e.g. in the Karviná and Ostrava regions.

Lignite is geologically younger than hard coal and has a lower calorific value. The calorific value of lignite is 18 MJ/kg, the calorific value again depends on the quality and type of lignite. The youngest lignite is called lignite and is the lowest quality. Lignite contains less carbon and more ash, sulphur and volatiles. Lignite is mostly mined in opencast quarries in Bohemia.

Each power plant has its own stock of coal, which would be sufficient for about a month of operation in case of a supply failure. This ranges from tens to hundreds of thousands of tonnes of coal, depending on the plant's output. This coal is stored in the same form in which it was mined in the landfill. Coal deliveries are made by rail.

Raw coal is stored in bunkers called bunkers. There may be several bunkers in one power plant. From the bunkers, the raw coal is transported to scales and then to the coal mills. Coal mills are designed according to the type of coal to be crushed and can be, for example, ball or hammer mills. In the mills, the coal is crushed into powder or into a coarser fraction, depending on the type of burners and the design of the boiler hearth. The powder is blown into the coal powder hopper by pressurised air. The storage of the crushed coal is referred to as inter-bunking. Inter-bunking is advantageous in terms of the consistent quality of the air-mixed fuel. Inter-bunking of lignite powder can be risky because of the higher volatile content. The coal from the intermediate bunker then enters the coal burners or forms a fluidised bed in the boiler firebox. The fuel in the form of coal powder is transported to the burners by pressurised preheated air, if the coal is in the form of a coarser fraction and forms a fluidised bed, then it is only supercharged by the air in the boiler firebox. The products of coal combustion are slag, ash and combustion gases containing carbon oxides, sulphur and NO_x.

In addition to lignite and coal, natural gas, gas oil, fuel oil, biomass and non-toxic waste are used as fuel. Non-toxic wastes, biomass and other inferior fuels are usually burned by atmospheric or pressurised fluidised bed combustion methods, which allow a more perfect combustion of the fuel. However, it is more common to use these methods for coal-biomass fuel combinations, coal-waste. All solid fuels always pass through a mill circuit where they are crushed to the desired fraction. Gas is mainly used in coal-fired power plants for boiler start-up and ignition of coal burners, or to stabilise boiler output.

Feedwater

This water is essential for the production of steam in the power plant. It is the water that enters the boiler and covers the losses of steam and condensate in the heat cycle. The losses are caused by leaks in the piping, the use of steam for heating and boiler stripping. The losses should not exceed 5 % of the total steam consumption. Losses must be replenished with feed water from the feed water source.

A watercourse or artificial reservoir is usually used as a source of feed water. The water in the reservoir is natural - it contains various dissolved salts, minerals and various other substances dispersed in the water. It is not permissible to allow such water into the boiler. The feed water must be free of all impurities and minerals. Substances contained in the water are the cause of scale, which can build up in the pipes of, for example, instantaneous boilers, where it reduces the thermal conductivity of the pipes and can cause overheating and rupture of the boiler pipes. The raw feed water must therefore be treated.

The water is stripped of coarse impurities, filtering removes fine impurities such as sand, coagulation (clarification) removes suspended organic matter, and lastly, dissolved salts and minerals that cause water hardness are removed. The hardness of water is given in degrees of hardness or in milligram-equivalents/litre. It is assumed that 1° hardness = 2.8 mg-eq/litre. Removal of hardness is carried out in ion exchangers. It is a device where ions are exchanged by the action of natural or artificial plastics. This is called water softening. For example, calcium and magnesium cations are exchanged for sodium cations. Water treated in this way is sufficient to feed medium-pressure boilers, but for high-pressure boilers (temperature and pressure) and flow-through boilers it is necessary to use water treatment by chemical demineralisation.

Ideally, only pure H_20 without any impurities would flow into the boiler, but there are always some salts left in the water, which concentrate in the boiler after the water has evaporated. The salts carried by the steam to the turbine cause it to become salty. To prevent this, the salt-concentrated boiler water is continuously discharged (de-leaching). The permissible leaching rate in the boiler water is determined by the salt content by weight per litre of water (mg/l) and is determined for each boiler by the operating regulations. It is usually lower for boilers of higher parameters. As much salt as is fed into the boiler must be discharged so that the boiler water effluent does not exceed the permitted limit.

The amount of leachate can reach up to 10% of the feed water volume. With the leachate, a considerable amount of heat is removed and recovered in the expanders. In these, the leachate becomes vapour, which is discharged back into the heat cycle. The unexpanded leachate at temperatures of 30 - 50 °C is discharged as waste. Feed water and condensate are pumped out by circulation pumps. These pumps are one of the most important pieces of equipment and their trouble-free operation is essential for the power plant's electricity production. Feed pumps are particularly important for boilers with low water content and therefore each boiler has at least 2 feed pumps. The feedwater is pumped by one of the pumps, the second pump is a backup in case of failure of the first pump. Each of the pumps must have the capacity to pump the required amount of feedwater at the maximum output of the boiler. More than two pumps may be connected to the boiler. In the case of pumps driven by an electric motor, the capacities of these drives are in the order of units to tens of MW depending on the amount of water to be pumped. The electric drive and the pump form a so-called electro-pump. Turbopumps are also used where the pump is driven by a steam turbine. The pump either has its own turbine or is connected to the shaft of the main block turbine. Large power plants, such as the Dětmarovice power plant, contain both electric and turbo pumps. The turbo chargers account for approximately 4-6 % of the power plant's own consumption. Centrifugal pumps are used.

❑ Regenerative heating

This is the heating of the feed water entering the boiler. The use of regenerative heating increases the overall efficiency of the plant because some of the heat of the expanded steam is returned to the boiler with the heated water. The water is heated in the heaters by steam drawn from the turbine to temperatures of around 250 °C. After heating, the water is still in a liquid state due to the high pressure. Regenerative heating also has an effect on the amount of fuel consumed, which is reduced by the practice of regenerative heating. The importance of reheating increases as the steam temperature in the boiler increases, where the amount of heat required to heat the water to the boiling point decreases with the use of reheating. In practice, the following arrangement of regeneration circuits is used:

- with surface heaters - here the steam taken from the turbine flows between the heater tubes in which the condensate flows, the pressure of the condensate must be higher than the pressure of the heating steam,
- with mixing heaters - the extracted steam mixes with the feed water and thus gives it its heat, they also have the function of degassers, they deprive the feed water of gases causing boiler corrosion, i.e. oxygen, carbon dioxide,
- combined - a combination of surface and mixing heaters is used.

The choice of the number of heating stages is based on the required amount of feed water and the desired temperature. Heating the feed water to the required temperature is not done in one heater, but it is advisable to use several stages to increase the heat gradient. The number of stages is practically limited by the economy of the individual heaters.

The steam flowing through the turbine (Fig. 2.4). The heating of the steam takes place in the boiler and has the effect of reducing the moisture content of the steam and increasing efficiency. The moisture of the steam in the last low-pressure section of the turbine is erosive to the turbine blades, so steam is extracted from the high-pressure section of the turbine, heated to inlet steam values, and the steam is routed to the medium- and low-pressure sections of the turbine. The moisture content of the steam should not exceed 15%.

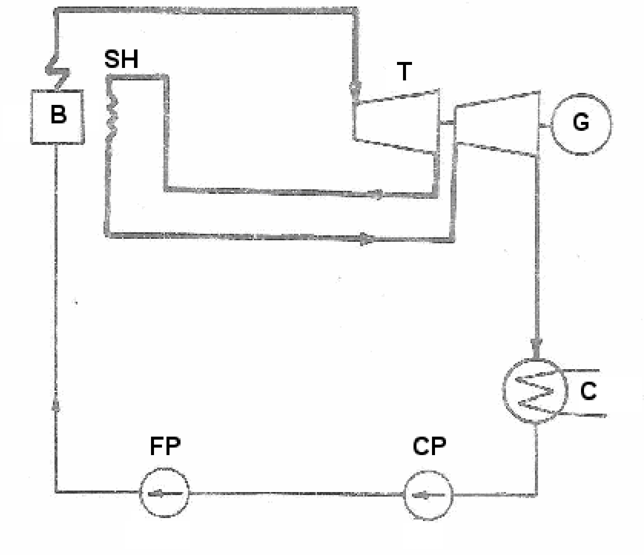

Fig. 2.4 Schematic of the steam regenerative heating system: B - boiler, T - turbine, SH - steam heater, G - generator, C - condenser, CP - condensate pump, FP - feed pump

Boiler

In the boiler, the fuel is burned, the feedwater is converted into steam of the desired parameters for the turbine and the steam is heated regeneratively. The output of the boiler is given in tonnes of steam per hour. This is usually tens to hundreds of tonnes of steam per hour. Boilers can be classified according to the type of fuel to be burned, the feedwater flow method and the steam parameters.

Division of boilers by fuel:

- solid fuels (brown and black coal, biomass, waste),
- liquid fuels (fuel oil, heating oils),
- gaseous fuels (natural gas, power gas).

Most solid fuel boilers are also capable of burning liquid and gaseous fuels. However, the burners of the boilers must be adapted for this purpose.

Division of boilers according to feed water flow:

- with natural circulation (Fig. 2.5),
- with forced circulation,
- flow-through (Fig. 2.6).

In boilers with natural circulation, the feed water flows due to flow. The heated water and steam differ in density from the relatively cold feed water, therefore the heated water and steam rise upwards, whereas the condensate with the feed water returns through the discharge pipes. The intensity of the circulation depends on the ratio of the clearances of the riser pipes to the clearances of the boiler tubes, the height difference between the upper cylinder and the collection chambers and the operating pressure in the boiler. The upper cylinder usually contains a trapping device to prevent salting of the turbine. Natural circulation boilers are used up to a pressure of 16 MPa. At higher pressures, a sudden increase in power may cause steam to build up in the boiler inlet pipework and thus stop the flow.

A circulation pump is typical for forced circulation boilers. These boilers again contain a cylinder which forms the feed water and steam reservoir. Water is pumped from the cylinder to the boiler evaporation system and the resulting steam is fed back into the cylinder or collection chamber. Here the steam is separated and continues to the superheated. The usual pressures for this type of boiler are 13 - 18 MPa. Advantages of these boilers include short start-up times and spatial adaptation of the boiler design. The disadvantage is the increase in self-consumption by the feed to the circulation pump.

The use of flow-through boilers is typical when trying to achieve the highest possible pressure of sharp steam. The evaporation path of a flow-through boiler takes place sequentially either in a single tube or in a system of parallel tubes. These boilers are particularly sensitive to the quality of the feed water because they do not contain an upper cylinder in which salts are removed. The operating pressures of these boilers are from 20 MPa upwards.

The type of fuel to be burned and the required steam parameters have a major influence on the overall boiler design. The boilers operate at high pressures, modern critical boilers above 23 MPa, and at steam temperatures above 550 °C, the temperature in the boiler firebox is usually around 1500 °C. This requires the use of suitable refractory steels. It is the materials suitable for the construction of the various parts of the boiler that are the biggest problem in achieving the highest possible steam parameters and thus the highest possible efficiency.

Preheated air is also injected into the boiler with the fuel. Oxygen is important for the combustion process. By controlling the amount of air it is possible to influence the composition of the boiler flue gas, in particular the amount of NO_x.

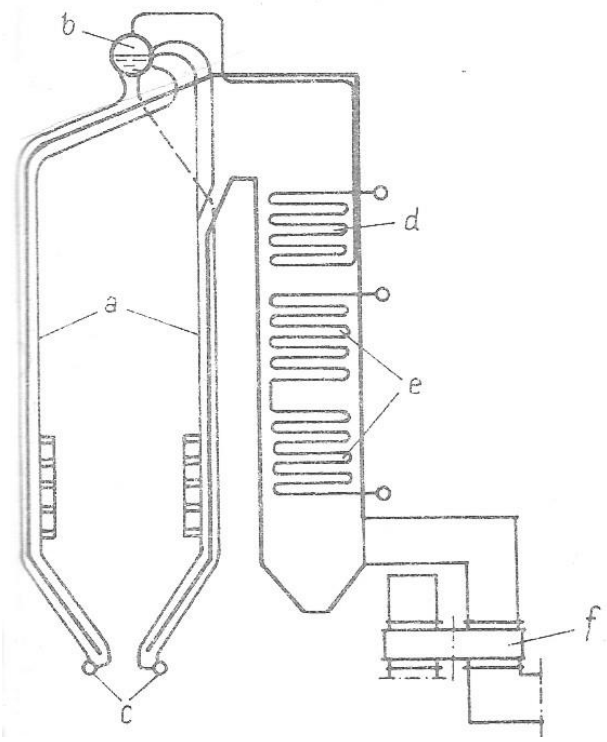

Fig. 2.5 Diagram of the boiler with natural circulation a - combustion chamber with cooking tubes, b - upper cylinder, c - collection chambers, d - steam super heater, e - feed water heater (economizer), f - air heater

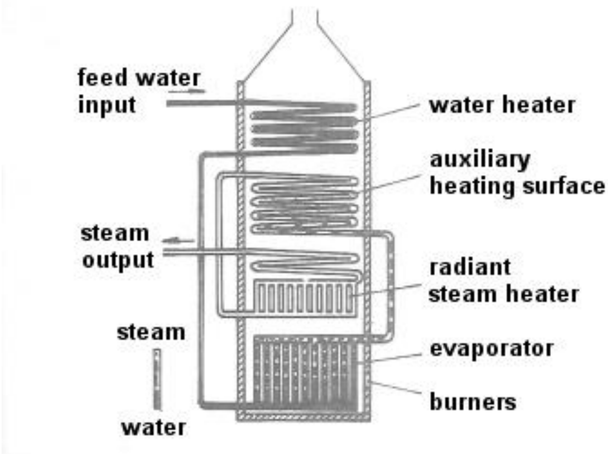

Fig. 2.6 Diagram of the flow-through boiler

❑ Turbine

A steam turbine is a device in which the energy stored in steam is converted into mechanical energy. The steam expands and rotates the turbine. The amount of mechanical work created by the turbine corresponds to the difference in enthalpies of the steam entering the turbine and the steam leaving the turbine. The enthalpy as well as the temperature of the steam decreases as it passes through the turbine. The turbine is further connected by a coupling to the turboalternator and forms its drive. A turbo feeder may also be connected to the turbine shaft. The mechanical efficiency of the turbines is around 95 %.

Each steam turbine contains basic parts which are turbine shaft, impellers, blades and nozzles. In the nozzle of the turbine, the steam acquires the discharge velocity and kinetic energy. Expansion takes place here. The steam passes between the blades and transfers its kinetic energy to the blades, while the temperature of the steam and the enthalpy value decrease steadily along with the pressure. The blades are anchored in the impellers and convert the kinetic energy of the steam into mechanical energy. This is transferred via the turboalternator shaft. The diameter of the impellers and the size of the blades vary according to the pressure value. It is common to divide turbines into high pressure, medium pressure and low pressure sections. The lower the steam pressure, the larger the blades and impeller diameter must be. The dryness of the steam is important for the efficiency and life of the turbine. The presence of moisture in the steam reduces efficiency and causes blade erosion.

Moisture is removed by heating the steam, this also causes a certain increase in efficiency. Also, the presence of salts in the steam is undesirable to avoid salting of the turbine. The salts are removed by de-scaling.

Current efforts to achieve the highest possible steam parameters are hampered by the materials used for turbine and boiler construction. Turbines, like boilers, operate at high temperatures and pressures, are subject to vibration and the turbine rotor must withstand high centrifugal forces. Depending on their design, steam turbines are divided into equal-pressure, positive-pressure and back-pressure turbines.

In straight turbines, the conversion of steam energy to kinetic energy takes place only in the nozzle and the steam passes through the blades under constant pressure.

In positive pressure turbines, steam expands both in the nozzle and between the blades and the steam pressure does not remain constant as it passes through the turbine, but decreases. The pressure, temperature and enthalpy of steam at the inlet to the turbine are therefore greater than at the outlet. The total heat gradient of the turbine consists of the gradient in the nozzle and in the blades. The turbine pressure drop is the ratio of the thermal gradient at the blades to the total gradient. The thermal gradients are around 1200 - 1500 kJ/kg.

The total heat gradient is divided between the turbine stages. The thermal gradient of one stage is determined by the steam temperature, e.g.: for temperatures around 500°C a gradient of 42 - 50 kJ/kg is used for equal pressure turbines and 17 - 25 kJ/kg for positive pressure turbines.

By designing the turbine with a greater number of pressure or speed stages, the speed of the turbine will be reduced, thus reducing the forces stressing the turbine parts. When pressure stages are used, the whole turbine consists of individual turbines connected in series on a common shaft. On this shaft are impellers with impeller blades. The steam is led through a valve to the nozzle chambers. Pressure stages are used for both equal-pressure and positive-pressure turbines.

Condenser

The condenser of a thermal power plant is used to convert steam coming out of the turbine back into water pumped back into the boiler. In the condenser the Rankine - Clausius cycle is closed, at the same time the greatest energy losses occur here, because the residual thermal energy of the steam is transferred without benefit to the cooling water and discharged to the cooling towers. Condensers are typical of condensing power plants. The condenser significantly influences the amount of steam required for the turbine.

Capacitors can be divided into 2 basic types - mixing and surface capacitors. Mixing capacitors contain a mixture of water and steam. The two phases are together. In surface capacitors, there is no contact between water and steam. Here, steam from the turbine flows in tubes and cooling water flows between these tubes. A high vacuum is maintained in the condensers. The pressure usually does not exceed 6 kPa, i.e. 94% vacuum, but usually the vacuum is even higher. In practice, pressures of 3-5 kPa are used. The vacuum value has a significant effect on the reduction in specific steam consumption, where a 1% increase in vacuum can mean a 2% reduction in steam consumption. Vacuum values depend on the cooling surface of the condenser, the amount of cooling water relative to 1 kg of steam and the inlet temperature of the cooling water. Increasing these parameters will increase the vacuum. The inlet water temperature cannot usually be influenced, it is usually approximately equal to the ambient outdoor temperature, but it is possible to increase the cooling surface area of the condenser or to increase the cooling water flow rate.

Increasing the cooling area is associated with larger condenser dimensions, thus making the condenser more expensive. Increasing the cooling water flow rate requires higher pump power and thus an increase in the plant's own power consumption. Due to the decrease in the final pressure (increase in vacuum value), the specific volume of steam increases and thus the dimensions of the turbine end section need to be increased.

The condensed steam is pumped back to the boiler by a condensate pump together with the feed water. The temperature of the condensate is around 30 °C. The cooling water passes through the condenser and continues to the cooling towers. Here it is sprayed, cooled and pumped back into the cooling circuit. Some of the cooling water escapes from the towers as steam through natural evaporation, so the cooling water is constantly replenished. Salts and impurities must also be removed from this water to prevent clogging of the pipes. The cooling water is present in the cooling circuit only in the liquid state because the temperature difference between the inlet and outlet cooling water is usually only 10 °C. The amount of cooling water required to cool a given amount of steam is called the cooling ratio.

The amount of cooling water is usually 50 - 60 times the amount of steam entering the condenser. The water is usually pumped from the water source, to which it is returned again, in case of insufficient capacity of the water source, circulating cooling is practiced, when water from the cooling tower pools is pumped back to the cooling system and only the losses of cooling water are covered from the source. The cooling towers may have a natural draft or an artificial draft. Artificial draught is made possible by fans.

❑ Combustion circuit

The product of coal combustion is both solid and gaseous emissions. Solid emissions such as slag and ash are used for the production of building materials, and desulphurisation produces energy gypsum as a by-product, also used in the construction industry. Gaseous emissions include SO_x and NO_x, i.e. sulphur and nitrogen oxides, which must be removed from the flue gas. Combustion of liquid fuels significantly reduces the amount of solid combustion products, but emissions of SO_x and NO_x still remain. Natural gas is the cleanest fuel for conventional thermal power plants.

Slag represents the coarsest fraction of the solid flue gas. Slag removal takes place directly in the boiler, either by depositing the slag on the bottom of the boiler and then washing it off with water to form granulated slag, or by periodically discharging the slag and washing it off again with water. The slag is usually melted once a day in the digesters. The digested slag is flushed with water through a flushing pipe to a slag crusher. Here the solidified slag is crushed and transported by water to the settling tank. The water is pumped back from the sump and the settled slag is distributed for construction purposes.

Fly ash is a fine solid fraction. Fly ash does not settle, but is instead entrained by gaseous exhalations and must therefore be filtered out of the flue gases. Cyclone separators and electrostatic precipitators are primarily used to remove fly ash.

Cyclone separators (Fig. 2.7) are used to mechanically remove the coarsest ash. The dusty combustion gas is injected into the inlet of the cyclone and the ash hits the walls of the separator by centrifugal force, on which it moves helically, loses velocity and settles in the collector. The efficiency of the cyclone is dependent on the volume of flue gas passing through the cyclone and can vary with changes in boiler output and thus with changes in the volume of boiler flue gas. Multicyclones are used to avoid such fluctuations. The efficiency of cyclone separators is 60 - 80%.

Electro filter (Fig. 2.8) works on the principle of creating an electrostatic field around the deposition electrode. Electro filters (electrostatic precipitators) follow the cyclones and remove the fine ash that has passed through the cyclones. The basic parts of the electrostatic precipitators are the discharge electrode, the settling electrode and the ash tray. The settling electrodes are in the form of wire screens, and the discharge electrodes are also made up of wire to allow the flue gas to pass through the electrodes. Both electrodes are connected to a high voltage source of 50 - 70 kV. A corona discharge is produced at the discharge electrode and ash is deposited at the deposition electrode due to the electrostatic field generated between the electrodes. The deposited ash is periodically peeled off the electrodes and into the reservoir. The efficiency of the electrostatic precipitators is up to 98%.

NO_x emissions can be controlled by the amount of combustion air and by controlling the temperature of the firebox. Today, the $DENO_x$ system is used to reduce NO_x emissions by injecting ammonia into the boiler firebox.

SO_x emissions are eliminated by $DESO_x$. This is the reaction of sulphur oxides contained in the flue gas with lime water. The resulting product of the reaction is energetic gypsum.

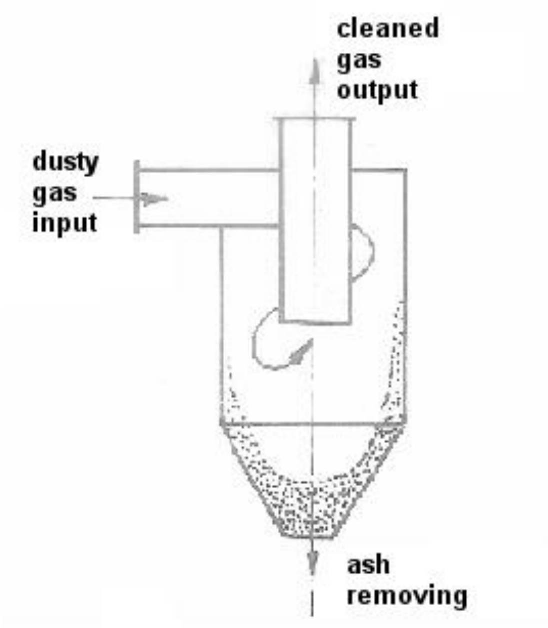

Fig. 2.7 Cyclone separator

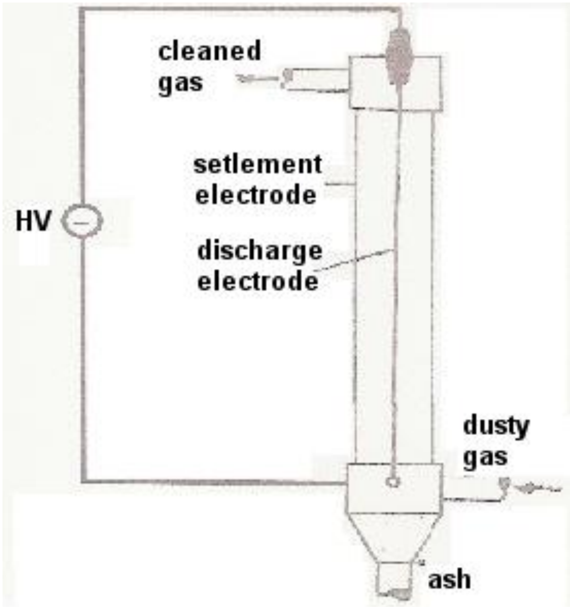

Fig. 2.8 Electrostatic separator

Summary of terms 2.2.

Fuel heating capacity, feedwater, regenerative heating, boiler, turbine, condenser, separators.

Questions 2.2.

1. What is the calorific value of coal?
2. How is the feed water treated?
3. Draw a diagram of the regenerative steam heating.
4. Divide the boilers according to the feed water flow.
5. What does a turbine consist of?
6. What is the pressure in the condensers?
7. How is the ash removed?
8. How is the amount of NO_x regulated?
9. What is the product of desulphurisation?

2.3. Gas and steam power plants

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- describe the parts of gas and steam power plants and their function

EXPLANATION

Steam power plants belong to the newer types of thermal power plants. They are usually built in a steam-gas concept, where a mixture of gas and air is burned in a gas combustion turbine and the resulting hot flue gases are used to produce steam for a steam turbine. A turbo generator is placed behind both the combustion turbine and the steam turbine, thereby significantly increasing efficiency by making greater use of the heat generated. If there is no steam turbine installed in the power plant, the combustion heat is used for heating purposes. The fuel for gas-fired power plants is natural gas. Power plants using combustion turbines may also use liquid fuels.

Generators in gas-fired power plants are primarily driven by combustion gas turbines. Turbo alternators are used as generators, as in steam power plants. A huge amount of heat is generated in gas combustion turbines. This heat is then used to generate steam for the steam turbines or for heating purposes. The use of combustion turbine heat increases the efficiency of the power plant. The thermal and electrical efficiency of steam-gas cycles is usually above 50 %.

The main advantages of steam power plants include very short start-up times, they can be started up almost immediately because there is no need to generate heat transfer medium (steam). The construction of gas-fired power plants is less expensive and the operation is incomparably cleaner than that of solid and liquid fuel power plants. The self-consumption is very low, usually below 2 %, as there is no need to power large drives such as coal mills and pumps. Steam power plants can be more easily and accurately controlled and automated. The explosiveness of natural gas mixed with air can be a risk.

The steam power plant complex consists of a fuel supply (usually natural gas), a set of equipment consisting of a prime mover, a compressor, a combustion chamber, a combustion turbine and a generator (Fig. 2.9). This unit is followed by the combustion boiler, and the steam turbine-generator unit.

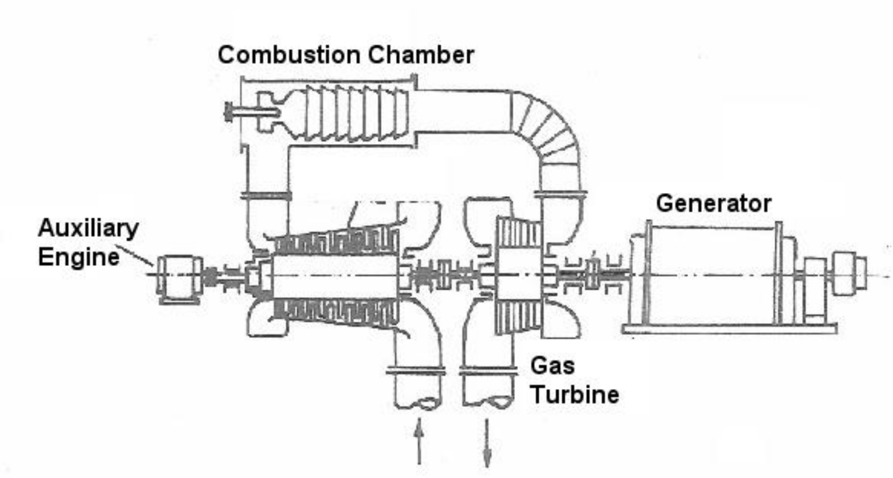

Fig. 2.9 Schematic of the combustion turbine system

Natural gas

Natural gas is usually supplied through long-distance pipelines. At the point of consumption there are stations adjusting the pressure and purity of the gas to operating parameters. The gas is also fed into the combustion chamber. Here it is mixed with pressurised air supplied by a compressor.

Compressor

The compressor is mounted on a common shaft with the turbine, inrunner and generator. Atmospheric air is drawn in at the compressor inlet and heated pressurised air flows from the outlet leading to the combustion chamber. The compressor is the largest mechanical load on the gas turbine and can consume up to 70 % of the gas turbine's power.

An important parameter of the compressor is the compression ratio. This is determined by the design of the compressor. Also important is the ratio of the temperature of the air before entering the turbine to the temperature before entering the compressor. The temperature ratio determines the thermodynamic properties of the cycle. These ratios interact with each other and also significantly affect the overall efficiency of the system.

Combustion chamber

The combustion chamber is a static device and it is here that the chemical energy of the fuel is converted into thermal energy. The mixture of gas and air is burned here at constant pressure, thus giving a constant pressure and volume of flue gas. The temperature in the combustion chamber reaches 1500 °C, so the fuel mixture contains a considerable excess of air, causing the flue gas to cool to approximately 600-800 °C. The design of the combustion chamber requires durable refractory steel. Liquid fuels can also be burned in the combustion chamber, but the flue gases must be cleaned before entering the turbine.

Combustion turbine

The working medium of a combustion turbine is a mixture of flue gas and air entering the turbine from the combustion chamber, where the pressure and temperature of the mixture are expanded and reduced. The combustion turbine can either operate in an open cycle, where the flue gas is discharged directly into the stack after expansion in the turbine, or it can be used for the steam cycle. The latter is used in steam power plants. The hot mixture of flue gases and air passes through the flue gas boiler before entering the chimney. The use of the flue gas and the steam cycle increases the efficiency of the plant and its installed capacity, because electricity is produced by both the generator on the shaft of the combustion turbine and the generator driven by the steam turbine.

Combustion boiler

The boiler has practically the same design, in terms of water circulation, as the boilers in coal-fired power plants. However, they do not contain any burners and there is no fuel combustion. They function as heat exchangers in which the flue gases transfer their thermal energy to the feed water, which produces steam. Flue gas boilers operate at pressures and temperatures at the level of subcritical boilers in coal-fired power stations. The heat cycle of steam is identical to that of coal-fired power plants.

When the steam power plant is ramping up, the ramping engine is used. It takes over the role of the turbine and turns the whole system, especially the compressor, which otherwise could not generate pressurized air. The start-up times of CCGTs are up to 20 minutes, in the case of open-cycle turbines in the order of minutes. The overall efficiency of the combustion turbine system is influenced by the air temperature ratio, the compression ratio and the efficiency of the compressor and turbine. The efficiency of the steam cycle can be influenced by the same means as for coal-fired power plants.

Summary of terms 2.3.

Natural gas, compressor, combustion chamber, combustion turbine, combustion boiler.

Questions 2.3.

1. What are steam power plants made of?
2. What influences the overall efficiency of a steam power plant?

2.4. Diesel power plants

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- describe the parts of diesel power plants and their function

EXPLANATION

Diesel power plants, also called diesel generators, have a primary function as backup sources of electricity. Diesel generator outputs range from units of kilowatts to units of megawatts. The use of diesel generators as sources of power, as is the case with coal and steam power plants, would be very uneconomical. However, they are often used in these plants as back-up power sources, covering the plant's own consumption and allowing the plant to be hired without outside power assistance. They are also used as backup sources of electricity in industry and the health sector. The advantage of diesel generators is their simple design - it is just a diesel engine coupled to a generator. The start-up of a diesel generator is virtually instantaneous, so the start-up time is meaningless. In the case of long-term operation, only the engine requires maintenance.

Functions of diesel power plants

As in all thermal power plants, the fuel is burned. The fuel is diesel. The calorific value of diesel is approximately 42 MJ/kg. The diesel is burned in a diesel engine, with the engine on a common shaft with the generator rotor. The diesel generator tends to be multi-pole, which reduces the engine speed required to maintain the mains frequency of 50Hz. Usually 4 pole generators are used. The output of the generator is a 3 x 230/400 V three-phase system. Permanent magnets are usually used as rotor excitation.

Diesel engines tend to be 4-cylinder or larger. The engines of large diesel generators are up to 16 cylinders. The function of a diesel engine is to inject diesel fuel into a cylinder in which air has been compressed by a piston to 3 - 4 MPa. The piston-compressed air is heated to 600 - 800 °C. The diesel is then gently sprayed by pressure into the space between the piston and the upper bore. This ignites and burns rapidly due to the hot air. The pressure in the cylinder rises sharply due to the hot exhaust gases. The exhaust gas expands and the piston moves towards the lower port. This is when the chemical energy of the fuel is converted into mechanical energy. Next comes the exhaust of the exhaust gases, then the re-compression of the air and the cycle repeats. The engine pistons are mounted on the crankshaft, which transfers the mechanical energy to the generator rotor. The engine includes a battery-powered starter. The engine also includes a fuel tank with a capacity in the hundreds of litres of diesel. Diesel consumption for the largest diesel generators can exceed 500 litres per hour.

Summary of terms 2.4.

Diesel engine, diesel, compression, injection.

Questions 2.4.

3. How does a diesel engine work?

2.5. Current trends

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- Modern power plant trends and prerequisites for the expansion of thermal power plants

EXPLANATION

The expansion of thermal power plants both in the Czech Republic and worldwide will be mainly influenced by the increasing size of electricity consumption. Thermal power plants represent the most massive and reliable source of generation. If the world's electricity consumption continues to increase, this trend can only be offset by the construction of thermal power plants, whether conventional or nuclear, because they can be built theoretically anywhere, unlike hydroelectric power plants, which are built only on suitable watercourses, and because the output of thermal power plants is not dependent on the weather or the season, as is the case with wind and solar power plants. The biggest current trend is the greening and increasing efficiency of power plants. For newly built thermal power plants, the use of critical and supercritical units, cogeneration and the use of clean coal technologies such as atmospheric fluidised bed combustion, pressurised fluidised bed combustion, and pressurised fluidised bed gasification are typical. In the case of older plants, upgrading, so-called retrofit, of all sections of power generation is being carried out. In order to meet emission limits, it is advantageous to build power plants with a steam-gas cycle, where the fuel is not only natural gas, i.e. a fossil fuel, but also an energy gas produced by gasification of coal, biomass and other fuels. Hydrogen power is also being developed.

❑ Critical and supercritical power plant units

Critical and supercritical power plant units achieve higher efficiencies than units with subcritical steam parameters. The steam parameters of each type of unit are broken down in the boiler classification table by steam parameters. The high steam parameters of critical and supercritical units require the use of modern materials in the construction of boilers, piping and steam turbines. These must withstand up to twice the pressures, and higher temperatures than in the case of subcritical units. Tungsten-alloyed steels and nickel-based alloys appear to be suitable construction materials. The use of modern types of power plant units increases the efficiency of power generation.

❑ Atmospheric fluidised bed combustion AFBC

Atmospheric fluid bed combustion (AFBC) is advantageous due to more efficient heat transfer to the feedwater, produces less gaseous exhalations and allows the combustion of lower quality fuels with lower calorific value.

This combustion takes place in the boiler under atmospheric pressure. The formation of the fluidised bed is made possible by a special grate located in the boiler firebox. Fuel in the form of grains up to 6 mm is fed onto this grate and primary air is drawn through the grate causing the fuel to rise. The principle of fluidised bed combustion is to achieve a condition where the fuel is lifted to a certain height above the grate by the primary air being drawn under the grate, forming a so-called fluidised bed where the fuel is burned without falling back onto the grate. Fuels for fluidised bed combustion may be liquid or solid. Solid fuels can be black and brown coal, peat, biomass and non-toxic waste.

The fluid bed consists of inert and sorbent. Inert, i.e. the inert component, is the name given to substances that modify the properties of the fluidised bed. These properties are specific gravity and density. Sand, gravel and ceramics are used as inerts. Sorbent is a substance that provides desulphurisation already in the fluidised bed in the boiler. The sorbent used is usually limestone. The inert, sorbent and fuel are supplied to the boiler continuously. All components are ground, but it is a much coarser fraction than in the case of fireplaces with powder burners.

A cyclone separator is placed at the outlet of the boiler flue gas, which returns the larger imperfectly burnt parts of the fuel back to the combustion chamber. The separator thus increases combustion efficiency and allows the use of lower quality fuels. This measure is also used in pressurised fluidised bed combustion.

The formation of oxides of nitrogen from primary air is limited by combustion temperatures in the range of 800 - 950 °C.

❑ Pressure fluid bed combustion PFBC

Pressurized fluid bed combustion (PFBC) differs from atmospheric combustion by increasing the pressure up to 1.6 MPa. The power generation efficiency is 6-8 % higher than atmospheric fluidised bed combustion. The overall efficiency is 44 %. The principle of pressurised fluidised bed combustion and the suitable fuels to be used are the same as for atmospheric fluidised bed combustion. The principle of flue gas desulphurisation is also identical. However, the PFBC boiler is considerably smaller in size, with the same output, than the AFBC boiler, as the combustion in PFBC takes place in a much smaller space. In addition, the entire boiler is housed in a pressure vessel. The amount of gaseous emissions is approximately comparable to atmospheric fluidised bed combustion. The amount of NO_x and other nitrogen oxides depends on the operating temperature and pressure. The PFBC boiler combines a steam generator and a gasifier. It is therefore suitable for use in a vapour-gas cycle. Pressurized fluidized bed combustion is demanding to control and regulate. A certain disadvantage of both types of combustion is the chemically unstable solid products of combustion unsuitable for use in the construction industry. These products have to be landfilled.

The advantages of both types of combustion are:

- the possibility of burning poor quality fuels,
- high combustion efficiency combined with ash recirculation,
- better heat transfer from the fluidized bed to the heat transfer medium,
- low SOx and NOx concentrations in the flue gases,
- suitability for operation in the vapour-gas cycle.

The disadvantages of both types of combustion are:

- high demands on the control of the combustion process
- complicated fuel transport and ash removal from the combustion chamber.

❑ Integrated gasification combined cycle (IGCC)

IGCC and gasification in general are processes in which gas is extracted from a feedstock to be used as fuel. The calorific value of the gas is approximately 5 MJ/m^3. Solid, lower quality fuels such as lignite, lignite and biomass are usually gasified. However, it is also possible to gasify liquid fuels. The gasification process takes place either at atmospheric pressure or as pressure gasification at pressures up to 2.5 MPa in gasification generators. Here, the raw material to be gassed forms a solid bed or a fluidised bed. A mixture of gasification feedstock, steam, hydrogen and a limited amount of oxygen is fed into the generator. The generators then partially oxidise the feedstock to produce a mixed gas containing mainly carbon monoxide and hydrogen. The oxidation reactions take place at temperatures ranging from 500 to 1500 °C, depending on the gasification method. The resulting gas is stripped of SO_x, the amount of NO_x is corrected by the steam and oxygen content of the mixture. The cleaned gas is usually used as a fuel for combined cycle steam-gasifier plants, so it is advantageous for the gasification generators to be part of the steam-gasifier plants.

- **Steam power plants**

Steam power plants are currently gaining interest due to their higher efficiency of electricity production, reaching over 50%, low self-consumption and lower environmental burden. They can also be used for combined heat and power generation. Another possibility for increasing the efficiency of steam power plants is the use of catalytic steam reforming on the steam turbine, where the fuel gas is refined, resulting in an increase in efficiency of up to 56 %. Furthermore, combustion chamber materials are being developed to withstand the highest possible temperatures, thereby increasing the thermal efficiency of the plant. However, this is associated with an increased generation of NO_x and CO. NO_x and CO emissions are limited by control of the combustion process and excess air in the combustion chamber.

The current concept of gas combustion turbines leads to machines with outputs in the order of hundreds of MW. Requirements include reliability and simplicity. A recognised modern design is the turbine with a combustion chamber that does not protrude from the contour of the machine. The so-called aero-type combustion chamber. The expansion of steam power plants will also be affected by the limits of coal mining. These limits determine the amount of coal that can be extracted and are set to prevent more damage to the environment than is strictly necessary. Unlike conventional coal-fired power plants, CCGTs do not need coal to function. If the extraction limits are not relaxed, coal-fired power stations will be phased out and replaced by CCGTs.

Summary of terms 2.5.

Critical and supercritical power plant units, fluidized bed combustion, steam power plants.

Questions 2.5.

1. What is typical for new-build thermal power plants?
2. What is a retrofit?
3. What are supercritical block materials exposed to?

ADDITIONAL RESOURCES 2

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[3] B. DOLEŽAL, Jaroslav, Jiří ŠŤASTNÝ, Jan ŠPETLÍK, Stanislav BOUČEK, Zbyněk BRETTSCHNEIDER. Nuclear and conventional power plants. Edition I. Prague: Czech Technical University, 2011. ISBN 978-80-01-04936-5.

3. NUCLEAR POWER PLANTS

3.1. Basic concepts of nuclear physics

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- define the basic concepts of nuclear physics
- describe the principle of a nuclear power plant

EXPLANATION

Today, nuclear power contributes about 17% of the world's electricity generation. Nuclear power is used to generate electricity in 31 countries. There are currently about 440 nuclear power units in operation, generating 2 300 TWh of electricity per year. A further 40 units are under construction and, according to the International Atomic Energy Agency's (IAEA) scenario, a steady increase can be expected. One of the most important benefits of using nuclear power for electricity generation is the reduction of carbon dioxide emissions, which are a major contributor to the greenhouse effect. In 1996, the global production of CO_2 was 22,700 Mt. Nuclear power is currently reducing this figure by more than 700 Mt of CO_2 per year. In addition, nuclear power generation contributes to the reduction of other harmful atmospheric emissions, not only of gases such as sulphur dioxide, nitrogen oxide, etc., but also of solids and radioactive elements contained in the fuel.

Nuclear power is clean - it does not produce CO_2, SO_2, NO_X or ash, and it does not consume oxygen. Nuclear power is compact - it produces steadily in all weather. Nuclear energy uses minimal fuel - one gram of uranium uses as much energy as a ton of coal or oil. In addition, recycling is well managed. Nuclear power is price stable - the price of nuclear fuel is not subject to sudden price fluctuations. Nuclear power produces minimal waste - about a million times less than the waste from burning oil, coal or natural gas. Moreover, the waste can be reused. Nuclear power is cheap - high investment costs, low operating costs and long lifetime. Nuclear power is responsible - as the only energy source, it includes charges for future disposal of waste and equipment in the cost of its product. Nuclear power is safe - two accidents in over half a century of nuclear power plant operation with a record of 4 000 lives lost. Nuclear power plants (NPPs) reduce air pollution, small fuel quantities - low transport requirements - location close to consumption - improved transmission ratios.

The thermal energy in NPPs, unlike in conventional thermal power plants where it is obtained by combustion, can be released during a nuclear reaction in two ways:

- Fission of atoms of some heavy elements (U, Pu) - fission reaction.
- Coupling - the synthesis of certain light elements (heavy hydrogen atoms) at extremely high temperatures - thermonuclear reactions.

Another difference is the problem of nuclear safety and the transport and storage of nuclear fuel (pool 6-7 years, intermediate storage 20-30 years, permanent storage).

- Atom - a particle consisting of a positively charged nucleus and negatively charged electrons orbiting around it, so that the atom as a whole is neutral. The atom has a diameter on the order of 10^{-10} m.
- The nucleus of the atom - is the central part of the atom The central part of the atom with dimensions on the order of 10^{-14} m, which concentrates almost all the mass of the whole atom in itself. It consists of positively charged protons (Z) and neutral neutrons (N), which are collectively referred to as the nucleon ($A = Z + N$). These particles attract strong attractive nuclear forces to each other.
- Electron shell - contains electrons in different layers (spheres). The number of electrons in the last layer determines the chemical properties of the elements.
- Electron - (e) is an electron shell particle of mass 0.00062 mu carrying an electric charge of $-1.609 \cdot 10^{-19}$ C.
- Neutron - (n) is a particle of an atomic nucleus without an electric charge with a mass of 1.00897 mu ($1.6747 \cdot 10^{-27}$ kg).
- Proton - (p) is a positively charged particle of the atomic nucleus with a mass of 1.00751 mu ($1.6729 \cdot 10^{-27}$ kg). The number of protons in the nucleus is equal to the number of electrons in the electron shell, so the atom is outwardly neutral.
- Nucleons - particles contained in the nucleus i.e. p and n.
- Atomic (proton) number Z - indicates the number of protons p in the nucleus of an atom.
- Weight number A - indicates the number of nucleons (the sum of protons and neutrons) in the nucleus and is also the nearest integer atomic mass number. The number of neutrons in an atomic nucleus is A - Z.
- Nuclide - a collection of identical atoms that have a uniquely determined equal number of protons and neutrons. Nuclides of the same element whose atoms have the same number of protons but different numbers of neutrons are called isotopes.
- Isotopes - atoms of the same element having the same atomic numbers Z but different mass A. E.g. hydrogen 1H1 - light hydrogen (protium), 1H2 - heavy hydrogen (deuterium, D), 1H3 - (tritium, T); uranium 92U238, 92U235, 92U234.
- Activity of a radioactive substance - is a quantity determined by the number of radioactive transformations taking place in a substance per unit time. If 1 transformation occurs in a substance in 1 second, it has an activity of 1 Becquerel (Bq). Since this unit is very small, in practice we may encounter units (kBq, MBq, GBq, etc.).
- Radioactivity - is the property of some atoms to spontaneously decay (transform) into simpler atoms while emitting electromagnetic radiation or particles.
- Ionizing radiation - this term includes radiation emitted by radioactive substances, X-rays (X-rays), radiation produced in particle accelerators or neutron radiation. Ionising is so called because it ionises the surrounding atoms as it passes through matter, either directly, if the radiation consists of electrically charged particles, or indirectly, if it is neutral particles. Sources of ionising radiation are either natural or artificial.
- Radionuclide - is an unstable nuclide undergoing spontaneous radioactive transformation.

- Radioisotope - is an unstable isotope of an element undergoing spontaneous radioactive transformation.
- Radioactive emitter - is a substance (solid, liquid or gas) that is radioactive, i.e. almost all substances. Radioactive emitters are characterized by their activity. They are divided into open and closed, according to their radiation to their surroundings.
- Atom designations - e.g. 92U238.
- Atomic unit of mass (mu) - is equal to 1/16 of the mass of the main carbon isotope C16 (mu = $1.66044 \cdot 10^{-27}$ kg).

Binding energy

Precise measurements on mass spectrographs have shown that the mass of atomic nuclei is not equal to the sum of the masses of all p and n. It is always smaller by the mass defect (deficit). When a nucleus is formed from free nucleons, attractive nuclear forces act between them and do work as they approach, which results in a decrease in the total energy of the system of nucleons. When the nucleus splits, we must supply the same energy. The amount of energy required to split the nucleons is the binding energy E and is proportional to the mass defect Δm according to Einstein's formula:

$$E = \Delta m \cdot c^2$$

where c is the speed of light as a mass-energy equivalence constant.

For the possibility of using at least a part of the binding energy of nuclei, it is not the total binding energy that is decisive, but mainly the binding energy per nucleon. In the release of energy by nuclear fusion, low-energy nuclei are fused; fission is applied to high-energy nuclei.

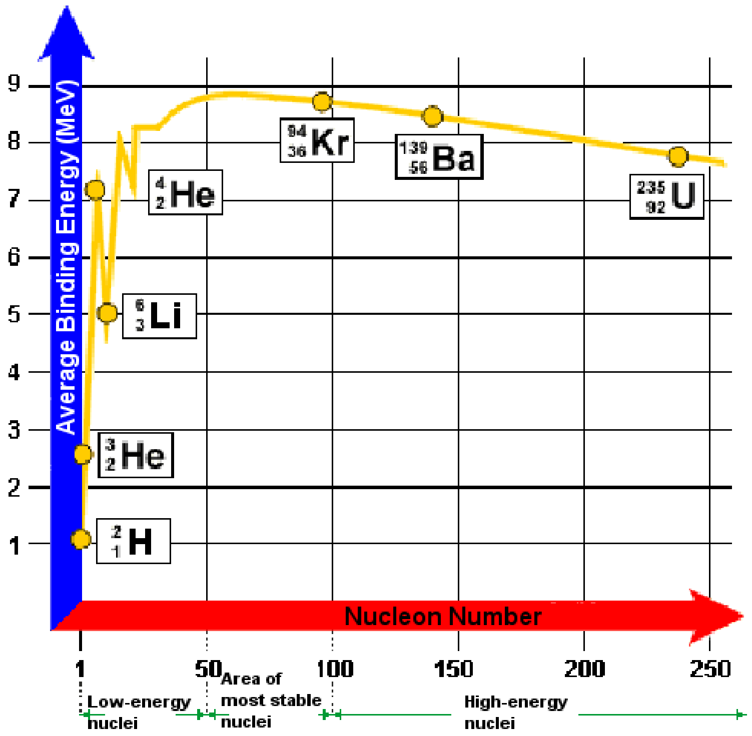

Fig. 3.1 Dependence of the average binding energy of nucleons on the number of nucleons

Summary of terms 3.1.

Nuclear physics, fission, nuclear fusion, binding energy.

Questions 3.1.

1. How can energy be released during a nuclear reaction?
2. Draw the dependence of the average binding energy of nucleons on the number of nucleons.

3.2. Nuclear reaction

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- define the basic principle of a nuclear reaction

EXPLANATION

Fission of atomic nuclei uranium - energy released

The fission reaction of an atomic nucleus releases an average of two to three neutrons, which can cause another nucleus to split. This produces a fission "chain" reaction.

To induce a reaction of nuclei with other nuclei or particles, the energy of the particles incident on the nucleus of the target substance must be large enough to overcome the Coulomb forces between the particle and the nucleons in the nucleus.

Start reactions:

- Bombardment of various substances with light nuclei i.e. protons, neutrons or α particles accelerated in cyclotrons, experimentally also e, γ and x.
- Increase in temperature to 107 - 108 °C - particles have sufficient energy to overcome mutual electrostatic repulsion. The thermonuclear reaction taking place inside the constants and is the source of their tremendous energy.

However, in practice, only the interaction of the neutron with atomic nuclei is used in nuclear reactors. The neutron does not have an electric charge and therefore does not have to overcome repulsive electrostatic forces when approaching an atomic nucleus, so even neutrons with low kinetic energy can be used.

The neutron imparts energy to the nucleus of the atom and the nucleus goes into an excited state - the nucleus has an ellipsoidal shape and begins to pulsate, if the energy is large enough, the strength of the nucleus is broken, Coulomb forces increase, nuclear fission occurs - 2.5 ± 0.1 neutrons and radiation particles are released.

$_{92}U^{235} + n_0^1 \rightarrow U_{92}^{236} \rightarrow F_{Z1}^{A1} + F_{Z2}^{A2} + 2\ n_0^1$

e.g.

$_{92}U^{235} \rightarrow _{38} Sr^{95} + Xe_{54}^{139} + 2\ n_0^1$

The relative atomic mass of Sr, Xe and 2 n is 235.918 mu, hence the mass defect Δm = 236.133 - 235.918 = 0.215 mu.

The energy in the fission of 1 uranium nucleus:

E = 931.48 · Δm = 931.48 · 0.215 = 200 MeV

It takes 200 MeV less energy to split 1 U nucleus than to split the nuclei of both fission products.

During fission, 2 - 3 neutrons are emitted immediately, but about 0.75 % are emitted with a delay of several min. These delayed n have an energy of 0.5 MeV.

Energy released by fission:

- kinetic energy of the light particles	100 MeV
- kinetic energy of heavy particles	70 MeV
- fission neutron energy	5 MeV
- instantaneous radiation energy γ radiation	5 MeV
- radioactive energy of the β and γ radiation	12 MeV
- neutrino energy	8 MeV
Total	200 MeV

The kinetic energy of the fission products is manifested as heat, the energy of the γ-rays is rapidly dissipated and the energy of the β particles from the fission products is gradually released during their radioactive decay. The energy of the neutrinos cannot be used.

Number of atoms in 1 kg of U^{235}:

$$\mathrm{N}_{235} = \frac{6{,}0225 \cdot 10^{26}}{235} = \frac{1}{m_{235}} = \frac{1}{235 \cdot 1{,}66 \cdot 10^{-27}} = 2{,}563 \cdot 10^{24} \ \ (\mathrm{atom} \cdot \mathrm{kg}^{-1})$$

When 1 kg of U^{235} is split, energy is released:

$E = 2.563 \cdot 10^{24} \cdot 200 \cdot 1.602 \cdot 10^{-13} = 8.21 \cdot 10^{13}$ J

$E = 22.81 \cdot 10^6$ kWh

When splitting 1 kg in 24 h, a heat output is developed:

1 kg U^{235}: $\mathrm{P_d} = \dfrac{22{,}81 \cdot 10^6}{24} = 950 \cdot 10^3 \ \ kW \cong 1000 \ \ MW$

From approximately 1 g of U^{235} we can get 1 MWd (megawatt-day).

About 10 – 20 % of neutrons are absorbed without fission, so from 1 g U^{235} we get 0.8 - 0.85 MWd or to produce 1 MWd we need 1.2 - 1.25 g U^{235}.

Controlled fission reaction

A fission reaction takes place in the fuel of a nuclear reactor, which is usually uranium dioxide, a mixture of uranium and plutonium oxides, or plutonium. The nucleus of an atom of a fissile element (uranium, thorium, plutonium) can split after the impact of a flying neutron under favourable circumstances. Two new fission product nuclei and two or three new neutrons are produced. The fission products have a very high kinetic energy, striking the surrounding nuclei and heating the environment. This creates a high temperature that we can use energetically. The new neutrons fly on and can fission other nuclei. A chain reaction is set in motion, the basis of nuclear power.

Even in nature, the uranium isotope 235 spontaneously fissions into two lighter nuclei and one or more free neutrons. However, the neutrons from spontaneous fission would not be enough to start a chain reaction in a reactor. An external neutron source is used to start the reactor. The neutron has high energy. The likelihood of it splitting the nucleus of the uranium 235 isotope in flight is small, rather it just bounces off the nucleus in a collision, like a ball bouncing off a wall. The neutron bounces off the nuclei without imparting any of its large energy to them, it just changes direction. In order to fission the nuclei, we have to slow it down. The neutron is best slowed down by colliding with a nucleus that is approximately the same size, e.g. the nucleus of a hydrogen atom, which is a single proton. The substance that slows down neutrons is called a moderator.

The fast neutron has turned into a slow neutron. It's hitting the uranium 235 nucleus again. This time, it doesn't bounce back. With a high probability of fission, a chain fission reaction occurs. To prevent the reaction from developing in a violent and uncontrolled manner, there is an absorber in the reactor to absorb the excess neutrons.

The fissile material in the fuel of the so-called slow reactors, which are the most widespread in the world, is the uranium isotope 235. This isotope is characterised by an increase in fission probability as the neutron rate (energy) decreases.

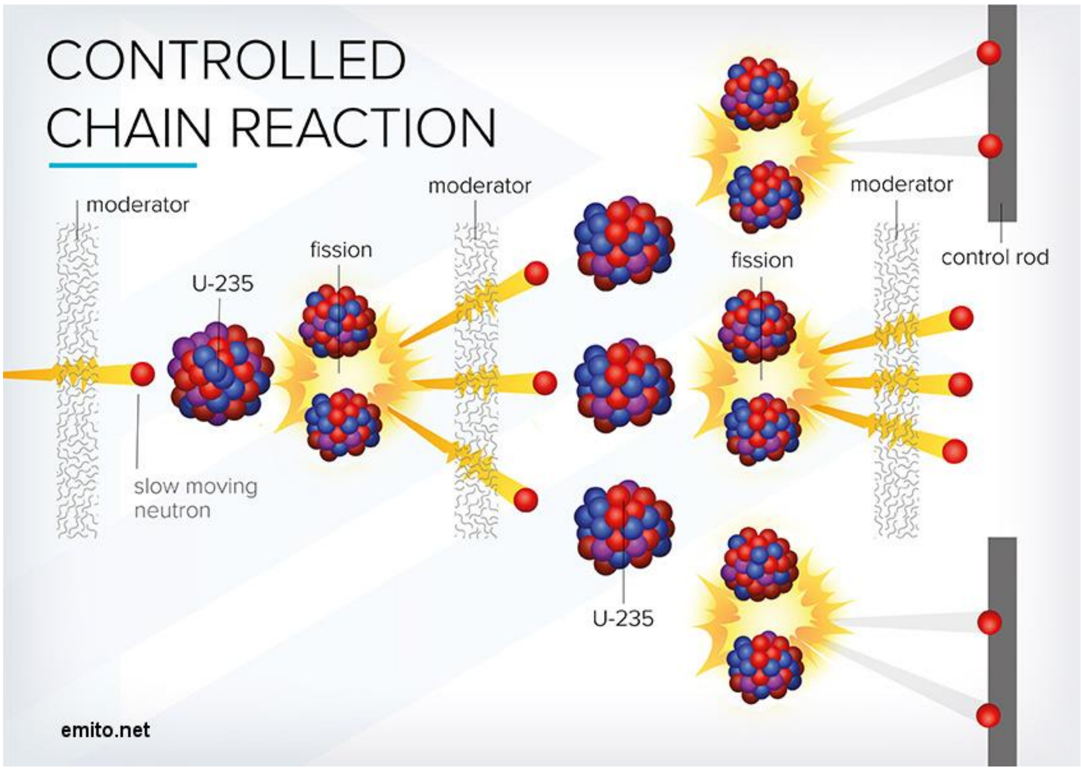

Fig. 3.2 Controlled fission reaction [7]

Reactor power control

The neutron flux and reactor power is controlled by a small change in the multiplication factor, i.e. by changing the neutron balance. This can be achieved in the following basic ways:

a) by changing the amount of fuel in the core (homogeneous reactors),

b) by changing the amount of absorbent in the active zone,

c) by changing the neutron leakage by relocating part of the reflector,

d) by changing the amount of moderators in the active zone.

In all these cases, the equilibrium is dynamic in nature and must be maintained by continuous control using a servo drive based on neutron flux measurements in the ionization chambers. Three groups of control rods are used to control the reactor power:

1) Control rods are used to start, stop and maintain constant reactor power (they also compensate the influence of temperature coefficient.

2) Compensation rods compensate for negative reactivity caused by fuel burnup, reactor poisoning and spallation.

3) Emergency rods that automatically intervene in case of sudden reactor surge and other reactor faults.

Reproduction of nuclear fuel

In addition to being a source of thermal energy, a reactor can also be a source of new fissile material, i.e. a regenerative reactor. In a thermal reactor with U^{235} and U^{238}, the nuclear fuel U^{235} is burned, while neutron absorption in U^{238} produces plutonium Pu^{239} according to:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U + \gamma \rightarrow ^{239}_{93}Np + \beta^{-} \rightarrow ^{239}_{94}Pu + \beta^{-}$$

Similarly, in a reactor with U^{235} and Th^{232}, burning U^{235} and absorbing neutrons in the thorium produces new nuclear fuel U^{233} according to:

$$^{232}_{90}Th + ^{1}_{0}n \rightarrow ^{233}_{90}Th \rightarrow ^{233}_{91}Pa + \beta^{-} \rightarrow ^{233}_{92}U + \beta^{-}$$

Summary of terms 3.2.

Fission of uranium atomic nuclei - released energy, controlled chain reaction, reactor power control, nuclear fuel reproduction.

Questions 3.2.

1. Write the equation for the fission of uranium U^{235}.
2. How much energy is released by fissioning 1 uranium nucleus?
3. How much energy is released by fission 1 g of $U^{235?}$

3.3. Description of the nuclear power plant

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- describe the function of the basic parts of a nuclear power plant

EXPLANATION

Nuclear power plants are basically thermal power plants, but the heat needed to convert water into steam is not generated by burning fuel, but by nuclear fission. Starting with the turbine that drives the generator, a nuclear power plant is essentially the same as a conventional coal-fired power plant. The only difference - but a major one - is in the heat source.

The primary (first) circuit is used to transfer heat energy from the active zone to the steam generator.

In the steam generator, the heat is transferred to the secondary (second) circuit. This is a closed system which prevents the leakage of radioactivity outside the system. The primary circuit consists of the reactor, water circulation piping, steam generator, volume compensator and circulation pumps.

The secondary (second) circuit is used to transport steam and convert its internal energy into the rotational motion of the turbine. The basic parts of the secondary circuit are: the secondary part of the steam generator, the piping systems of the secondary circuit, the turbo generator, the condenser and the pumps. As with the primary circuit, it is a closed system to prevent possible leakage of radioactivity.

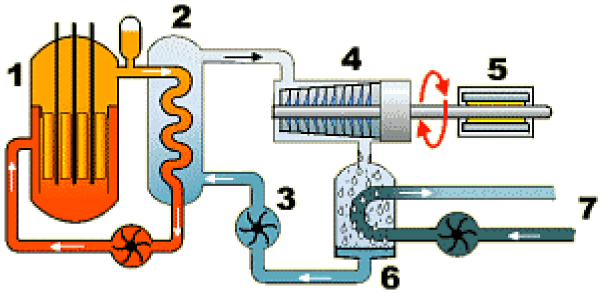

Fig. 3.3 Diagram of a nuclear power plant: 1 - Reactor, 2 - Steam generator, 3 - Pump, 4 -Turbine, 5 - Generator, 6 - Condenser, 7 - Cooling water inlet and outlet

Nuclear power plant efficiency

As the fuel price is not a significant component in the price per kWh produced, as in conventional power plants, the specific fuel consumption is not a basic indicator of the NPP efficiency. In general, we distinguish between gross efficiency (gross), i.e. the efficiency of the conversion of heat into electricity, and net efficiency (net), which includes the actual consumption of the NPP. The self-consumption of NPPs is 15 - 20 % of the total electrical output (the main contribution is from the circulators). The net efficiency of NPPs ranges between 25 - 33 %. Fuel consumption also depends on the burn-out depth of the fuel cells.

Nuclear reactors

In a nuclear reactor, nuclear energy is released and converted into thermal energy. The energy source is a controlled fission chain reaction in the nuclear fuel. The nuclear reactions taking place in the reactor are also a source of radioactive radiation.

The mean energy of neutrons released during fission is about 2 MeV. These are fast neutrons and to convert those to thermal (slow) neutrons, it is necessary to reduce their speed, which is what the moderator is used for. Materials with low atomic mass and low neutron absorption capacity are used as moderators. By multiple collisions of neutrons with moderator particles, the energy of fast neutrons is reduced to that of thermal neutrons. From an energy point of view, a nuclear reactor is a generator of heat that is released in a fission chain or thermonuclear reaction.

For a reactor to work successfully, we need to put in fuel, moderator, absorber and coolant to dissipate the heat generated by nuclear fission. Depending on the type and configuration (assembly) of these components, reactors are divided into many different types.

The fuel is usually made up of fuel rods. Small fuel tablets are stacked on top of each other to form a wand about 9 mm in diameter. The bundle of these wands forms the fuel cartridge. In a VVER 1000 reactor, for example, over 47 000 fuel rods are inserted into the reactor in hexagonal fuel assemblies, 317 in each assemblies. The part of the reactor where the fuel is inserted and where the fission reaction takes place is called the core. The fuel rods are protected by a coating of a special alloy, usually zirconium-based, which ensures that the heat from the fuel is transferred to the coolant and does not leak radioactive fission products. In some types of reactors, the fuel is in the form of spheres which are freely lowered into the core.

The moderator is usually water, but also graphite or heavy water (D_2O) in a reactor where the fission is performed by slow neutrons. In reactors that operate on the basis of fast neutrons (i.e. the fissile isotope is uranium 238 or plutonium), the moderator is absent.

The absorber is also inserted into the active zone in the form of rods, similar to the fuel. The fuel cartridges sometimes have two parts - the lower one contains the fuel, the upper one the absorber. The reactor power is then regulated by the height at which the cartridges are pulled or pushed into the core. Emergency rods are provided in the event of an immediate stoppage of reactor power. These have a much higher absorber concentration than the control rods.

The emergency rods are extended upwards above the active zone, where they are held by electromagnets. If necessary, an emergency signal will trip the electromagnets and the rods will free fall into the active zone, stopping the split reaction. In some reactors, the rods are even injected into the core, making their impact even faster.

The coolant is a medium that dissipates heat. As the nuclei fission, new nuclei (fission fragments) fly off, strike the surrounding nuclei and cause the surrounding area to heat up with their kinetic energy. The heat transfer medium transfers this heat to where it can be used. The fissile material needs to be cooled continuously to avoid melting the coating on the fuel rod and leakage of fission products. Common water, heavy water, carbon dioxide, helium, sodium and some salts or alloys work best as coolants. Reactors have one or more cooling circuits.

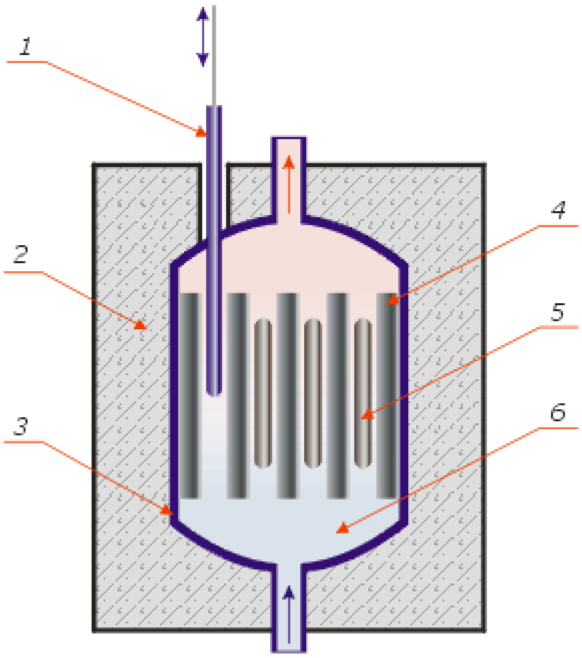

Fig. 3.4 Basic parts of a nuclear reactor (1 - control and protection rods, 2 - biological protection, 3 - thermal protection, 4 - moderator, 5 - fuel elements, 6 - coolant)

❑ Containment

Containment - a protective enclosure of reinforced concrete around the reactor and primary circuit. The containment prevents the "free" spread of radioactive substances to the surroundings in accidents with damage to the primary circuit.

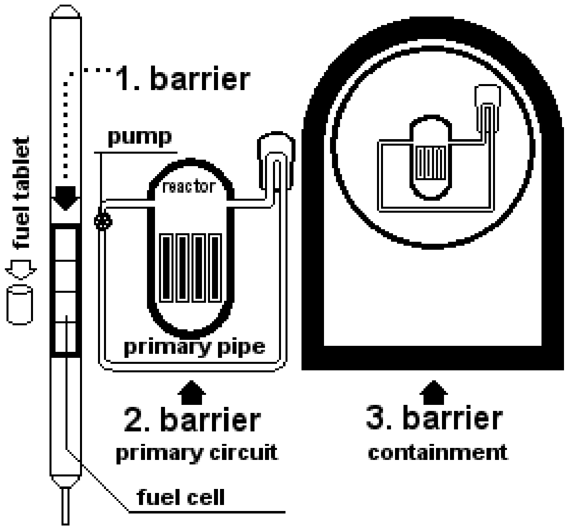

Fig. 3.5 Protective barriers

❑ Volume compensator

Volume compensator - is one of the important components of the primary circuit of a nuclear power plant. A change in reactor power is accompanied by a transient or permanent change in mean coolant temperature and, in a closed circuit, a change in coolant pressure. Large pressure changes are undesirable for the reliable operation of a nuclear power plant and therefore a volume compensator, which is usually a separate vessel with a closed auxiliary volume and a gas or steam cushion above the coolant level, is used to limit them.

Sorting of nuclear reactors

Reactor types are distinguished by different combinations:

- fuels - uranium 235, uranium 233 and plutonium 239
- refrigerants - water, deuterium oxide (D_2O - heavy water), carbon dioxide, helium and sodium
- moderator - water, heavy water, graphite or without moderator

Thermal reactors - fission of nuclear fuel mainly by thermal neutrons (up to 1eV).

Fast reactors - fission of nuclear fuel mainly by fast neutrons (above 0.1 MeV), new fissile material is produced - set reactors.

Označení typu	Plný význam anglicky	Český pojem
AGR	Advanced Gas Cooled, Graphite Moderated Reactor	pokročilý plynem chlazený, gafitem moderovaný reaktor
BWR	Boiling Light Water Cooled and Moderated Reactor	varný, lehkou vodou chlazený a moderovaný reaktor
FBR	Fast Breeder Reactor	rychlý množivý reaktor
GCR	Gas Cooled, Graphite Moderated Reactor	plynem chlazený, grafitem moderovaný reaktor
HTGR	High Temperature, Gas Cooled, Graphite Moderated Reactor	vysokoteplotní, plynem chlazený a moderovaný reaktor
HWGCR	Heavy Water Cooled, Graphite Moderated Reactor	těžkou vodou chlazený a moderovaný reaktor
LWGR	Light Water Cooled, Graphite Moderated Reactor	lehkou vodou chlazený, grafitem moderovaný reaktor
PHWR	Pressurized Heavy Water Moderated and Cooled Reactor	tlakovou těžkou vodou chlazený a moderovaný reaktor
PWR	Pressurized Light Water Moderated and Cooled Reactor	tlakovou lehkou vodou chlazený a moderovaný reaktor
SGHWR	Steam Generating Heavy Water Reactor	varný těžkovodní reaktor

Tab. 3.1 Designation of reactor types

Summary of terms 3.3.

NPP efficiency, nuclear reactors, containment, volume compensator, JR sorting.

Questions 3.3.

1. What is the self-consumption of NPP?
2. Draw the basic parts of a nuclear reactor.
3. What is containment?
4. What is the purpose of the volume compensator?

ADDITIONAL RESOURCES 3

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4. HYDROELECTRIC POWER PLANTS

4.1. Basic concepts

TIME TO STUDY:

2 hours

TARGET:

After studying this paragraph, you will be able to

- list the different parts of the power plant
- describe the function of a hydroelectric power plant

EXPLANATION

A hydropower plant is a technological device for generating electricity. The plant can convert the potential of water energy into another potential, namely electrical energy. A hydroelectric power station and all the relevant components together constitute a hydroelectric power station within the meaning of the applicable legislation.

The main part of the power plant consists of a turbine, to which water flows through an inlet channel and spins the turbine. The turbine is coupled to the power generator by a common shaft. The generator and the turbine together form a unit called a hydroalternator. The water flowing through the inlet channel represents the energy which the hydroalternator converts into electrical energy by electromagnetic induction. In effect, it is a circular loop rotating in a magnetic field in which an alternating electrical voltage is induced. The electrical energy produced is further transformed to the required voltage value and discharged to the points of consumption.

We can convert the flowing water energy into another kind of energy. According to the way the energy is used, we then distinguish between types of water machines. Water energy is represented by two physical quantities, namely flow - the energy of motion, kinetic energy, and pressure - the energy of potential, pressure energy. In the conversion to electrical energy, we use flow and pressure separately or simultaneously.

Potential (pressure) energy

It is created by obtaining the potential differences of the water level, when the water flowing from the higher level passes through a suitable feeder to the potential with the lower level. The difference in height between the upper and lower levels then creates pressure, which is used in what we call pressure-reaction machines. These include turbines of the Kaplan, Francis...

- potential

$$E_h = m \cdot g \cdot H \qquad (4.1)$$

where E - energy (J), m - weight of water (kg), g - gravitational acceleration ($m \cdot s^{-2}$), H - height difference (gradient) (m).

- Pressure

$$E_p = m \cdot \frac{p}{\rho} \qquad (4.2)$$

where E is the energy (J), m is the weight of water (kg), p is the pressure (Pa), and ρ is the density of water (kg·m^{-3}).

Kinetic energy

It is determined in watercourses by the velocity of the flow. The energy is used by rotating water machines based on equal pressure, so-called equal pressure machines. The water machines are mainly water wheels, turbines of the Banki and Pelton type.

$$E_x = \frac{1}{2} \cdot m \cdot v^2 \qquad (4.3)$$

where E - energy (J), m - weight of water (kg), v - velocity of water (m·s^{-1}).

Main objects of the waterworks

The purpose of a hydroelectric dam is to concentrate the hydroelectric power of a site. A hydropower plant consists of many structures, buildings, technological, mechanical and electrical equipment.

- Upper and lower reservoir - in the case of run-of-river hydropower plants, both reservoirs are formed by a dam or weir. The reservoirs contain regulating passage devices, such as weirs, for spilling and discharging large volumes of water, ice and silt. In storage power stations, the upper reservoir is connected to the lower reservoir by a conveyor, which is constructed by means of a pressure pipe.
- Dewatering device - it is formed by dams or weirs. It serves to raise the water level and direct the water into the inlet.
- Levees - are characterized by a greater height of water surface elevation, area of flooded area and a larger volume of retained water compared to a weir. The construction of the dam itself is a very costly investment in ecological and economic terms. The use of existing dams is often advantageous, for example, they can be used to regulate water flow.
- Weirs (also called rafting) - serve to raise and stabilize the water level in the river bed. Usually, most of the main flow is maintained and only some water is taken out of the main channel, thus providing free passage for aquatic animals. Weirs have a lower head and a much smaller volume of retained water than dams. A weir is usually a prerequisite for the construction of small hydropower plants on a river with a lower flow.
- Feeders - concentrate the runoff to the installation site of the water turbine, their task is to bring water to the turbine. They consist of a non-pressure feeder (they are mostly constructed by excavation, e.g. an embankment, canal or adit) or a pressure feeder, usually consisting of a shaft, a gallery (they are usually implemented by steel pipes).
- The combs - prevent the entry of coarse and fine dirt into the turbine brought in from the surroundings by the water, so they are an important part of the water works. Most often two combs are placed behind each other, for coarse and fine silt. They are made of grid-shaped steel banding and are often equipped with automatic cleaning.
- Drains - return water to its original channel.

- The building of the hydroelectric power plant itself - it mainly includes a machine room with hydraulic and electric machines, a turbine and a generator, which are mostly on a common shaft. The main machinery includes e.g. safety gates, regulators, compressors, pumping units, cranes, etc. The facility includes the main operating building, the high voltage substation, the compressor room and the so-called "Control room". The control room consists of control, regulation, measurement and monitoring equipment.
- Operational and safety equipment - including equipment for safe and smooth operation. These include the worm gear cleaning machines, the closures and their mechanisms, including piping, synchronous and vent valves, the water depletion shaft and the equalization chambers. The chambers serve to improve the control of water pressure fluctuations caused by sudden closure of the pipeline or sudden shutdown of the turbine and prevent the progression of pressure waves when a hydraulic shock occurs further up the supply pipeline.
- Special objects and facilities - include locks and timber rafting facilities, fishways, outlets with sluice gates, etc.

❑ Volume of permanent detention (standing stock; Vpd)

The lowest state of the water level in the reservoir, at which point no further water can be drawn from the reservoir.

❑ Useful content (volume; Vu)

The volume of the reservoir between the permanent storage and the highest operating level, i.e. the highest operating level.

❑ Retention content (volume; Vr)

The volume of a reservoir above the usable capacity used to capture flood waves.

❑ Energy equivalent (Ee)

The value of the stored electrical energy in the useful content.

❑ Fallout

It represents the difference in height between the upper and lower water levels. There are two types of gradient:

- Total (gross) gradient - The total gradient given by the difference between the upper and lower levels immediately below the outlet of a water works. May be determined by a leveling instrument. For rough estimates, it can be determined from chart datum.
- Useful (net) gradient - Obtained by subtracting from the gross gradient the hydraulic losses that occur just upstream of the turbine, downstream of the turbine, in the inlet and in the outlet.

❑ Flow

Indicates the total volume of water that flows through a given stream profile in a given time, given in m^3 /s. The flow can be estimated, calculated or accurately determined using data from the Czech Hydro meteorological Institute or the river basin administration. Less important for the use of water energy are the so-called M-day flows, which indicate the guaranteed flow of water through a river for a certain number of days. The resulting values are usually given after 30 days of the year.

- **Turbine capacity**

  Maximum turbine flow for a given gradient.

- **Hydropower plant power**

$$P = g \cdot \rho \cdot Q \cdot \eta \cdot H \tag{4.4}$$

where P power (W), ρ - specific gravity of water (1 000 kg/m^3), g - gravitational acceleration (9.81 m/s^2), Q - flow through the water turbine (m^3/s), H - net gradient (m), η - efficiency

- **Energy equivalent of the storage tank volume**

  Potential energy of the usable volume of the reservoir.

$$E = g \cdot \rho \cdot V_U \cdot \eta \cdot H \tag{4.5}$$

where V_U - the usable volume of the tank (m^{-3}).

Summary of terms 4.1.

Kinetic energy, potential energy, dam, weir, comb, turbine head, energy equivalent, payload.

Questions 4.1.

1. How do we divide potential energy?
2. What is the difference between a dam and a weir?
3. What are combs for?
4. What is the turbine girth?
5. Write the formula for calculating the output of a hydroelectric power plant.
6. Write the formula for calculating the energy equivalent.

4.2. Hydropower plants

TIME TO STUDY:

2 hours

TARGET:

After studying this paragraph, you will be able to

- to classify hydropower plants according to each criterion.
- basic types of hydropower plants.
- describe the function of a hydroelectric power plant

EXPLANATION

- **According to the energy use of the water flow**

  - River - the hydroelectric power plant is located directly on the riverbed, the water does not leave the riverbed and flows immediately through the power plant.
  - Derivational - water is fed to the hydroelectric power plant from an artificially created channel that is built next to the original channel. The flow through the diversion channel is provided by means of lifting devices and gates, which allow part of the water to flow in the original channel. Derivation plants do not disturb the water flow as much as river power plants.

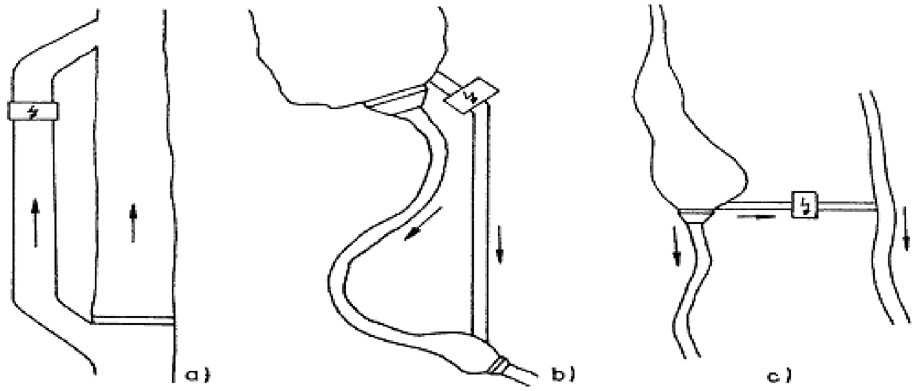


Fig. 4.1: Schematic diagram of the derivational hydropower plants; a) Open channel; b) Pressure channel; c) Adit

- **According to the size of the gradient**

  - low pressure - gradient less than 20 m, they are usually built on a raft. Most often Kaplan turbines are installed in the power plant,
  - medium pressure - gradient between 20 and 100 m. Mostly Francis turbines are installed in the power plant, less Kaplan turbines,
  - high pressure - gradient in the range of 100 to 200 m. These plants are equipped with either some type of Francis turbine or Pelton turbine.

- **Depending on the method of operation and energy storage**

  - flow-through hydroelectric power plants - they have no space to store water. They are built in suitable locations that have a constant and large flow. They operate mostly into the base load portion of the daily load chart.
  - storage power plants with natural water storage - they have space for a permanent water supply thanks to a dam built on the watercourse. It is necessary to ensure a constant flow to avoid total depletion of water. They operate as peaking or semi-peaking hydroelectric power plants.

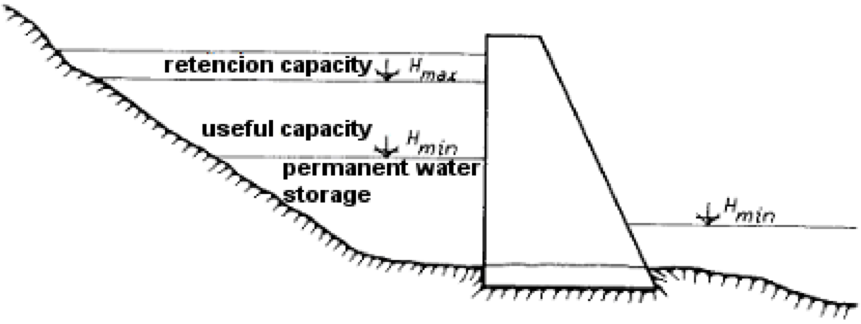


Fig. 4.2 Parts of the water content of the storage tank

- storage power plants with artificial water accumulation = pumped storage power plants - PVE artificially accumulate cheap night energy from thermal and especially nuclear power plants by pumping water from the lower reservoir to the upper storage reservoir during times of reduced load on the electricity system. The water energy reserves in the upper reservoir are used to generate electricity during peak periods.

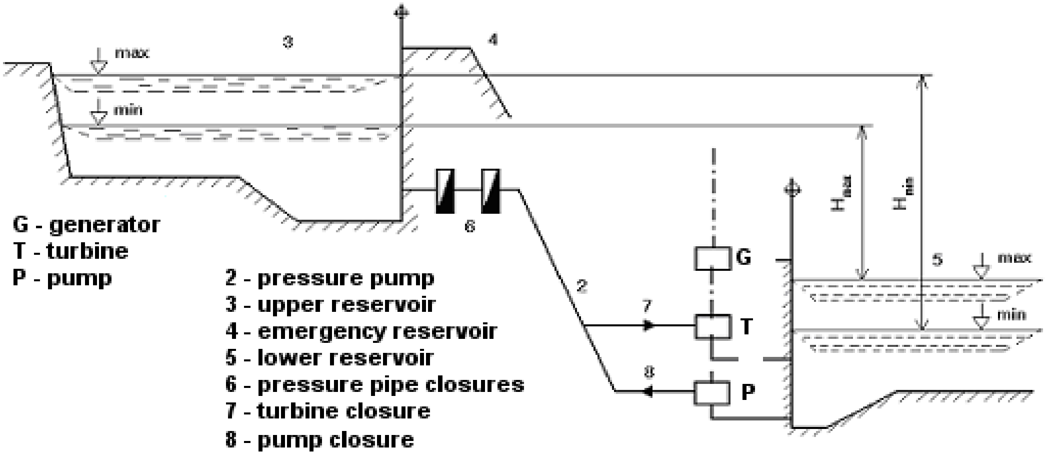


Fig. 4.3 Section through the layout of a pumped storage power plant

According to the installed power

- high hydroelectric power plants over 200 MW
- medium hydropower plants from 10 MW to 200 MW
- small hydropower plants up to 10 MW, industrial power plants over 1 MW, mini power plants (small power plants) up to 1 MW, micro power plants up to 100 kW, domestic power plants up to 35 kW

By load mode

- Base HPPs - these are flow-through HPPs that operate throughout the day (up to 16 h) to cover the base part of the daily load diagram,
- Semi-tidal HPPs - operate as flow-through and short-term peak flow (within the allowed range of concentrated flow in their upper reservoir) in the semi-tidal part of the daily load curve,
- High HPPs - they work to cover the top part.

STORAGE HYDROPOWER PLANTS

They have space for a constant supply of water. A dam or weir built on a watercourse in a suitably flat geographical location is essential for their function. Due to the amount of water retained we can get medium to high gradients and also higher outputs. Dams are usually built up to a maximum height of 100 m, but they can reach heights of over 300 m. In the mountainous areas between the valleys, so-called valley dams are built and allow hydroelectric power plants to be installed in a favourable position. The water is fed into the engine room through high-pressure pipes. Due to the high gradient, a high overpressure of up to 200 bar (20 MPa) is generated. The output is not dependent on the river flow, but it is necessary to ensure a relatively constant flow to avoid total depletion of the water. In the engine room, the water drives turbines that power generators and produce electricity.

Storage HPPs have an important role not only in power generation, they combine multiple roles at the same time. They often serve as a source of drinking, process or irrigation water for the surrounding area. They stabilise water flows in the river channel below the dam and protect against flooding, sometimes also supporting the navigability of the stream. The banks of dikes can be used as a recreational site.

Dike - for large water works, this is a technically complex structure interwoven with a network of control tunnels. It must be secured against overflow by lower outlets and upper spillways, which also allow for continuous adjustment of the reservoir level. The weirs can be constructed in two ways:

- Bulk dikes - Built by gradually weighing in material, using construction equipment to gradually choke and pour concrete. It is built with pieces of stones and crushed materials (sand, gravel...) to reinforce the dam. The dam must be sufficiently bulky to withstand the pressure of the accumulated water. The fill dam is one of the most used in the Czech Republic and is used at power plants such as Lipno, Slezská Harta, Dalešice (the highest dam in the Czech Republic and the second largest fill dam in Europe).
- Arched - a relatively thin, arched reinforced concrete structure resists water pressure. The reinforced concrete arched dam of the Vrchlice waterworks is the only dam of this type in the Czech Republic, but it does not serve as a hydroelectric power station. Concrete is advantageous because of its property: its strength continuously increases with time and high pressure.

The dike shall be provided with bottom outlets and top overflow edges to prevent overtopping during high inflows. These measures also allow the water level to be continuously adjusted. At the same time, a special reservoir called a boiling pond is being constructed below the dam to absorb the water leaving the reservoir and to act as an energy buffer. The water flowing out of the turbine is energy-rich and often reaches high velocities, so the water is calmed in this basin and continues to flow into the river without further harmful consequences.

The location of the power plant itself varies. However, the principle remains to use the retained water with maximum efficiency. It depends on the shape of the terrain, the height and gradient and the amount of water available.

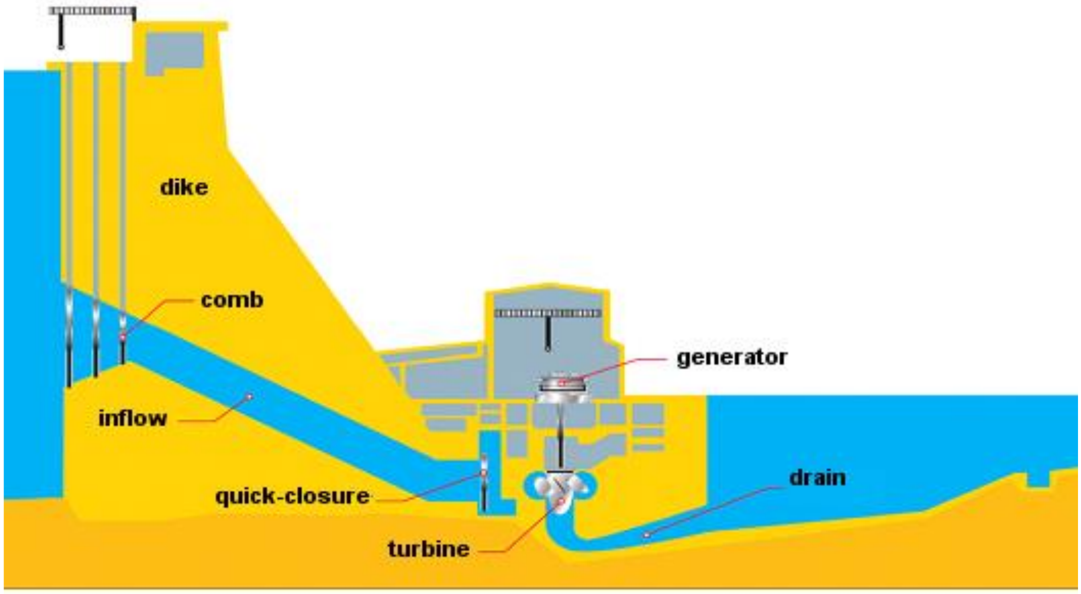


Fig. 4.4 Principle of storage hydropower plant

FLOW-THROUGH HYDROPOWER PLANTS (RUN-OF-RIVER HPPs)

Sites with high flow rates and large elevation differences are ideal for the construction of a flow-through power plant. A smaller dam or weir is needed to make the power station functional; these will create a surge, thus directly creating a difference in water level in front of and behind the power station. The power plant operates without storage, more precisely, "the time taken to fill the reservoir by the accumulation of water flow is practically negligible and uses only the instantaneous amount of water flowing through the riverbed".

The actual buoyancy will ensure the amount of water the plant is designed to handle, so that the turbine's capacity is close to maximum. If the flow rate is higher than the maximum turbine head, the remaining water flows idly through the weir. To use the flow as efficiently as possible, larger power plants are designed with multiple turbines and the water drives several turbines running in parallel. If low water levels occur, some of the turbines are shut down. This measure prevents the efficiency of the turbines from decreasing during partial operation.

Flow-through hydroelectric power plants do not achieve high power outputs because the gradient is not very high, reaching only a few metres, for this reason they have a power output of up to 100 MW. The disadvantage is poor power regulation, because the water flow in the river cannot be reduced and they can only supply the grid with an hourly current. Excess water must be allowed to flow unused through the power station.

Power plants can present an obstacle to boats and aquatic life due to the presence of weirs and dams. Therefore, a lock for boats to overcome the height difference and a fish passage for aquatic animals usually has to be built. Flow-through hydropower plants operate in the base load portion of the daily load chart.

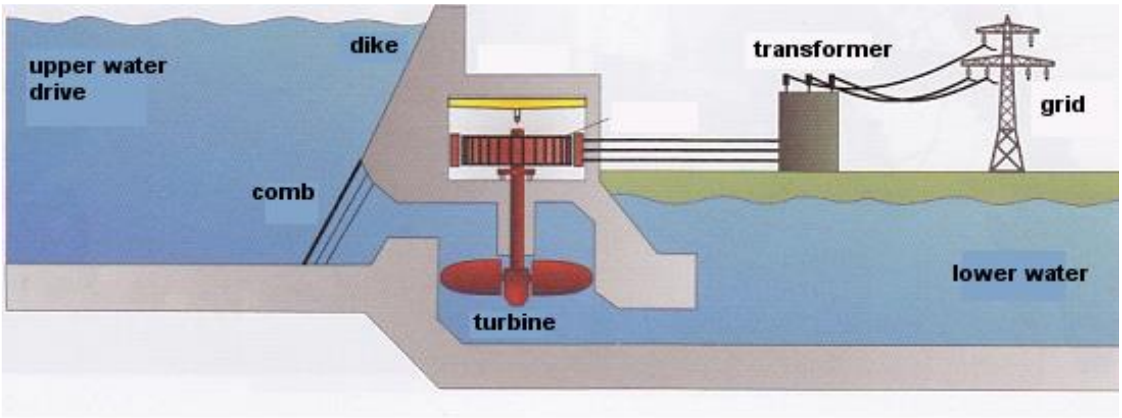


Fig. 4.5 Principle of a flow-through hydroelectric power plant

PUMPED STORAGE HYDROPOWER PLANTS (PSHPPs)

They represent an irreplaceable role among the sources in the electricity system. At present, we cannot store electricity to any great extent, so the electricity system has to supply as much energy as demand at any given time. Pumped storage hydroelectric power plants have therefore been created to cover and regulate the actual consumption of electricity. This type of grid demand regulation can be seen as a temporary storage of electricity. The cost of building a power plant is very high, but even so, the payback period is around 7 years of operation (e.g. the return on the Dlouhé Stráně PSHPPs was around 6 years). Despite this fact, expensive investments have many advantages over other types of power plants.

For the operation of the power plant, two tanks must be built in advance with a mutual height difference according to the required output. The height difference of the levels should be as large as possible to achieve a large gradient and power output. Very favourable geographical conditions are needed for construction. A natural inflow of water is required, which discharges into a lower or upper reservoir depending on the site. However, there may be so-called pure pumping dams that do not have a natural inflow of water. The power plant performs the main basic functions:

- Static function (so-called accumulator)

It occurs when we need to supply electricity to the grid or, conversely, consume excess electricity in the grid. In generator mode, the turbine draws power from the water and the alternator supplies power through a transformer to the grid. The water flows from the upper tank through a pressure pipe to the turbine and then flows to the lower tank. In reverse, pump mode, the power plant draws power from the grid, the electric machine works as an electric motor driving the turbine, which pumps water from the lower tank to the upper tank. This mode is used when there is a surplus of electricity in the grid. This circuit is called the small pumped storage cycle of PVE. It takes advantage of the difference in the price of electricity, which is approximately four times more expensive at peak times than at off-peak times.

- Dynamic function (so-called coverage of rapid fluctuations)

The ability of the power plant to act as a reserve power source for the system.

- Regulatory function

The power plant participates in the voltage regulation of the grid.

Classification according to machine arrangement:

- The four-machine arrangement consists of a turbine-alternator and an electric motor with a pump. This design is historically the oldest.

- The three-machine arrangement consists of a motor-generator, a turbine and a storage pump.
- The two-machine arrangement consists of a motor-generator with a reverse turbine. The unit can operate as either a source, consumer or synchronous compensator for supplying or withdrawing reactive power, with respect to the power system. The advantage of the two-machine arrangement is mainly the lower investment.

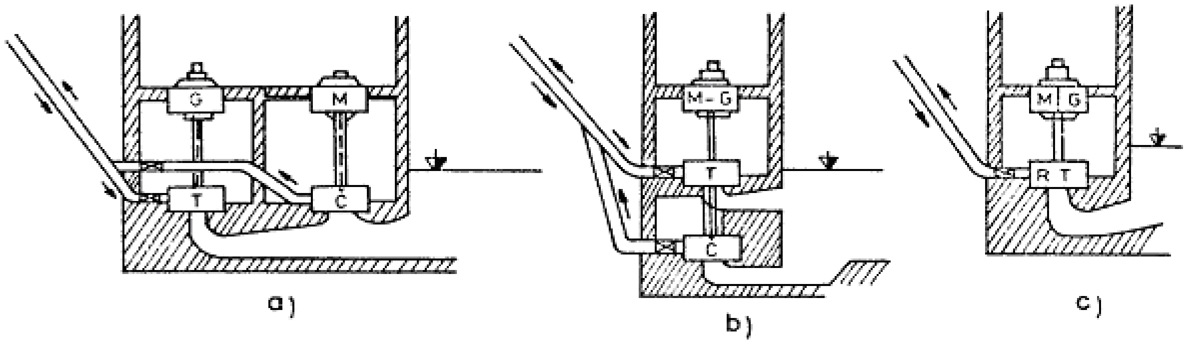


Fig. 4.6 Arrangement of machines in PVE

All three PSHPPs located in the Czech Republic (Dlouhé Stráně, Dalešice and Štěchovice II with a total installed capacity of 1.145 MW) are designed in this arrangement. Modern and newly built plants show small cycle efficiencies between 70-80 %.

By small cycle efficiency we mean without considering the losses in the transfer of energy to the customer and the losses from the source to the pump. The motor operation consumes a large amount of energy; approximately 70 % of the electricity can be recovered through the generator operation (1.3 kWh spent yields 1 kWh). Despite the losses incurred by this principle, these power plants are economically very attractive. It is by pumping into the upper reservoir that they make use of cheap energy at times of surplus electricity (e.g. at night). At peak times, when there is a need for more energy in the grid (morning hours), it is fed back into the grid. The energy produced is fed back into the grid at a significantly higher price. Pumped storage plants have come into their own mainly in recent years, when the power supplied to the grid from wind and photovoltaic plants fluctuates considerably and needs to be regulated; pumped storage plants can play this role.

The advantage of power plants is very fast start-up and running of the turbine. It usually takes only a few minutes to get the plant up and running and to supply electricity to the grid.

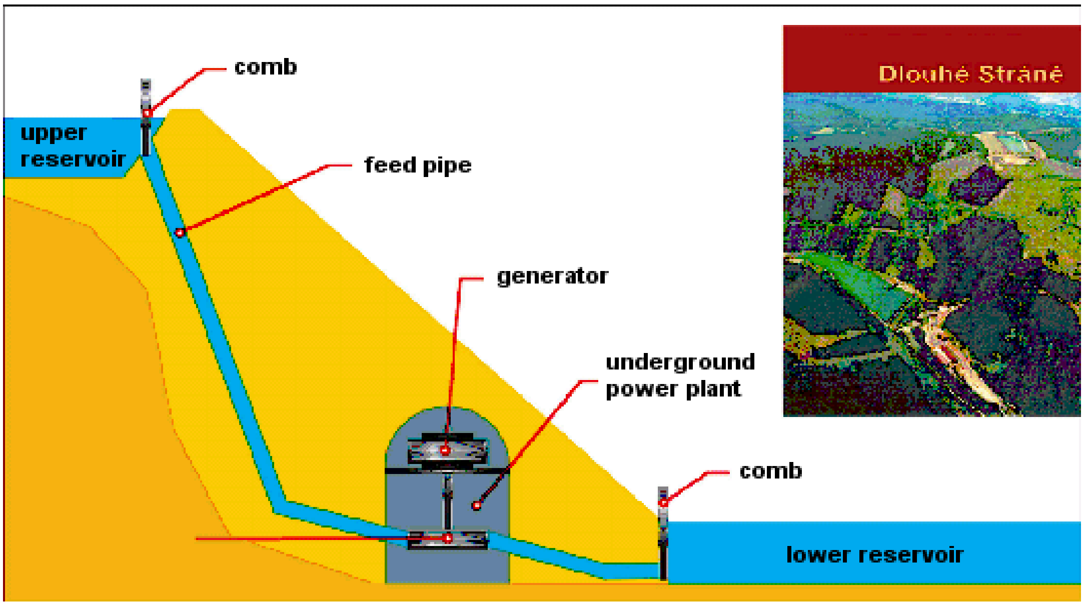


Fig. 4.7 Principle of pumped storage hydroelectric power plant

Summary of terms 4.2.

Storage hydropower plant, flow-through hydropower plant, pumped storage hydropower plant.

Questions 4.2.

7. List the basic types of hydroelectric power plants.
8. What is meant by static and dynamic functions in PVE?
9. What is the most common PVE machine arrangement today?

4.3. Water turbines

TIME TO STUDY:

2 hours

TARGET:

After studying this paragraph, you will be able to

- list the basic types of turbines
- select the appropriate turbine for the given conditions
- understand the principle of turbine function

EXPLANATION

To make the most efficient use of the given plant conditions, the selection of the appropriate turbine is most important. Water turbines are the most technically advanced mechanical engines ever, achieving up to 95% efficiency. The Czech Republic uses most often reaction type turbines, namely Francis or Kaplan turbines, which are used in a wide range of modifications and are the most useful for the given conditions of Czech rivers.

Water turbines are the core of the whole hydroelectric power plant, it is a rotating mechanical machine used to convert the energy of flowing water into electrical energy by extracting the energy of water.

The pioneer and founder of the foundations of turbine theory was the Swiss-born 18th century physicist Leonhard Euler. The findings of the Swiss physicist were used as a basis for the French engineer Benoit Fourneyron, who built the first pressurized water turbine in 1827. Twenty years later, the Francois turbine was successfully built, which again works on a pressurized system. In 1880, the American Lester Pelton built a simple turbine. The turbine worked on the principle of equal pressure, so it was an equal pressure turbine called the Pelton turbine. These three types of turbine are the main prerequisites for converting hydroelectric power today.

Today's water turbines have little in common with historic water wheels. The choice of turbine type depends on the specifications of the hydropower installation site. The important parameters for selection are the water gradient and the amount of water flow, and the optimum turbine is selected according to these parameters.

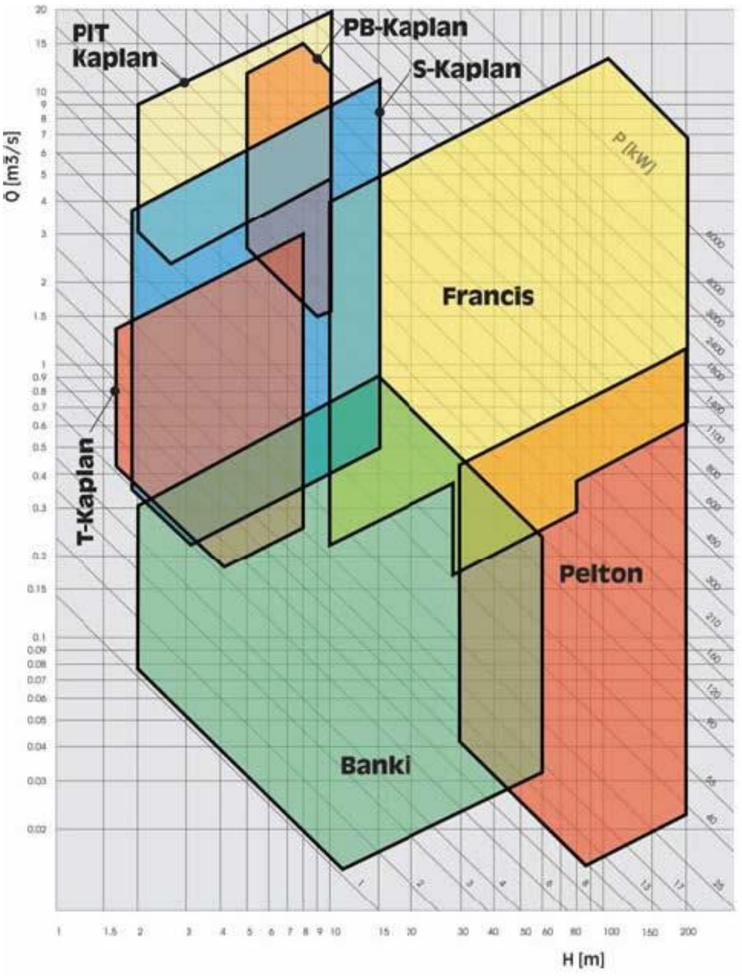


Fig. 4.8 H-Q diagram showing the optimum use area of different water turbines

Main types

- action turbines - use only kinetic energy of water, turbines are equal pressure. The water is fed to the turbine from a certain height, we can imagine the whole system as a type of water mill wheel drive.
- reaction turbines - they use both kinetic and pressure energy of water. Turbines are fundamentally pressurised, using the different pressure of the liquid in front of and behind the turbine. The water is at a certain pressure in front of the turbine, enters the turbine, spins the turbine and gradually the pressure of the water decreases as it passes on. The resulting pressure is higher upstream of the turbine.

Subtypes

- radial,
- axial.

According to the overall design:

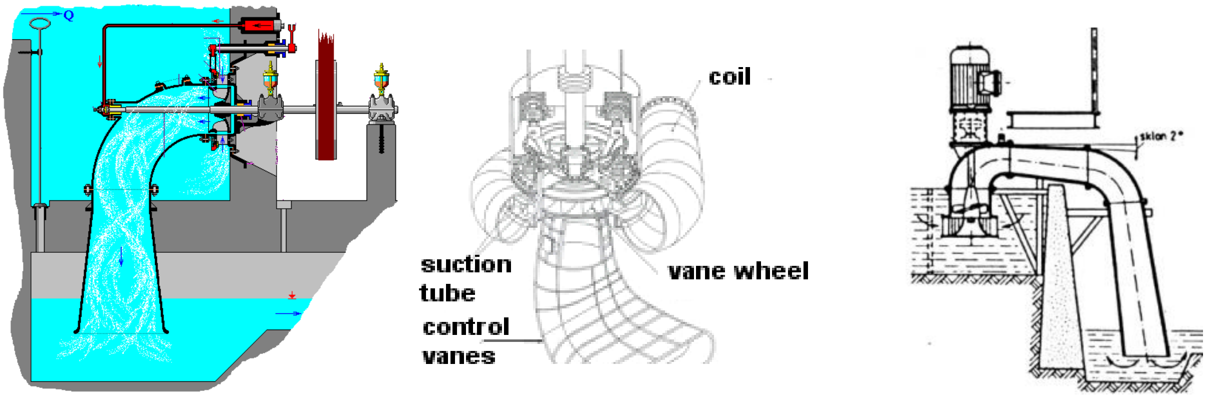
- Pelton turbine
- Francis turbine
- Kaplan turbine
- Banksy's turbine

For small hydropower plants

- Francis - fountain - horizontal (with wet suction, with dry suction), vertical (spiral)
- Kaplan - horizontal, vertical, axial, straight flow
- Banki (modern Ossberger turbine)
- Pelton

Today, the Francis is not very efficient for SHP, replaced mostly by the Kaplan turbine.

The above turbine types are basic, of course there are various modifications and solutions.



a) b) c)

Fig. 4.9 Examples of turbines for SHP: a) fountain with wet suction, b) fountain spiral, c) axial flow

Pelton turbine

The Pelton turbine is a tangential equal pressure turbine reaching up to 95% efficiency. The turbine has bowls around the perimeter, to which water is supplied tangentially from nozzles. The water does not therefore reach the turbine around its entire circumference, but enters the turbine only in some parts. The nozzle is a circular device used to restrict the flow of liquids, its course is continuously variable. The inlet edge is rounded and the outlet edge is sharp. From the nozzle, water flows through a circular pipe to the spoon-shaped blades. The piping can be divided into several sections so that water reaches several blades simultaneously. The blades are set perpendicular to the direction of the water flow, so that the water is rotated by pressure. The circular motion of the turbine is directly transmitted to the shaft of the alternator, which generates electricity. The Pelton turbine is most efficient when the feedwater pressure is high. As the water flows to the turbine blades through the nozzle, it is possible to control the flow optimally and thus vary the pressure applied to the turbine. The water flow is regulated by changing the nozzle outlet cross-section by retracting the regulating needle, which is controlled by a servomotor. The supply pipe can be diverted to ensure that water does not fall on the turbine blades if the turbine output needs to be reduced quickly. The rotating turbine is directly coupled to the rotor of the alternator.

The H-Q diagram shows that Pelton turbines are used for high water gradient and low flow. They come in many sizes, the smallest turbines measuring only a few tens of centimetres, and are used for small hydroelectric plants with high head. Vertical storage is used in the power industry, with output up to 200 MW. The range of application is from 15 m to 1800 m.

Francis turbine

The Francis turbine is a subtype of the water turbine developed by James B. Francis. It is a pressurized turbine improved from a water wheel with an overall efficiency of 90%.

The Francis turbine has two variants according to the shaft arrangement:

- Vertical
- Horizontal

The Francis turbine is based on the pressure principle, i.e. the fluid transfers energy to the turbine during its journey through the pipe due to the change in pressure. In front of the turbine there is a tapering high-pressure water inlet, and behind the turbine there is a tapering low-pressure inlet from which water flows out with minimum energy (velocity). Next to the turbine, controller-controlled distribution vanes are installed around the perimeter of the pipe to direct the flow of water to the turbine rotor. The rotating water under pressure contributes to the efficiency of the turbine. The water flow directed by the vanes enters the turbine impeller. In the impeller it hits the curved inter-blade channels, changes direction and velocity and gradually transfers its rotational speed and pressure to the rotor.

It is important to mention here the cavitation phenomenon: Cavitation occurs when the pressure in a liquid drops, creating an implosion (the opposite of an explosion, the body or mass collapses into its own volume). This drop in pressure is usually caused by a local increase in velocity (called hydrodynamic cavitation). The cavitation is initially filled with a vacuum, but later gases from the surrounding fluid may enter. When the vacuum that created the cavitation disappears, the bubble collapses to form a shock wave with a destructive effect on the surrounding material. It is formed, for example, on the blades of water screws, turbines on pumps and other devices that move at high speed in the liquid. Cavitation causes noise, reduces the efficiency of machinery and can cause damage. The cavitation is mainly influenced by the magnitude of the vacuum, the cohesiveness (surface tension) of the fluid and the temperature (the lower the temperature, the less cavitation)."

Fig. 4.10 Cavitation on the impeller of the Francis turbine

The Francis turbine is one of the most widely used. The turbine can be used for medium and higher flow rates and gradients. Francis turbines are particularly common in pumped storage power plants. For example, our largest pumped storage power plant, Dlouhé Stráně, uses two Francis turbines with a capacity of 325 MW.

Kaplan turbine

The turbine was invented by Viktor Kaplan (an Austrian citizen), a professor of Brno technology. It differs from the Francis turbine by the smaller number of blades and the shape of the impeller.

The Kaplan turbine is a pressurized axial turbine. Again, it must use distributor blades to function. The greatest advantage of the turbine is its ability to control the pitch of the blades of both the impeller and the impeller. The turbine has three to eight adjustable blades and looks like a large propeller driven by flowing water.

It is often used in locations where higher gradients and flows cannot be provided due to the possibility of very good regulation. It is generally used especially for large flows and small gradients that are not constant. The turbine can also be installed in small machine rooms and has a low building height. The disadvantage of double-controlled turbines is the considerable mechanical complexity, which makes the price high and the maintenance costs higher. Therefore, the installation of this turbine should be considered more for advantageous hydropower potentials. This turbine has become the most important type of turbine used in large hydropower plants around the world.

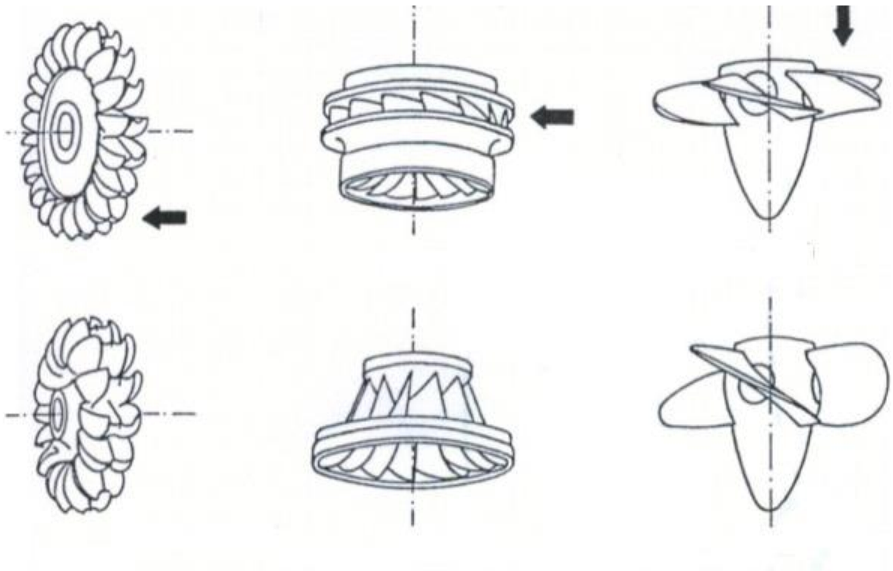


Fig. 4.11 From left: Pelton turbine, Francis turbine, Kaplan turbine

Summary of terms 4.3.

Pelton turbine, Francis turbine, Kaplan turbine, cavitation.

Questions 4.3.

1. List the basic types of turbines.
2. Which turbine is suitable for high gradients?

4.4. Current trends in HPPs

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- to estimate the development of hydropower plants.
- list the new types of hydropower plants

EXPLANATION

The current trend in the development of HPPs is mainly focused on the expansion of small hydropower plants and their reconstruction. This step can achieve a significant increase in capacity and supply several thousand households. Thanks to the development of electronics, power plants boast automatic control and remote operation. Sites for the construction of large-scale power plants are essentially exhausted for the country or the cost of implementation is very high. In 2011, a study by the Ministry of Industry and Trade came out stating that the Czech Republic has plans to build another pumped storage plant, with a total of 6 suitable sites selected. However, the construction costs are in the range of tens of billions of CZK and should be paid for by private investor funds, as the CEZ Group is not planning the construction. It should be a modern power plant to regulate power output as the number of renewables connected to the grid continues to grow.

In the world, many suitable sites are also exhausted and therefore many studies are being conducted on new and modified principles of existing HPPs (e.g. use of mountain springs, vortex power plants) for maximum efficiency. A major development is in China, where at least 13 new plants with a total capacity of 20 GW have been approved for construction in 2006. Nowadays, many studies are starting to appear on the use of hydro for HPPs of up to 1 kW, new turbines and the use of wind-based HPPs in coastal areas or deep rivers. Projects are emerging for implementation in less favourable locations. In addition, the development of small hydropower plants (SHPPs) contributes to the stability of the grid, as the supply does not have to be transported far and large losses are not incurred. One example of taking advantage of a less suitable location was implemented in Canada, where the designers took advantage of the mountain flow of a river, piped it through an inhospitable landscape to a valley where they spin two hydro turbines.

❑ Vortex turbine

The turbine was developed by a scientific team in 2000, and its overall design and construction were fully fine-tuned in 2001. It is a new type of propeller water turbine design with a two-bladed impeller without a distributor. As a result, it is a modification of the Kaplan turbine, but with a higher speed and often without the need for gears. The absence of distributor control rings, which are costly to manufacture and are used on the Kaplan turbine, has led to a large reduction in purchase price, which supports future development of HPPs. The turbine is designed for very low gradients of 1-3 m and high flows. The first studies were carried out in 2000 at a gradient of 2.5 m and the turbine showed an efficiency of 86 %.

Fig. 4.12 Vortex turbine

SETUR water motor

It is a vertical vaneless water motor invented in the Czech Republic. It works on the principle of rolling the rotating body in the discharge confuzor. It can use water or gases as working medium. The principle of operation of this rolling fluid engine differs considerably from other turbines. The function is based on the so-called hydrodynamic paradox. This is a phenomenon that causes a sphere (or other curved body) to be drawn towards the wall the faster the fluid flows between it and the wall. The sphere is suspended elastically, and tangentially entering water causes the sphere to rotate. Due to the overall flow of the liquid, the sphere gains rotation and gradually moves around its circumference. It is used in previously unused hydrodynamic principles, e.g. water and sewage systems up to smaller reservoirs. Depending on the design, efficiency ranges from 40 to 75% for various gradients from 0.6 m to 20 m at flow rates from 4 to 500 litres/s. Motor power ranges from 0.075 - 7 kW.

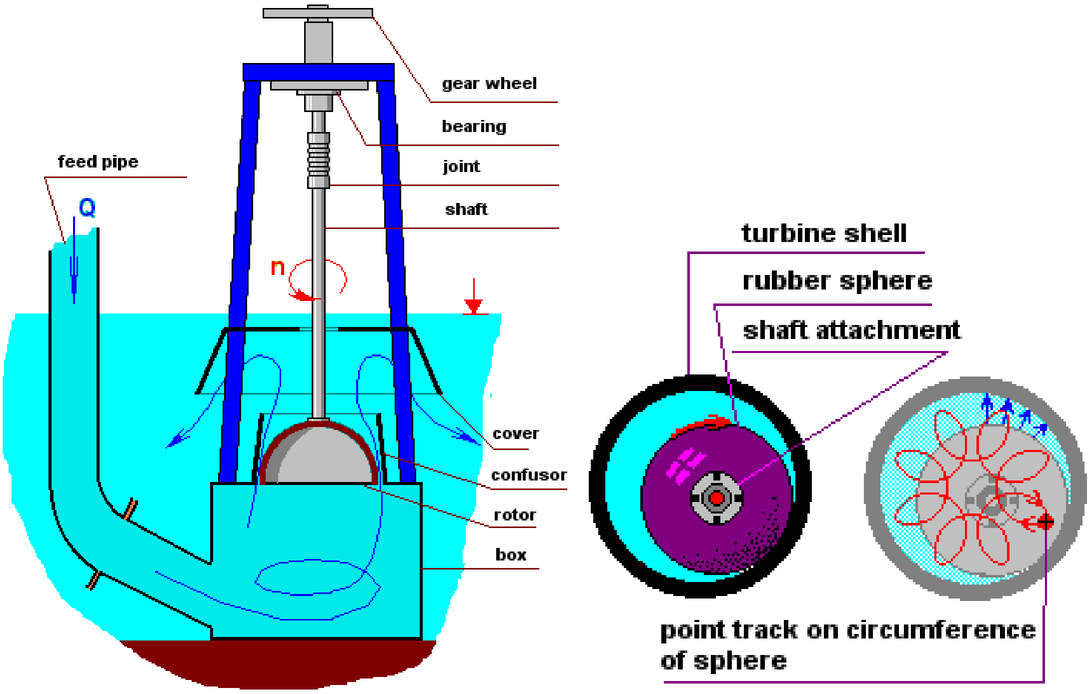


Fig. 4.13 Principle of SETUR water motor function, rotor movement

Vortex power plant

Austrian invention in the prototype stage. Drainage 0.5 - 2 m, power 0.2 - 160 kW

Fig. 4.14 Left: vortex power plant, Right: Zotlöterer turbine

Utilization of HPP in Water Industry

An important opportunity is the construction of hydroelectric power plants by water companies and the use of the hydroelectric potential of the incoming water. Therefore, some of the water companies in the Czech Republic have taken advantage of this energy and built HPPs on water intakes to water treatment plants or reservoirs.

The simplest system consists of an asynchronous generator and a modified suitable pump operating in turbine mode.

In the Czech Republic there are about 30 SHPPs in water supply systems and they produce about 25 GWh in total. The total installed capacity of these SHPPs is about 8 MW. The payback rate is about 4 years, moreover, the SHPP helps aeration and mixing of water treatment agents.

Summary of terms 4.4.

Vortex turbine, Setur turbine, vortex power plant.

Questions 4.4.

1. Which turbine type is the design of the vortex turbine based on?

ADDITIONAL RESOURCES 4

[1] Holata, Miroslav. Small hydropower plants - design and operation. Academika, 2002, 271 pp. 80-200-0828-4

[2] MOTLÍK, J. et al. Renewable energy sources and their potential application in the Czech Republic: a study analyses the current status and assumptions for development in the longer term. Prague: ČEZ, 2007. 183 p.

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[6] Vodní elektrárny - princip, rozdělení, elektrárny v ČR. Available: https://oenergetice.cz/obnovitelne-zdroje/vodni-elektrarny-princip-a-rozdeleni

5. RENEWABLE ENERGY SOURCES

Share of renewable energy sources (RES) in gross electricity consumption in the Czech Republic:

- Gross household electricity consumption in the Czech Republic in 2022 = 78.8 TWh
- Share of RES in gross household consumption = 18.2%

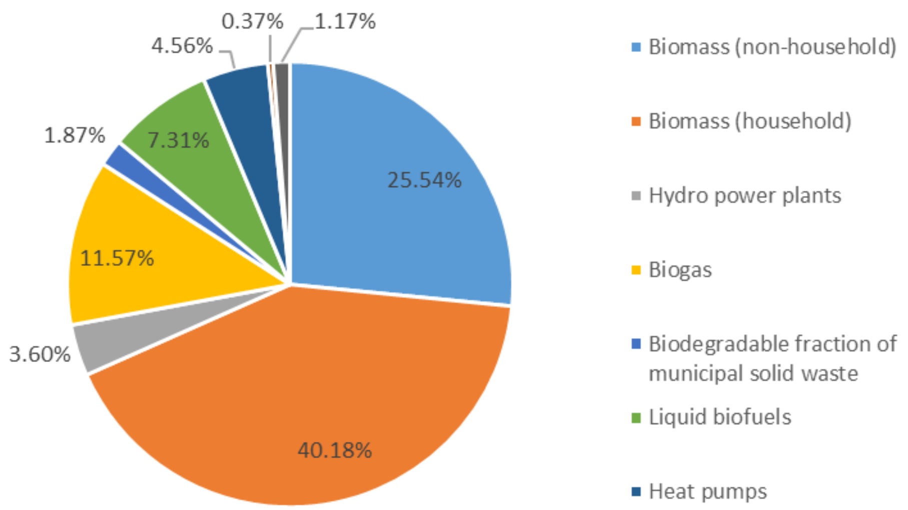


Fig. 5.1 Structure of RES in the Czech Republic

	Benefits	Disadvantages	Restrictions
Biomass	Combustion of purpose-grown biomass does not increase CO_2 emissions into the air; biomass can be used for biofuel production.	NO_x emissions to air during combustion; use of agricultural land for biomass cultivation.	Need for agricultural land for biomass production, degradation of arable land, creation of monocultures.
Water energy	No CO_2 emissions into the air; zero waste production; ability to quickly connect to the grid.	High investment costs; environmental impacts - damage to biodiversity; variable hours of operation.	Availability of a suitably located water source; ocean energy requires coastal infrastructure; investment in the grid.
Waste	Direct incineration or biogas production; solving the waste disposal problem.	Emissions of greenhouse and hazardous gases into the air; risk of odour nuisance to the surrounding area.	Location close to where waste is produced or near a landfill.
The Wind	No emissions of CO_2 into the air; zero waste production; zero waste production during operation.	High investment costs; potential noise; intermittent power generation.	Requires a suitable location; high investment in the grid; necessary accessibility of the building for heavy equipment.
The Sun	No CO_2 emissions to air; zero waste production; zero waste production during plant operation; low operating costs.	Used cells are hazardous waste; dependence on time and intensity of sunlight.	Suitable location and orientation to the sun; investment in the grid.
Geothermal energy	No CO_2 emissions to air; zero waste production; zero waste production during plant operation; continuous energy supply.	High investment costs; possibility of leakage of toxic volcanic gases.	Highest efficiency in geologically suitable areas.

Tab. 5.1 Advantages and disadvantages of RES

5.1. Wind power plants

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- list the different parts of the power plant
- describe the function of a wind power plant

EXPLANATION

Wind is caused by the uneven heating of the Earth's surface by solar radiation. From the heated surface, the adjacent layer of air is heated and the warm air tends to rise upwards. The whole process is strongly influenced by the rotation of the Earth and the alternation of day and night, resulting in pressure differences in the Earth's atmosphere. The equalization of the pressure differences produces a wind that always blows from pressure high to pressure low. Around the pressure low in the northern hemisphere, the spinal motion is counter clockwise, at the pressure high clockwise. In the southern hemisphere, the sense of rotation is reversed for the pressure high and low.

Resulting equation for wind power:

$$P_v = \frac{1}{2} \cdot \rho \cdot v^3 \quad \left(W.m^{-2}\right)$$

where v represents the air velocity and ρ its density.

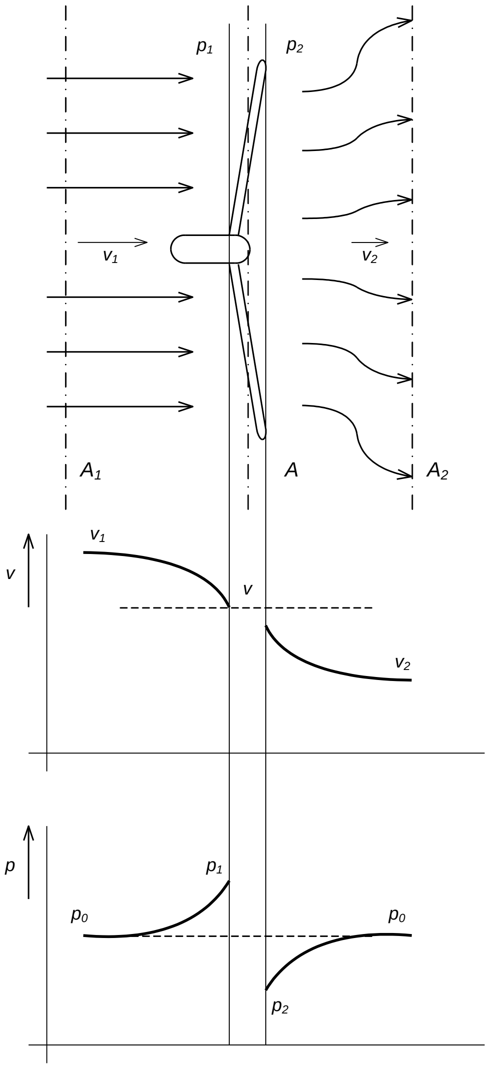


Fig. 5.2 Air pressure and wind speed as the turbine passes through the turbine

Division of wind engines

Wind engines are devices that are used to convert the kinetic energy of the wind into mechanical energy. In wind turbines, the kinetic energy of the wind is first converted into mechanical energy, which is then transformed into electrical energy. The classification of wind power plants can be made according to many different aspects, but the basic division is made according to the aerodynamic principle of the wind motor function, namely:

- resistive motors
- buoyancy motors

Wind motors can be further classified according to the rotation axis arrangement (horizontal and vertical), the installed power and the speed coefficient into slow-speed and fast-speed.

For the axial force F_a acting on the wind motor blades and for the wind power P we can write the equations:

$$F_a = \frac{1}{2} \cdot \rho \cdot A \cdot \left(v_1^2 - v_2^2\right)$$

$$P = \frac{1}{4} \cdot \rho \cdot A \cdot \left(v_1^2 - v_2^2\right) \cdot \left(v_1 + v_2\right)$$

Wind power equipment

Asynchronous and synchronous generators are used to produce electricity in wind power plants.

Compared to a synchronous generator, an asynchronous generator is simpler, less expensive and more reliable in terms of operation. The disadvantage of the asynchronous generator is the small speed range. On the other hand, the advantage of an asynchronous generator is its easy start-up, connection to the grid and power control.

The synchronous generator can only be operated at synchronous wind turbine speed. In order to operate the synchronous generator over a wider range of speeds, it is necessary to rectify the generated electricity and then convert it back to grid frequency using an inverter.

A typical wind power plant design is shown in the figure below Fig. 5.3. A wind power plant consists of the following basic parts: 1 - wind engine with rotor head, 2 - rotor brake, 3 - gearbox, 4 - clutch, 5 - generator, 6 - servo drive for winding the machine room, 7 - machine room brake, 8 - bearings, 9 - sensor for sensing wind speed and direction, 10 - power plant tube (mast), 11 - concrete power plant foundation, 12 - power distribution equipment and control circuit, 13 - electrical connection.

Wind motor regulation

Fixed blades - rotation of the rotor up to 90° against the wind direction, flaps, extendable protrusions, separate blade ends rotating around the radial axis of the blade when exceeding a set speed, or rotating blades.

Brakes - hydraulic and or small blades at the end of the large.

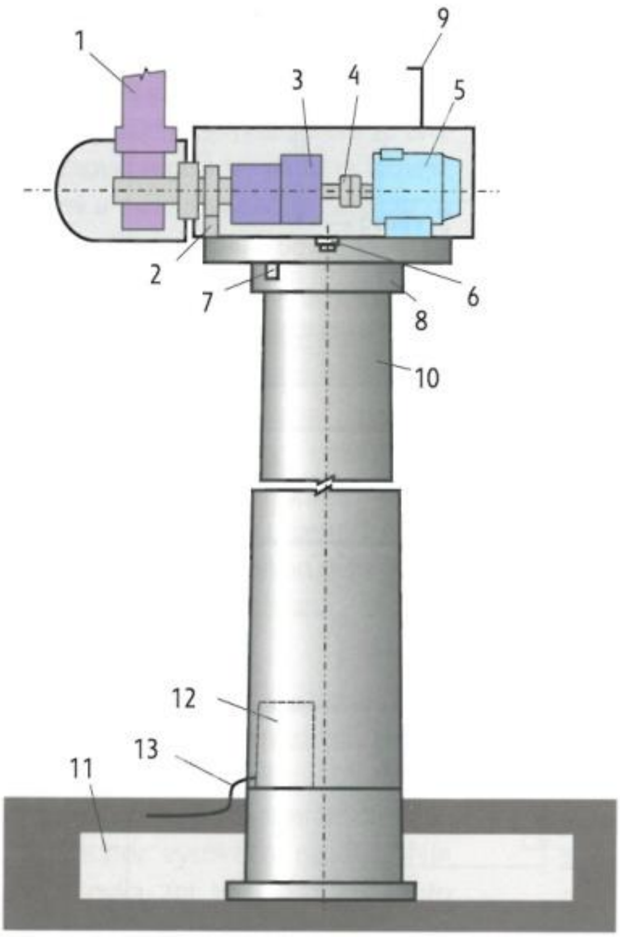


Fig. 5.3 Wind power plant design

Summary of terms 5.1.

Wind engines, wind power, VE equipment.

Questions 5.1.

1. Draw how air pressure and wind speed behave when passing through a turbine?
2. What does the performance of a wind motor depend on?
3. What are the main parts of a wind power plant?

5.2. Photovoltaic power plants

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to
- list the different parts of the power plant
- describe the function of a photovoltaic power plant

EXPLANATION

Basic principle of PV cell

The basic principle of the PV cell is the photoelectric effect, in which electrons are released from the substance due to the absorption of electromagnetic radiation by the substance. The absorption is caused by the interaction of light (photons) with particles of matter (electrons and nuclei).

For the PV cell to work, it is essential that a photon from the sun's radiation releases an electron in the substance to form an electron-hole pair. In metals, however, there will be an immediate recombination of the two, which must be prevented and the resulting charge removed from the cell. For this purpose, semiconductors are used in which the electrons and holes are separated by the internal electric field of the PN transition.

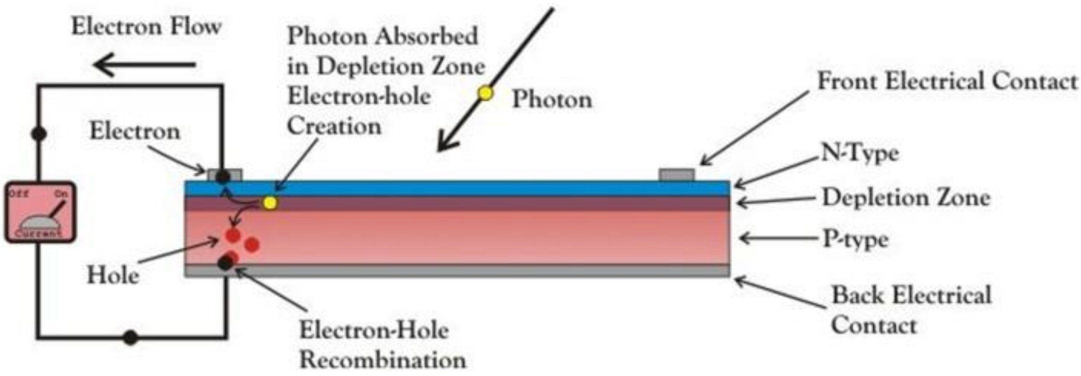


Fig. 5.4 Structure of a photovoltaic cell [6]

Materials for PV

The most widely used material for the production of photovoltaic cells is silicon (Si). Due to the width of the forbidden band, very high efficiency of free carrier generation by incident solar radiation can be achieved for silicon. At the same time, for silicon, as a basic material for microelectronics, all the technological operations needed to create structures have been very well mastered.

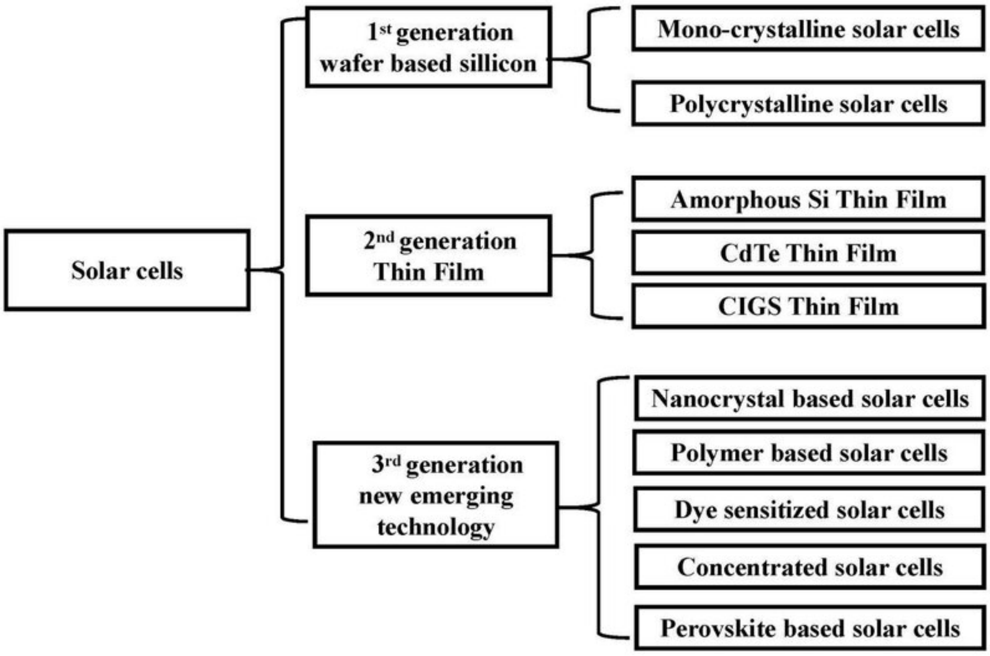


Fig. 5.5 Materials for photovoltaic cells [7]

Solar nanocells - materials made up of individual atoms improve the ability of solar cells to harness light by a factor of ten.

Effects on the function of solar panels

In order to increase the efficiency of a PV plant, the following influences must be considered in the design:

- Directional orientation (optimum azimuth 180 ±10°)
- Tilt angle of PV panels (year-round 45°, adjustable -60° for winter operation, 35° for summer operation)
- Custom design of PV panels ("colour" of cells, surface texture)
- Quality of PV system design and execution (professional experience with installations)
- Location in the terrain (screening by surrounding objects or trees)
- PV system pollution
- Location within the Czech Republic (negligible differences between installations in the Czech Republic)

Summary of terms 5.2.

Photoelectric phenomenon, materials for photovoltaics, effects on PV power plants function.

Questions 5.2.

1. Explain the principle of the photoelectric effect.
2. What is the basic material for manufacturing PV cells?
3. What are the influences on PV function?

5.3. Use of biomass

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- describe the possibilities of biomass utilisation

EXPLANATION

Biomass is an inherent part of renewable energy sources. Biomass can be described as converted solar energy captured by plants and stored as chemical energy. If land is used economically, biomass could be said to be available all the time. Its great advantage is its minimal impact on the amount of CO_2 in the air when it is burned.

Biomass is a CO_2 neutral fuel - i.e., when used rationally, emissions of this major greenhouse gas are equal to its consumption in newly growing biomass; emissions of other pollutants are also lower than those of the most commonly used fossil fuels when standardized biofuels are burned efficiently.

Plants are the primary producers of biomass, as they are able to use the light energy captured in the green dye chlorophyll to produce carbohydrates and subsequently protein. These are the basic "building blocks" of all living organisms - biomass. This reaction is the synthesis of atmospheric CO_2 and water using the energy of sunlight (photosynthesis).

Theoretically, all forms of biomass can be used for energy production, because the basic building block of living matter is carbon and the carbon bond that contains the energy.

❑ Benefits of :

- Closed CO_2 cycle,
- safe transport and storage,
- positive energy balance (the energy spent on extracting biomass is less than that released in its energy recovery),
- RES comes from the region,
- fossil fuels expensive - finance to other countries,
- lower dependence on fossil fuels,
- farmers and foresters produce biomass but also know how to use it for energy (local level) - increase jobs (regional development).

❑ Biomass in terms of generation

1. residual biomass from agriculture

- crop residues from primary agricultural production, especially cereal and rape straw
- organic residues from agricultural production, especially manure
- organic or vegetable residues from the processing industry, especially dairy and food processing (e.g. vegetable oilseed packaging - sunflower, fats)

2. residual biomass from forestry

- logging waste from forest management (e.g. from pruning, thinning, clearing)
- combustible waste from sawmilling, wood and paper industries

3. 1st generation energy crop biomass

- rapeseed and oil palm, wheat and maize (oil, bioethanol)
- Rye (for pellets)

4. 2nd generation energy crop biomass (lignocellulosic crops)

- woody plants: e.g. poplars, willows, eucalyptus
- non-woody plants: energy sorrel, ornamental plants, millet, etc.

thermochemical transformation	pyrolysis (gas, oil production)
	gasification (gas production)
biochemical transformation	fermentation, alcoholic fermentation (ethanol production)
	anaerobic digestion, methane fermentation (biogas production)
mechano-chemical transformation	oil pressing (production of liquid fuels, oils)
	esterification of crude bio-oils (production of biodiesel and natural lubricants)
	chipping, crushing, pressing, pelletizing, weeding (production of solid fuels)

Tab. 5.2 Use of biomass in the energy sector

Combustion, gasification of biomass

- Dry biomass releases flammable gaseous components, called wood gas, when exposed to high temperatures.
- With air - simple combustion
- Without air access - exhaust to the combustion chamber, part of the heat used for gasification of other biomass

The advantage is easy power regulation, lower emissions, and higher efficiency.

Biomass is a very complex fuel because the proportion of the parts gassed during combustion is very high (70 % for wood, 80 % for straw). The gases produced have different combustion temperatures. Therefore, it also happens that only part of the fuel actually burns. The prerequisites for perfect combustion are a high temperature, efficient mixing with air and enough space for all the gases to burn well and not burn up in the chimney.

❑ Biomass calorific value

The calorific value of biomass varies with the type of wood, the plant and with the moisture to which these fuels are more sensitive

The energy content of 1 kg of wood with zero water content is about 5.2 kWh. With a residual water content of 20% of the dry weight of the wood, part of the energy is consumed in the combustion process to evaporate the water, the energy content will be 4.3 - 4.5 kWh per 1 kg of wood.

❑ Biogas

Biogas is produced by the decomposition of organic matter (manure, green plants, sewage sludge) in closed tanks without oxygen.

Of the agricultural wastes, manure, possibly also straw manure, straw, grass residues, corn stalks, potato stalks and others are mostly used for energy.

Straw, sawdust and other waste can also be processed in this way, but the process is slower.

In a biogas plant, the biomass is heated to operating temperature in an airtight reactor. The usual temperature is 37 to 43 °C for mesophilic bacteria and 50 to 60 °C for thermophilic bacteria. The principle of developing biogas is very simple, but because safety standards must be met, the equipment becomes complex and therefore more expensive.

❑ Fermentation of biomass

By fermenting sugar solutions, ethanol (ethyl alcohol) can be produced. Suitable materials are sugar beet, grain, corn, fruit or potatoes. Sugars can also be made from vegetables or cellulose. Theoretically, from 1 kg of sugar, 0.65 l of pure ethanol can be obtained, which is a highly valuable liquid fuel for internal combustion engines (advantage - environmental purity and anti-knock properties, disadvantage - ability to bind water and cause engine corrosion. Research is underway in the USA to produce ethanol from cellulose using specially bred micro-organisms. Ethanol can then be extracted from wood or grass.

Summary of terms 5.3.

Biomass, combustion, gasification, biomass calorific value, biogas, fermentation.

Questions 5.3.

1. What is biomass?
2. What are the benefits of using biomass?
3. What is the approximate calorific value of wood?

5.4. Fuel cells

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- describe the function of a fuel cell
- list the different parts of the power plant

EXPLANATION

The basic principle of the fuel cell

A fuel cell is a galvanic cell that generates electricity from the energy released by the chemical reaction of a continuously fed fuel with an oxidizing agent. Usually this term refers to an oxygen-hydrogen fuel cell. They produce electricity directly and should therefore be more efficient, simpler and more reliable.

A fuel cell consists of two electrodes separated by a membrane or electrolyte. The fuel is fed to the anode and oxidised there. The cathode receives the oxidising agent, which is reduced there. Electrodes - metals or carbon nanotubes, coated with a catalyst (higher efficiency). Electrolyte - acids or bases, ceramics or membranes. The electrical voltage is around 1.23 V and depends on the fuel type and cell quality; multiple cells are included in series.

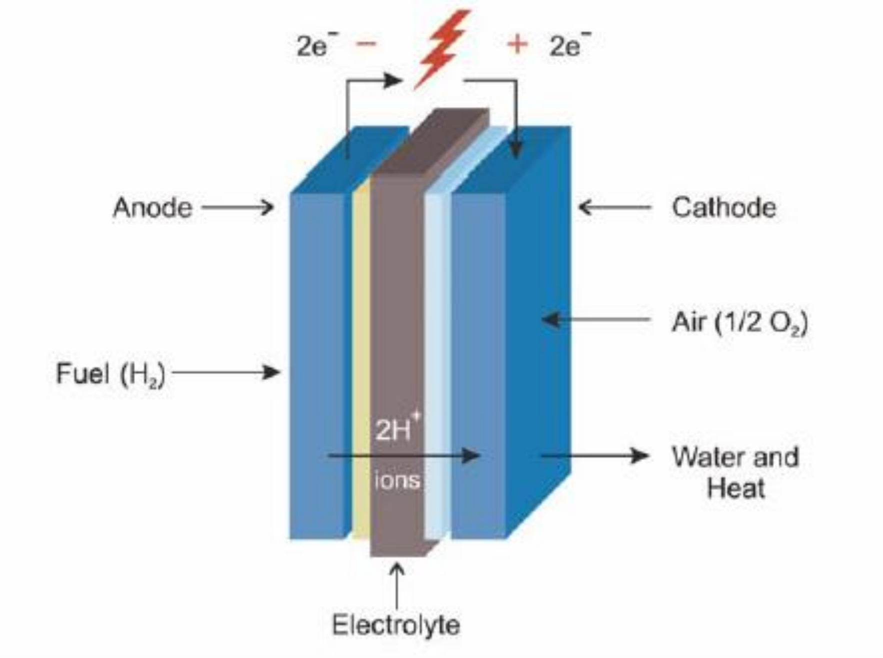


Fig. 5.6 Composition of the fuel cell

Reactions

The fuel (e.g. H) is catalytically converted to cations (H^+) at the anode. The released electrons are picked up by the anode and produce an electric current which flows through the electrical appliance to the cathode. At the cathode, the oxidizing agent (usually O) is reduced to anions (O_2^-), which then react with the H^+ ions to form water.

Oxidation / electron donation

$$\text{Anode}: 2H_2 \rightarrow 4H^+ + 4e^- \quad (5.1)$$

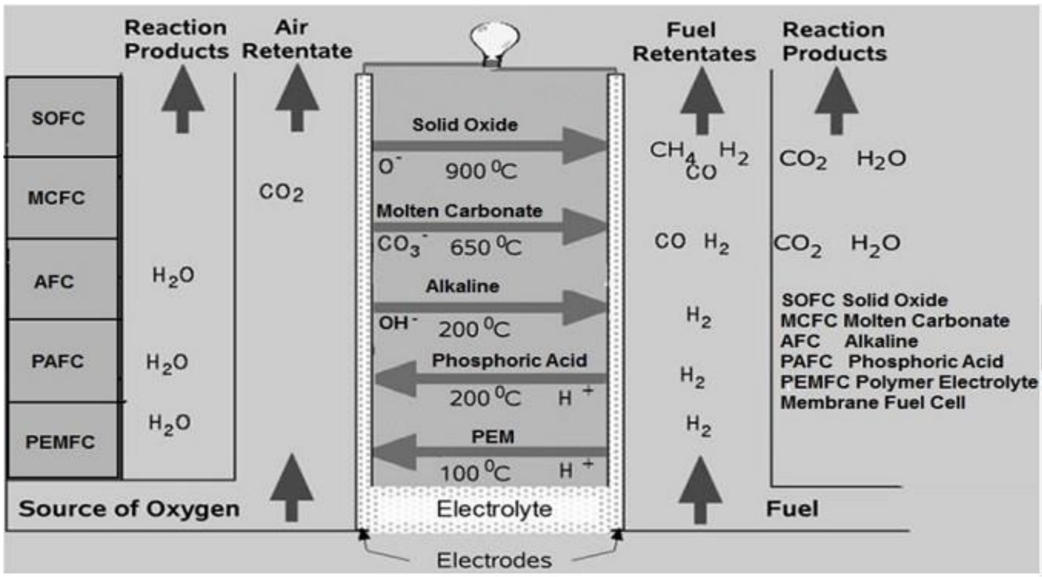
Electron reduction/reception

$$\text{Cathode}: O_2 + 4e^- \rightarrow 2O_2^- \quad (5.2)$$

$$2.\text{step}: 2O_2^- + 4H^+ \rightarrow 2H_2O \quad (5.3)$$

Redox reactions

$$\text{Result}: 2H_2 + O_2 \rightarrow 2H_2O \quad (5.4)$$



Tab. 5.3 Types of fuel cells [8]

Benefits of fuel cells

- free of pollutants,
- higher thermodynamic efficiency,
- operate at low operating temperatures,
- Combined heat and power (CHP) applications,
- low noise level,
- simple design.

Disadvantages of fuel cells

- difficult to produce and store,
- require relatively clean fuel,

- very expensive,
- PEM FC must not dry out,
- removal of residual water.

Summary of terms 5.4.

Fuel cell, reaction, oxidation, reduction.

Questions 5.4.

1. Describe the principle of a fuel cell.
2. Write the chemical reactions that take place at the electrodes.

ADDITIONAL RESOURCES 5

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6. ELECTRICAL PART OF POWER PLANTS

6.1. Alternators

TIME TO STUDY:

3 hours

TARGET:

After studying this paragraph, you will be able to

- describe the types of alternators, their design features and parameters
- explain the operation of alternators
- list the types and explain the principles of alternator protection describe the function

EXPLANATION

In most power plants, synchronous alternators are used to generate electricity, only in small hydro and wind power plants are asynchronous generators (both short-armature and winding armature) sometimes used for this purpose. Alternators are available in a wide range of outputs and output voltages.

Important parameters of alternators

- Turns:

The synchronous speed of the alternator n_S depends on the number of pole pairs p of the machine and the frequency f of the network to which it operates.

$$n_s = 60 \cdot \frac{f}{p} \; (Hz; -; ot \cdot \min^{-1}) \qquad (6.1)$$

The speed can also be expressed in terms of the angular velocity ω:

$$\omega = \frac{2 \cdot \pi \cdot n_s}{60} \; (ot \cdot \min^{-1}; rad \cdot s^{-1}) \qquad (6.2)$$

The mechanical power on the shaft of the PM machine is calculated by multiplying the torque M and the angular velocity ω.

$$P_M = M \cdot \omega \; (N \cdot m; rad \cdot s^{-1}; W) \qquad (6.3)$$

- Power factor (PF):

The effect of the machine can be changed by changing the excitation. For large machines, it reaches values of 0.85 to 0.95. The choice of power factor depends on the location of the machine and its role in the power system. The price of the alternator also increases as the power factor decreases. For an alternator in island mode, its power factor is determined by the mix of appliances it supplies.

- Short-circuit ratio - is the ratio of the stator short-circuit current I_{KO} to the rated stator current I_N during excitation corresponding to the rated voltage of the machine. It can also be expressed as the inverse of the synchronous reactance.

$$\nu = \frac{I_{KO}}{I_N} \quad (A; A; -) \tag{6.4}$$

The size of this parameter affects a number of machine characteristics. As the ratio decreases, the influence of the armature reaction increases and this leads to changes in the clamp tension (the machine is so called soft). From the point of view of the static stability of the machine, it is desirable that the short-circuit ratio of the machine is as large as possible. However, as the short-circuit ratio increases, the weight and therefore the price of the machine also increases. In general, the lower the short-circuit ratio, the greater the requirements for the dynamic properties of the excitation controller.

- Reactance:

When supplying power to the grid, the alternator has an impedance that depends on the operating condition of the machine and its design. Since the active resistance of the winding is small compared to its reactance, it is usually not considered. Therefore, we only talk about the reactance of the machine. The values of the individual reactances can be expressed in either absolute or ratio values. Their measurement is dealt with in standard IEC 34-4.

Parameter		Turbo-alternators	Hydro-alternators
synchronous longitudinal reactance	-	1.2 - 3	0.7 - 1.4
synchronous transverse reactance	-	1.1 - 2.2	0.45 - 0.9
transient longitudinal reactance	-	0.15 - 0.3	0.2 - 0.4
longitudinal impact reactance	-	0.09 - 0.3	0.15 - 0.35
impact reactance transverse	-	0.1 - 0.25	0.15 - 0.7
transient time constant at idle	s	2 - 10	3 - 10
zero reactance	-	0.02 - 0.15	0.03 - 0.15
reactance	-	0.09 - 0.3	0.12 - 0.4
transient time constant short	s	0.6 - 1.5	0.8 - 2.5
impact time constant short	s	0.02 - 0.08	0.04 - 0.1
time constant of the DC component	s	0.05 - 0.5	0.1 - 0.4

Tab. 6.1 Overview of turboalternator reactance ratios

- **Hydroalternator**

In contrast to steam turbines, it is difficult to achieve high speeds with water turbines. Multi-pole machines with protruding poles, called hydro alternators, are therefore used. These have rated speeds in the tens to hundreds of revolutions per minute. The arrangement of the machine is most often vertical, but especially in small power plants it can also be inclined or horizontal. Cooling of the machine is easier than for a turboalternator due to the larger rotor area and the gaps between the protruding poles. The rotors of large machines are cooled by air, the stator can be cooled by water.

The excitation winding consists of coils which are placed on the cores of the individual poles. The pole extensions may then contain damping windings in the form of rods.

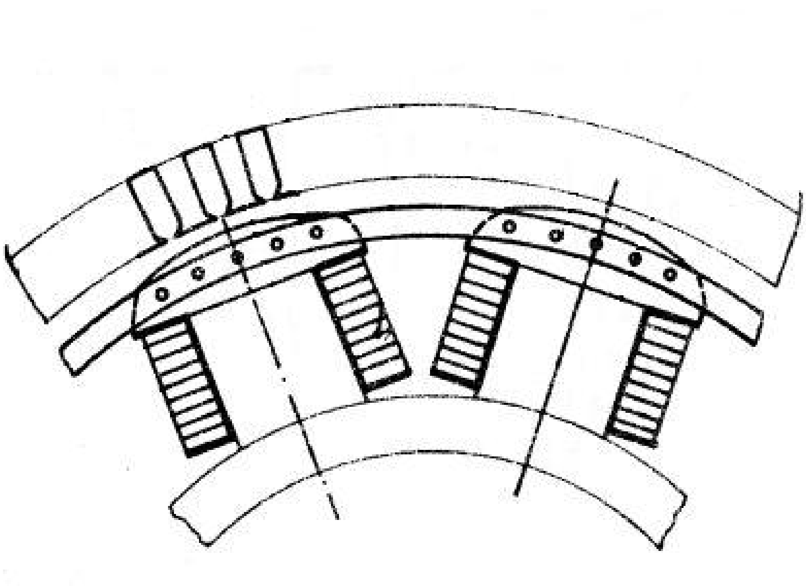


Fig. 6.1 Part of the rotor and stator of a hydroalternator

Fig. 6.2 Stator and rotor of hydroalternator (Štěchovice power station)

Turboalternator

Turboalternators in steam and nuclear power plants are smooth rotor machines, most often two-pole (i.e. 3000 rpm for 50 Hz). This is because a steam turbine has its highest efficiency at speeds in the thousands per minute range. Only very high power machines use a four-pole rotor due to its limited mechanical strength.

On the rotor of the turboalternator there are grooves in which the excitation winding is placed. The winding is secured in the grooves by wedges made of non-magnetic materials, which can also act as a damper (shock absorber). Due to the high speed of the rotor, the rotor is subject to considerable centrifugal forces and it is therefore desirable to keep the rotor diameter as small as possible. However, as the rotor diameter decreases, the rotor length increases, which complicates the situation - the longer the rotor, the more vibration is generated during machine operation. In addition, there is a risk of sagging. That is why high power machines are equipped with an electric motor that continuously rotates the rotor during downtime, eliminating the risk of shaft sagging.

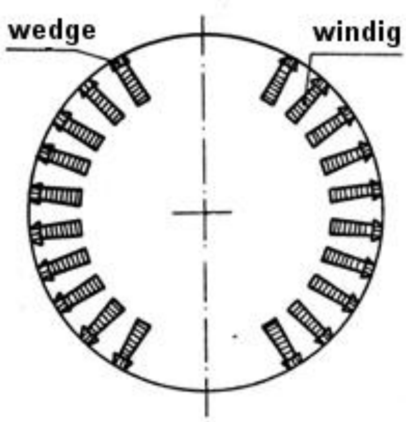


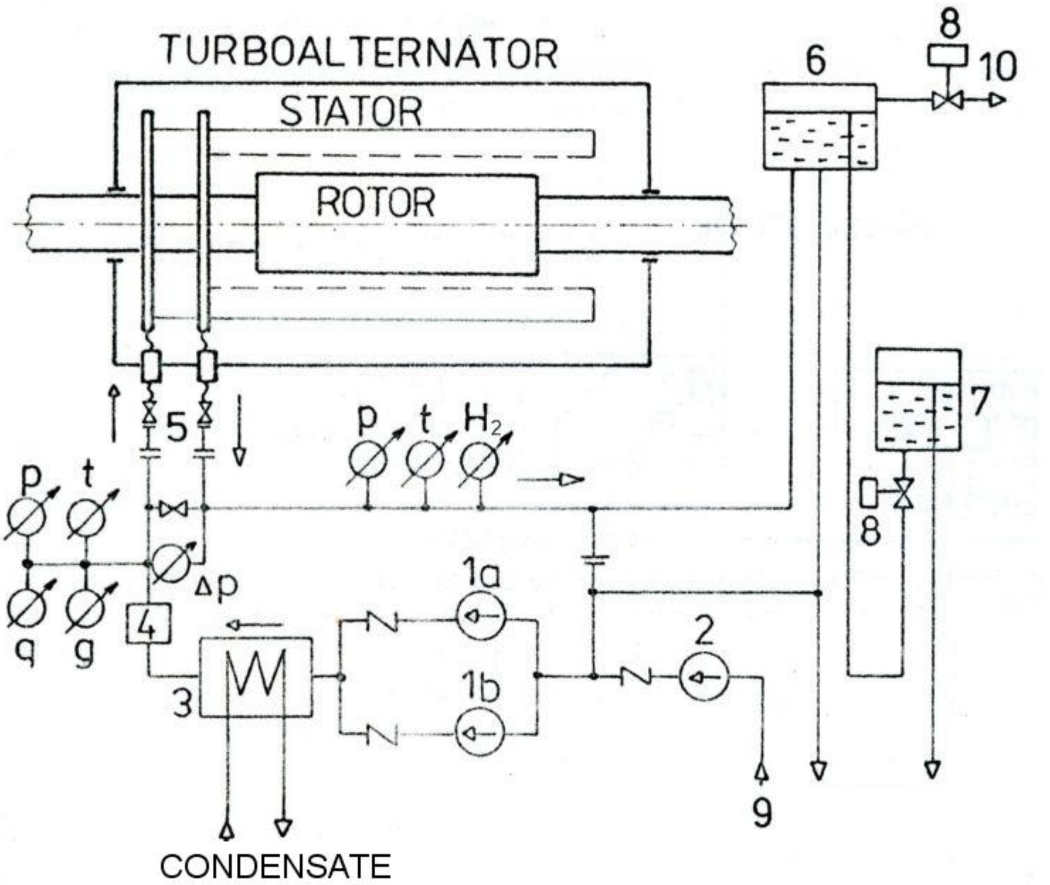
Fig. 6.3 Cross-section of the turboalternator rotor

Fig. 6.4 Stator of turboalternator and its exciter (Dětmarovice power plant)

Cooling

Although the efficiency of alternators is considerable (up to 99%), they develop a large amount of heat that must be dissipated. It is also desirable to keep the temperature of the windings constant, thus avoiding mechanical stresses that shorten the life of the insulation. For low-power machines, air cooling is sufficient, but the waste heat cannot be used in any way and there is a risk of fire in the event of an accident. Cooling of high power machines is therefore provided by other media - usually hydrogen, water or a combination of both.

The stator winding is most often cooled by water (e.g. feed water via an exchanger). The water flows either through hollow conductors or through special inserts in the winding. The magnetic circuit of the machine can also be cooled by axial channels. The advantage of water is its non-flammability, low viscosity and it also does not chemically affect the insulation material.

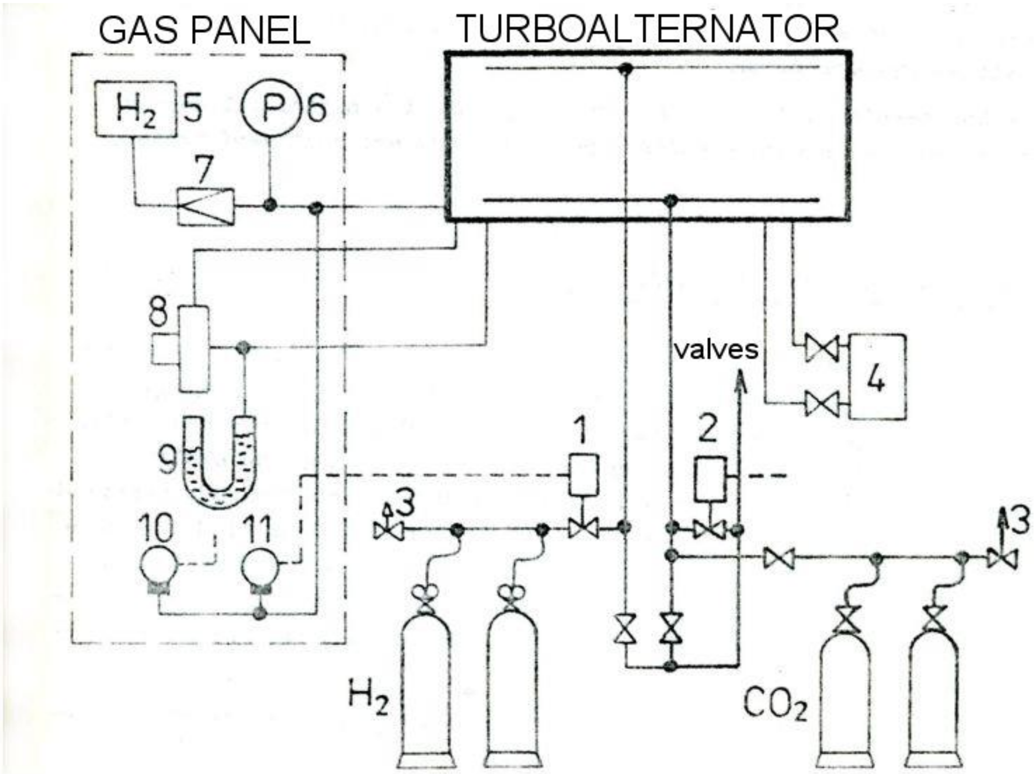


1 - working pump
2 - feed pump
3 - cooler
4 - mechanical filter
5 - removable pads

6 - balancing vessel
7 - overflow tank
8 - automatic closure
9 - clean water from filter station
10 - outlet to degassing pump

Fig. 6.5 Water cooling of the turboalternator

The rotor is usually cooled by hydrogen. Compared to air, it has a higher heat capacity and due to its low density, there are lower ventilation losses. The hydrogen atmosphere also protects the rotor from possible fire in the event of a crash and prevents ozone oxidation of the insulation. The alternator is housed in an airtight enclosure and the shaft pins are fitted with oil seals. Hydrogen circulation is provided by a compressor which can be driven by the turbine itself. During initial filling, the alternator housing must first be filled with inert gas to prevent the formation of a shaky mixture. The pressure of the hydrogen is higher than the pressure of the stator cooling water - so if there is a leak, hydrogen will leak into the cooling water where it can be detected quite easily. The waste heat can be supplied to the feed water via an exchanger.



1, 2 - overflow valves
3 - safety valve
4 - hydrogen desiccant with silica gel
5 - hydrogen thermal conductivity analyser
6 - pressure measurement
7 - constant flow regulator
8 - measuring fan
9 - gas purity measurement during filling
10 - pressure indication
11 - automatic hydrogen admission

Fig. 6.6 Hydrogen cooling of the turboalternator

❑ Damping winding (shock absorber)

It is a rotor winding permanently short-circuited. In steady synchronous operation, it is not applicable as the mutual speed of the rotor and stator magnetic field is zero. However, when the operating point changes, currents begin to induce into it and the resulting electromagnetic forces and fields affect the machine characteristics. The use of a damping winding brings a number of advantages: it reduces rotor heating under unbalanced loads, protects the excitation circuit against overvoltages and current surges, reduces rotor sway and improves static and dynamic stability. It also reduces the overvoltage resulting from an unsymmetrical short circuit on the unaffected phase. If the damping winding is properly sized, it can be used to start the machine. Its disadvantages are, however, the higher cost of the machine and the greater stress on the pole attachments, and it increases the current surges during short circuits.

The winding itself can be implemented in several ways. They can be flat wires placed in each groove under the locking wedge. The locking wedges themselves can also be used as a damper if their faces are properly connected. In hydroalternators, the damping winding is formed by the rods in the pole extensions or by the pole extensions themselves (if they are made of solid material).

Alternator outlets

Alternator outlets can be made in several ways. For low power machines, cables or strip wires are used. However, for high power machines, the forces acting on the conductors during a short circuit must be taken into account. Therefore, encapsulated conductors insulated with SF_6 gas are used.

The use of encapsulated conductors brings a number of advantages. The individual phases are safely separated from each other, thus avoiding possible inter-phase short circuits. The magnetic field around the conductors is also reduced, so that eddy currents are not induced in the surrounding metal structures. Losses due to eddy currents induced into the housing body can be reduced by suitable bonding and earthing.

Alternator excitation

The excitation winding of the alternator is fed from the exciter by DC current. The magnitude of the excitation current influences the amount of reactive power produced and thus the power factor of the machine (the exciter power is about 0.5% of the alternator power). The parameters of the exciter significantly affect the stability of the alternator and therefore considerable demands are placed on the exciter. The exciter must be reliable, allow a rapid change of excitation current and have a high excitation ceiling (in case of a mains failure, the alternator may need to be stepped up).

Wake-up can be done as direct or indirect. In direct excitation, the rotary exciter is located on a common shaft with the alternator. In indirect excitation, the rotary exciter is driven by its own motor, or the exciter is implemented by a static source. Direct excitation is most often used, indirect excitation is usually used only as a backup in case of failure of the direct exciter.

- Derivative exciter - consists of a derivative dynamo, which is located on a common shaft with the alternator. This system is used only for small alternators, as it is not able to provide continuous regulation of the alternator voltage at low values of excitation current.

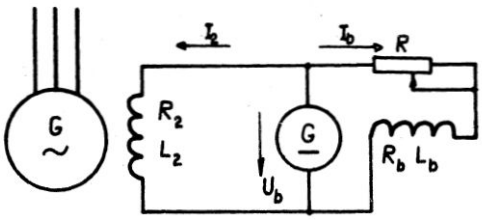


Fig. 6.7 Derivative exciter

- Auxiliary exciter - The alternator is located on a common shaft with the main and auxiliary exciter. The auxiliary exciter energizes the main exciter which supplies the alternator excitation. While this arrangement has less operational reliability, it allows for smooth control over a wide range.

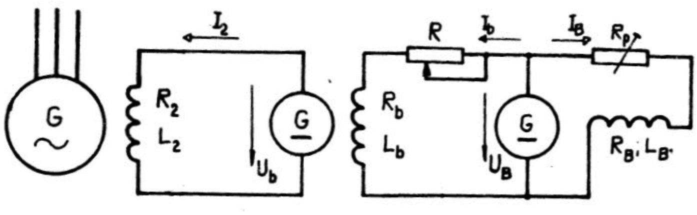


Fig. 6.8 Auxiliary exciter

- Power Diode Exciters - This system consists of an AC exciter and an auxiliary AC exciter that are on a common shaft with the alternator. The auxiliary exciter feeds the main exciter through a controlled rectifier, which uses power diodes to power the alternator excitation. The excitation is regulated by a controlled rectifier between the auxiliary and main exciter. The advantage of this system is the possibility of using AC exciters, which are more reliable (no commutator) and less maintenance intensive.

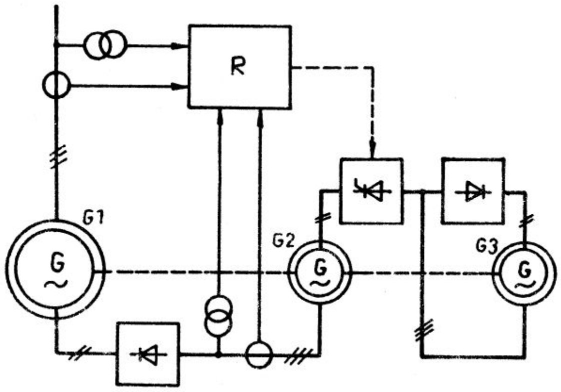


Fig. 6.9 Exciter with power diodes

- Exciters with power thyristors - The alternator is excited via a controlled rectifier from an exciter located on a common shaft or from an external source. This system has excellent dynamic characteristics and also allows the alternator to be quickly excited without the use of an exciter. Power to the thyristors is provided either by another rotary exciter or by an external source.

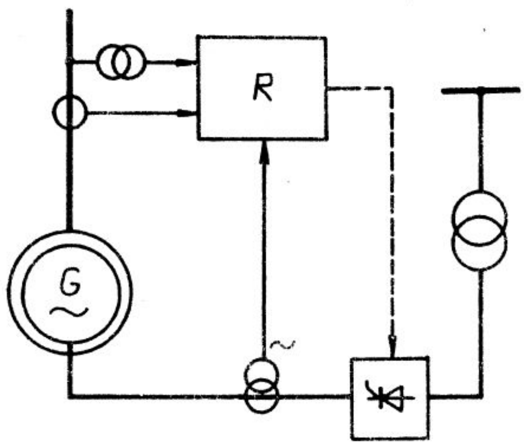


Fig. 6.10 Exciter with power thyristors

❑ Alternator deexcitation

Deexcitation are used during emergency conditions in which the alternator cannot be disconnected from the fault location (short circuits at the terminals and pins of the alternator, faults of block transformers, internal short circuits of the alternator, etc.). In these faults, the excitation cannot simply be disconnected as the resulting overvoltage could damage the insulation of the excitation winding. The job of the arrester is to thwart the rotor energy as quickly as possible to prevent damage to the equipment. In some cases, the exciter itself can act as a de-energiser (if it allows inverter operation). The rebuild is considered complete when the alternator terminal voltage drops below 500 V.

- Exciter with damping resistor - To the excitation winding of the alternator is connected in parallel a so-called damping resistor, in which the rotor energy is thwarted into heat (the size of this is one to three times the resistance of the excitation winding). The switch first short-circuits contacts 1 and 2 (to prevent current interruption and thus overvoltage in the excitation winding) and then permanently switches to contact 1. These de-energisers are used in alternators up to 100 MW.
- Extinguisher with extinguishing chamber - This extinguisher consists of an extinguishing chamber which is connected in series with the excitation winding and is bridged by contacts 1 and 2 during normal operation. The energy of the excitation winding is dissipated into heat in the quench chamber. When the excitation current drops to zero, the arc is extinguished. The de-energizing process is approximately 4 times faster than with a damping resistor.
- Exciter re-polarization - In this de-energization we re-polarize the excitation voltage source. However, it is necessary to continuously measure the terminal voltage of the alternator so that the exciter can be disconnected in time (otherwise the current of the opposite polarity would start flowing through the excitation winding). The actual implementation of the re-polarization depends on the design of the exciter. If the excitation winding is supplied by a controlled rectifier, re-polarisation is achieved by suitable control of the thyristors (inverter operation).

Alternator phasing

By rewired alternator we mean connected to the external network. In practice, we use two methods of phasing.

- Synchronous - This type of phasing is the most common as it does not involve large current and mechanical shocks. However, it is time consuming and requires complex automation. Several conditions must be met for a successful machine connection to the grid. The alternator must have the same phase sequence as the network to which we want to connect it. The voltage difference must be within 5 % (up to 20 % deviation is allowed in emergency conditions), the phase difference within 12 % and the frequency difference less than 0.1 %. The current surge is reactive in the case of a voltage difference and active in the case of a phase difference. Synchronous phasing was done manually in the past, using three bulbs. These bulbs bridged the contacts of each phase of the alternator switch and therefore flashed at twice the differential frequency of the alternator and the mains. The extinction of the bulbs signalled the minimum voltage difference between the alternator and the mains (so-called "dark phasing"), which is a good time for rephasing. In modern power plants, phasing is implemented by automatic systems.
- Asynchronous - It is used mainly in emergency situations where the voltage and frequency fluctuate in the network. In these cases, the synchronous phasing time is disproportionately long and there is a risk of unsuccessful rephasing due to changing network parameters. The derived machine is spun up to near-synchronous speed, phased and then spiked. The rotor pulls itself into synchronism. This type of synchronisation always produces a reactive current surge. This type of synchronisation is best done in machines with damping windings.

Extraordinary alternator operating states

- Asynchronous operation:

The asynchronous operation of the alternator occurs when the machine loses excitation, when the excitation current and the magnetic flux of the rotor starts to drop exponentially to zero (if the excitation circuit is not interrupted). The alternator ceases to be "braked" by the network, the load angle exceeds 90° and the machine falls out of synchronism. The rotor goes into over-synchronous speed and the machine starts to draw reactive power from the grid, which may result in a local voltage drop. In this mode, the alternator behaves like an asynchronous generator and currents with a slip frequency are induced in the rotor (for turboalternators the slip is in the range of 0.2 - 0.7%, for hydroalternators 3 – 5 %). The machine is still able to supply active power to the grid, but localised heating in the rotor body occurs. In addition, in the event of an interruption of the excitation circuit, dangerous overvoltages are generated in the excitation winding. Also, the stator current increases due to the magnetizing current, which increases with increasing short-circuit number of the machine. Turboalternators can therefore only be operated continuously in this condition at 30 % power or at half power for ten minutes. Asynchronous operation is not recommended for hydroalternators due to their high slip.

- Unbalanced load:

With unbalanced loads, a return current component of twice the grid frequency is generated. The reverse component induces currents in the rotor body that cause local heating. In addition, these currents generate electromagnetic forces that increase vibration during operation. For these reasons, the difference in currents in the individual phases must not exceed 10 % for turboalternators and 20 % for hydroalternators.

Alternator protection

As the alternator is a very expensive piece of equipment, it needs to be properly protected against faults and abnormal operating conditions to prevent damage or shortening of its life. The alternator should also be disconnected if its operation disturbs the stability of the electricity system. Therefore, the alternator is equipped with a protection system.

- Differential protection:

It is a protection with excellent selectivity, which finds application mainly in the detection of internal short circuits. These protections are further divided into longitudinal and transverse. Longitudinal protection compares the input and output of an object, transverse protection compares the inputs (or outputs) of two identical objects. If the difference of the measured quantities exceeds the set value, the protection is equipped. Transverse protections are used as protections for parallel branches of stator windings, longitudinal protections for block transformers and self-consumption transformers.

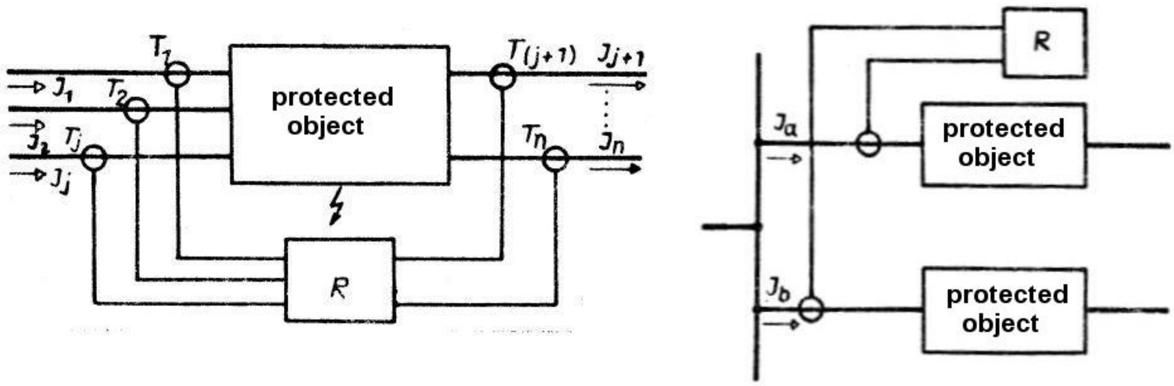


Fig. 6.11 Differential protection

- Overcurrent short-circuit protection:

This protection protects the alternator from short circuit and also acts as a backup for the differential protection. It is usually supplemented with an undervoltage cell to prevent false switching of the protection. In the event of a short circuit, the overcurrent link will switch on and the time machine will start (to ensure selectivity). After the set time has elapsed, the protection is equipped.

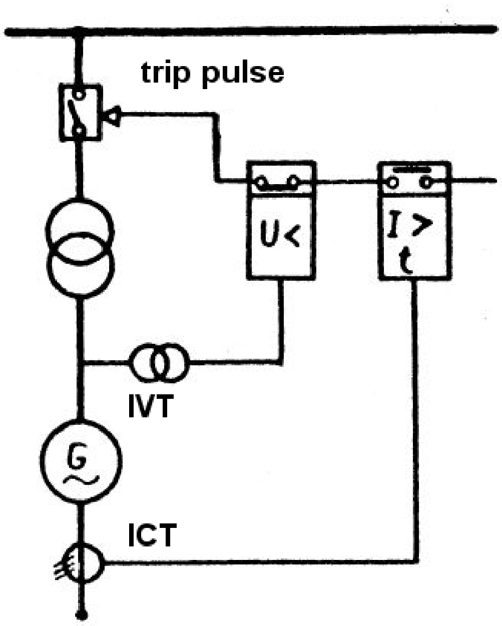


Fig. 6.12 Overcurrent short-circuit protection

- Impedance (distance) protection:

This protection measures the impedance of the short-circuit loop and thus protects the alternator from short-circuiting. In contrast to overcurrent short-circuit protection, it has better selectivity as its action does not depend on the magnitude of the short-circuit current and can thus operate without time delay.

- Ground protection of the alternator stator:

Protects the alternator stator from ground faults. Ground faults must be detected in time to prevent damage to the machine from ground faults (asymmetrical loading also occurs). The wiring of the protection varies according to the way the alternator is connected to the grid.

If the alternator operates in one block with the transformer, the protection evaluates the voltage between the machine node and ground or the current flowing from the node to ground. In this way, a ground connection can be detected within 95% of the windings.

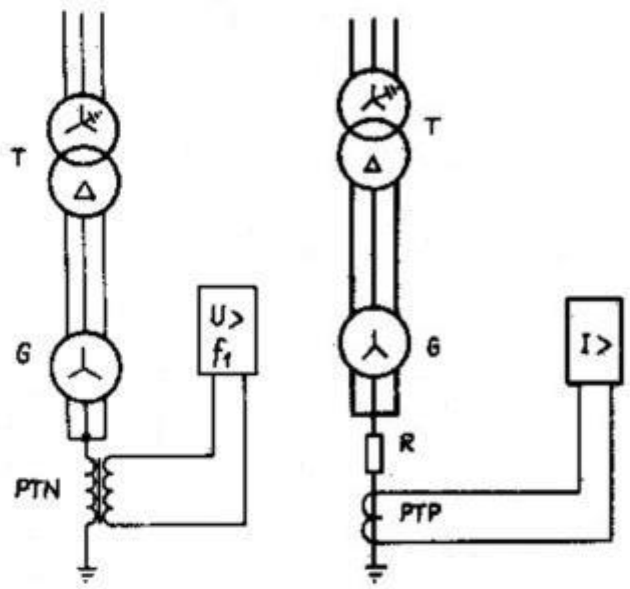


Fig. 6.13 Stator ground protection in block arrangement

If the alternator operates into busbars, it is first necessary to make calculations of the alternator and grid ground capacitance currents. In this case, the protection is equipped with a reactive cell that determines the direction of the capacitive current flow and thus can determine whether a ground connection has occurred in the grid or in the alternator.

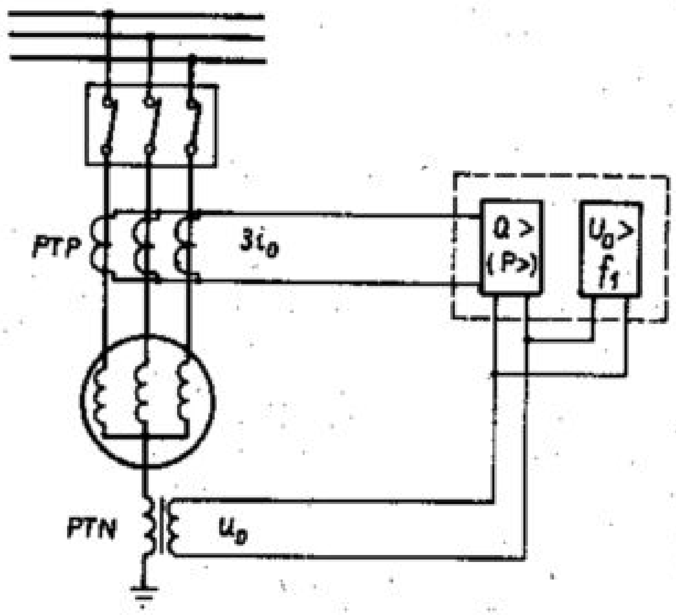


Fig. 6.14 Stator ground protection, alternator working into busbars

- Ground protection of the alternator rotor:

The ground connection of the alternator rotor occurs when the insulation of the excitation winding and its connection to the rotor body is damaged. If the connection occurs in only one place (so-called single connection), the machine can still be operated. However, if a second connection is made, a short circuit in the excitation circuit will occur and a severe alternator crash may occur. This protection does not stop the alternator, it only signals the connection. AC and DC superposition methods are used to indicate a ground connection. In both cases, the protection contains a current cell that detects the increase in current that occurs when a ground connection is made.

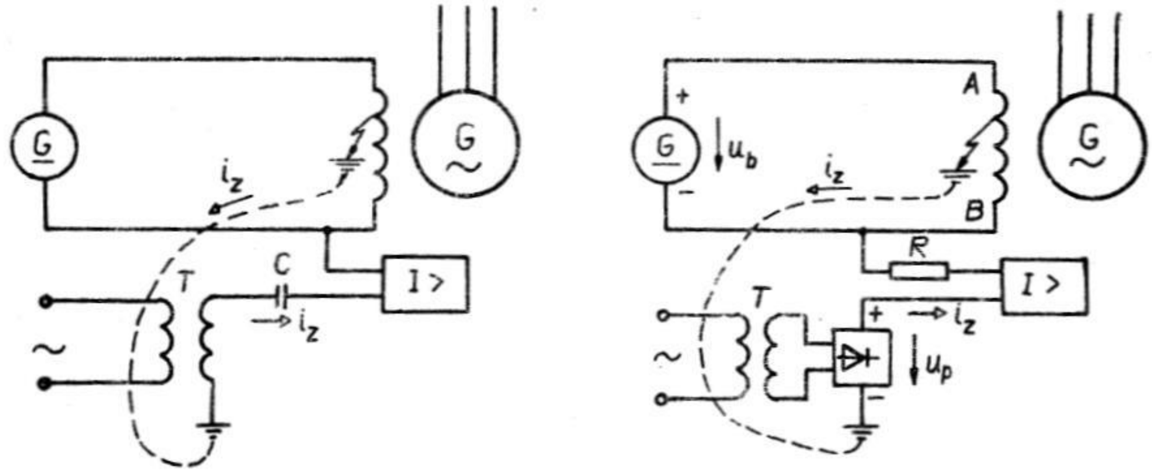


Fig. 6.15 Rotor ground protection

- Overcurrent protection:

It protects the alternator from excessive heat that would cause accelerated insulation aging. Time-delayed independent current protectors are used.

- Overvoltage protection:

It protects the alternator during sudden load shedding, voltage regulator failure and turbine spinning. The voltage is measured by a measuring transformer and the protection continuously evaluates its magnitude.

- Protection against power backflow (wattmetric):

This protection disconnects the alternator in the event of a flow from the mains to the machine (alternator switches to motor operation). The protection is time-delayed to prevent it from being activated during power fluctuations.

- Protection against asymmetry:

Using current measuring transformers in each phase, it continuously evaluates the reverse current component and disconnects the alternator if it becomes unlawfully warm.

- Protection against wake-up loss:

This protection ensures that the power of the machine is reduced when it loses excitation and goes into asynchronous operation. After a set time (if the excitation is not restored) the alternator disconnects.

- Protection against sub-synchronous speed:

Blocks the machine's voltage regulator until it reaches rated speed. This prevents the excitation current of the machine from increasing and thus prevents oversaturation of the magnetic circuits.

- Protection against bearing currents:

Since the magnetic field of the alternator is not perfectly symmetrical, a voltage is generated between the rotor shaft and the machine stator during operation. To prevent current flow through the bearings, the bearing pans are isolated. This protection therefore controls the insulation of the bearing pans. It consists of a current measuring transformer, through the centre of which the rotor shaft of the alternator passes. If current flows through the bearings, the protection will equip.

- Protection against self-excitation:

Self-excitation of the machine can occur if the alternator is operating into a capacitive load (e.g. long line idling). Self-excitation will be manifested by an increase in the machine's clamp voltage. This protection consists of a surge protector which is blocked by a minimum excitation current.

Summary of terms 6.1.

Turboalternator, hydroalternator, exciter, de-energizer, phasing, alternator protection.

Questions 6.1.

1. What are the basic types of alternators?
2. What are the alternator cooling options?
3. How can I excite the alternator?
4. List the alternator protections.

6.2. Transformers

TIME TO STUDY:

1 hour

TARGET:

After studying this paragraph, you will be able to

- list the types and explain the principles of transformer protection
- describe the design of transformers

EXPLANATION

Several types of transformers are used in each power plant, which differ in their purpose and thus in their design. The transformers are used to export the power of the alternators to the grid, cover the self-consumption and transform the self-consumption voltage to the appropriate voltage levels.

Transformer protection

Transformers, like other equipment, must be protected against fault conditions. Transformer faults can be divided into through faults (occurring due to the connected load) and internal faults (faults of the transformer itself). When a fault occurs, the transformer can become dangerously hot, leading to a shortened lifetime or even the destruction of some of its parts. Discharges inside the transformer itself, or power manifestations of fault currents, are also dangerous. That is why we equip transformers with a protection system that disconnects the transformer in case of exceeding the set parameters and thus prevents its damage.

- Differential protection:

Protects the transformer from internal faults. The implementation of this protection is more complicated than for other objects, because different currents flow through the input and output of the transformer. Therefore, current measuring transformers with different gear ratios are used. It is also necessary to consider phase shifts between currents and the magnetizing current surge when the transformer is switched on. Therefore, auxiliary transformers are added to the circuits or the sensitivity of the differential relays is reduced.

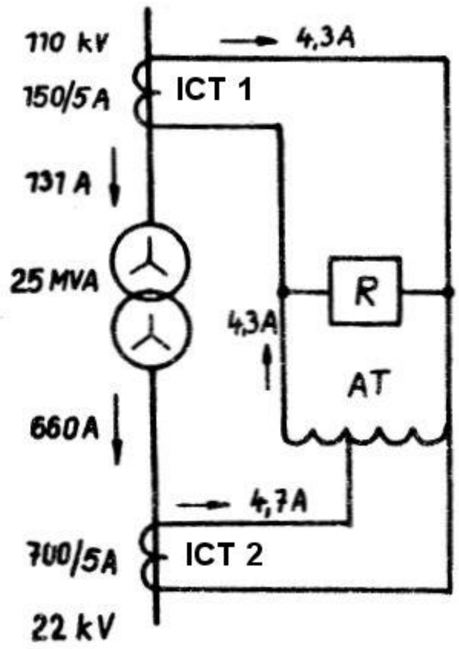


Fig. 6.16 Transformer differential protection

- Vessel protection:

This protection is provided when there is a voltage jump on the transformer bushings or when the winding is connected to the transformer frame. The transformer is placed isolated from the ground, the ground wire passes through the current transformer. If a voltage occurs on the transformer frame, current starts to flow through the earth conductor and the protection is equipped.

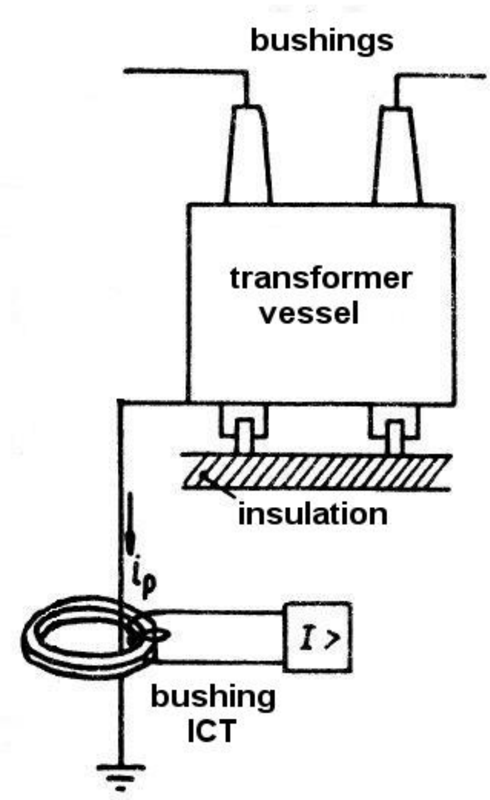


Fig. 6.17 Transformer vessel protection

- Overcurrent protection:

The same means are used as for the protection of other objects. Three-phase, time-delayed overcurrent protection is common. If the protection needs to be made insensitive to remote short circuits, undervoltage blocking is used.

- Gas relay:

This protection finds its application in transformers with oil cooling. Some transformer failures are accompanied by the escape of gases from the cooling oil. The protection is located between the transformer cover and the preservative and is equipped with two floats. The P1 float reacts to a slow evolution of gases (e.g. during overload), the P2 float reacts to a drop in the oil level (e.g. during short circuits, vessel leakage, etc.). The P2 float can be equipped with a flap which speeds up the protection function in case of short circuits (oil starts to flow from the container into the preservative). When float P1 is activated, only the fault is signalled, float P2 causes the protection to be activated immediately.

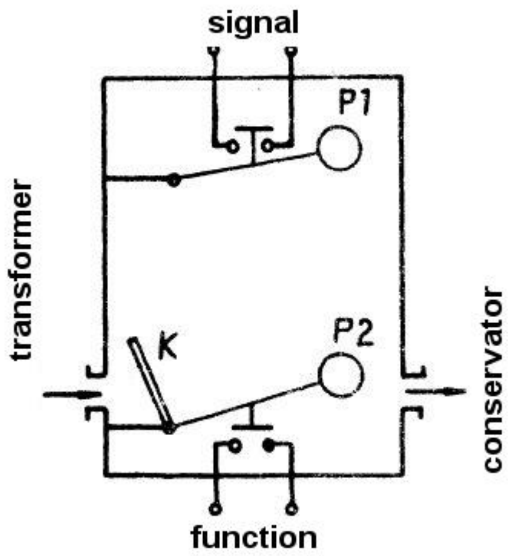


Fig. 6.18 Transformer vessel protection

Main transformers

The main transformers are used to output the power of the plant when the alternator is not working directly to the grid. They transform the voltage of the alternator to a voltage level suitable for transmission, and can also be equipped with a tap to supply the plant's own consumption (if the self-consumption is not covered by a tap from the alternator terminals). For large capacity units, two parallel transformers are usually used, and it is also possible to run several alternators into one transformer. In the case of a block design of a power plant we speak of so-called block transformers.

The power of the transformer is determined by the power of the alternator to which it is connected (however, it is necessary to take into account possible short-term overload). If the self-consumption of the power plant (or the unit) is covered by the terminals of the alternator, the power is selected lower by the self-consumption. The transformer is either a three-phase unit or consists of three single-phase units. The use of single-phase transformers has its advantages - they are simpler to manufacture and transport, and it is cheaper to implement a possible backup (only one single-phase transformer for the whole power plant is sufficient as a backup, which will replace the affected unit in the event of a fault). The disadvantage, however, is the higher price. The cooling is oil, and can be located outside the transformer itself. Oil circulation is natural or forced.

The primary winding is almost always connected in a triangle, as this makes it quite easy to reduce the third harmonic content and at the same time to better distribute the load to the individual phases (especially in the case of asymmetrical short circuits). Also, the currents are lower when connected in a triangle, which allows the use of conductors of smaller cross-section. If it is intended to cover the self-consumption during the start-up of the block from this transformer, an alternator switch is connected between the primary and the alternator. If the self-consumption during starting of the block is covered by another transformer, the alternator is connected directly to the transformer and the switch is located on the secondary side.

The secondary winding is connected to the star, the grounding of the node can be connected through the disconnector because of various tests and measurements. The short-circuit voltage depends on the transformer design itself and is normally up to 15%. The secondary may be equipped with taps that can be used to adjust the conversion ratio (or it may be made as an autotransformer), especially if it is connected to multiple voltage levels simultaneously.

- **Tap transformers**

These transformers provide for the power plant's own consumption. They can be powered directly from the alternator or from the external grid. In some cases, they must also cover the power plant's consumption during start-up. They are usually backed up. The secondary winding of these transformers can be doubled to limit short-circuit currents. The insulation of the windings is usually cast for reasons of reliability and explosion-proofness, but oil-cooled transformers can be found, especially in older installations.

Summary of terms 6.2.

Transformer protection, main transformers, tap transformers.

Questions 6.2.

1. List the transformer protections.
2. How are the main transformers cooled.

6.3. Internal consumption of the power plant

TIME TO STUDY:

20 minutes

TARGET:

After studying this paragraph, you will be able to

- describe the different designs of self-consumption of the power plant, list their advantages and disadvantages describe the function

EXPLANATION

The self-consumption of the power plant can be ensured in several ways, which differ in both reliability and investment costs. The implementation of the self-consumption of the power plant also depends on its main electrical scheme. A special group is nuclear power plants, where it is necessary to provide power to certain parts at all times to avoid damage to the equipment or a nuclear accident.

Switching between the individual sources is done either by short-term parallel connection or by simple switching (in this case, however, a short power failure occurs).

Work power supplies

The working power supply covers the supply for self-consumption during normal operation. In this state we can cover our own consumption from different sources.

- Connection to the external network:

Historically probably the oldest version. The plant's own consumption is fully covered by the external grid. The investment costs are low, but in the event of an external grid failure, the plant is unable to operate.

- Auxiliary alternator:

In this case, the power plant's own consumption is covered by a separate alternator, which is located on a common shaft with the main alternator or is driven by a separate turbine. This solution is characterised by high reliability, but is expensive in terms of investment and operation.

- Connection to the main alternator:

This is the most common solution, especially for power plants in block design. The actual consumption is covered by a tap from the main alternator. If the voltage of the alternator is the same as the voltage of the self-consumption network, the connection is direct or via the reactor. If the voltages are different, a transformer is inserted in the tap. The advantage is the relatively high reliability in relation to the investment and operating costs.

Backup power supplies

The backup power supply covers the supply for self-consumption in case of failure of the working power supply. As a rule, a grid substation is chosen as a backup source. In the event of an outage, a switchover takes place automatically and the backup power supply takes over automatically.

For safety reasons, nuclear power plants are powered from multiple sides, with diesel generators and storage batteries acting as backup sources in the event of a complete failure of external power supply.

Run-up and run-down supplies

These supplies cover the power plant's internal consumption during the start-up and shut-down of production. As in the previous case, this function is usually performed by the grid substation; in nuclear power plants, the run-time supplies are backed up by backup supplies (for the safe cooling of the reactor core).

Summary of terms 6.3.

Working sources, backup sources, run-on and run-off sources.

Questions 6.3.

1. In what operation does the working power supply cover the supply for its own consumption?
2. What are the starting and stopping sources used for?

6.4. Trends in electrical parts

TIME TO STUDY:

30 minutes

TARGET:

After studying this paragraph, you will be able to

- explain the principle of contactless wake-up call
- describe powerformer

EXPLANATION

Current trends in the power industry are towards increasing the efficiency and reliability of power sources. The electrical part of the power plant (as opposed to the non-electrical part) has a high efficiency which has practically reached its limits. Further improvements in efficiency are therefore mainly dependent on research into new materials for the construction of magnetic circuits for alternators and transformers, and also on the development of superconducting materials.

Reliability of power supplies is being improved by the introduction of new fail-safe diagnostic methods that can detect an emerging fault before it affects machine operation or a potential crash. This allows better use of downtime for machine maintenance and improves the overall utilisation of installed power, thus reducing the payback period for the investment in its construction.

Contactless alternator excitation

The transfer of electrical energy between rotating and stationary parts of the machine is most often realized by sliding contacts. The sliding contact consists of a carbon block (called a brush) that sits on a ring or commutator located on the machine shaft. During operation, both the carbon block and the ring or commutator are subject to wear and tear and it is therefore necessary to continuously check the sliding contacts. In addition, they may spark (by carbon bounce, skipping between commutator blades) which is a source of RF interference and reduces its service life. Since this is a very fault-prone part, we can increase the reliability of the machine by so-called non-contact excitation.

- Brushless exciters with power diodes:

The excitation system consists of an AC exciter in the so-called inverted design (the working winding is on the rotor), located on a common shaft with the alternator. The excitation current is directed by diodes located on the shaft of the unit. This system is used for low power machines as it has poor dynamics and slow wake-up.

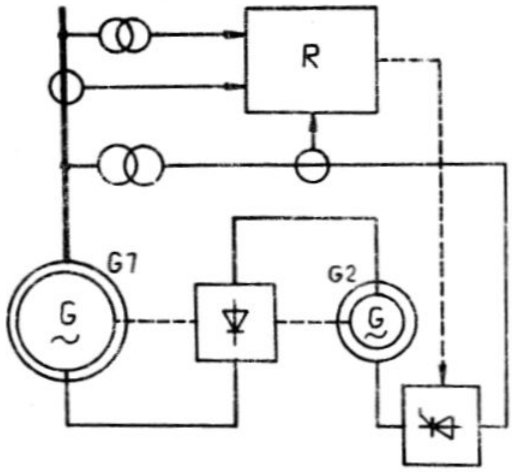


Fig. 6.19 Brushless exciter with power diodes

- Brushless exciters with power thyristors:

The excitation system consists of an AC exciter, located on a common shaft with the alternator. The exciter feeds the excitation winding of the alternator by means of thyristors located on the shaft of the system. The individual gates of the thyristors are powered by a special rotary converter. The power supply to the stator of the exciter is also realized by a controlled rectifier with thyristors. This system has excellent dynamic characteristics and very fast decoupling. However, due to its high cost, it is only applicable to high power alternators.

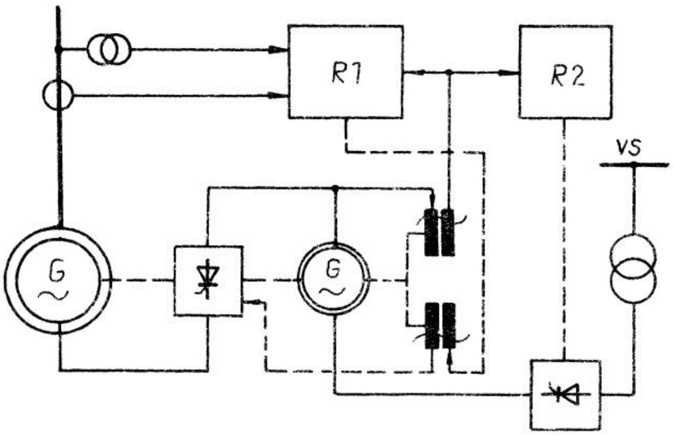


Fig. 6.20: Brushless exciter with power thyristors

Powerformer

It is a high voltage generator developed by ABB, which has high efficiency. Unlike conventional alternators, the winding of this machine is made up of high voltage cables. This increases the reliability of the machine and allows it to operate up to 400 kV. This eliminates the need to use a transformer to output power, which is very costly in terms of investment, increases its failure rate and reduces the efficiency of the plant.

The stator winding of the machine is made up of special high voltage cables that are insulated with polyethylene. The insulation is stepped (it gets thicker as the number of turns increases) and is supplemented on both sides by a semi-conductive layer, the outer one being directly connected to the earth potential. The cable has a coaxial layout which makes its electric field more homogeneous than that of rectangular conductors.

Summary of terms 6.4.

Contactless wake-up call, powerformer.

Questions 6.4.

1. List the advantages and disadvantages of contactless wake-up calls.
2. Describe the principle of the powerformer.

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7. ELECTROTHERMAL TECHNOLOGY

7.1. The basics of heat transfer

TIME TO STUDY:

3 hours

TARGET:

After studying this paragraph, you will be able to

- define basic concepts in electrothermal technology
- describe and explain heat transfer by conduction, convection and radiation
- solve simple examples on heat transfer

EXPLANATION

Concepts, symbols, quantities, units

- **Thermodynamic (TD) system** is a defined part of space with its substance filling. Outside it is its surroundings. The system is separated from its surroundings by boundaries, whether real or imaginary. The properties of this boundary determine its character in terms of:
  - the permeability of the substance:
    - open boundary - energy and matter can pass through it,
    - a closed boundary - only energy can pass in both directions, not matter,
  - energy throughput:
    - The uninsulated boundary allows the transfer of heat and mechanical work,
    - an insulated boundary does not allow the transfer of heat and mechanical work between the system and its surroundings,
  - homogeneity:
    - homogeneous - the properties of the system are the same in all parts,
    - inhomogeneous - the properties of the system change in some parts by leaps and bounds.
- **Thermodynamic variables** are appropriately chosen functions (quantities) that express the properties of the TD system and its interaction with the environment.
- **Thermodynamic process** expresses the changes that occur in a system or at its boundary with its surroundings. It is a sequence of states of the system in which the TD variables change in space and time.
- **Thermodynamic equilibrium** is a state of the system when the TD of the variable does not depend on the place in the system, nor on time. This state occurs in an

isolated and closed system after a certain time has elapsed. Full thermodynamic equilibrium is a thermal, mechanical, chemical equilibrium.

- **Energy** is a TD variable expressing the ability of the system to do work. From a physical point of view, it is necessary to distinguish between external and internal energy.
- **The external energy** is related to the motion and position of the system in the field of external forces. It represents kinetic energy.
- **The internal energy** is related to the internal state of the system and the microphysical movements within it. The internal energy of a system is equal to the total energy that must be supplied to it to move from one state to another.
- **Heat** is a TD variable that expresses the gain or loss of internal energy of a system when this energy does not do work and when chemical reactions and changes of state do not take place in the system. It is therefore the part of the internal energy of the system that can be exchanged with the environment through microphysical interactions. Heat as a form of energy transfer is an expression of the action of undirected microscopic forces. It is therefore not a state quantity, since it depends on the way the system interacts with its environment.
- **Work** is also a form of energy transfer and one of the ways in which the TD system interacts with its environment. Unlike heat, work is related to the action of macroscopic directed forces (e.g. pressure). Like heat, it does not depend on the state of the system but on the interaction with the environment. Therefore, it is also not a state quantity. Work is a description of an ordered reversible transfer, whereas heat is a description of a perfectly chaotic transfer.
- **Thermodynamic temperature** is a TD state variable that expresses the thermal state of the system and is a measure of its total internal energy. It is a quantitative quantity. It can be measured through changes in other physical properties of the system such as volume and pressure.
- **Temperature difference** - If there is a temperature difference in the TD system, then energy is exchanged and balanced in the form of heat transfer. Each element of the system has its own internal energy, i.e. temperature, and thus creates a scalar temperature field.
- **Heat power** *P* is the heat *Q* per unit time *t* ($J\text{-}s^{-1}$ = W), is equal to the heat flux □. It is a scalar quantity.

$$P = \frac{Q}{t} \tag{7.1}$$

- **Heat flux density** *q* has a direction given by the normal and expresses the amount of energy passing through a given cross-section in a given time. The unit is $W\text{-}m^2$.

$$q = \frac{\mathrm{d}P}{\mathrm{d}S} \tag{7.2}$$

- **Specific heat capacity** *c* ($J \cdot kg^{-1} \cdot K^{-1}$) is the heat capacity of one kilogram of a substance.

Calorimetric calculations

Calorimetric calculations belong to the basic tasks of thermal engineering. The type of material determines how much heat must be supplied to 1 kg of a substance to heat it by 1 temperature degree. The ability of a substance to store heat is determined by the specific heat capacity *c*. This is usually a constant over a certain temperature interval. Tab. 7.1 gives the values of this quantity for the most common substances and materials.

Substance	*c* ($J \cdot kg^{-1} \cdot K^{-1}$)	Substance	*c* ($J \cdot kg^{-1} \cdot K$)$^{-1}$
water	4187	Iron	450
air (°C)	1003	copper	383
ethanol	2460	zinc	385
led	2090	aluminium	896
oil	2000	tin	227
dry wood (°C)	1450	lead	129
oxygen	917	gold	129
silicon	703	platinum	133

Tab. 7.1 Specific heat capacity of substances and materials

The basic question of calorimetric calculation is how much heat is required to heat (cool) a substance of mass *m* at a temperature difference of ΔT. The calorimetric equation then takes the form

$$Q = m \cdot c \cdot \Delta T \tag{7.3}$$

The conversion of electrical energy to thermal energy is carried out with the efficiency of η. The total energy delivered then depends on the electrical input of the equipment and on time. For the electrical energy, the relationship applies:

$$Q_e = P \cdot t \tag{7.4}$$

where *P* is power (W), *t* is time (s).

Combining the two equations and including efficiency gives the resulting relationship for the balance of thermal and electrical energy:

$$m \cdot c \cdot \Delta T = P \cdot \eta \cdot t \tag{7.5}$$

The following table shows the relationships between the most commonly used units.

Unit	J	Wh	cal
J	1	2,778· 10-4	0,239
Wh	3600	1	860
cal	4,186	1,163· 10-3	1

Tab. 7.2 Relationships between units

Energy transfer and heat transfer

When heat is used for both industrial and heating applications, its dissipation follows the general principle of energy dissipation, i.e. from a location with a higher energy density to a location with a lower energy density. The volumetric energy density ($J \cdot m^{-3}$) is the amount of energy *W* per unit volume of the medium, i.e.

$$w = \frac{dW}{dV} \tag{7.6}$$

The intensity of the energy transfer is then expressed by the heat flux P (power)

$$P = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{7.7}$$

Heat flux density *q* (W·m^{-2}) is considered as the passage of a given heat output through an area S = 1 m^2.

$$\boldsymbol{q} = \frac{\mathrm{d}P}{\mathrm{d}\boldsymbol{S}} = \frac{\mathrm{d}^2 Q}{\mathrm{d}\boldsymbol{S} \cdot \mathrm{d}t} \tag{7.8}$$

The transfer of energy (heat) through the environment is realized by means of energy carriers. These are particles that are present in the environment but have a higher energy than particles in their vicinity or that enter the environment from the surroundings. For this reason, the type, speed and mode of movement of the particles are different and depend on the type of environment. These can be elementary particles (electrons, atoms), but also electromagnetic waves, which transfer energy via photons.

There are two specific ways of moving particles (energy carriers) and they depend on the concentration of the particles in the environment. The first way is mainly applied in environments with a high concentration of particles (solid or liquid state). Then particles moving against the energy density gradient are in constant contact with other particles in the environment. Thus, it is a natural transfer of heat from places of higher thermal concentration to places of lower concentration. Energy is transferred through constant collisions between particles.

The second and different mode of energy transfer takes place in low-particle environments. The transfer of energy carriers takes place by radiation. This can take the form of light, for example. These principles describe the transfer of heat through the medium and the following three modes of heat transfer are derived for them [1]:

- heat conduction,
- heat convection,
- heat radiation.

Heat transfer by conduction

Inside solid bodies or in close contact with them, heat is transferred by conduction. Heat, like magnetic or electrical energy, creates a so-called thermal field around itself. The heat field is the set of instantaneous temperatures of all points in the part of space under study and is a scalar field. In terms of space it can be one, two, or three dimensional, in terms of time it can be stationary or non-stationary. In general, temperature is a function of coordinates and time.

$$\vartheta = \vartheta(x, y, z, t) \tag{7.9}$$

If follow equation is valid,

$$\frac{\partial \vartheta}{\partial t} = 0 \tag{7.10}$$

then the field is stationary - the temperature does not change over time. When calculating heat loss and thermal comfort of the environment, a steady state is assumed, i.e. the case of a stationary temperature field is considered.

Connections of points with the same level of thermal energy (same temperature) are called isotherms (Fig. 7.1), or isothermal surfaces. If the properties of the material in terms of heat conduction are the same in all directions, it is an isotropic environment.

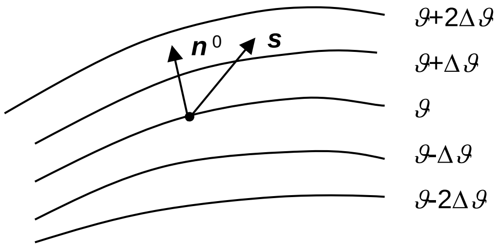


Fig. 7.1 Isotherms

The largest temperature changes occur in the direction of the normal to the isothermal surface. The limiting value of the temperature gradient is the temperature gradient.

$$\text{grad}\ \vartheta = \lim_{n\to 0}\frac{\Delta\vartheta}{\Delta n}\boldsymbol{n}^0 \qquad (7.11)$$

It is a vector perpendicular to the isothermal surface. The set of temperature gradients form a vector field. The existence of a field (if non-zero) means that heat propagates in space.

❑ Heat conduction through a plane wall

Heat flux Φ (W) through a homogeneous plane wall with thickness *l*, area *S*, thermal conductivity coefficient of the material λ and the surface temperature difference ϑ_1-ϑ_2 (Fig. 7.2a) is

$$\Phi = \frac{\lambda}{l}\cdot S\cdot(\vartheta_1 - \vartheta_2) \qquad (7.12)$$

The temperature ϑ decreases linearly with distance *x* from the value ϑ_1 at the left interface to the temperature ϑ_2 at the right interface (equation 2.17). The dashed line on Fig. 7.2 and above the linear waveform show the actual waveform for ceramic materials, and below the linear waveform for pure metals. In Fig. 7.2b the isothermal surfaces are shown in dashed lines.

$$\vartheta = \frac{\vartheta_1 - \vartheta_2}{l}\cdot x + \vartheta_1 \qquad (7.13)$$

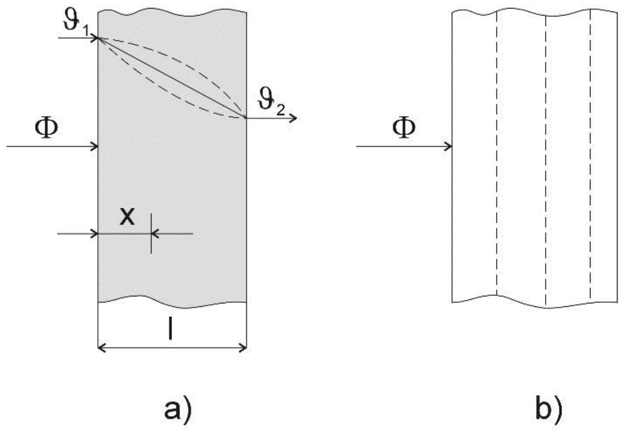


Fig. 7.2 Heat conduction through a single plane wall

If the wall is composed of several different layers of materials with different thermal conductivity (Fig. 7.3), then the heat flux through the structure is

$$\Phi = \frac{S \cdot (\vartheta_1 - \vartheta_2)}{\frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + \ldots + \frac{l_n}{\lambda_n}} \tag{7.14}$$

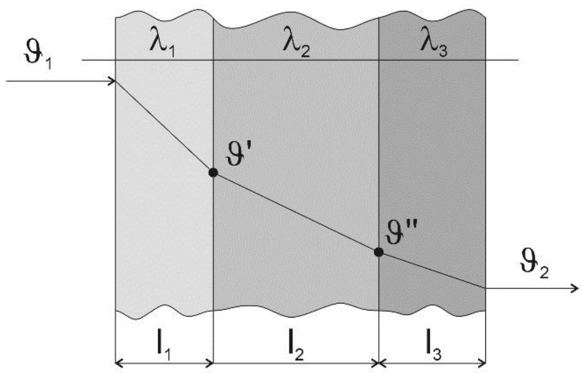


Fig. 7.3 Heat flux through a composed plane wall

For a composite planar wall, the following relationships hold for the temperature at the layer interface:

$$\vartheta' = \vartheta_1 - \frac{\Phi \cdot l_1}{\lambda_1 \cdot S} \tag{7.15}$$

$$\vartheta'' = \vartheta_2 + \frac{\Phi \cdot l_2}{\lambda_2 \cdot S} \tag{7.16}$$

Heat conduction through the cylindrical wall

When heat is conducted from the inner surface of a thick-walled cylindrical tube to the outer surface (Fig. 7.4), as the diameter increases, the area through which the heat passes also increases. The temperature versus radius curve therefore takes the form of a logarithmic curve. For the heat flux, the relation

$$\Phi = \frac{2\cdot\pi}{\frac{1}{\lambda}\cdot\ln\frac{r_2}{r_1}}\cdot l\cdot(\vartheta_1-\vartheta_2) \qquad (7.17)$$

For a composed cylindrical wall (Fig. 7.4), the relation

$$\Phi = \frac{2\cdot\pi\cdot l\cdot(\vartheta_1-\vartheta_2)}{\frac{1}{\lambda_1}\cdot\ln\frac{r_2}{r_1}+\frac{1}{\lambda_2}\cdot\ln\frac{r_3}{r_2}+\ldots+\frac{1}{\lambda_n}\cdot\ln\frac{r_{n+1}}{r_n}} \qquad (7.18)$$

The temperatures at the interface of the layers are then calculated according to

$$\vartheta' = \vartheta_1 - \frac{\Phi}{\pi\cdot l}\cdot\frac{1}{2\cdot\lambda_1}\cdot\ln\frac{d'}{d_1}$$
$$\vartheta'' = \vartheta_2 - \frac{\Phi}{\pi\cdot l}\cdot\frac{1}{2\cdot\lambda_3}\cdot\ln\frac{d_2}{d''} \qquad (7.19)$$

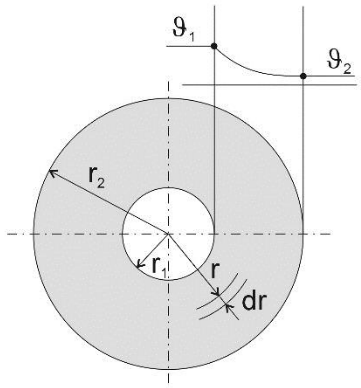


Fig. 7.4 Heat conduction through the cylindrical wall

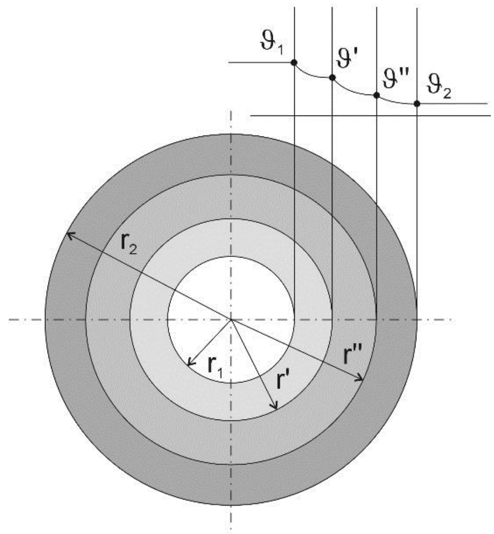


Fig. 7.5 Heat conduction through the composed cylindrical wall

The following table gives the thermal conductivities of selected materials.

Type of material (substance)	**Thermal conductivity λ (W·m^{-1} ·K^{-1})**
air	0.025 (at 20°C)
water	0.6 (at 20°C)
led	2,2
thermal insulators	0,03 - 0,1
Wood	0,1 - 0,5
building materials	0,2 - 1,2
stone	15 - 3,5
pure metals	50 - 400
alloys	10 - 200

Tab. 7.3 Thermal conductivities of selected materials

heat transfer by convection

Convection is a mode of heat transfer that involves the transfer of matter of a certain internal energy from one place to another. From a macroscopic point of view, it is not a transfer of heat, but a transfer of matter to which heat is bound. This movement is initiated either by a temperature gradient or also by an external action (e.g. a fan). Thus, two possibilities are distinguished:

- natural convection,
- forced convection.

When a solid medium of temperature T_p is flowing over a surface and a fluid of temperature T_i is flowing, the equation for the heat flux density is

$$\mathbf{q}_k = \alpha \cdot (T_p - T_i) = \alpha \cdot \Delta T \qquad (7.20)$$

This means that the heat flux density through the flow is directly determined by the temperature difference between the surface and the fluid. The magnitude of the heat flux density is influenced by the heat transfer coefficientα (W·m^{-2}·K^{-1}). This depends on the pressure, temperature and velocity of the fluid, the type of flow (laminar or turbulent) and the physical properties of the fluid (density, specific heat capacity, thermal conductivity and viscosity) as well as the shape, dimensions and roughness of the body being flowed around. The following table gives the values of this coefficient for some known cases.

	α_{min} (W·m^{-2}·K^{-1})	α_{max} (W·m^{-2}·K^{-1})
calm air	12,5	125
air flow	40	2100
flowing liquid	8400	21000
boiling liquid	16800	25100
condensing steam	29000	50000

Tab. 7.4 Heat transfer coefficient values [2]

Heat transfer by convection is one of the most difficult computational problems in thermal engineering. It is dealt with in many scientific literatures. In important cases, it is best to determine the heat transfer coefficientα ourselves by measuring it on a model as close as possible to our case using the given relations in whichα occurs. For the heat transfer through the flow (Fig. 7.6), Newton's law applies:

$$\Phi = \alpha_1 \cdot (\vartheta_{p1} - \vartheta_1) \cdot S \qquad (7.21)$$

$$\Phi = \alpha_2 \cdot (\vartheta_2 - \vartheta_{p2}) \cdot S \qquad (7.22)$$

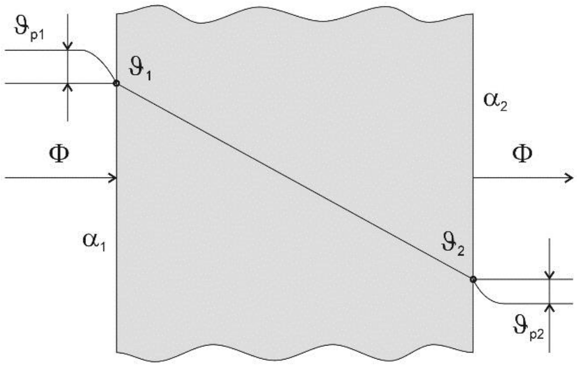


Fig. 7.6 Heat transfer by flow

There is a temperature difference between the ambient temperature and the surface temperature, even at steady state, due to the fact that there is always a thin layer of gas or liquid adhering to the surface of the wall which is not involved in the flow. Through this layer the heat flow is only conductive, and since the thermal conductivity of gases and liquids is small, a temperature jump occurs.

❑ Heat transfer by radiation

Heat transfer by radiation differs from conduction and convection by a different transfer mechanism. The transfer of energy, or heat, occurs by means of electromagnetic waves over a range of wavelengths. Electromagnetic waves are generated by any opaque body with a temperature greater than 0 K while absorbing the surrounding radiation.

The radiation can be decomposed into individual components, corresponding to individual wavelengths, to obtain the emitted spectrum.

The body also receives heat flux from other bodies in space. Of course, heating of a body occurs when it receives more energy from its surroundings than it radiates and vice versa. The amount of energy radiated is proportional to the active surface area of the body and to the fourth power of its thermodynamic temperature. It also depends on the nature of the surface of the body. The energy flux incident on a body can be divided into three parts:

- A - absorbed flux (A is the relative absorbance - absorption),
- B - reflected flux (B is the relative reflectivity - reflection),
- C - transmissed flux (C is the relative permeability).

They following have to apply:

$$A + B + C = 1 \qquad (7.23)$$

The following extremes can be defined:

A = 1- absolute black body (all the energy of the heat flux is absorbed by the body),

B = 1- absolute white body (all energy is reflected by the body),

C = 1- transparent environment - diatomic gases and air,

C = 0- thermally opaque environment - e.g. metals.

These coefficients can be dependent on the frequency of the electromagnetic wave, so it is possible to define their spectral values, and for all wavelengths the following must be true

$$A_\lambda + B_\lambda + C_\lambda = 1 \tag{7.24}$$

The laws of radiation

Radiation heat transfer is governed by the laws of physics. The surface of a heated absolutely black body emits a continuous spectrum of radiation of different wavelengths ().

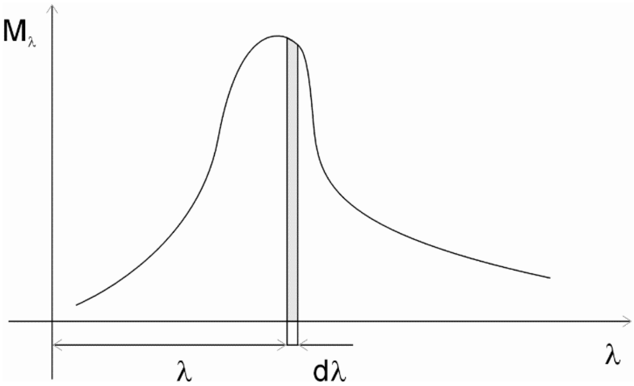


Fig. 7.7 Spectral radiance versus wavelength

Snell's Law

Snell's law expresses the nature of the propagation of radiation as it passes from one medium to another (Fig. 7.8). For the direction of spread, the relationship applies:

$$\frac{\sin\alpha}{\sin\beta} = \frac{v}{v'} = n \tag{7.25}$$

where *n* is the refractive index, *v* and *v'* are the transfer velocities in the given media.

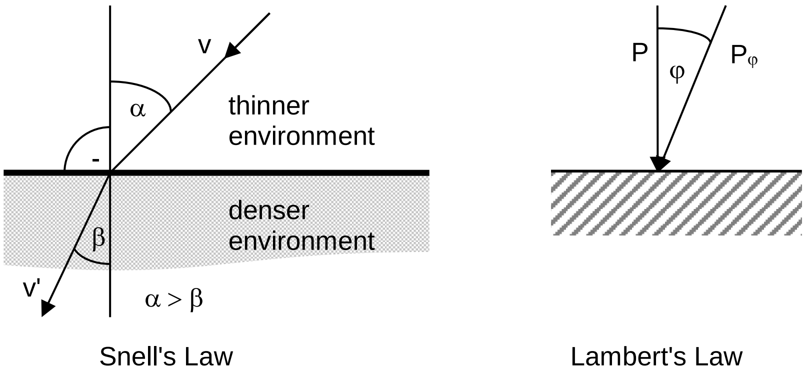


Fig. 7.8 Radiation spreading at the transition of two environments [4]

Lambert's Law

Lambert's law states that only the perpendicular part of radiation is applied in terms of power.

$$P = P_{\varphi} \cdot \cos\varphi \tag{7.26}$$

where φ is the angle of incidence of the radiation, P_{φ} is the energy in the direction of the angle φ.

Stefan-Boltzmann law

The Stefan-Boltzmann law describes the total radiation intensity of an absolutely black body. This law states that the radiant intensity M ($W \cdot m^{-2}$) increases with the fourth power of the thermodynamic temperature of the glowing body

$$M = \sigma \cdot T^4 \tag{7.27}$$

Where σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$, T is the thermodynamic temperature (K).

Planck's law

Planck's law determines the dependence of the spectral intensity of radiation M_{λ} ($W \cdot m^{-3}$) of an absolutely black body on its surface temperature

$$M_{\lambda} = f(T, \lambda) = \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda \cdot T}} - 1 \right)} \tag{7.28}$$

where $C_1 = 3.74 \cdot 10^{-16}$ $W\text{-}m^{-2}$, $C_2 = 1.44 \cdot 10^{-2}$ $m \cdot K$.

Equations (7.28) gives the radiated power from a 1 m^2 area for only 1 wavelength □. The total radiated power will be the sum for all wavelengths, i.e., for $\lambda = 0$ to $\lambda = \infty$.

$$M(T) = \int_0^{\infty} M(T, \lambda) \cdot \mathrm{d}\lambda = \int_0^{\infty} \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda \cdot T}} - 1 \right)} \cdot \mathrm{d}\lambda \tag{7.29}$$

By integrating and inserting constants we get the relation

$$M(T) = \sigma \cdot T^4 \tag{7.30}$$

which is the relationship expressing the Stefan-Boltzmann law - see equation (7.27).

Wien's law

The spectral intensity of radiation M_{λ} is most intensive at a given temperature for a wavelength λ_m, which is inversely proportional to this temperature T. It follows that a body emits only long-wave (infrared) radiation through its surface at low temperature. So not only does the radiance of the body increase with increasing temperature, but the maximum of the emitted spectrum also shifts to shorter wavelengths - Wien's displacement law.

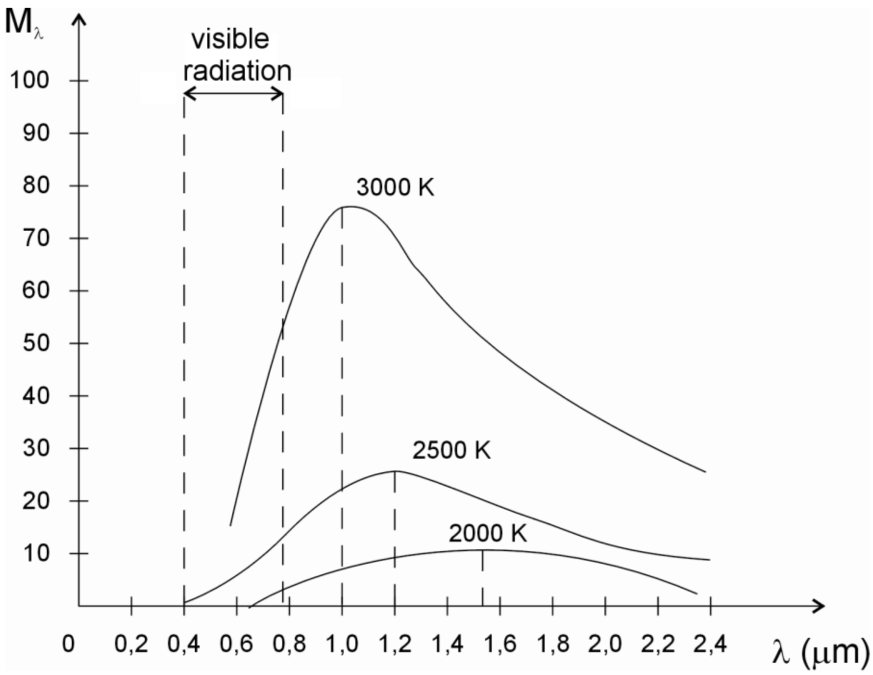


Fig. 7.9 Wien's displacement law

$$\lambda_{\mathrm{m}} = \frac{2892}{T} \tag{7.31}$$

The human eye is adapted to solar radiation, which has a maximum in the yellow-green region, corresponding to a wavelength of λ = 500 nm. Substituting this value into Wien's law gives the temperature of the solar surface

$$T = \frac{2892}{0{,}5} = 5784\,\mathrm{K} \tag{7.32}$$

Kirchhoff's Law

Kirchhoff's law applies to spectral and total radiance of grey bodies relative to bodies with an absolutely black surface.

Ratio of total radiance to relative absorptivity of a grey body depends only on the absolute temperature of the body *T* and does not depend on the colour of the surface. We can therefore write Kirchhoff's law for radiation also in this form - for spectral radiance:

$$\frac{M_{\mathrm{G}}}{A_{\mathrm{G}}} = f(T) = \frac{M_{\mathrm{B}}}{A_{\mathrm{B}}} = M_{\mathrm{B}} \tag{7.33}$$

$$\frac{M_{\lambda\mathrm{G}}}{A_{\lambda\mathrm{G}}} = f(T, \lambda) = M_{\lambda\mathrm{B}} \tag{7.34}$$

where M_{G}, M_{B} ($M_{\lambda\mathrm{G}}$, $M_{\lambda\mathrm{B}}$) are the total (spectral) radiance of the gray and black surfaces and A_{G}, A_{B} ($A_{\lambda\mathrm{G}}$, $A_{\lambda\mathrm{B}}$) are the relative (spectral) absorptions of the gray and black surfaces.

From the curves on Fig. 7.9 we see that the absolute black body emits a continuous spectrum of radiance, uninterrupted by gaps. For most real, i.e. physically grey surfaces, the spectral radiance curve is also unbroken and is similar to that of a black body (Fig. 7.10). We can therefore write:

$$\frac{M_{\lambda G}}{M_{\lambda G}} = \text{konst.} = \varepsilon \tag{7.35}$$

Or else:

$$A_G = \frac{M_G}{M_B} = \frac{\varepsilon \cdot \sigma_B \cdot T^4}{\sigma_B \cdot T^4} = \varepsilon \tag{7.36}$$

So we can say that the relative absorption A_G is numerically equal to the degree of blackness ε of the surface under consideration.

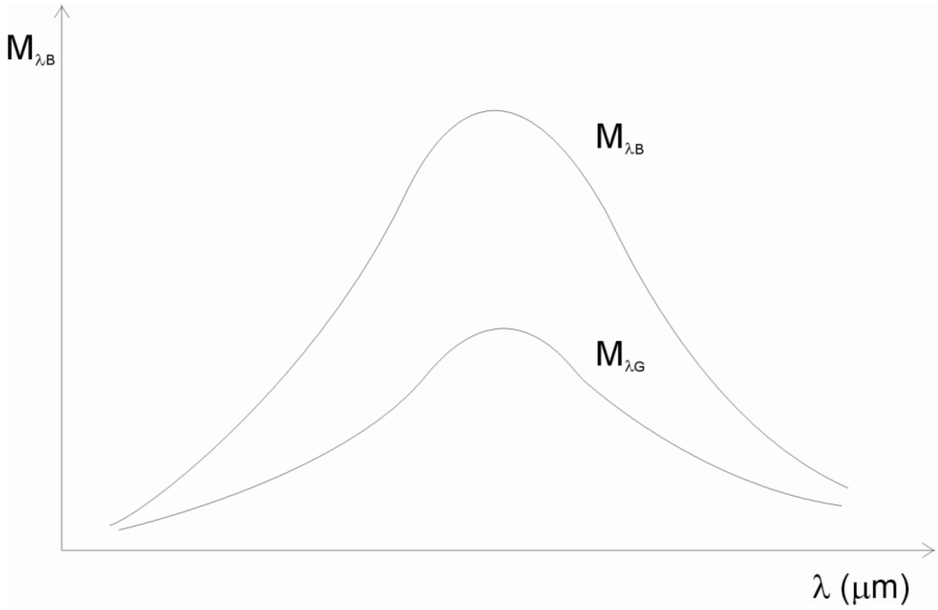


Fig. 7.10 Spectral radiance for black and grey surfaces

Informative emissivity values are given in the following table.

Material	**Emissivity** ε **(-)**
absolutely black body	1
carbon black, graphite	0,95
oxidized steel	0,85-0,95
oxidized copper	0,7
burnt brick	0,9
fireclay brick	0,8
oxidised aluminium	0,3
shiny aluminium	0,1
polished steel	0,29
polished nickel	0,07
polished silver	0,02
water, ice (smooth surface)	0,96
glass	0,94

Tab. 7.5 Emissivity values [2]

Mutual irradiation of body surfaces

A body of area *S* emits a radiant flux

$$\Phi = M \cdot S = \sigma \cdot T^4 \cdot S \qquad (7.37)$$

We will consider two bodies with surfaces S_1, S_2, thermodynamic surface temperatures T_1, T_2, and emissivities ε_1 and ε_2. Then, for the radiative heat flux in the steady state

- the case of two parallel, equal sized surfaces where $S_1 = S_2 = S$

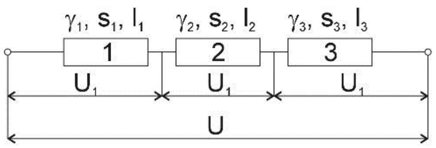
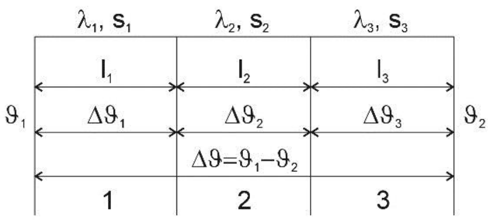
$$\Phi = \frac{S \cdot \sigma_B \cdot \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad (7.38)$$

- the case of two bodies where one completely surrounds the other spatially, i.e. $S_1 << S_2$

$$\Phi = \frac{S_1 \cdot \sigma_B \cdot \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{S_1}{S_2} \cdot \left(\frac{1}{\varepsilon_2} - 1\right)} \qquad (7.39)$$

Analogy between temperature and electric field

The analogy greatly simplifies heat transfer calculations in simpler systems and in steady state. The stationary current field and the stationary temperature field are non-vortex, non-swirling, therefore Laplace's theorem applies. Tab. 7.6 gives examples of the analogy between electric and temperature fields.

Electric field	**Temperature field**
Potential Zero potential is at infinity scalar quantity, unit (V)	**Thermodynamic temperature** Absolute zero = -273.15 °C Scalar quantity, unit (K)
Voltage $U = V_1 - V_2$ (V)	**Temperature difference** $\Delta T = T_1 - T_2$ (K)
Conductivity γ (S-m)$^{-1}$	**Thermal conductivity** λ (W-m^{-1}·K^{-1})
Resistance $\rho = \frac{1}{\gamma}$ (Ω·m)	**Specific thermal resistance** $\frac{1}{\lambda}$ (m·K·W^{-1})
Electrical conductivity $G = \frac{\gamma \cdot S}{l}$ (S)	**Thermal conductivity** $G = \frac{\lambda \cdot S}{l}$ (W·K^{-1})
Electrical resistance $R = \frac{l}{\gamma \cdot S} = \frac{\rho \cdot l}{S}$ (Ω)	**Thermal resistance** $R = \frac{l}{\lambda \cdot S}$ (K·W^{-1})
Electric current $I = \int_S \boldsymbol{J} \cdot d\boldsymbol{S}$ (A)	**Heat flux** $\Phi = \int_S \boldsymbol{q} \cdot \mathrm{d}\boldsymbol{S}$ (W)
Resistances in series  $R = R_1 + R_2 + R_3$	**Heat conduction through a composite wall**  $R = R_1 + R_2 + R_3$

Tab. 7.6 Examples of electrothermal analogies [3]

Summary of terms 7.1.

Heat, temperature, heat flux, temperature gradient, heat flux density, heat output, isotherm, heat conduction, flow, radiation, heat transfer coefficient, total radiance, spectral radiance, relative absorption, absolute blackbody, emissivity.

Questions 7.1.

3. Define the terms heat, temperature, specific heat capacity of a body.
4. Explain the concepts of stationary temperature field and isotropic environment.
5. For which bodies heat is transferred by conduction, explain the principle.
6. What is the heat transfer coefficient of a line λ? Specify the unit.

7. Explain what is the heat transfer coefficient of a flow α, what does it depend on, its unit.
8. Explain the concept of temperature jump in flow.
9. Give examples of absolutely black, absolutely white, transparent bodies.
10. List the laws that apply in radiant heat transfer.
11. What is the displacement law, explain.
12. Explain the concepts of total and spectral radiance, write the relationships.
13. Explain the concept of emissivity to the surface ε.

7.2. Resistance electrothermal devices

TIME TO STUDY:

3 hours

TARGET:

After reading this paragraph, you will

- know the principle of direct and indirect resistance heating
- be able to describe the use of resistance heating in practice
- know the design elements of electric resistance furnaces
- be able to design the required power of the resistance furnace

EXPLANATION

Direct resistance heating

In direct resistance heating devices, heat is generated by the direct passage of current through an electrically conductive solid charge or an electrically conductive liquid electrolyte surrounding the charge. The theoretical basis of direct resistance heating is simple (Joule's law). If a current I passes through a conductor of resistance R for a time t, heat Q is generated in the conductor.

$$Q = R \cdot I^2 \cdot t = P \cdot t \qquad (7.40)$$

The resistance of a wire of length l (m) and cross-section s (mm^2) is

$$R = \frac{\rho \cdot l}{s} \qquad (7.41)$$

Where ρ is resistance of material. This is temperature dependent for most materials. When warmed by ΔT is

$$R_{\vartheta} = R \cdot (1 + \alpha \cdot \Delta T) \qquad (7.42)$$

where α is the temperature resistance coefficient, which is positive for most metals, negative for ceramic materials and is strongly temperature dependent.

The calculations and design of these devices are not easy. Here, the difficulties related to the non-linear dependence of the physical properties of the charge or electrolyte on the temperature become apparent. These include in particular resistivity, specific heat capacity and also thermal conductivity. These quantities affect the thermal balance of heating, which can be expressed by the relation

$$Q = Q_u + Q_z \tag{7.43}$$

where Q is the heat generated by the passage of the current, Q_u is the useful heat required to heat the charge and Q_z is the heat loss. The above heat balance forms the basis for determining the required power:

$$P \approx \frac{dQ}{dt} \tag{7.44}$$

This depends on the time course of the bet heating. The total power consumption P_c of the electrothermal device is increased by the heat losses caused by the plant, by the cooling of the charge, by the power required to drive the mechanisms and by the losses of the respective transformer.

According to the heat generation, direct resistance heating equipment can be divided into two basic types:

- equipment for heating the solid charge,
- equipment for heating the liquid charge.

Heating of long metal rods, wires, belts, etc.

The principle of resistance heating is shown schematically in Fig. 7.11. The length of the heated rod must be at least 10 times longer than its diameter to ensure that the heating is sufficiently uniform along its entire length. A large current is introduced into the rod 1 of constant cross-section from the control transformer 2 by the contacts 3. The heating is very fast and efficient.

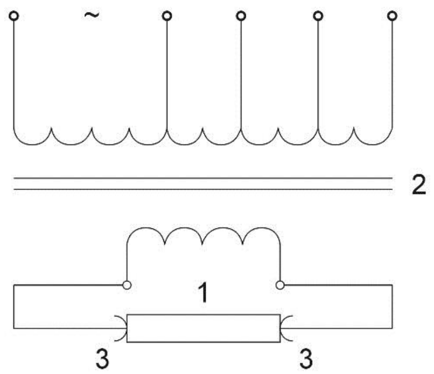


Fig. 7.11 Heating of long metal rods, wires and belts

The optimum conditions occur when the active resistance of the bar is equal to the impedance of the entire supply line. A cold copper rod approaches this. However, the resistance of steel increases up to 7 times when heated from 20 °C to 1200 °C. To make the impedance matching acceptable, we increase the voltage across the bar during heating in line with the resistance increase by switching taps on the input winding of the transformer. The ends of the rods must be as clean as possible, the contacts are copper, water-cooled and are pressed against the heated rod pneumatically or hydraulically.

Direct current heating is advantageously applied for power outputs up to 100 kW and in particularly suitable cases. For single-phase installations above 500 kW, a symmetrizing device must be used.

The power, temperature and loss histories for direct resistance heating of a steel bar without voltage switching are shown in Fig. 7.12. The power input decreases as the resistance of the rod increases with temperature, and the heat loss increases. If the power input equals the losses, the temperature has reached its limiting value. The heating temperature must be less than the limit.

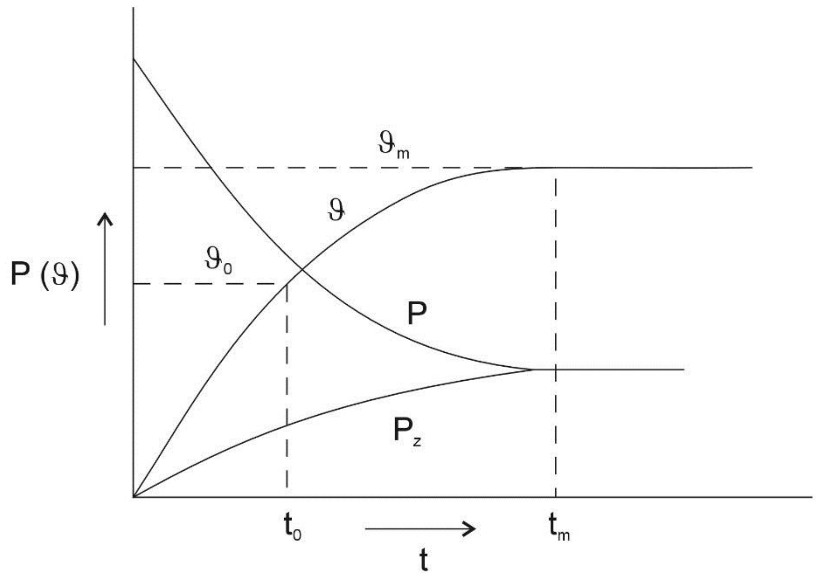


Fig. 7.12 Power, temperature and loss waveforms [5]

The PF is low for direct resistance heating, this is because the reactance of the leads to the contacts is significantly applied at high currents. By switching the transformer on and off during heating, there is a voltage fluctuation in the network. For single-phase equipment above 500 kW, a symmetrizing device must be used.

In the direct heating of steel ferromagnetic rods by alternating current, a significant surface effect is applied. The greatest heat (86.4 %) is generated at approximately the so-called penetration depth *a*. This can be determined by the relation

$$a = \sqrt{\frac{2 \cdot \rho}{\omega \cdot \mu_0 \cdot \mu_r}} \qquad (7.45)$$

where ρ is the rod resistivity, ω is the angular velocity, μ_0 is the vacuum permeability, and μ_r is the relative permeability.

For conventional structural steel (magnetic) up to a temperature of 768 °C (Currier point - loss of ferromagnetism), the depth of penetration *and at a* frequency of 50 Hz is in the order of mm. Above 768 °C, ρ is about 7 times larger and the penetration depth is about 70 mm.

The device for continuous heating of the wire or strip is shown schematically on Fig. 7.13. The wire or strip 1 is connected to the current circuit of the output side of the transformer 2 by pulleys 3 (or graphite blocks).

The final heating temperature can be achieved by changing the tension between the pulleys, changing their mutual distance, changing the wire stretching speed. The described heating is used e.g. for soft annealing of copper wires and strips before sheath insulation, for heating of steel bars for forging, for bending, hardening of wires in prestressed concrete, etc.

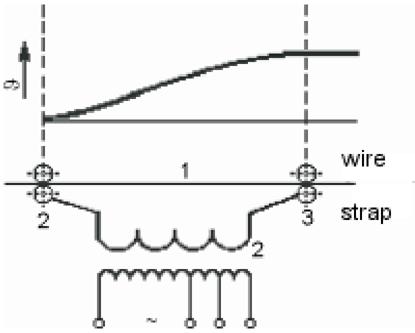


Fig. 7.13 Continuous heating equipment

Graphite and silicon carbide furnaces

Graphite and silicon carbide (carborundum) are produced in Acheson furnaces (Fig. 7.14). Graphite is produced from carbon by so-called graphitization, a chemical process occurring at a temperature of about 2500 °C, in which amorphous carbon is structurally transformed into graphite with excellent physical, chemical, and mechanical properties.

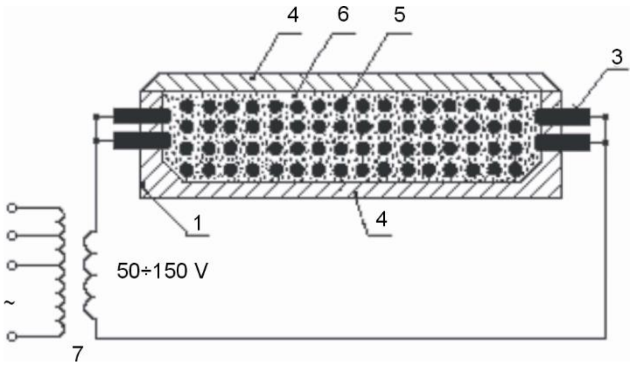


Fig. 7.14 Acheson's graphite furnace

In Fig. 7.14 1 is the furnace bottom, 2 is the front wall, 3 is the graphite blocks, 4 is the furnace lid, 5 is the liner, 6 is the backfill mixture, and 7 is the power transformer.

The furnaces are up to 20 m long with a weight of 50 t or more. Transformer power up to 10 MVA. The supply voltage is regulated in the range of 50 V to 150 V. These furnaces have a small *cosφ* (around 0.5) and load the power grid unevenly. Therefore, for furnaces with large outputs, a symmetrizing device is used. With a DC supply, both compensation and symmetrization are eliminated and power control is easier.

Depending on the size of the furnace and the type of products, the electricity consumption for the production of 1 kg of graphite ranges from 4 kWh to 6 kWh, and for 1 kg of silicon carbide about 8 kWh. The heating takes 2 to 4 days, after switching off the furnace cools down for 10 to 14 days, then the charge is removed from the furnace.

Thermal electrolysis

Electrolyte is heated by the direct passage of direct current during simultaneous electrolysis or refining. The most common thermal electrolysis is the electrolytic production of aluminium, and it is also used to produce sodium and magnesium.

Aluminium is produced from bauxite (Al_2O_3), which has a melting point of about 2050 °C. However, by dissolving bauxite in molten cryolite (aluminium-sodium fluoride), aluminium can be obtained by electrolysis as early as 950 °C, which is technically much more advantageous.

Depending on the size and technical condition of the equipment, the electricity consumption for the production of 1 kg is 16 kWh to 22 kWh.

Electrode salt baths

Salt baths are mainly used to heat steel components for hardening, e.g. balls or rings for ball bearings. They are also used for heat treatment of non-ferrous metals or alloys at temperatures up to 1 400 °C. They are divided into two basic types:

- The current passes not only through the electrolyte but also through the charge immersed in the electrolyte, the power consumption depends on the charge. At Fig. 7.15 are 1 the electrodes, 2 the ceramic crucible and 3 its thermal insulation.
- The insert is placed in the salt in a place where there is no electric field and no current passes through the insert, the power does not depend on the insert.

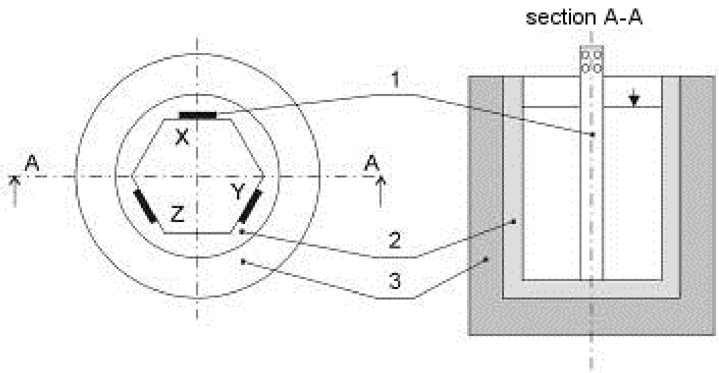


Fig. 7.15 Salt bath type 1

The electrodes have large contact areas to prevent excessive local overheating. The heat is generated by the passage of an electric current through the molten salt. The salts used are non-conductive in the solid state. It is therefore necessary to use an additional resistive heating element which melts a thin layer of salt and then disconnects. Further heating occurs as the current passes through this layer. As the salt is heated, its resistance decreases, so a transformer with secondary voltage regulation capability between 4 and 24 V is required to supply the power. Depending on the operating temperature of the salt bath, the salt mixture that best suits the application is selected.

Mixture composition (%)	Operating temperature (°C)
55 KNO + 45 $NaNO_3$	230 ÷ 480
28 NaCl + 72 CaCl	550 ÷ 870
50 Na_2 CO_3 + 50 KCl	600 ÷ 820
65 Na_2 CO_3 + 35 NaCl	650 ÷ 880
20 KCl + 80 $BaCl_2$	850 ÷ 1350

Tab. 7.7 Chemical composition of some of the salts used and range of applications

The main advantage of salt baths is the fast, precise and uniform heating of the embedment without air access. The heating rate is due to the large value of the heat transfer coefficient of the flow between the electrolyte and the solid charge. Salt baths must comply with strict safety operating regulations, e.g. extraction and cleaning of escaping fumes from molten salts.

Electrode water heating

For the preparation of hot water and steam production, the heat generated by the direct passage of the current through the heated water is used. The current is fed through graphite electrodes (for low power input) or metal electrodes (for high power input). Alternating current is used to prevent the development of explosive gases and corrosion. The current density through the electrode surface is selected up to 1.5 A·cm^{-2}, usually around 0·5 A-cm^{-2}. The electrical conductivity of water depends on its composition and especially on its temperature.

Many different designs of electrode boilers are used. They are constructed not only for 231 V and 400 V, but also for voltages as high as 30 kV. Instantaneous water heating boilers are built from a few kilowatts to several megawatts. Often water is heated by night current as a storage medium for heating and technology in the paper, textile, food industry, etc. For example, electrode steam boilers are usually used for cooking (Fig. 7.16), which is distributed to the cooking boilers and returned as condensate. For industrial hot water and steam production, boilers are built with a capacity of up to 60 MW at an operating voltage of 30 kV and an overpressure of up to 4 MPa.

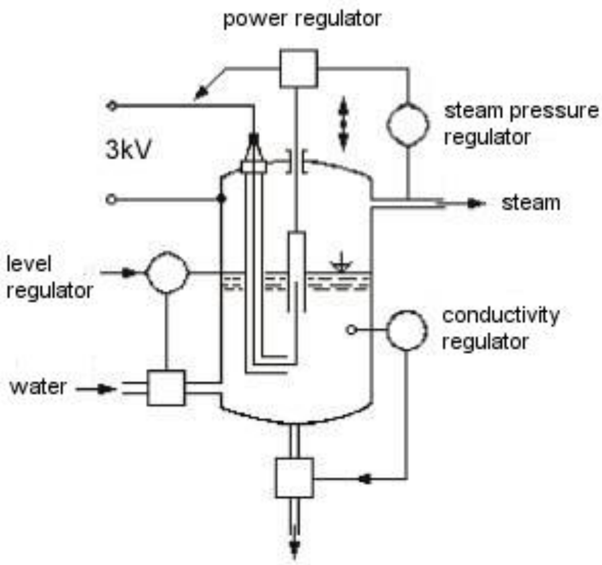


Fig. 7.16 Single-phase electrode boiler

The power of the electrode device at a given voltage can be controlled in the following ways:

- by adjusting the conductivity of water,
- flat electrodes - by covering with insulating sleeves (porcelain or cross-shaped tubes), shortening, lengthening,
- by zooming in and out of the electrodes,
- by dividing the electrodes into groups that are switched and reconnected in different ways,
- mechanical immersion and emergence of electrodes from water,

- by changing the water level in the boiler by means of a pump with fixed electrical boards suspended from above,
- by changing the number of nozzles in so-called jet electrode high voltage boilers.

Indirect resistance heating

In plants with indirect resistance heating, heat is generated in heating elements located directly in the furnace space. The heat is then transferred to the batch mainly by radiation from the heating elements and lining, by the flow of the atmosphere in the furnace space, or even by conduction. Electric resistance furnaces with indirect heating, so-called resistance furnaces, can be classified according to several aspects (e.g. according to IEC 60050-841).

According to the temperature of the furnace:

- low temperature up to 600 °C,
- medium temperature from 600 °C to 1100 °C,
- high temperature above 1100 °C.

According to the atmosphere in the furnace room of the furnace:

- with normal atmosphere (air),
- with controlled atmosphere (e.g. for carburizing, nitriding, to prevent oxidation),
- working with vacuum - vacuum furnaces.

According to the use in furnace operation:

- for heat treatment of metals,
- for melting metals,
- for melting glass,
- for cooling the glass,
- for laboratories, for households,
- with infrared heating, etc.

Depending on whether the stake does not move or moves during heating, the furnace:

- with stable - non-moving bet, with intermittent operation,
- with a charge passing through the furnace - continuous furnaces, with moving bottom, with uninterrupted operation.

This last criterion is decisive for the distribution of furnaces, and we will therefore follow this method in the following.

Resistance furnaces with stable charge

The most common furnaces in which the charge does not move during heating are chamber, carriage, shaft, hatch (bell), elevator and crucible melting furnaces.

Chamber furnaces

Chamber furnaces are one of the oldest types of electric resistance furnaces. They are very versatile and therefore widely used. The heating elements are usually located on the sides, sometimes in the floor, in the back wall and in the door, also on the ceiling. Chamber furnaces are built up to temperatures of 1100 °C with metal heating elements, and up to 1400 °C with elements made of silicon carbide (SiC) or other materials (called cermets).

Shaft furnaces

Shaft furnaces have a vertical axis and a circular or square cross-section. The furnaces are sometimes 10 m to 20 m deep, called deep shaft furnaces, and are usually sunk below the floor. To achieve a higher heating rate and even temperature distribution in the furnace, fans are sometimes installed in the bottom or lid to circulate the atmosphere in the furnace.

Shaft furnaces are not as versatile as chamber or carriage furnaces, but they are easy to seal and insulate against heat loss.

Hood furnaces

Hood furnace (Fig. 7.17) has a well-insulated heating hatch 1 (bell) of circular or square cross-section and has a heating winding 6 on its inner surface. The insert is covered by a heat-resistant muffle 2 (hatch) against direct radiation from the heating elements and thus against local overheating. The furnace has several working platforms and muffles. Hood furnaces are built to outputs of several hundred kilowatts.

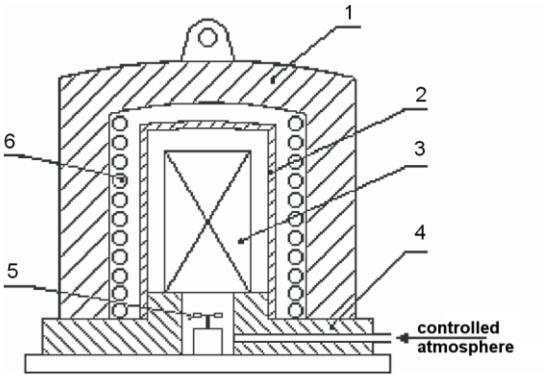


Fig. 7.17 Hood furnace

Elevator furnaces

Elevator furnaces are among the largest resistance furnaces with a stable charge. The furnaces operate with good efficiency, they are designed for temperatures of up to 1000 °C to 1200 °C with outputs of 500 kW to 2000 kW. Elevators furnaces are suitable for large sizes and large weights (tens of tons). Their great advantage is that they can be integrated into a continuous production line, as the carriage with the charge, after heating, continues in the direction of arrival at the furnace.

Crucible melting furnaces and melting tanks

They are designed for melting metals or alloys with lower melting points (Sn, Pb, Al, Zn, etc.). Around the metal or ceramic crucible is a heating winding. Outside the heater is the thermal insulation and the furnace frame. Usually these furnaces are hinged so that the molten metal can be poured out.

The melting tanks are of various designs, e.g. they have a heating winding with thermal insulation on the outside of the bath, they are not tilting (for galvanizing, tinning, alloying, etc.). For remelting (egalization) of aluminium, they have a heater in the ceiling and are tilted on swivel pulleys during casting.

❑ Continuous resistance furnaces

They are used where heat treatment is prescribed for a large number of products. A number of different types of continuous furnaces, which are usually rated for lower temperatures, are built. In these furnaces, prescribed heating, holding and cooling can be carried out according to the technological process. Generally, the furnaces have several temperature zones which are independently supplied and regulated. In the case of slow cooling of embedded parts, a cooling chamber is connected to the furnace, which is equipped with either thermal insulation or water cooling, depending on the required cooling rate.

Several continuous furnaces can form one fully mechanized and automated unit. In most cases, quenching and tempering furnaces are combined with quenching tanks, cleaning and drying equipment.

The furnaces are designed for continuous operation. Depending on the type of mechanism used to transport the charge, the most common furnaces are: belt and chain, roller, ramming, shearing, stepping, stretching, drum and carousel.

Conveyor belt furnaces

Charge to the conveyor belt furnace (Fig. 7.18) is loaded manually or by means of a special automatic machine via the feeding table 5 onto the conveyor belt 3 passing through the furnace. The belt is made of metal mesh for light components and of stamped plates for heavy components, which are connected to each other by pins and couplings. It is tensioned by means of a device 7, 4 is the belt drive. At the end of the furnace, the material is removed from the working area 6. The 2 NiCr heating elements are mostly located on the ceiling and bottom, below the upper level of the belt. A refractory lining 1 surrounds the furnace working area. The belt furnaces are designed for heat treatment of smaller parts up to a temperature of 900 °C.

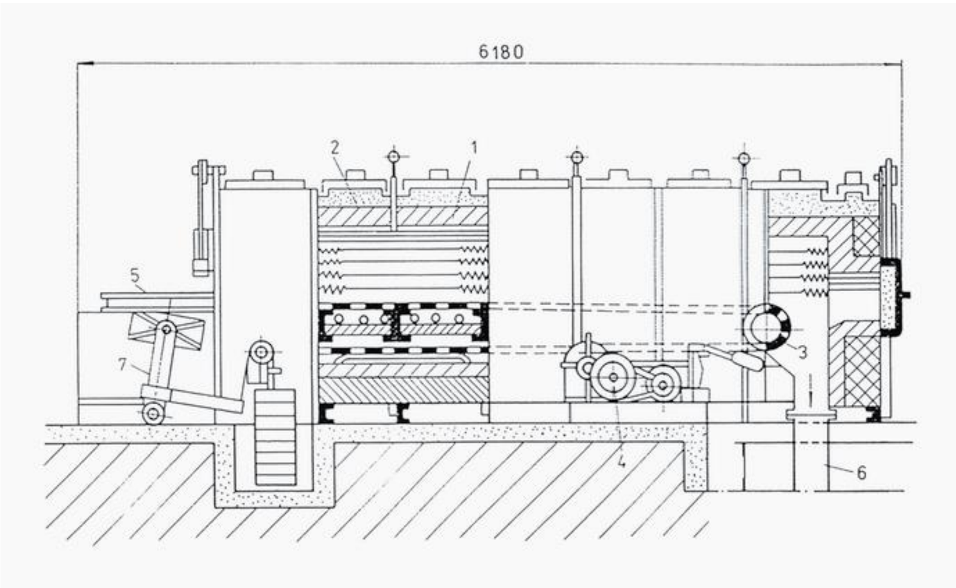


Fig. 7.18 Belt furnace

Roller furnaces

It is designed for temperatures up to 900°C. The roller track runs through the entire furnace and is composed of refractory rollers, with the axis perpendicular to the direction of movement, with bearings outside the furnace on both sides. The charge is placed directly on the rollers or on the pads so that it is well supported. The design must take account of the thermal expansion of the rollers and the furnace lining.

Pusher furnaces

The working temperature of the pusher furnace is up to 1000 °C.

Jolt ramming furnaces

Jolt ramming furnaces are designed for heating small piece-pieces to temperatures up to 900 °C.

Step furnaces

Walking beam furnaces are built for heating large forgings and castings to medium and high temperatures. The walking beam mechanism is outside the furnace working area. When moving forward, the charge is lifted and moved. When moving backwards, the mechanism drops and prepares for the next forward step, driven by a hydraulic or electric motor.

Drawing furnaces

Drawing furnaces are designed for heating wires and strips, especially of non-ferrous metals (also steel), which are drawed in the furnace. Uniform heating is achieved. For high outputs, furnaces with vertical movement of wires in several loops are used (production of enamelled wires).

Drum furnaces

The drum of the drum furnace is made of expensive refractory material, is subject to considerable thermal and mechanical stress and has a limited service life. A precise and uniform temperature is achieved in the furnace. These furnaces are suitable for the heat treatment (hardening, annealing, etc.) of washers, screws, smaller bearing rings and balls, but also for the splitting of mica.

Carousel (rotary) furnaces

Carousel furnaces are designed for the highest temperatures because the furnace mechanisms are completely outside the working temperature area. The furnace cross-section is in Fig. 7.19. The actual furnace body 1 is rotary, with heating elements 2. The floor of the furnace 3 is rotatable and the charge 4 is placed on it. The rotation is provided by an electric motor 5. The charge is inserted into the furnace through a door opening 6 and after one rotation it is removed from the exit opening with the door next to the entrance. The door is closed by a device 7. The heating time of the charge varies according to the change in the rotation speed of the floor.

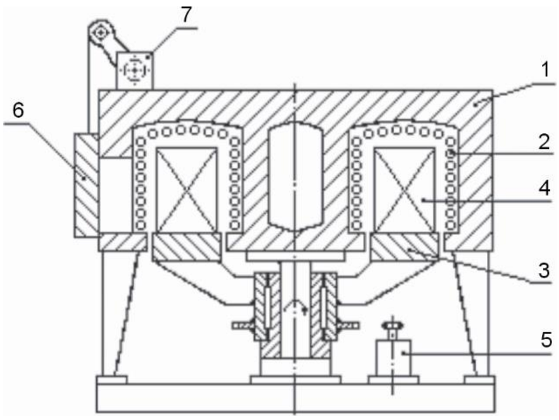


Fig. 7.19 Carousel furnace

❑ Materials and components of electric resistance furnaces with indirect heating

A classic resistance furnace with indirect heating consists of the following basic parts:

- refractory lining,
- thermal insulation,
- furnace enclosure,
- heating elements,
- feeding mechanisms and their drives.

In addition, the furnaces can be equipped with devices for the production of a protective atmosphere or vacuum. All furnaces are equipped with instruments for temperature measurement and control.

The refractory lining encloses the working area inside the furnace. It must be sufficiently resistant to heat at the working temperature, sufficiently strong and chemically stable. In resistance furnaces, we most often use chamotte parts composed of 38% to 44% alumina Al_2O_3, the rest being silica SiO_2.

Materials for thermal insulation have natural or artificial porosity (magnesite, slag, alumina, glass wool).

The enclosure and structure are usually made of steel sheet and steel profiles. Some components are made of cast iron and steel. These components operate at normal temperature and no special requirements are applied on them.

High demands are applied on the materials for heating elements, they should have the following properties:

- heat resistance at the working temperature of the element,
- high mechanical strength of the insulation,
- resistance to chemical influences of the furnace atmosphere and the ceramics with which they are in contact with,
- high resistivity to allow larger cross sections and appropriate wire lengths and to allow direct connection to the mains,
- a small temperature coefficient of resistance, which ensures a small difference between the resistance of the element cold and warm,
- stability of resistivity throughout the lifetime of the element,
- small thermal expansion,
- good workability to various shapes.

These above mentioned requirements are very demanding. In practice, only some of them can be met at the same time, or a compromise solution is chosen to achieve maximum durability.

Materials for heating elements are divided into two basic groups:

- metal materials,
- non-metallic materials.

❑ Materials for metal heating elements

Metal materials include Ni, Cr, Fe, Al non-magnetic and magnetic alloys, pure metals, steel and special alloys.

Austenitic alloys

Austenitic alloys are non-magnetic, so called chromnickel alloys. Ni+Cr alloy and Ni+Cr+Fe alloy are used for heating elements. These alloys are the highest quality, have good heat resistance, and can withstand frequent switching on and off. They are well welded and shaped. They have high resistivity and low temperature coefficient of resistance, do not age, are stable.

Ferritic alloys

Ferritic alloys are magnetic Cr+Al+Fe alloys without nickel, highly refractory with higher resistivity than the previous group. These include alloys with the trade names Kanthal, Alsichrom, Alkrothal, Chromal, Aluchrom, Thermal, etc. The resistivities of wires made of these alloys are around 1.4 μΩ·m at 20 °C and change very little with temperature. These materials are suitable for operating temperatures up to 1375 °C.

Pure metals

Pure metals are expensive, hard to melt, such as platinum, tungsten and molybdenum. They are used for heating elements in laboratory or other special furnaces where very high temperatures are required.

<u>Platinum</u> does not oxidize but carbonizes intensely, it cannot be used in a reducing atmosphere. Because its resistance changes greatly with temperature, switching it on in the cold will cause a big current surge.

<u>Tungsten</u> is very fragile. The heating elements are usually in the shape of a tube, the inner space of which is directly the working space. The power inlets are cooled by water. Tungsten heating elements operate in a vacuum or protective atmosphere up to 2600 °C.

<u>Molybdenum</u> is used for temperatures of 1400 °C to 2000 °C. It requires a protective atmosphere (e.g. alcohol vapour or hydrogen) and evaporates in a vacuum at 1650 °C.

Steel and special resistance alloys

<u>Steel wire</u> can be used up to 900 °C, but only in a hydrogen atmosphere. In a normal atmosphere only up to 400 °C. It is inexpensive and is used in drying furnaces.

<u>Constantan</u> (56% Cu + 44% Ni) and Nickel (65% Cu + 34% Ni + 1% Fe) are special alloys whose resistance not changes with temperature. They are mainly used in measuring and control technology. However, they can also be used for heating elements in small appliances and for low temperatures.

❑ Non-metallic materials for heating elements

The operating temperatures of metallic heating elements are at most 1 375 °C, so materials were sought which, with the same basic properties as metallic ones, can operate at higher temperatures in a normal atmosphere.

Silicon carbide (SiC)

Silicon carbide is the most commonly used non-metallic material for heating elements with trade names Silit, Globar, Crusilir, Cesiwid, etc. The resistivity is considerably higher than that of metallic materials (0.6-3.0 mΩ·m), which allows heating elements to be made e.g. in the form of rods with reinforced ends. The diameters of the rods range from 1.2 to 5 cm and the lengths from 8 to 200 cm.

The applicability of the SiC heating elements is up to a temperature of 1500 °C. The temperature coefficient of resistance is negative up to 800 °C, positive above 800 °C. The lifetime of the heating elements is between 3000 and 10000 operating hours.

Cermet elements

They are produced by powder metallurgy. The basic material is a mixture of molybdenite silicates ($MoSiO_2$) with silica (SiO_2). The elements are most often U-shaped (hairpin). They can also be in the shape of rods, tubes.

The operating temperatures of the elements are 1600 °C to 1700 °C. The refractoriness is due to the protective SiO_2 layer formed on the element surface during operation. Cermet elements are fragile and do not tolerate shocks. They are resistant to oxidizing, nitrogen, argon and CO atmospheres. They are damaged by sulphur and chlorine. The resistivity varies considerably with temperature (at 20 °C, ρ = 0.25 μΩ·m, at 1600 °C, ρ = 3.5 μΩ·m), so they are connected via control transformers.

Carbon and graphite heating elements

The basic raw materials and graphite production were described in Fig. 7.14. Heating elements are produced in the form of rods, tubes, etc. Operating temperatures are up to 2000 °C in a vacuum or controlled atmosphere to prevent oxidation. Under normal atmospheres, oxidation occurs from about 400 °C for carbon elements and from about 600 °C for graphite elements. The resistance of the carbon decreases with increasing temperature, e.g. at 1400 °C to about 67 % of the full value at 0 °C. For graphite, from 100 % at 0 °C, the resistivity first decreases with increasing temperature, to about 77 % at about 400 °C and then increases again. At 1400 °C the resistivity is about 96 % of the original value.

❑ Basic use of resistance furnaces in industry and engineering

The main application of electric resistance furnaces in industry is heat treatment. These are processes in which metal objects in a solid state are subjected to certain temperature changes to achieve the desired material properties. In particular, this involves increasing the strength and stress limits while maintaining the shape of the heat treated object. If this process is influenced by the chemical effect of the environment, it is chemical-heat treatment.

The following processes of ČSN EN 10052 are used in resistance furnaces for heat processing, mainly of engineering components made of steel or non-ferrous metals and their alloys:

- **Annealing** reduces hardness, improves machinability, reduces internal stresses and causes the desired microstructure to be achieved. Steel parts are heated to 700 °C (up to 800 °C for brass, 960 °C to 1200 °C for nickel), held at this temperature for 2 hours and then slowly cooled. Types of annealing are e.g. brightening, normalizing, isothermal, recrystallizing, etc.
- **Hardening** Increases the hardness of steel components that are heated above the recrystallization temperature and then rapidly cooled by immersion in water or oil. Types of hardening include thermal, isothermal, intermittent, surface, etc.
- **Tempering** usually follows quenching. Hardened steel objects are very hard but also very brittle, so they are further heat treated by tempering. They are heated to temperatures ranging from 150 °C to 600 °C and slowly cooled after a delay at the tempering temperature.
- **Case hardening** causes a high hardness of the surface layer of steel components while maintaining the toughness of the core. Cementation is the saturation of the

surface of a steel object with carbon in a solid, liquid and especially gaseous environment at a temperature of about 900 °C.

- **Nitriding** increases the abrasion resistance of the surface layer of steel components. Nitriding is the saturation of the surface of steel components with nitrogen in a gaseous or liquid environment at temperatures between 470 °C and 580 °C.
- **Refining treatment** of steel products. High strength, hardness and toughness are achieved by hardening. Before the last mechanical treatment, annealing is carried out, followed by quenching in oil or water and then tempering with a delay and subsequent controlled cooling.

Electric resistance furnaces have applications in the heat treatment of glass products. Automatic heat treatment lines for semi-finished and finished products are being extended to a wide variety of production areas, including the textile industry, food industry, etc.

❑ Connecting and controlling of electric resistance furnaces

The most common electrical wiring of a resistance furnace is shown in Fig. 7.20.

Electric resistance furnace, connected according to Fig. 7.20, is connected to the three-phase network with a neutral conductor via contactor 2. The heating elements of the furnace are represented by resistors of the same value R_1, R_2, R_3. The furnace is switched on by switch 5. By switching off this switch, we close the auxiliary switching circuit consisting of the following elements: contactor coil 3, mercury switch of the automatic temperature controller 4, fuse heating wire in the furnace 6, door contact 7. At the same time, the motor of the automatic temperature controller 10 starts. When the switching coil 3 is energized, the contactor 2 switches on and connects the heating elements to the mains. The thermocouple 9 supplies voltage to the instrument indicating the temperature in the furnace. When the desired temperature is reached, the mercury switch of the automatic temperature controller 4 is flipped, the current in the control circuit is interrupted and contactor 2 disconnects the heating elements from the mains. In the diagram Fig. 7.20. it is only possible to control the temperature in the furnace by switching off and on the total power supply.

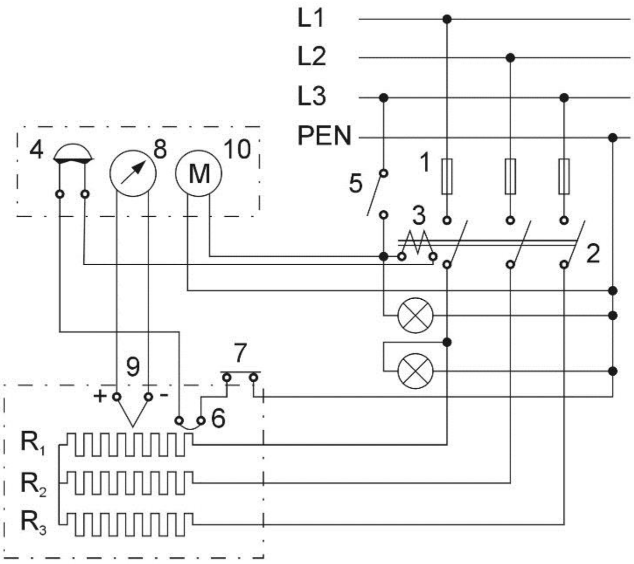


Fig. 7.20 Resistance furnace wiring

❑ Automatic temperature control in resistance furnaces

The task of the electric furnace temperature control is to maintain the desired temperature of the working area permanently and accurately, or to react to changes according to a predetermined program. In industry, step or continuous control is used.

Step control is most easily achieved by switching off and on the entire power input of the furnace. We can also use the switching of star-delta resistive sections or switching of groups of resistive cells. The temperature and power waveform for a resistance furnace with single-pole and double-pole step control is shown in Fig. 7.21.

In the first part Fig. 7.21 shows the single-pole on-off control. The second part of the figure shows dipole temperature and power control using star-delta resistive section switching.

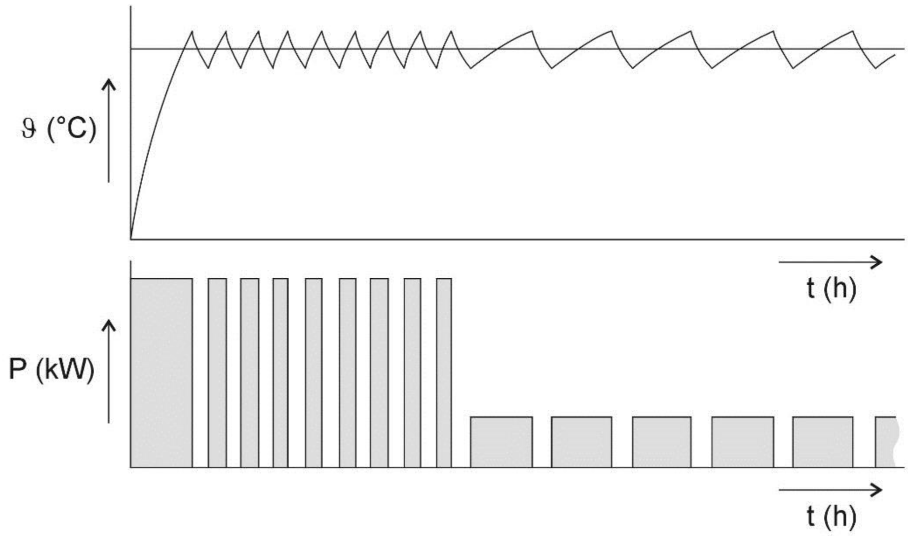


Fig. 7.21 Temperature and power waveform of a resistance furnace with single and dipole step control

By using this infinitely variable control the resistance furnace results in a significant flattening of the temperature profile, as shown in Fig. 7.22.

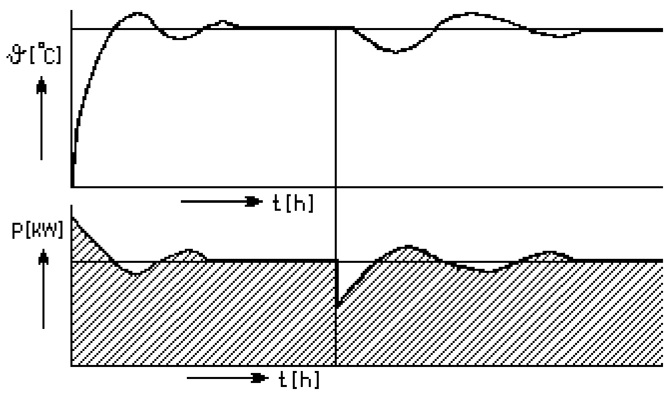


Fig. 7.22 Continuous control of resistance furnace

Calculations of resistance electrothermal devices for indirect resistance heating

Basics of design and calculation of resistance furnaces

For the correct determination of the type of furnace for the required heat treatment of the insert, the following aspects are crucial:

- technological requirements for heat treatment of the charge,
- the type of charge and its size,
- the weight of the charge to be processed per unit time,
- temperature regime, maximum temperature (heating rate, final temperature, dwell time at a specific temperature, cooling rate, etc.),
- uniformity and accuracy of temperature compliance,
- natural or controlled atmosphere in the furnace,
- intermittent or continuous operation,
- space available,
- the price of the furnace.

For piece or small batch production, we choose a furnace or a group of furnaces with a stable charge, for mass production, continuous furnaces or fully automatic continuous furnace lines are preferable.

Furnace design requires many technical compromises, experience and economic considerations. Usually, the preliminary basic parameters of the furnace (size, mechanisation, power input, etc.) are determined for a given purpose by experience or an indicative calculation. The furnace is then roughly designed structurally, including the choice of thermal insulations, their thicknesses, etc. This first approximate design is checked by more detailed calculations. Appropriate corrections are made and another, more precise design is drawn. This second design is again checked by calculation in much greater detail. In particular, the basic dimensions of the furnace are checked in terms of the production technology for which the furnace is intended, thermal insulation and heat losses, power input, efficiency, temperature curves, production capacity, etc.

Calculation of the total power input of the furnace

For the developed basic structural design of the furnace at a known temperature or temperature distribution in the furnace, calculate the steady-state power loss P_z of the furnace.

The power losses is determined by the losses:

- the individual walls of the furnace,
- leaks (e.g. door and carriage leaks in furnaces with a non-moving charge),
- at the inlet and outlet of continuous furnaces,
- when opening and closing the door,
- heat transfer by conveying mechanisms in continuous furnaces (belts, chains, etc.),
- for heating muffles, pallets, washers, etc.

The loss power can be divided into the idle loss power P_{z0} (not dependent on the operation of the furnace with charge) and the losses P_{zv} related to the operation of the furnace with charge.

The following applied

$$P_z = P_{z0} + P_{zv} \tag{7.46}$$

P_{z0} is related to the first three items above. P_{zv} is related to the second three. The calculation of P_{z0} and P_{zv} is carried out according to the general laws of heat transfer in steady state and according to the specific heat capacity, temperature and weight for losses through pallets, muffles, pads, etc.

Useful performance

Energy is required to heat a charge of mass *m*, specific capacity *c*, from temperature ϑ_0 to temperature ϑ_k

$$W_u = \int_{\vartheta_0}^{\vartheta_k} c \cdot m \cdot d\vartheta \tag{7.47}$$

If we introduce the mean specific heat capacity c_{av} , the relation (3.13) simplifies to the form

$$W_u = c_{av} \cdot m \cdot (\vartheta_k - \vartheta_0) \tag{7.48}$$

If the specification specifies a heating time t_h, the useful input power would be given by

$$P_u = \frac{W_u}{t_h} \tag{7.49}$$

and the theoretical power requirement of the furnace would be given by

$$P_p = P_z + P_u \tag{7.50}$$

Since we have to take into account a certain inaccuracy of the calculation, a margin for voltage drop in the network, aging of heating elements, increase of furnace losses, etc., we choose a certain safety factor k_s = 1.2 to 1.7. Then the input power of the furnace is given by the equation (7.51). In practice, however, we usually do not know the heating time of the charge t_h, and have to calculate it.

$$P_p = k_s \cdot (P_z + P_u) \tag{7.51}$$

Summary of terms 7.2.

Resistance heating direct and indirect, salt bath, thermal electrolysis, electrode boiler, resistance furnace, heating element, depth of penetration, temperature control.

Questions 7.2.

1. Explain the principle of direct resistance heating.
2. What materials can direct resistance heating be used to heat, what must be met? Draw a diagram.
3. Draw the waveforms of power input, losses and temperature in direct resistance heating.
4. Explain the principle of electrode heating of water.
5. How can I control the power of the electrode boiler?
6. Describe the principle of heat transfer to the insert by indirect resistance heating.
7. According to what aspects are resistance furnaces divided?
8. List basic parts of resistance furnace.
9. For what heat treatment of materials can resistance furnaces be used?
10. Explain and draw the process of step temperature control of a resistance furnace.
11. Explain and draw the process of continuous temperature control of a resistance furnace.

7.3. Electric arc heating equipment

TIME TO STUDY:

3 hours

TARGET:

After reading this paragraph, you will

- know the principle of DC and AC arc formation
- be able to describe the different types of electric arc and their parts
- understand the optimisation of melts according to working characteristics

EXPLANATION

DC arc formation in an electric field

The origin of the electric arc will be explained using the simple example of an electrical circuit powered by a DC voltage source *E,* containing a control resistor R and a variable arc resistance R_o (Fig. 7.23).

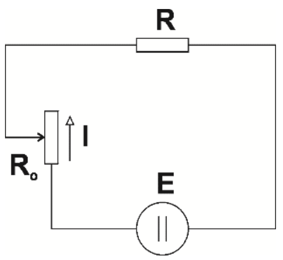


Fig. 7.23 Example of an electrical circuit powered by a DC source

The arc is formed between two electrodes. The cathode is connected to the negative pole of the source, the anode to the positive pole. If we get the two electrodes into contact with each other, then a current I will flow through the circuit, given by the circuit quantities E, R. We determine these quantities so that the current flowing through the circuit is greater than 0.5 A.

If we move the electrodes away from each other, then when the contact between them is broken, a conductive path starts to form between them due to ionization of the environment between the two electrodes. The conductive elements between the electrodes are ionised vapours of the material of the two electrodes and air. An electric arc is formed.

The circuit current decreases as the arc resistance R_o increases. The resistance of an electric arc R_o is highly nonlinear and depends on the nature of the arc and varies rapidly from zero to infinity.

Arc discharge consists of an ionised column through which a current flows and surrounding gases (aureole) at high temperature. The length of the arc then bounds the electrodes, cathode and anode (Fig. 7.24).

As the arc continues to burn, the cathode is shaped into a cone, while the anode shows a deepening in its central part. Immediately adjacent to the cathode is the cathode conduction region. The length of this part is insignificant, about 10^{-5} cm and does not depend on the length of the arc. In this cathode region, ionisation processes into elementary particles take place.

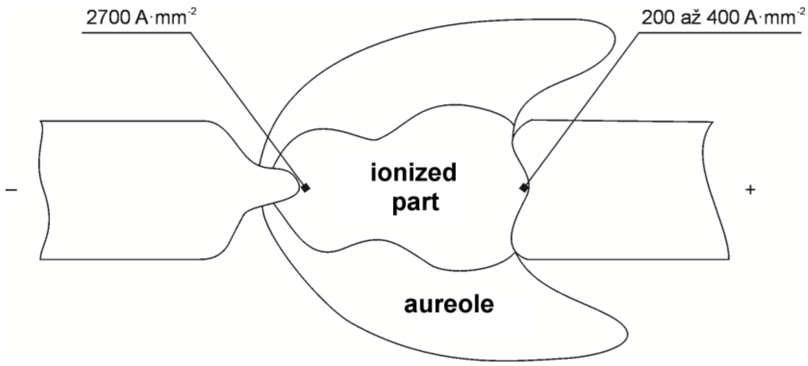


Fig. 7.24 Electric arc

In the middle of the cathode is the so-called cathode spot. The current density in the cathode spot (2700 $A \cdot mm^{-2}$) is considerably higher than in the surrounding areas of the cathode surface. The cathode region is then connected to the column forming the longest part of the conductive path between the electrodes. It consists of an ionized column containing ionized particles that allow current to pass between the electrodes. In this ionised column, the basic part of the electrical energy is transformed into thermal energy.

The anode part of the arc is connected to this ionized column. Its length is also insignificant and does not depend on the length of the arc. According to research, the current densities of the cathode spot have been laboratory determined to be in the range of 2700 $A \cdot mm^{-2}$ to 2900 $A \cdot mm^{-2}$ and the anode spot in the range of 200 $A \cdot mm^{-2}$ to 400 $A \cdot mm^{-2}$.

A very important area of the arc is the cathode region, from which electrons are transported to the anode by thermoelectric emission.

DC arc characteristics

The interrelationship between the basic properties of an electric discharge is called the arc characteristic. The basic characteristic of an arc is the volt-ampere characteristic.

The best known of the empirical relations expressing the electrical properties of a DC arc is Ayrton's formula

$$V = a + b + l + \frac{c}{I} + \frac{d \cdot l}{I} \qquad (7.52)$$

where *a* (V), *b* (V.cm^{-1}), *c* (W), *d* (*W*.cm^{-1}) are electrode material dependent constants, *l* is the arc length, V is the arc voltage and *I* is the current intensity.

According to Ayrton's relation, they are constructed (Fig. 7.25) two volt-ampere characteristics of the DC arc. It can be seen that as the current increases, they asymptotically approach the steady-state voltage value. Curve 1 is for an arc length of 2 cm, curve 2 for an arc length of 6 cm.

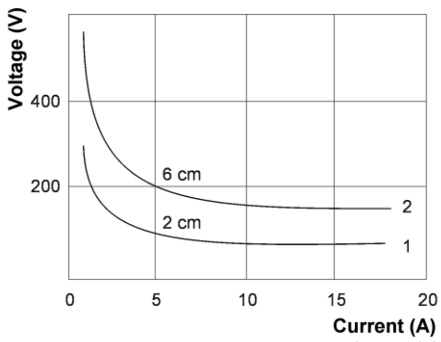


Fig. 7.25 Volt-ampere characteristics of the DC arc

Characteristics of the AC arc

To derive the characteristics of the AC arc, we use the alternate circuit diagram with arc according to Fig. 7.26.

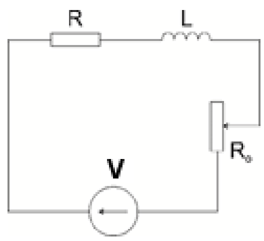


Fig. 7.26 Alternate circuit diagram with AC arc

In the circuit are represented the elements of the AC source *V*, the active resistances of the circuit *R* and R_o and the inductance of the circuit *L*.

If we increase the voltage of the source at a constant distance between the electrodes, then at a certain value of voltage, a breakdown will occur and an electric current will start to flow between the electrodes through the arc.

With a periodic, sinusoidal voltage change, forced pauses in arc burning occur during the period when the arc voltage is below the V_{min} value.

At Fig. 7.27 shows the voltage and current waveform in a circuit containing only ohmic resistance without inductance.

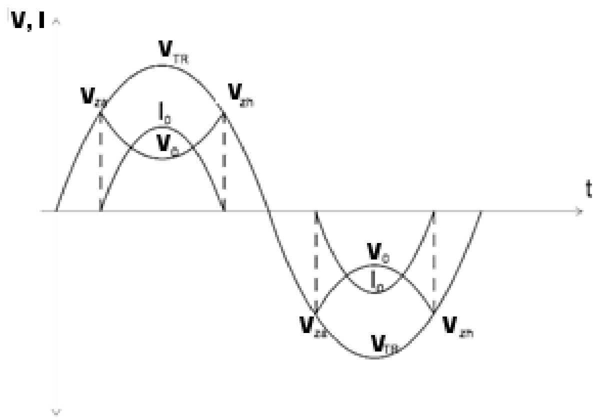


Fig. 7.27 Voltage and current waveform in the circuit

Once the transformer voltage U_{TR} reaches the arc ignition value U_{za}, current will begin to flow through the circuit until the transformer voltage drops below the extinction voltage U_{zh}. The extinction voltage is usually slightly lower than the arc ignition voltage. This process is repeated at each half wave. The arc voltage has a saddle due to the negative V-I characteristic of the arc.

Stabilization of an AC arc by phase shifting

If we connect an inductance in series to the arc circuit, not only a phase shift between voltage and current occurs, but also a prolongation of the arc burning due to the inductance of the inductor.

It can be shown by calculation that a minimum phase shift of PF = 0.85 is required for sustained arc burning. Fig. 7.28 shows the idealised voltage and current waveform at PF = 0.85. The voltage on the arc is rectangular. This is characteristic of arcs for very high currents, where there is virtually no more change in voltage as a function of current.

Stabilization of AC arc by increasing the voltage on the transformer

The stabilization of the AC arc by increasing the voltage on the transformer is shown in Fig. 7.28 in dashed lines.

In industrial electric arc furnaces, in addition to a change in current, there is also a change in the electrode. If in the first half-period the cathode is a carbon electrode, then in the second half-period the molten material takes over this role. This material has different electrical and thermal properties compared to the carbon electrode. This is particularly evident at the beginning of the melting process when the charge is relatively cold and the cathode spot cools rapidly during the first half-period due to the good thermal conductivity of the metal. The result is that in the half-period when the electrode (cathode) is a carbon electrode, more current flows through the circuit than in the second half-period when the polarity is reversed.

The cold furnace charge requires higher voltages at lower arc currents due to its poorer emissivity. The non-uniformity of the emission causes strong fluctuations. Even arc breaks sometimes occur. This must be eliminated by short-circuit of the circuit and subsequent separation of the electrodes.

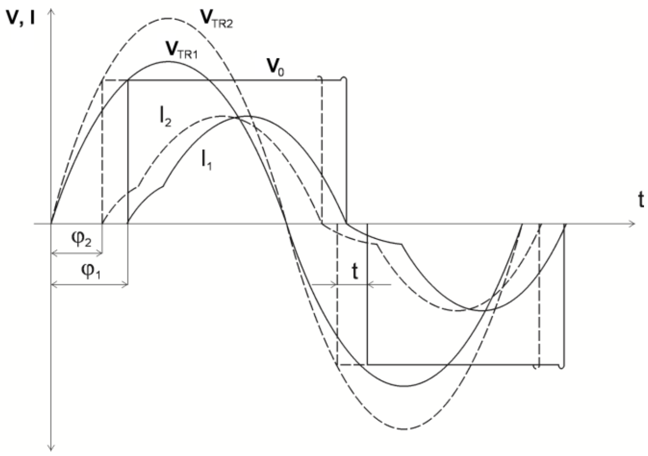


Fig. 7.28 Stabilization of the AC arc

Theoretical basics of electric arc furnaces

The current circuit of an electric arc furnace consists of a constant ohmic and inductive resistance, determined by the properties of the conductive material and the geometric shape of the leads and surrounding components of the electric arc furnace. These components mainly influence the value of the reactive losses and thus the voltage drop across the electrode terminals.

Furthermore, the arc resistance is represented in the current circuit, which can be replaced by a variable ohmic resistance (Fig. 7.29).

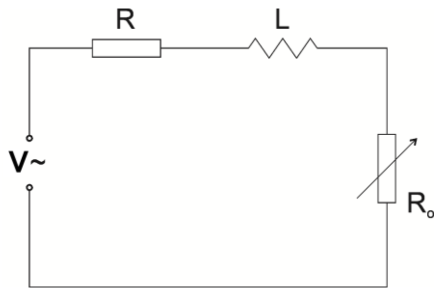


Fig. 7.29 Example of an electrical circuit

The fictitious arc resistance R_O is a variable value. This value is obtained by dividing the arc voltage by the furnace circuit current. It can vary from zero when the electrodes are in short circuit to infinity when the circuit is broken and the arc is not burning. The ratios in the furnace can be well represented by the vector diagram on Fig. 7.30.

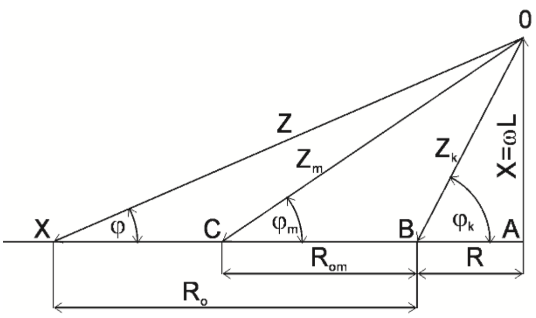


Fig. 7.30 Vector diagram

From the diagram on Fig. 7.30 shows the **short-circuit impedance**. The short-circuit impedance determines the short-circuit furnace current. The operating point moves along the line BX depending on the magnitude of the arc resistance. The resistance of the furnace then also determines the instantaneous value of the furnace impedance, where Z_m is the impedance for the maximum output of the furnace.

$$Z = \sqrt{(R + R_o)^2 + (\omega \cdot L)^2} \tag{7.53}$$

In the relationship (7.53), R_o is the variable value of the arc resistance. From the vector diagram, the furnace power factor PF can also be determined.

For the value of PF (short circuit - R_o = 0)

$$PF = \frac{R}{\sqrt{R^2 + (\omega \cdot L)^2}} \tag{7.54}$$

For any work point marked *X,* the following applies:

$$PF = \frac{R + R_o}{\sqrt{(R + R_o)^2 + (\omega \cdot L)^2}} \tag{7.55}$$

The arc current is inversely proportional to the variable value of the impedance *Z*.

$$I = \frac{U}{Z} = \frac{U}{\sqrt{(R + R_o)^2 + (\omega \cdot L)^2}} \tag{7.56}$$

We assume that during operating short circuits, the magnetic materials of the circuit (inductor, transformer coils, conductors, structure) operate in the direct part of the magnetization characteristic. Thus, the reactances *X* do not depend on the passing current. Similarly, the constant part of the active resistances *R* (except for the arc resistance) does not depend on the passing current. Under this assumption, the end points of the current vectors for different values of the arc resistance R_o will move in a circular direction.

In Fig. 7.31 is a circle with the points A´, B´, C´, X´, *O´* marked. These individual points are equivalent to the inverted value of the impedance *Z*, which varies depending on the value of the arc resistance.

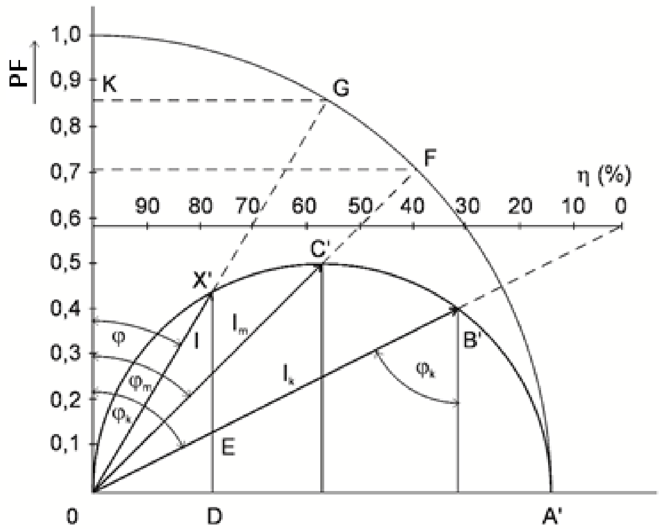


Fig. 7.31 Circular diagram

Point A in Fig. 7.30 corresponds to point A′ on the circle (Fig. 7.31). The line 0B = Z_K (Fig. 7.30) corresponds to the line 0B′, expressing the short-circuit current. The line segment C0 (Fig. 7.30) corresponds to the line C0′ (Fig. 7.31) is the point for maximum furnace output. The line 0X (Fig. 7.30) i.e. the arbitrary arc current, corresponds to the line segment 0X′ in the circular diagram.

If the arc resistance R_o converges to infinity, we reach the point 0′ on the circular diagram when the arc is broken. If we plot the voltage vector U perpendicular to the diameter of the circle, 0A′, then the angles φ_K, and φ are the phase shifts between the voltage and the instantaneous furnace current. We can plot a scale for the furnace power factor $\cos\varphi$ on the vertical axis.

The intersection of the elongated current vector with the circle A′FG, whose radius is the diameter of the circular diagram, indicates on the vertical (y-axis) the value of PF with which the furnace operates at a given current.

The efficiency η for the individual furnace currents is obtained from the intersection of the elongated vectors of these currents with the efficiency line. The efficiency line is constructed by extending the short current vector I_K and dividing the perpendicular from some point of this vector I_K evenly on the vertical *y-axis*.

By reducing the current, the stability of the electric arc is adversely affected. The criterion for assessing this stability is the ratio of

$$\frac{I}{I_{SC}} = \frac{\text{working current}}{\text{short circuit current}} \qquad (7.57)$$

Increasing the current will increase this I/I_{SC} ratio at the cost of reducing the theoretical electrical efficiency of the furnace.

From the point of view of the reverse effects on the network, these are more damped at a smaller difference, i.e. if the current vector on the circular diagram approaches the point B′ (Fig. 6.14), corresponding to the short-circuit current I_K .

On the circle diagram we distinguish three basic areas:

- unstable operating area - section 0'X' - long arc
- optimum operating area - section X'C'
- guaranteed stable operating area - section C'B' - short arc

Three-phase arc furnace equipment

The electrical equipment contributes a substantial part of *the cost of* electric arc furnaces and significantly influences their operation. The different parts of the electric arc furnace equipment can be best divided according to their function:

- High current electrical circuit
- Automatic electrode movement control circuit
- Measuring instruments, protection, interlocking and signalling
- Control computer

The most important group is the power circuit. It represents the bulk of the value of the furnace electrical equipment and has a significant effect on the operation of the furnace. The second essential part is the automatic electrode movement control circuit. The function of the power circuit is to conduct electrical energy into the furnace working area and convert it into heat. The power circuit of a three-phase arc furnace is shown schematically in Fig. 7.32.

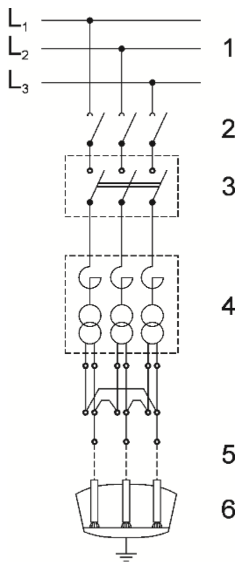


Fig. 7.32 Power circuit of a three-phase arc furnace

Description of the power circuit of a three-phase electric arc furnace (Fig. 7.32):

1 – Supply network; 2 - Disconnector; 3 - High voltage power switch; 4 - Furnace transformer and chokes; 5 - Short network; 6 - Electrodes

❑ High voltage power supply network

In terms of energy, electric arc furnaces are one of the largest consumers of electricity, concentrated in one point of the metallurgical plant's power grid. The HV power supply network of electric arc furnaces is loaded by irregularly varying peak currents, which range from zero values at arc breaks to three times the rated current at short-circuiting of the melt electrodes. This irregular variation of currents causes voltage fluctuations at the respective impedances of the power supply network which adversely affect other electrical equipment supplied from the same system. In addition, this fluctuation causes a reduction in the electrical power transmitted by the arc to the melt.

X-ray equipment, televisions and data transmission systems are particularly sensitive to these voltage fluctuations. Therefore, the requirements for the high-voltage power supply network of electric arc furnaces are precisely defined and determined mainly by the power of the furnace transformer and the melting process.

An important factor for the design of the HV power supply network of electric arc furnaces is the short-circuit power at the point of connection of the furnaces to the power system. In particular, it is necessary to isolate the power supply system of electric arc furnaces from appliances, especially those that are sensitive to voltage changes.

However, in some cases we cannot make this separation. These are mainly smaller steel plants supplied with high voltage of 22 kV and lower, where other customers are connected to common busbars. In these cases, it is necessary to calculate whether the short-circuit power at the point of connection of the electric arc furnace guarantees that the disturbance effects on the network are kept within acceptable limits.

❑ Disconnector

The disconnect switch is only used to disconnect the entire arc furnace electrical equipment from the high voltage supply during repairs or inspection of the equipment. Otherwise, it does not have a direct effect on the electric arc furnace and therefore will not be discussed further.

❑ High Voltage Power Switch

The purpose of the high-voltage switch is to switch and disconnect the power circuit at the beginning and end of melting, during melting, in case of dangerous overload of the transformer and in emergency cases. Power switches are highly stressed. They often perform 60 to 70 trips in a 24-hour period. The operation of the entire electrical equipment of the furnace depends on their smooth and trouble-free operation. For example, failure to switch off a long-lasting short circuit between the electrode and the melt can result in serious damage or even destruction of the electrical equipment due to the effects of short-circuit currents. The most commonly used types are pressurized air vacuum SF_6 switches.

❑ Furnace transformer

The output of the furnace transformer limits the heat input to the furnace and thus the output of the furnace. This is particularly evident in the melting stage of the charge, where the duration of this process depends mainly on the amount of heat supplied. The selection of the furnace transformer output is made according to the size of the furnace charge and the selected operating mode (Fig. 7.33).

Furnace transformers in electric arc furnaces are very different from normal power transformers as they operate with highly variable loads with frequent short circuits. A specific feature is the relatively low secondary voltage and high secondary current. Since the requirements for the amount of energy fed into the furnace during melting vary considerably, the transformer must be able to regulate the secondary voltage within wide limits.

Voltage regulation on the secondary side would be very difficult for the high secondary currents (10 to 60 kA) of conventional medium power furnaces. Therefore, it is done by changing the number of turns of the primary winding. Switching the primary winding in a triangle to star circuit is made possible by doubling the number of voltage stages. Most of our existing arc furnaces use transformers with voltage stage switching when the power switch is off, more modern ones also under load.

The selected ultra-high productivity melting (UHP) mode is characterised by a short arc. The ratio of the furnace transformer outputs for UHP mode and normal mode is 2.1 to 2.4 (Fig. 7.33.)

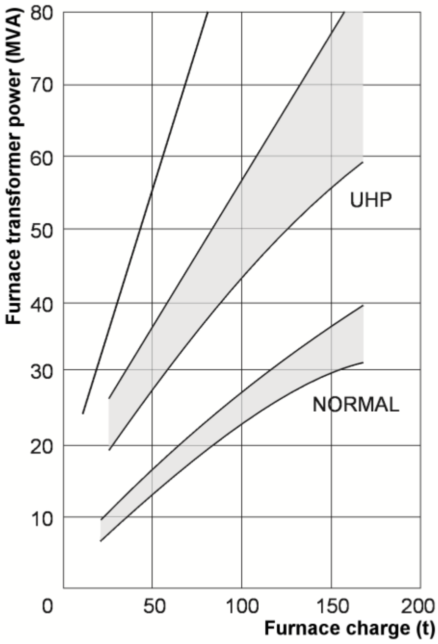


Fig. 7.33 Ratio of furnace transformer powers for UHP and normal mode

Chokes

The chokes, which are connected in the power supply network between the power switch and the furnace transformer, have the task of limiting the value of short-circuit currents when the electrodes touch the melt. They are located in a common vessel with the transformer and may have several degrees of reactance. A reactor is usually included when the transformer primary is connected in a triangle, i.e. at higher voltage levels. When switched to star, the inductor is then de-energized. The ideal condition would be in the case of continuous control of the reactance of the inductor.

The downside of chokes in electric arc furnaces is the deterioration of the overall efficiency of electric arc furnaces. With a lower degree of reactance or with the choke completely removed, the furnace is operated especially in the second part of the melting process, i.e. in the period when the arc is shorter, more stable and when short circuits are less frequent. Working with a lower reactance of the inductor allows to increase the arc power and thus to speed up the melting while reducing the energy consumption. However, this requires the ability to control both the switching of the reactance stages of the inductor and its complete deactivation.

A short network

The short network is called the power line from the pins of the secondary winding of the furnace transformer to the furnace working area. The design of the short network may vary from furnace to furnace. However, we can always divide this short network into the following parts:

- crawler part
- flexible ropes
- electrode holder arm wires
- electrode holders
- electrodes and couplings

High currents flow through the short network, so even though the resistances in the short network are tiny, on the order of 10^{-3} Ω, the losses in the line are significant. At a current of A 10^4, the voltage drop across the 10^{-3} Ω resistor is 10 V. Thus, we lose 100 kWh of energy in one hour. The short network reactance has an even more significant effect on the voltage drop. Although it does not directly cause energy loss, it reduces significantly the voltage on the arc itself and thus reduces the power supplied to the furnace working area.

The reactance of individual phases is influenced not only by the length of their conductors, but also by their relative position and the position of the surrounding steel structures of halls and cranes. Uneven power distribution in the individual phases has an adverse effect on the furnace operation and the life of the lining. The most advantageous measure to reduce the asymmetry is to implement a short network bifurcated line (Fig. 7.34).

A condition for the implementation of the bifilar connection are suitable terminals of the secondary winding of the furnace transformer that can be reached outside the transformer itself. However, perfect inductance compensation can only be achieved with a bifilar connection up to the electrodes and with the connection of the transformer secondary winding leads up to the electrodes.

In smaller ore-thermal and steel furnaces up to about 15 MVA, the short network is made by a belt with a supply of flexible ropes in a parallel bundle arrangement. For larger arc furnaces, the short network is made of copper tubes cooled by water flow.

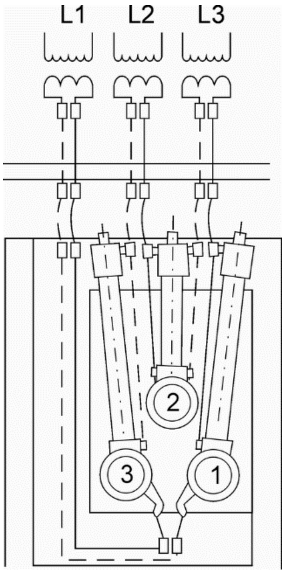


Fig. 7.34 Bifilar design of the short path

Electrodes

The electrodes, enclosing part of the electrical equipment, are a very important part of the electrical circuits of electric arc furnaces. The heat losses in the electrodes, as well as the cost of the electrodes consumed, account for a significant part of the operating costs.

The main requirements for electrodes are:

- Good electrical conductivity
- High mechanical strength
- High oxidation temperature
- Low ash and sulphur content

Three types of electrodes are practically used for arc heating:

- Carbon electrodes
- Graphite electrodes
- Hopper electrodes (Söderberg)

Primary and secondary metallurgy

At present, the electric power plants use a technological system with the following aggregates (in the given order):

- EAF (electric arc furnace)
- LF furnace (ladle furnace)
- Vacuuming

The system of a modern steel mill is characterized by a massive volume of material flow, where the input material (scrap and additives in lump or bulk) is transformed into continuous ingots. In addition to these ingots, waste is generated, namely slag and unwanted impurities. The transformation takes place in a sequential material transfer EAF - LF - Vacuum. In practice, of course, not all aggregates have to be used, but it always starts in the EAF.

EAF - Electric Arc Furnace - Fig. 7.35 (low wall furnace)

- represents the so-called primary metallurgy
- the furnace unit is used to produce liquid "crude" steel
- energy for production is supplied mainly by electric arc, but we can help with oxygen burners or by burning carbon

LF furnace - ladle furnace

- belongs to the so-called secondary metallurgy equipment
- this device maintains or increases the temperature of the liquid steel in the casting pan
- it is also used for final alloying, breaking away from the pan (adding legur)

Vacuuming

- another of the so-called secondary metallurgy facilities
- the equipment is used to improve the quality of the steel produced
- definitively gets rid of residual unwanted gases

A classic electric arc furnace is shown on Fig. 7.35

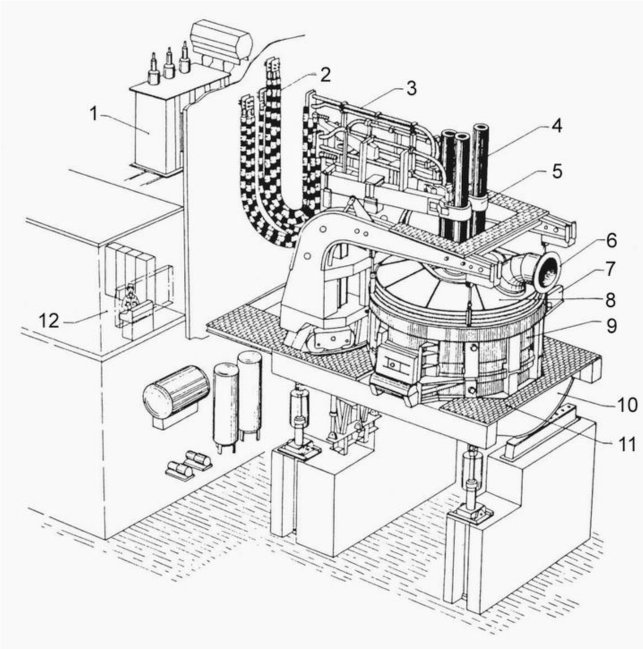


Fig. 7.35 Three-phase electric arc furnace [6]

Description of three-phase electric arc furnace Fig. 7.35:

1 - Furnace transformer; 2 - Flexible water-cooled cables; 3 - Horizontal water-cooled tubular conductors; 4 - Electrodes; 5 - Electrode holders; 6 - Furnace compartment gas outlet; 7 - Steel outlet during tipping; 8 - Water-cooled furnace lid; 9 - Furnace compartment; 10 - Furnace tilting mechanism; 11 - Assembly platform; 12 - Control workstation.

❑ Types of EAF according to the arc used

Electric arc furnaces are most often connect directly on three-phase AC current. They usually have three electrodes and the arc burns between the electrodes and the charge. The charge usually does not have a reverse zero wire, so it develops a medium potential against which the individual arcs burn.

Furnaces with a direct arc

In these furnaces, the arc between the electrode and the charge burns. Sometimes these furnaces are called dependent arc furnaces. These furnaces are mainly used to produce steel and cast iron. Since the current circuit is closed across the melt by the burning of the arc between the electrode and the charge, the heat transfer to the charge is direct, which contributes to a higher heating rate of the melt. Reducing the melt time and thus reducing the wall heating time reduces losses and increases efficiency. Vertical electrode placement reduces the possibility of electrode breakage and failure rates.

Furnaces with indirect (independent) arc

The arc burns between the two electrodes and the heat enters the charge exclusively by radiation, which is why these furnaces are called radiant arc furnaces. An arc burning independently of the charge is called an independent arc. The furnaces are used to produce cast iron, bronze, copper, iron-alloys, carbides and some alloy steels. However, these furnaces have several disadvantages compared to the previous furnaces, mainly in the greater consumption of electricity per unit of charge, and in the horizontal arrangement of the electrodes, which often break and thus carburize the charge, which is not good from a metallurgical point of view. Due to the independent burning arc, there is more wear on the walls. The advantages of these furnaces are lower investment costs and ease of operation.

Furnaces with covered arc

The arc again burns between the electrodes and the charge, but the electrodes are immersed in molten slag and covered with a load of ores and impurities, so the arc is completely covered. Some current passes between the electrodes through the slag and the charge, which are well conductive when hot. This actually results in simultaneous resistive heating of the slag and the charge by the direct passage of an electric current, which is why the furnaces are also called arc-resistance furnaces. This mechanism is mainly used in ore thermal furnaces.

❑ Operating characteristics steel melting arc furnaces

Steel arch furnaces have a bath lined with an alkaline lining. The content of the charge is up to 100 tonnes of steel. The electrical input power reaches tens of MW. The optimum operating mode of electric steel arc furnaces depends on a number of technological factors, furnace design, electrode quality, lining composition, etc.

The main influencing factor, however, is the correctly selected electrical mode of the furnace. This mode can be controlled either by changing the voltage applied to the furnace electrodes or by changing the arc length - i.e. the current.

The first method is commonly used in the individual stages of melting in an electric arc furnace and is directly related to the metallurgical process. The second method is defined by the operation of automatic electrode motion control, which maintains a constant, optimum power input to the melt at a given voltage level.

For a proper understanding of the optimum operation of an electric arc furnace, we will become familiar with the dependence of the main electrical quantities of furnace circuits, i.e. power, power factor, efficiency, on the independently varying current.

The electrical characteristics of an electric arc furnace can be determined either by calculation or graphically using an electric arc furnace ring diagram, or by measurements on specific electric arc furnace equipment.

Let's express the power circuit of an electric arc furnace by a simple substitute diagram according to Fig. 7.36. The single-phase elements of the electric arc furnace electrical equipment are connected in series. By successive simplifications we obtain a transformed replacement scheme for the resistors R_N, X_N, R_o, thus starting, of course, from certain simplifications that cannot be ignored in practice.

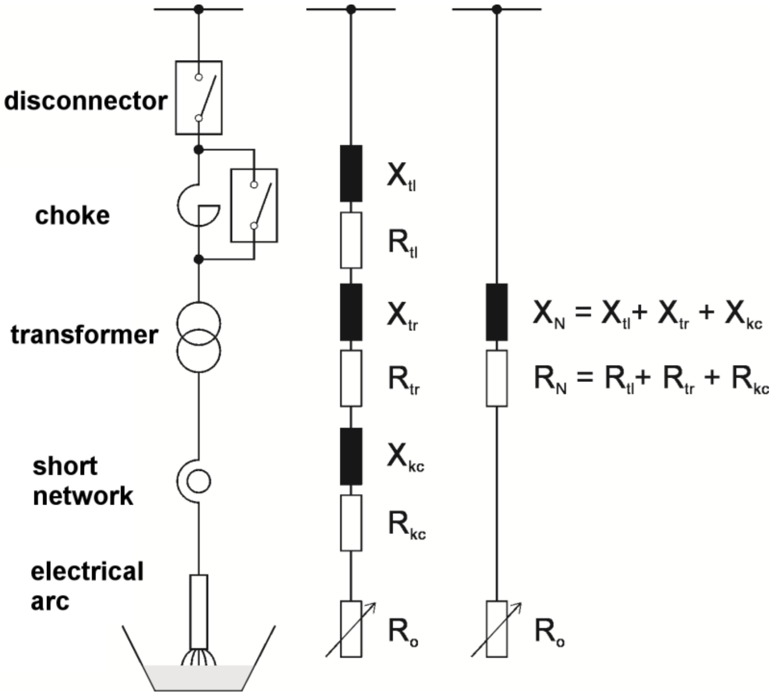


Fig. 7.36 Diagram of the arc furnace electrical system

The mains voltage is symmetrical and independent of the load. The impedances of the individual phases (excluding arc resistance) are equal and independent of current. The arc resistance is linear. The transformer no-load current is zero. The values of the surrogate resistances X_N and R_N are usually found during short-circuit measurements.

The actual electrical characteristics can then be constructed using circular diagrams. An example of the theoretical characteristics are shown in Fig. 7.37.

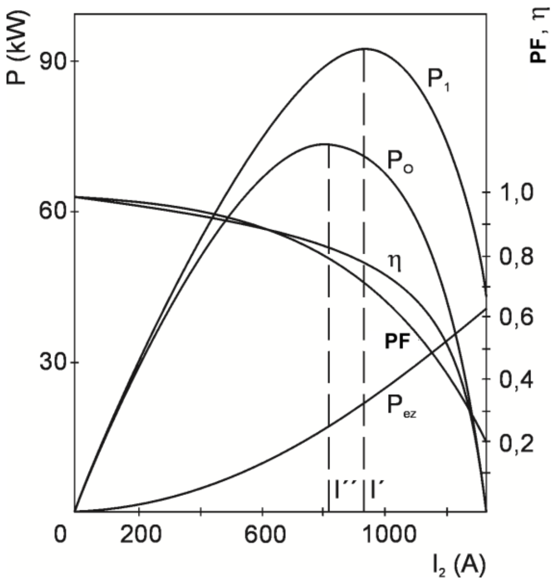


Fig. 7.37 Theoretical operating characteristics

The characteristics can be marked with the current corresponding to the maximum primary power *I´* and the maximum arc current *I´´*. This current is sometimes mistakenly considered as the optimum current corresponding to the highest melting rate. However, determining the optimum current value only from the theoretical characteristics is a much reduced approach.

Above all, these simplifying assumptions cannot be accepted in practice. Furthermore, it is necessary to consider the heat losses (especially at the end of melting), which are greater than the electrical losses and thus affect the melting rate and the specific power consumption. These heat losses can be considered constant and essentially independent of the electrical quantities. The power to compensate for these heat losses is subtracted from the electric arc power. The useful power is therefore equal to

$$P_{up} = P_1 - P_{el} - P_{tl} \qquad (7.58)$$

where P_{tl} is the power to compensate for thermal losses; P_{el} is the power to compensate for electrical losses.

The energy efficiency of melting can be expressed by

$$\eta_{en} = \frac{P_{up}}{P_1} \cdot 100 \qquad (7.59)$$

The specific power consumption *w* will be equal to

$$w = \frac{W_u}{\eta_{en}} \qquad (7.60)$$

where W_u is the energy consumed to melt one tonne without considering losses.

The relationship for the melt rate is given by the ratio of the total useful power consumed to melt the charge alone to the useful energy input.

$$G = \frac{P_{up}}{W_u} \qquad (7.61)$$

According to the variables in the relations (7.58) - (7.61) we can assess the cost-effectiveness of the EAF operation.

Thus, we see that considering the effect of heat loss allows us to express energy efficiency, specific energy consumption and melting rate as a function of current. In Fig. 7.38 are the operating characteristics of a 10-tonne electric arc furnace for a voltage level of 220 V.

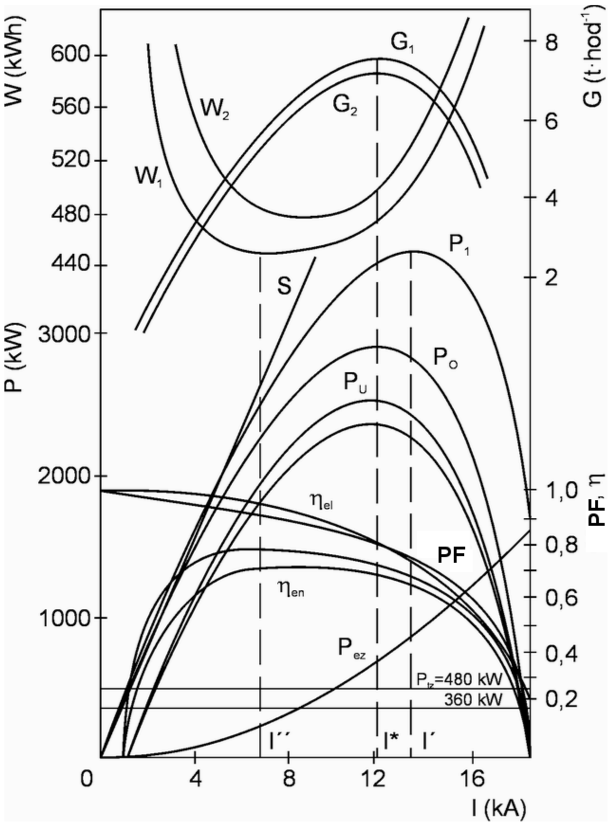


Fig. 7.38 Operating characteristics of a 10 tonne electric arc furnace for 220 V voltage level

From the graph we can find the value of the current *I´´* corresponding to the maximum energy efficiency η_{en} and the minimum specific energy consumption w_1, w_2. It is true that *I´´* < *I*.* This means that the minimum power consumption regime is achieved at a lower power input than the maximum melting rate regime.

Therefore, it can be said that the characteristic values of currents *I´´* and *I** for a given voltage level and for a given value of heat losses define the operating mode range.

It is irrational to work outside this area according to theoretical work characteristics. It is also possible to consider the effect of higher heat losses on the individual dependent variables.

The graphical dependencies show that higher heat losses result in a decrease in the melting rate, an increase in specific power consumption and a shift of its minimum to higher current intensities. However, the position of the maximum melt rate is not affected by the amount of heat loss.

DC electric arc furnaces

A new technology in the field of arc heat recovery is the DC power supply for arc furnaces (Fig. 7.39).

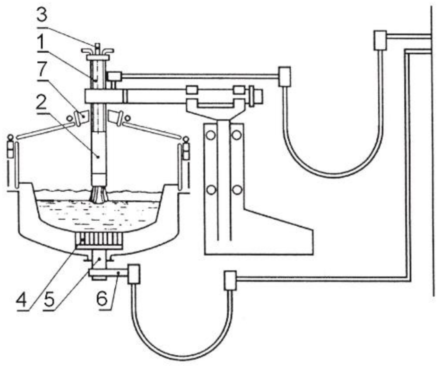


Fig. 7.39 Diagram of a DC arc furnace

Description of DC arc furnace by Fig. 7.39:

1 - electrode cooling; 2 - graphite part of the electrode; 3 - Ar or N_2 supply; 4 - conductive bottom (anode); 5 - bottom electrode; 6 - DC power supply circuit; 7 - ceramic electrode cap.

A rectifier is placed between the transformer and the arc furnace. The electrical path and the furnace itself are different from the traditional AC power supply method. The power supply is composed of a control transformer and the actual transformer with fixed conversion to low voltage. In addition, a fully controlled six-pulse rectifier in a bridge circuit is included to ensure good transformer power utilization and to meet the dynamic requirements of the arc furnace.

In the DC part of the furnace power supply circuit, there is a DC reactor. This inductor limits the stress on the thyristors by operating short circuits and helps to stabilize the arc.

Power factor compensation and higher harmonic filtering devices are not necessary for DC furnaces. It is only used when the local power system has insufficient short-circuit power at the point of connection of the DC arc furnace (Fig. 7.40).

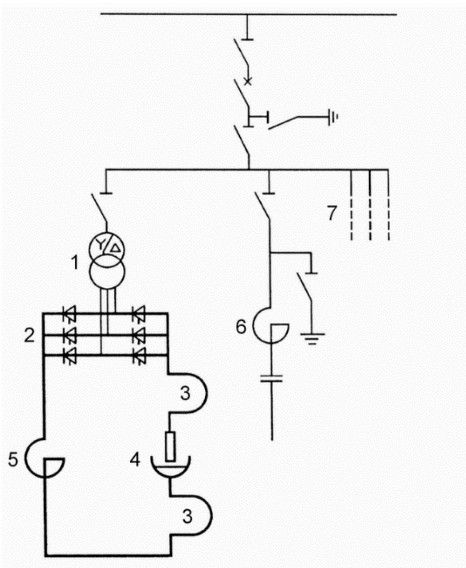


Fig. 7.40 Electrical wiring diagram of a DC arc furnace [7]

Description of DC arc furnace by Fig. 7.40:

1 - control transformer; 2 - six-pulse bridge rectifier; 3 - short network; 4 - arc furnace; 5 - choke; 6 and 7 - filter-compensation devices.

The DC arc furnace bath itself must have a conductive bottom and a special design to conduct the circuit current through the bottom electrode system. The greatest advantage of DC arc furnaces is the substantial reduction in graphite electrode consumption, which in some cases reaches up to 50 %. Furnaces with one electrode are designed up to 30 tons of charge. These then show less wear on the furnace linings due to the uniform distance of the electrode from the furnace walls. Another advantage is the elimination of disturbing influences on the supply network, especially dynamic voltage variations. The operating noise is reduced from 110 dB to 90 dB compared to AC power. The DC arc furnace is operated with a long arc and therefore the highest possible voltage level in the power transformer. The long arc requires the use of foam slag. The electrically conductive bottom of the DC furnace needs to be operated with liquid charge immediately at the start of melting. Therefore, a portion of the liquid steel is left in the furnace after casting to allow the electrical network circuit to be connected. The advantage is that existing AC arc furnaces can be converted to DC with the original power transformer retained.

Summary of terms 7.3.

Electric arc, electric arc furnace (EAF), vector diagram, circular diagram, working characteristics, primary and secondary metallurgy.

Questions 7.3.

1. Explain the formation of DC and AC arc, draw diagrams.
2. Draw the shape of the anode and cathode in a prolonged burning DC arc.
3. Draw the time waveform of voltage and current in an alternating arc.
4. Explain and draw the stabilization of an alternating arc by inductance.
5. Explain what primary and secondary metallurgy is.
6. How do we sort the EAF according to the arc used? Describe the different furnaces.
7. Draw the volt-ampere characteristics of a DC arc.
8. What are the parts of power EAF circuit?
9. What are the parts of the short EAF network?
10. What are the operating characteristics of EAF? Draw.
11. Which parameters characterize the operation of the EAF?

7.4. Induction electric heat

TIME TO STUDY:

2 hours

TARGET:

After reading this paragraph, you will

- to know the principle of heat generation in a plant during induction heating
- be able to explain the principle of heating in crucible and channel induction furnaces
- know how to connect induction furnaces to the power supply network

EXPLANATION

The principle of heat generation in induction devices

Induction heating is only possible with electrically conductive material. Eddy currents are induced in a conductive material which is placed in a magnetic field and heats it up. It is often simplistically compared to a transformer, where the secondary winding is the load and is short-circuited. The heat transfer to the load is therefore not by thermal gradient as in, for example, resistive devices with indirect heating. The heat is transferred by a magnetic field and is generated directly in the load. The die is the hottest object in the whole system, while everything else may be cold. The generation of heat directly in the charge, which is not mechanically coupled to anything, is one of the greatest advantages of induction heating.

Induction heating allows unusually high specific power inputs to the charge. By selecting the frequency of the current that powers the heating winding (inductor) and in whose magnetic field the die is placed, the distribution of heat developed in the die can be suitably influenced.

Every induction device always consists of a coil through which alternating current passes, a source and a charge that receives the electromagnetic waves radiated by the coil. By passing of current through a plane emitter produces plane electromagnetic waves in its surroundings. By passing of current through a cylindrical emitter produces cylindrical electromagnetic waves in the surroundings of the emitter. The cylindrical coil through which an alternating current passes radiates cylindrical electromagnetic waves into its cavity.

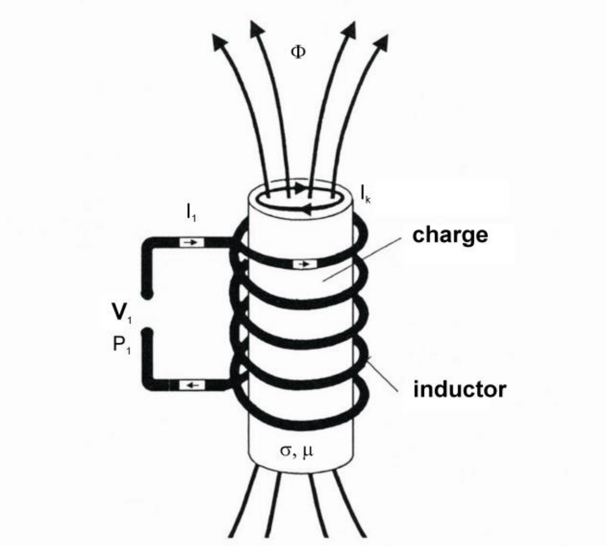


Fig. 7.41 Induction device principle

If we pit a cylindrical electrically conductive charge in the coil, then the incident electromagnetic waves enter the charge through the surface and cause induced currents, which heat up the charge. The penetrating electromagnetic waves are damped and their energy is converted into thermal energy. The depth of penetration of the radiation depends on the frequency.

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \sigma}} = \sqrt{\frac{2}{2\pi \cdot f \cdot \mu \cdot \sigma}}_r \qquad (7.62)$$

where δ is the penetration depth (m), f is the frequency (Hz), μ is the permeability ($H \cdot m^{-1}$), σ is the conductance ($S \cdot m^{-1}$).

Dependence of penetration depth of electromagnetic waves on frequency is in Tab. 7.8 and is shown in Fig. 7.42.

Frequency (Hz)	**Penetration depth (mm)**					
	Cu		**Al**		**Steel**	
	20 °C	1100 °C	20 °C	660 °C	20 °C	800 °C
50	9,5	31,8	12,2	31,5	8	71,2
1000	2,1	7,1	2,7	7	1,8	15,9
10000	0,67	2,25	0,86	2,2	0,56	5
1000000	0,067	0,22	0,086	0,22	0,056	0,5

Tab. 7.8 Dependence of penetration depth on frequency

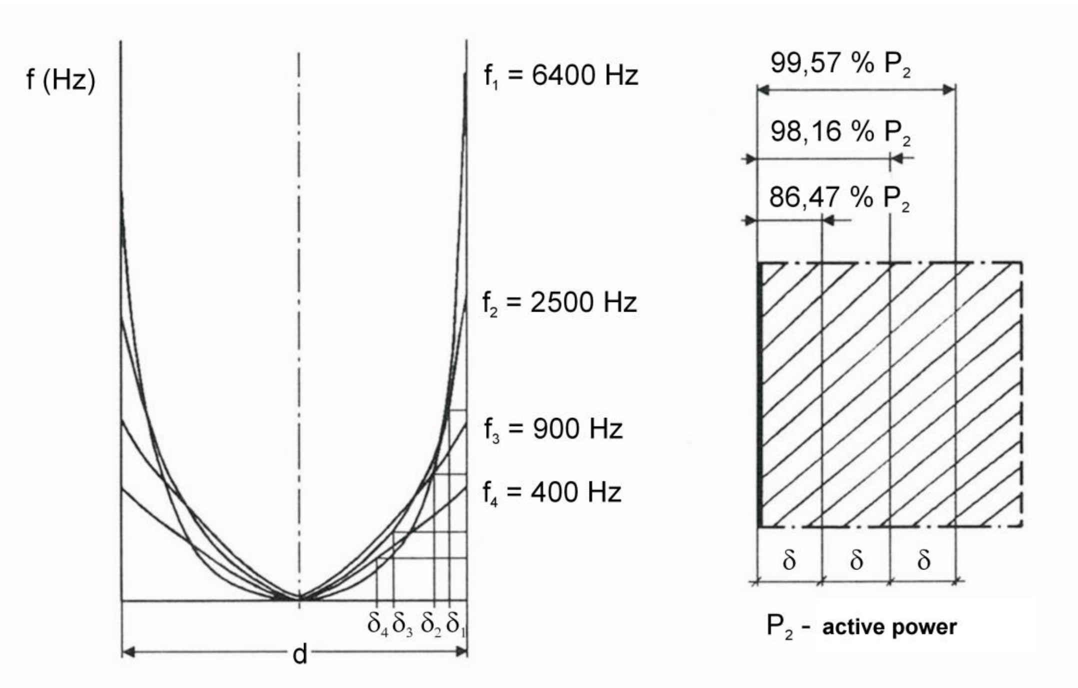


Fig. 7.42 Dependence of electromagnetic wave penetration depth on frequency

The electrical efficiency of induction heating depends on the ratio *d/δ* - Fig. 7.43. The material of the heated object and its temperature also affect the resulting induction heating efficiency.

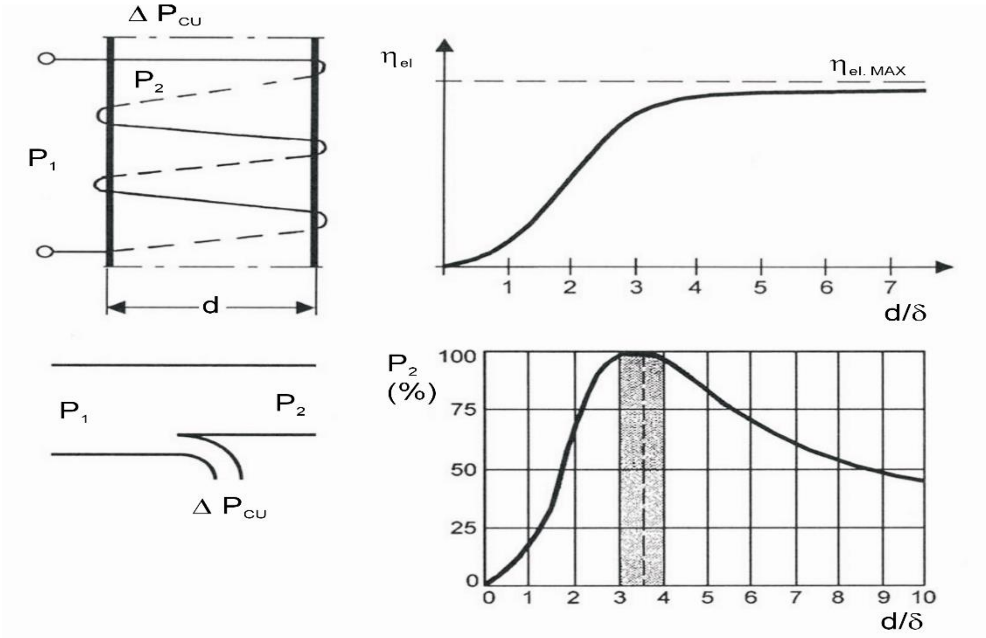


Fig. 7.43 Electrical efficiency of induction heating

❑ Induction crucible furnaces with non-conductive crucible

The coil contains a crucible which is filled with ceramic material. The furnace has either a copper shielding jacket or a steel jacket that carries bundles of transformer plates on the inside (Fig. 7.44). A schematic of this type of furnace is shown in Fig. 7.45.

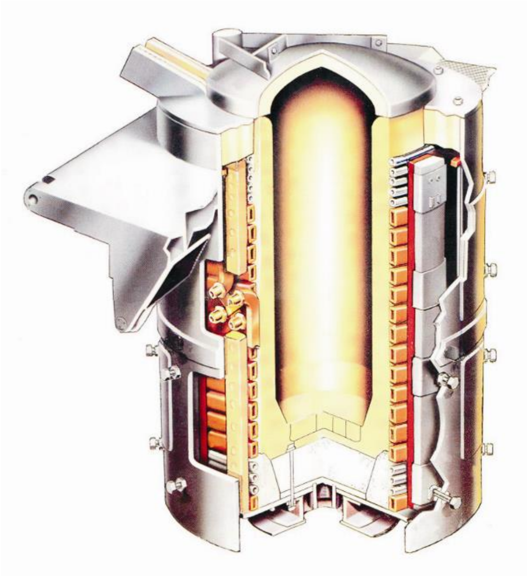


Fig. 7.44 Induction crucible furnace

Induction crucible furnace with conductive shielding

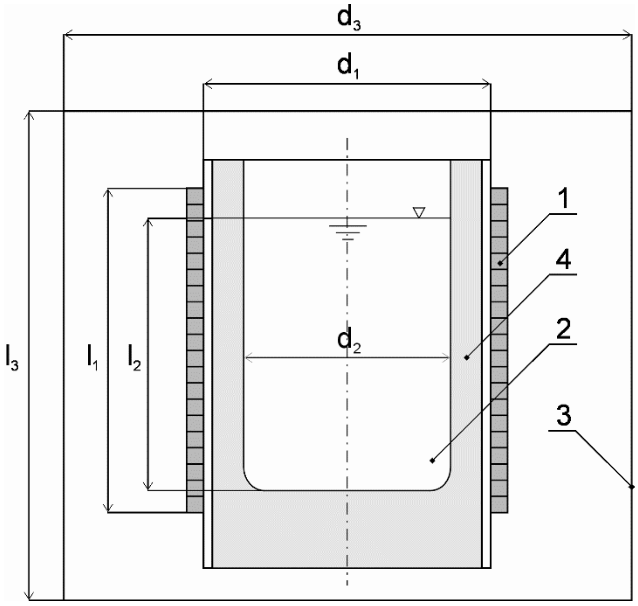


Fig. 7.45 Induction crucible furnace with conductive shielding

A ceramic crucible 4 of cylindrical shape, electrically non-conductive, containing a charge 2, is wrapped by a coil 1. The coil is usually wound from a copper tube of rectangular cross-section. The coil carries a current of increased frequency (500 to 1000 Hz) or a current of mains frequency 50 Hz. The inner surface of the coil emits electromagnetic waves into its cavity, which fall perpendicularly on the surface of the coil, are absorbed by it, and the electromagnetic energy is converted into thermal energy. A magnetic flux passes through the cavity of the coil and is enclosed outside the coil. Appropriate measures must be taken to keep the intensity of the magnetic field outside the furnace as low as possible to prevent heating of the furnace support structures. This can be achieved either by providing the furnace with a shielding jacket of a well conducting material of suitable diameter or by placing a core of iron plates outside the coil to enclose the magnetic flux. Induction crucible furnaces always have shielding, either as a conductive shielding jacket or as a core of transformer plates outside the coil. However, when calculating smaller furnaces, we can neglect the effect of the shielding and calculate the furnace as if it had no shielding. In the calculation we consider only the coil and the load, i.e. only two interacting electrical circuits. This simplifies and shortens the calculation.

Induction crucible furnace with iron core outside the coil

If the induction crucible furnace is equipped with a conductive shielding jacket, the magnetic field strength outside the jacket is reduced very significantly. A similar effect can also be achieved by placing an iron core made of a large number of transformer sheet bundles outside the coil instead of the shielding conductive sheath, according to Fig. 7.46. The bulk of the magnetic flux excited by the coil will be confined outside the coil by a magnetically well-conducting path, i.e., bundles of transformer plates fixed on the inside of the furnace shell of boiler plate. The inclusion of the magnetically conductive bundles will reduce the magnetic resistance for the magnetic flux excited by the coil, so that the flux will increase somewhat. The intrinsic inductance of the furnace coil, i.e. the magnetic flux for a unit current, is increased. The self-inductance and mutual inductance of M_{12} will also increase. A shielded furnace requires a coil with a somewhat higher number of turns and a larger capacitor bank than a core furnace. The useful power is lower and the losses in the coil are higher in a shrouded furnace than in a core furnace. The electrical efficiency is significantly lower for a shell furnace than for a core furnace. The most important result of the comparison made is the finding that the efficiency of the furnace with an iron core is almost 5 % higher than that of the furnace with a shielded jacket. This results in considerable savings in electricity in operation, especially for large furnaces with continuous operation. The design of the induction crucible furnace with an iron core is therefore a technically superior solution. However, this furnace is more expensive to manufacture and, if the crucible melts during operation, the damage to the furnace is usually worse or the furnace is completely destroyed.

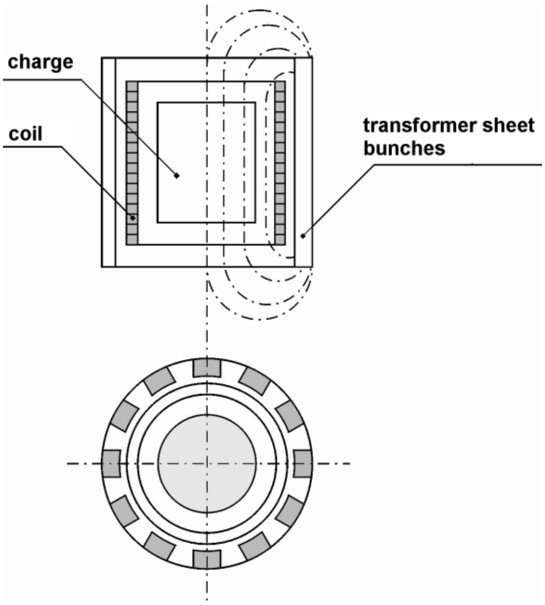


Fig. 7.46 Induction crucible furnace with transformer sheet bunches

❑ Induction crucible furnace with conductive crucible

An induction furnace with a non-conducting crucible has a low electrical efficiency when melting well conducting materials such as copper and its alloys, aluminium and its alloys, etc. The electrical efficiency increases considerably if the furnace is fitted with a conducting crucible schematic by Fig. 7.47 (for melting Al and Cu). For lower temperatures, such as those involved in the melting of aluminium and its alloys, the crucible is made of steel. For higher temperatures, so-called graphite crucibles are used. They are made of a mixture of fireclay and graphite. The more graphite, the more conductive the crucible. However, high conductivity is not desirable. There is a ceramic insulating layer between the crucible and the coil, which reduces the heat loss from the hot crucible to the water-cooled coil. If a current is introduced into the coil, the electromagnetic waves radiated by the inner surface of the coil impinge on the outer surface of the conducting crucible, enter its wall, induce a current in the wall, and through its passage the crucible is heated. It then transfers the heat to the insert in its cavity. The proportions are usually such that a larger part of the incident electromagnetic energy is converted into heat in the wall of the crucible, but a smaller part passes through the wall and heats the insert directly. The ratio between the wall thickness $š_3$ and the penetration depth d_3 is crucial. If the penetration depth is small compared to the wall thickness, all the electromagnetic energy in the crucible wall is absorbed. The calculation is the same as for two coaxial cylinders in a furnace with a non-conducting crucible. In the calculation, we consider the crucible as an insertion. However, if there is no $d_3 << sh_3$, a significant amount of electromagnetic energy will pass through the crucible wall into the charge.

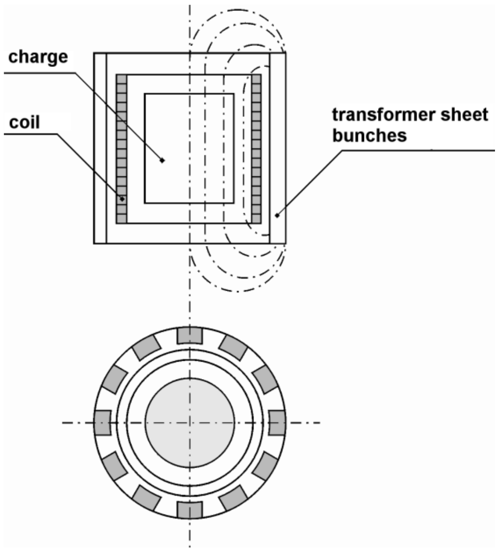


Fig. 7.47 Induction crucible furnace with conductive crucible

❑ Induction heat-soaking device

In plants where components are made by forging or hot pressing, uniform heating of the material is an important issue. Metal forgings of cylindrical or square shape, usually steel, must be heated to forging temperature (steel C° 1150 to C° 1250). In older forges, fuel-fired furnaces heated by gas, pulverized coal or oil are used to heat the forgings. However, it takes too long to heat evenly throughout the cross-section and during this time the material oxidises on the surface. Several per cent of the material is destroyed and, in addition, the resulting scaling damages the dies and shortens their service life during the next operation. In contrast, heating in an induction furnace takes a very short time, so that there is virtually no oxidation on the surface. The economic advantages are the reason for the rapid introduction of induction heating in newly built forges. The induction furnace (induction heater) for forging is usually cylindrical in shape, schematically according to Fig. 7.48.

The main part of the induction heater is the induction coil 1, usually about 1 m long. Its diameter is chosen according to the diameter of the coils to be inductively heated. The inductor usually has a larger number (4 to 7) of coils of the same length.

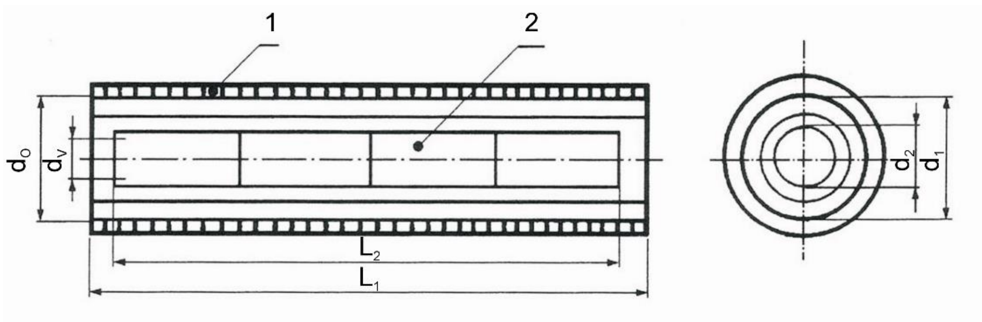


Fig. 7.48 Induction heat-soaking scheme

Frequency and heat-soaking time selection

Uniform heating occurs by spreading the heat from the surface layer where it originates by conduction into the interior of the cylinder. From this point of view it is preferable that the layer in which the heat develops is not too weak, which in other words means that the frequency must not be too high. It is therefore necessary to choose a suitable frequency and thus the layer in which the heat is developed so that the energy is absorbed with good efficiency but the surface does not overheat. The optimum frequency is one at which approximately r_2 = *(2.5 to 3.0)* - δ_2. We take the penetration depth for a material already heated, i.e. magnetic if it is steel. In practice, the frequency for induction heating of steel is chosen depending on the diameter of the forgings according to Tab. 7.9. From the table we see that each frequency can be used for diameters varying over a considerable range.

f (Hz)	50	500	1000	2000	4000	8000
d (mm)	160÷500	80÷280	50÷180	35÷120	22÷70	15÷50

Tab. 7.9 Frequency selection for induction heating of steel

From the chart shown on Fig. 7.49 shows that the specific consumption in kWh to heat 1 kg of steel to 1200 °C increases as we approach the lower end of the range of averages. The material becomes electromagnetically transparent. For a diameter d_2 = 10.0 cm of steel, the specific power consumption of the grid is about 0.40 kWh·kg^{-1} at a frequency of 1000 Hz. The time *t* required to heat the steel uniformly is usually not calculated and is taken from the relevant diagram according to Fig. 7.50.

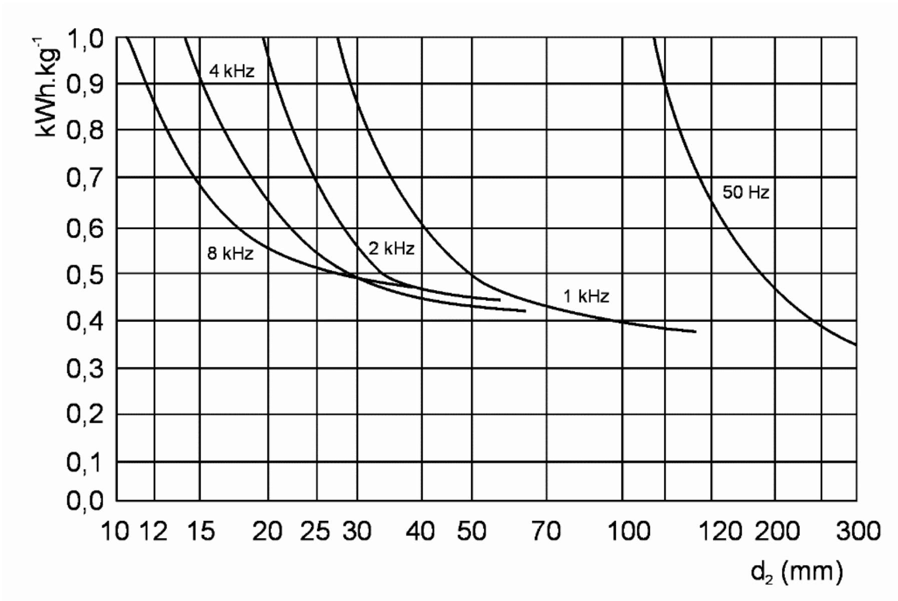


Fig. 7.49 Graph of specific consumption

The uniformity of the heating of the barrel is sufficient if, at the end of the heating process, the temperature difference between the surface and the axis is not greater than 100 °C. The unevenness is further reduced during the additional, usually several tens of seconds that elapse between the end of the heating and the forging operation in the press. From Fig. 7.50 we can deduce that the appropriate time to heat a steel forging with a diameter of d_2 = 100 mm is about 7 min, at the considered frequency of 1000 Hz. The heating time can be reduced by about one third in the case of so-called rapid heating. In fast heating, the part of the coil at the beginning of the inductor through which the cold coils enter is made with thickened coils. In this part, there are more N_{11} threads per 1 cm of coil length. This will increase the magnetic field strength $H_1 = N_{11} I_1$ (A·cm^{-1}) at the inlet of the inductor, and since the heat developed depends on the square of H_1^2 , the pieces inserted in this part of the inductor will heat up faster to a higher temperature and the overall heating time will be reduced. The larger temperature difference at the surface and in the axis of the roll is then compensated for in the subsequent slower heating process. [8].

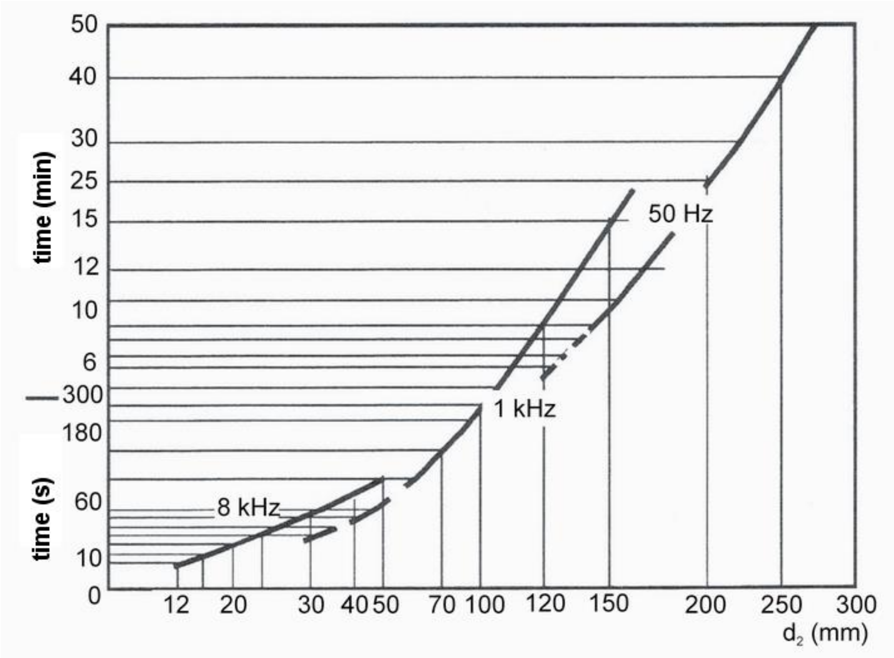


Fig. 7.50 Diagram of the time to heat-soaking a steel rolled product

❑ Induction equipment for surface heating

For surface heating of objects up to a depth of 10 mm we use high frequencies, in the order of 10^4 to 10^6 Hz. In industry, induction heating devices, inductors, are used for these technological purposes:

- Hardening
- Soldering
- Welding
- Refining remelting

The depth of the heated layer depends on the frequency as follows Tab. 7.10.

Frequency *f* (kHz)	Penetration depth δ (mm) (steel 1000 °C)	Depth of heated layer g = (2 to 3) δ (mm)
10	5,00	10 - 15
100	1,60	3,2 - 5
1 000	0,50	1 - 1,5
10 000	0,16	0,3 - 0,5
30 000	0,09	0,2 - 0,3
100 000	0,05	0,1 - 0,15

Tab. 7.10 Depth of heated layer as a function of frequency

Hardening

For hardening we use specific power in the range of 1 to 20 $kW \cdot cm^{-2}$. The optimum frequency is calculated from the relation

$$\frac{0{,}015}{d^2} < f < \frac{0{,}25}{d^2} \qquad (7.63)$$

where d is the hardening depth (mm), f is the frequency (kHz).

In Fig. 7.51 and in Tab. 7.10 it is possible to observe the depth of cloudiness d depending on the frequency and hardness of the steel used. Curve 1 is for f = 400 kHz, 2 is for f = 10 kHz and 3 is for f = 4 kHz.

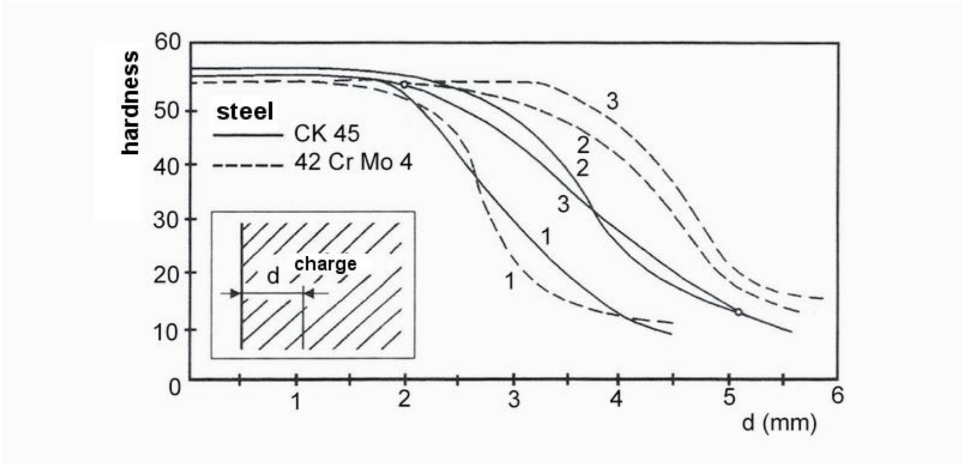


Fig. 7.51 Depth of hardening zone

Soldering

When soldering, we use a frequency in the range of 2 kHz to 2.5 MHz. The principle of soldering via a special inductor is shown in Fig. 7.52 a Fig. 7.53 Special inductor for soldering three different shapes simultaneously. The brazing uses a power output of 0.5 to 5 kW for temperatures from 150 to 450 °C. Brazing uses 3 to 30 kW for temperatures from 450 to 1 050 °C. At Fig. 7.53 1 is the inductor, 2 is the soldering iron.

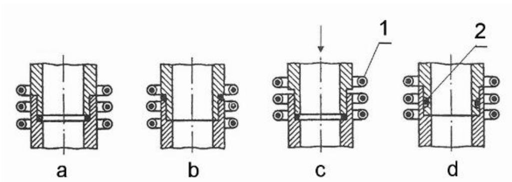


Fig. 7.52 Principle of induction soldering

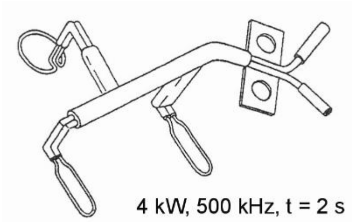


Fig. 7.53 Special inductor for soldering three different shapes simultaneously

Welding of pipes

The principle of pipe welding using a sliding inductor is shown in Fig. 7.54. Power sources with a frequency of 8 to 500 kHz and outputs of 50 to 700 kW are used, depending on the different depth of heating.

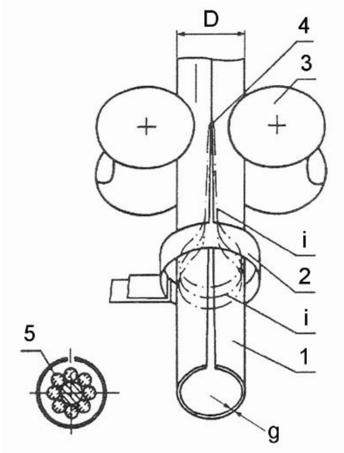


Fig. 7.54 Principle of induction welding of tubes

1 - tube, 2 - inductor, 3 - pulleys, 4 - weld, 5 - magnetic core, i - induced current, v = 15 - 100 $m \cdot min^{-1}$, f = 8 - 500 kHz, P = 50 - 700 kW, g = 0.4 - 12 mm, D = 8 - 500 mm.

Refining remelting

The principle of refining is illustrated in Fig. 7.55where 1 is the inductor and 2 is the charge (Si). Sources with a frequency of 400 kHz to 5 MHz at powers of 10 to 50 kW are used.

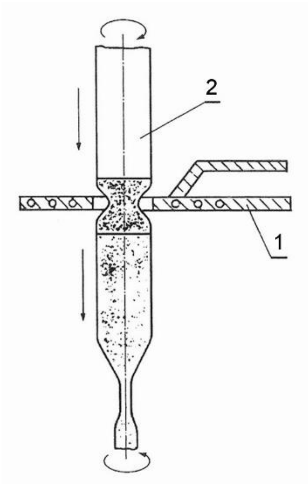


Fig. 7.55Principle of refining remelting

❑ Channel induction furnaces

Channel induction furnace design

An induction channel furnace is essentially a transformer with a closed iron core, with a primary coil connected to the mains. The channel filled with molten metal is the secondary side of the transformer. It's actually a short-circuited coil Fig. 7.56.

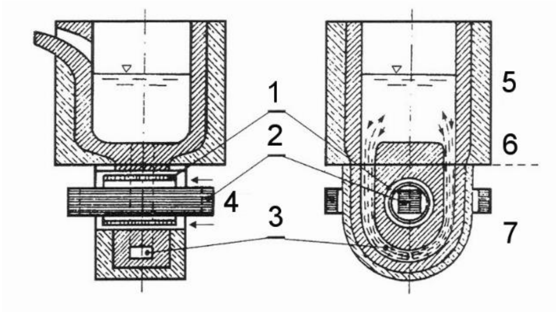


Fig. 7.56 Channel induction furnace

1- air cooled heating coil (marked by arrows), 2-core of transformer plates of shell type, on the middle column of which is the heating coil 1, 3-channel, which surrounds the heating coil as a short coil, 4-cooling air, 5-bath furnace, 6-separating gap, 7-inductor.

Electric induction channel furnaces are used for melting non-ferrous metals, especially copper and its alloys, aluminium and its alloys, or for heating cast iron melted beforehand, for example in the cupola. When increasing the power input to the furnace with an exposed channel, it was found that an undesirable effect, the so-called 'squeaking effect', occurs when a certain critical value of the current in the charge is exceeded. Due to the electrodynamic forces acting in radial planes in all directions perpendicular to the surface of the liquid conductor, the continuous ring of molten metal is broken. At this moment, however, the electrodynamic action ceases, the ring rejoins and the phenomenon repeats. Surges are generated which prevent the furnace from operating properly. This phenomenon has been partly counteracted by a suitable design of the furnace coil. However, a solution with a covered channel embedded in the bottom of the furnace proved to be even more suitable. The hydrostatic pressure of the molten metal largely prevents the creep phenomenon. During casting, about one-third of the charge is left in the furnace, filling the channel and the bottom of the furnace, so that heat can be generated in the closed thread after the transformer is switched on. The furnace is then filled with the charge, which is melted by immersion in a superheated bath at the bottom of the furnace. In these furnaces, heat is generated only in the charge found in the channel. By the action of electrodynamic pressure, the metal is continuously forced out of the channel into the crucible and the cooler metal from the crucible flows into the channel. This transfers the heat from the channel to the entire charge in the substrate. If the channel has a vertical surface, the temperature difference helps the hot metal to penetrate intensively from the channel, because the hotter metal is lighter.

❑ Connecting channel furnaces to the network

Single-phase furnaces

Single-phase furnaces usually have one channel. They are connected to a 3 x 400 V, 50 Hz mains phase or line voltage. Single-phase furnaces are manufactured up to an apparent power input of 150 kVA. There are usually a larger number of similar furnaces in the smelter and by connecting them to different phases in a staggered manner, the load is roughly balanced on all three phases. The connection of a single-phase induction furnace with one channel is shown schematically on Fig. 7.57.

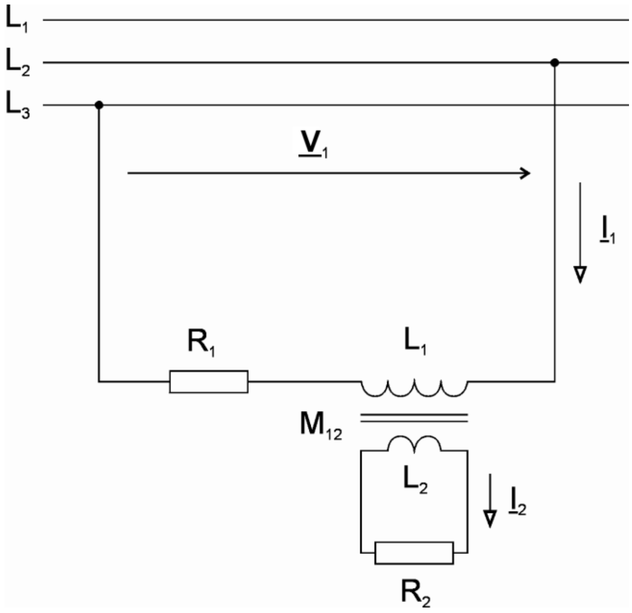


Fig. 7.57 Connection of single-phase induction furnace

Symmetrical loading of a three-phase network by a tuned single-phase furnace can be achieved by using a so-called symmetrizing device. It is an artificial load consisting of three branches. In one branch there is a resistance R_Z, replacing the tuned induction furnace, in the second branch there is an inductance L of suitable size and in the third branch there is a suitably sized capacitance C. These three branches of the symmetrizing device can be connected in a triangle or a star. In either case, if the phases are properly sequenced, exactly symmetrical loading of all three phases can be achieved by PF = 1.0.

In Fig. 7.58 shows the symmetrizing device in a delta connection.

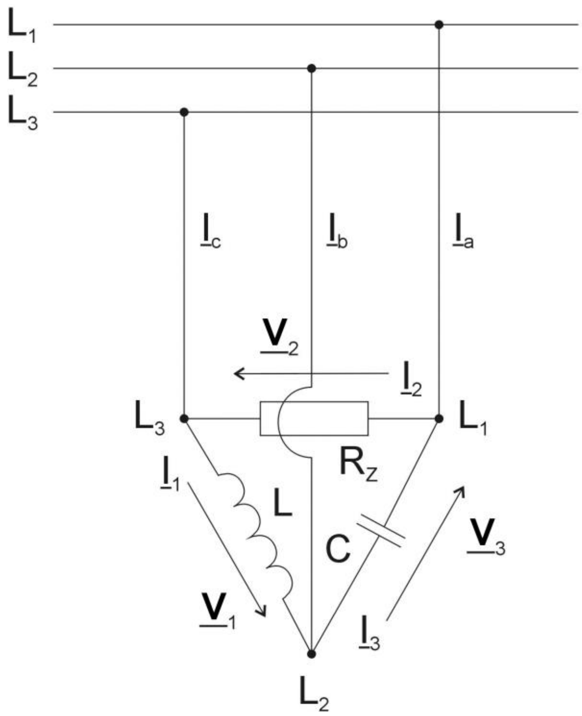


Fig. 7.58 Delta connected symmetrizing device

For the value of the required inductance *L* and capacitance *C*:

$$L = \frac{\sqrt{3} \cdot R_Z}{\omega}; \; C = \frac{1}{\omega \cdot \sqrt{3} \cdot R_Z}; \; \omega L = \frac{1}{\omega C} = \sqrt{3} \cdot R_Z \qquad (7.64)$$

When installing a furnace with a symmetrizing device, ammeters shall be inserted in all three inlets. With the correct phase sequence, all ammeters show the same deflection. If the phase sequence is incorrect, the ammeters in phases *a* and *c* show a higher current than in phase *b*. If any two leads are swapped, the correct phase sequence is obtained.

The connection of the symmetrization device to the star is in Fig. 7.59.

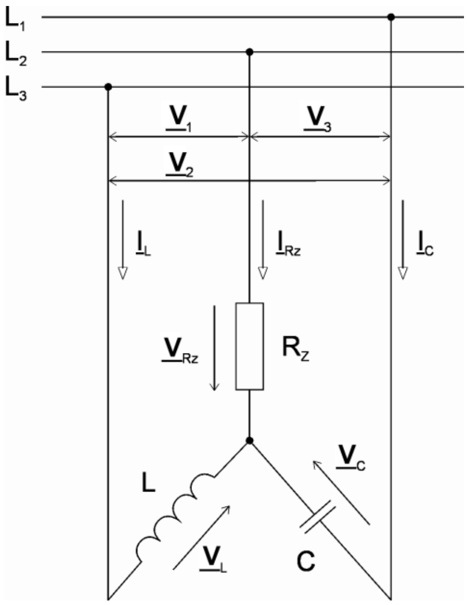


Fig. 7.59 Symmetrization device connected to a star

The furnace will experience an increased voltage U_R equal to three times the phase voltage, which is advantageous for larger furnaces. For the magnitude of the required inductance *L* and capacitance *C* the following applies:

$$L = \frac{R_Z}{\sqrt{3} \cdot \omega}; \; C = \frac{\sqrt{3}}{\omega \cdot R_Z}; \; \omega L = \frac{1}{\omega C} = \sqrt{3} \cdot R_Z \qquad (7.65)$$

If we compare the equation (7.65) with the equation (7.64), we see that in the symmetrical star connection, the required inductance is 3 times smaller and the required capacitance 3 times larger than in the triangular connection - in both cases based on the load resistance R_Z. Since in the star connection, for a furnace of the same input power, the load resistance R_Z is 3 times larger (the voltage across the furnace is $3^{1/2}$ times larger), the actual values of *L* and *C* are exactly the same in both cases.

Two-phase furnaces

These are induction furnaces with two or even four channels, two of which are always connected in parallel and have a common furnace transformer for both channels. A symmetrical distribution to all three phases of the network is achieved either by using two furnace transformers in a Scott circuit or a special symmetrization circuit can also be used. See Fig. 7.60 is a furnace with two identical channels in a Scott circuit.

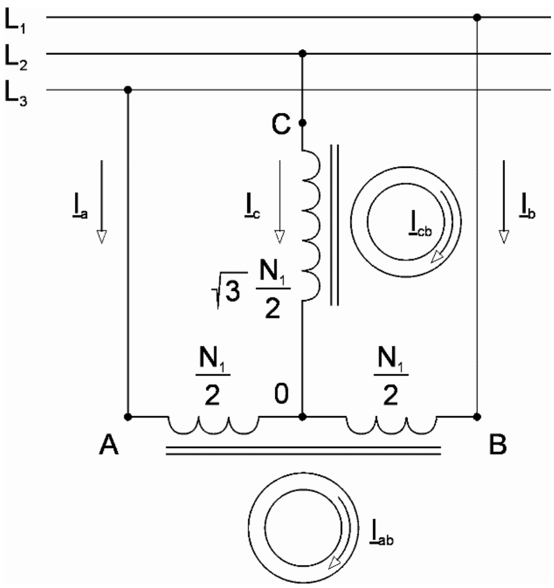


Fig. 7.60 Scott's circuit of a two-phase induction furnace

Each of the two channels has its own furnace transformer, connected to the three-phase network. Between points A and B on Fig. 7.60 is connected to the so-called "main" transformer, which has the primary winding divided into two equal parts. We have denoted the number of turns in each part by N_1 /2. Between the third phase (point C) and the centre of the winding of the main transformer (point 0) is connected an "auxiliary" transformer with a number of turns of $3^{1/2}$ /2. N_1. Both channels are exactly the same. In this arrangement, the currents drawn from each phase are equal. The currents induced in both channels are also the same, and therefore the amount of heat developed in them is also the same.

Three-phase furnaces

Three-phase furnaces with three or six channels, two of which are always connected in parallel to a common core. These furnaces have a three-phase furnace transformer in either a core or shell design. Each of the three cores carries a furnace coil, around which is either one or two identical channels in parallel. All three coils are connected to the mains in either a triangular (coils are on line voltage) or star (coils are on phase voltage) connection. The load of all three phases is symmetrical, to improve the PF a three phase capacitor bank must be connected. In Fig. 7.61 is a three-phase furnace with three channels and a three-phase transformer, designed for melting non-ferrous metals. This furnace symmetrically loads a three-phase network [9].

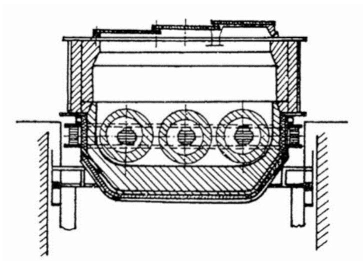


Fig. 7.61 Three-phase furnace with three channels

Summary of terms 7.4.

Induction heating, inductor, eddy currents, depth of penetration, crucible furnace, channel furnace, symmetrization device.

Questions 7.4.

1. Explain the principle of induction heat.
2. Write the relationship for the depth of penetration in induction heating.
3. List the basic types of induction furnaces.
4. What is the difference between an induction furnace with a conductive and a non-conductive crucible?
5. How is the frequency selected for induction heat-soking devices?
6. For what technological purposes is induction surface heating used?
7. How do we classify induction channel furnaces in regard to connection to the power supply network?
8. Explain the nature of symmetrization in connecting a single phase induction channel furnace to a three phase power supply network.

7.5. Electric heating

TIME TO STUDY:

3 hours

TARGET:

After reading this paragraph

- you will understand the issues of thermal comfort and environmental thermal status
- you will be able to calculate the heat loss of rooms
- you will be able to choose the appropriate type of electric heating
- understand the meaning and basic principles of heating control

EXPLANATION

Thermal comfort issues of a human in a room

The main task of heating is to ensure favourable thermal conditions in closed rooms during the cold winter period, when the outside temperature is lower than the desired room temperature and when other weather influences (e.g. wind) cause the rooms to cool down. It is about ensuring so-called thermal comfort.

This means that thermal conditions must be achieved in such a way that one feels comfortable. A person's thermal comfort is influenced by his or her health, age, and the type of activity he or she performs. The feeling of good thermal comfort is essentially determined by the balance of a person's thermal regime with the environment in which he or she is.

An important component of the human thermal regime is the sharing of heat from the body surface to the environment, which is governed by physical laws and can therefore be expressed mathematically. During the metabolic transformations taking place in the human body, a certain amount of heat is released, which depends mainly on the intensity of physical exertion and the weight of the person. This heat must be dissipated into the environment. Thermal equilibrium, i.e. a state in which the environment removes as much heat from the human body as the person is currently producing, is therefore the first and essential prerequisite for thermal comfort.

The human body is cooled by conduction, convection, radiation and, in addition, by evaporation of sweat and respiration. With little physical exertion, most of the heat is removed from the surface of the body by convection and radiation - dry cooling. Achieving thermal equilibrium in dry cooling, without excessive sweating, is the second prerequisite for human thermal comfort.

If the ambient temperature rises above a certain threshold or heat production increases during physical exertion, dry cooling is not sufficient and the excess heat is dissipated by evaporation to ensure thermal balance - wet cooling.

Thermal equilibrium condition can be generally expressed by the relation

$$\Phi_{\mathrm{M}} = \Phi_{\mathrm{V}} + \Phi_{\mathrm{D}} + \Phi_{\mathrm{K}} + \Phi_{\mathrm{S}} \qquad (7.66)$$

where Φ_{M} is the heat flux produced by the human body (W), Φ_{V} is the heat flux removed by evaporation, Φ_{D} is the heat flux removed by respiration, Φ_{K} is the heat flux removed by convection (flow), Φ_{S} is the heat flux removed by radiation.

Heat flow by convection and radiation first passes through the layer of clothing, is conducted through it, and only on the outer surface is the heat transferred to the surroundings. The thermal equilibrium equation then changes as follows:

$$\Phi_{\mathrm{M}} - \Phi_{\mathrm{V}} - \Phi_{\mathrm{D}} = \alpha \cdot A \cdot (T_B - T_C) = \Phi_{\mathrm{K}} + \Phi_{\mathrm{S}} \qquad (7.67)$$

where α is the permeability of the garment ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$), A is the total body surface area ($\mathrm{m^2}$), T_{B} is the body surface temperature (K), T_{C} is the clothing surface temperature (K).

Thermal state of the environment

Thus, several factors determine the thermal sensation of a person in enclosed rooms: the degree of physical exertion (internal heat production Φ_M), the thermal insulation capacity of clothing (thermal transmittance α), the ambient air temperature ϑ_V , the effective temperature of surrounding surfaces ϑ_p , the humidity of the surrounding air (relative humidity), and the airflow velocity.

The factors ϑ_V , ϑ_p, humidity and air velocity characterize the thermal state of the environment, which is reflected in the resulting thermal effect of the environment on humans. However, we usually try to express the thermal state of the environment in a single, easily measurable quantity.

Air temperature in the room

The air temperature ϑ_v measured in the area where the human is staying will be used to assess the thermal state. Air temperature can be considered a satisfactory measure of the thermal state of an environment where it is an environment of near-calm air and where the temperature of the surrounding surfaces differs only slightly from the air temperature. In these circumstances, the air temperature also coincides with the resulting temperature ϑ_r.

The air temperature ϑ_v is usually not the same throughout the room, and therefore it is necessary to assess its local variation, unevenness. The vertical non-uniformity of the air temperature in heated rooms, which is caused by uneven heat input and uneven cooling of the individual walls, floors and ceilings of the rooms, is very important. The vertical distribution of room temperatures for different heating methods is shown in Fig. 7.62.

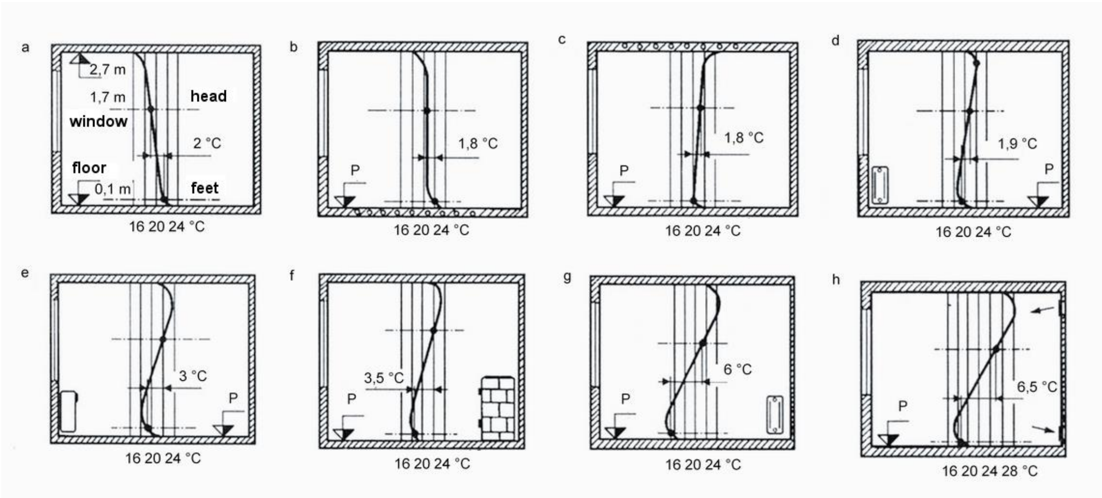


Fig. 7.62 Vertical temperature distribution in the room for various heating systems

a-ideal heating, b-floor heating, c-ceiling heating, d - hot-water heating, e-convector heating, f-local heating with a tiled stove, g - hot-water heating (radiator on the inside wall), h - hot-air heating.

The temperature of the lower air layer at the feet (0.1 m above the floor) is decisive for a comfortable feeling. Next, we are interested in the air temperature at head level (1.7 m above the floor) and then the difference between these two temperatures, which has a great influence on the thermal comfort in the room.

The ideal heating is such that the temperature at foot level is approximately 21 °C and at head level for a standing person approximately 19 °C. In terms of thermal comfort, the temperature difference between head and foot level should therefore be no more than 2.0 °C for a standing person and 1.5 °C for a sitting person. For each heating method, the relevant temperature difference is always indicated in the figure. It is clear from the figure that underfloor heating is the most advantageous in terms of vertical temperature distribution.

Effective ambient temperature

In order to be able to assess the resulting radiative effect of the surrounding surfaces with a single quantity, the so-called effective temperature of the surrounding surfaces is introduced ϑ_p. This temperature is defined as the common temperature of all surrounding surfaces at which the total radiant heat flux between the body surface and the surrounding surfaces would be the same as in reality. For the effective temperature of the surrounding surfaces, if the temperatures of the individual surrounding surfaces do not vary much, the follows relation is valid:

$$\vartheta_p = \sum_{i=1}^{n} \varphi_i \cdot \vartheta_i \qquad (7.68)$$

where φ_j are the ratios of the irradiance of each surrounding surface by the area of the human body (-) , ϑ_i are the temperatures of the surrounding surfaces (°C).

The effective temperature therefore depends on the temperatures of all surrounding surfaces and on the irradiance ratios relative to the area of the human body. In practice, however, this requirement is waived and the values are related to an elementary sphere, a point usually located in the centre of the object.

Resulting room ambient temperature

Starting from the relation for thermal equilibrium expressed in terms of heat fluxes to the body surface *A* and using a simplification for the convection and radiation heat transfer coefficients $\alpha_k = \alpha_s$ (for air flow velocities less than -0.3 m·s^{-1}), we obtain the equation for the resulting temperature of the environment required for providing of thermal comfort.

$$\vartheta_i = 0{,}5 \cdot \vartheta_v + 0{,}5 \cdot \vartheta_p \qquad (7.69)$$

It follows that the thermal comfort of a person depends only on the air temperature and the effective temperature of the surrounding surfaces for a given internal heat production and a given thermal transmittance of the garment. However, the ratio of the two temperatures ϑ_v and ϑ_p cannot be completely arbitrary. If the air temperature ϑ_v is assumed to be between 15 °C and 25 °C in rooms where the resulting temperature ϑ_i = 18.5 °C and 21.5 °C is required, the effective temperature of the surrounding surfaces ϑ_p may vary between 12 °C and 28 °C. This 'thermal comfort zone' is shown by the scraping in Fig. 7.63 [10].

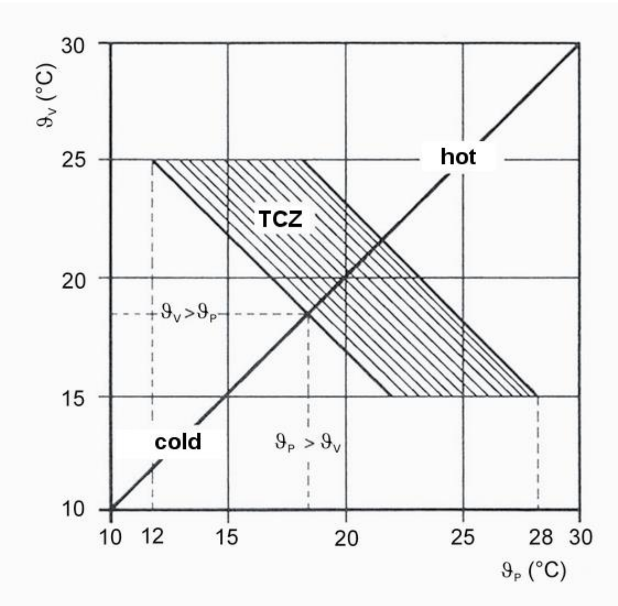


Fig. 7.63 Thermal comfort zone (TCZ)

❑ Practical calculation of heating devices

From the point of view of sizing the heating system, it is necessary to know the maximum value of the heat losses of the building, i.e. the amount of heat that pass from the indoor environment of the rooms with temperature ϑ_i to the cooler outdoor environment with temperature ϑ_e. The heating system must be sized for this maximum value in the year. The calculation of heat losses is based on ČSN 06 0210, Heat Losses Calculation.

The suitability of a building for electric heating is assessed on the basis of the calculated heat loss and heat consumption per^2 1 m of living area. The following documents are required for the calculation of the heat loss of buildings with central heating:

- site plan showing the location of the building in relation to cardinal points, the height and distance of surrounding buildings, the elevation of the site and the prevailing wind direction and intensity,
- floor plans of each floor of the building with all main dimensions, including window and door dimensions, at a scale of at least 1:100,
- sections through the building with all main heights (rooms, height of window sills, etc.),
- data on the materials and construction of walls, floors, ceilings and roofs to determine or calculate the heat transfer coefficient,
- data on the material and construction of windows and doors needed to calculate heat loss through penetration and infiltration,
- data on the use of individual rooms to determine the indoor temperature ϑi,
- description of the intended method of heating each room.

❑ General procedure for calculating heat losses

The total heat loss of a room Φ_c according to CSN 06 0210 is equal to the sum of the heat loss through walls Φ_p and the heat loss through ventilation Φ_v minus the permanent heat gains Φ_z [11]

$$\Phi_c = \Phi_p + \Phi_v - \Phi_z \qquad (7.70)$$

The heat loss through walls is determined from the (basic) heat loss by adding allowances according to

$$\Phi_p = \Phi_o \cdot (1 + p_1 + p_2 + p_3) \qquad (7.71)$$

where Φ_o is the basic heat loss through heat transfer (W), p_1 is the surcharge to compensate for the effect of cold structures (-), p_2 is the surcharge to accelerate the heating (-), and p_3 is the surcharge to the cardinal direction (-).

The basic heat loss Φ_o is equal to the sum of the heat fluxes through the individual walls enclosing the heated room to the outside environment or adjacent rooms.

$$\begin{aligned}\Phi_o &= \alpha_1 \cdot S_1 \cdot (\vartheta_i - \vartheta_{e1}) + \alpha_2 \cdot S_2 \cdot (\vartheta_i - \vartheta_{e2}) + \ldots \\ &+ \alpha_n \cdot S_n \cdot (\vartheta_i - \vartheta_{en}) = \sum_{j=1}^{n} \alpha_j \cdot S_j \cdot (\vartheta_i - \vartheta_{ej})\end{aligned} \qquad (7.72)$$

where S_j is the area of the wall to be cooled (m^2), α_j is the heat transfer coefficient (W·m^{-2}·K^{-1}), ϑ_i is the calculated internal temperature (°C), ϑ_{ej} is the temperature on the outside of the j-th wall (°C).

If the temperature on the outside of one of the walls is higher than the temperature in the heated room, the heat flux through this wall is negative. In this case, the heat gain Φ_z, which reduces the basic heat loss Φ_o.

Tab. 7.11 shows the values of the calculated indoor temperature ϑ_i for different room types.

Type of heated room	Internal temperature ϑ_i (°C)
living room, like a living room	
bedrooms, study rooms, children's rooms	20
kitchens	20
bathrooms	24
toilets	20
hallways, corridors	15

Tab. 7.11 Calculated indoor temperature values ϑ_i for different room types

The cold wall allowance p_1 allows the indoor air temperature to be raised so that the desired indoor temperature ϑ_i, for which the basic heat loss is calculated, is achieved in the heated room at the lower surface temperature of the cooled walls ϑ_p. This allowance depends on the average heat transfer coefficient α_c of all the walls of the room, which can be expressed by

$$\alpha_c = \frac{\Phi_o}{\sum S \cdot (\vartheta_i - \vartheta_e)} \qquad (7.73)$$

where $\sum S$ is the total area of all structures that enclose the heated room (m^2), ϑ_e is the calculated outdoor temperature for a specific area given by the standard (°C).

The premium to compensate for the effect of cold structures p_1 can then be determined from the relation $p_1 \sim 0.15\text{-}\alpha_c$ or approximately determined from Tab. 7.12.

α_c (W·m^{-2} ·K)$^{-1}$	up to 0.1	0,1 - 0,9	0,9 - 1,5	1,5 - 2,0
p_1	0	0,03 - 0,12	0,15 - 0,21	0,25 - 0,30

Tab. 7.12 Allowance to compensate for the effect of cold structures p_1

The surcharge for accelerating the flooding p_2 is only taken into account in residential construction, hospitals, etc. in cases where uninterrupted heating operation cannot be ensured even at the lowest outside temperatures. Under normal circumstances, the p_2 surcharge is not taken into account. For intermittent operation, it is selected according to the heating time as follows p_2 = 0.1 for daily heating times longer than 16 hours, p_2 = 0.2 for daily heating times shorter than 16 hours.

The position of the most cooled building structure of the room determines the amount of the surcharge to the world side p_3, in case of more cooled structures the position of their common corner. The values of the surcharge p_3 are given by Tab. 7.13.

Cardinal direction	S	SW	W	NW	N	NE	E	SE
p_3	-0,05	0	0	0,05	0,1	0,05	0,05	0

Tab. 7.13 Markup amount p_3 by cardinal direction

The ventilation heat loss Φ_v expresses the heat loss due to natural ventilation by infiltration or forced ventilation by negative pressure and is calculated according to the relation

$$\Phi_v = c_v \cdot V_v \cdot (\vartheta_i - \vartheta_e) \tag{7.74}$$

where c_v is the volumetric heat capacity of air at 0 °C, c_v = 1300 J·m^{-3}·K^{-1}, V_v is the volume flow of ventilation air (m^3·s^{-1}).

As can be seen, the calculation of heat losses of buildings according to ČSN 06 0210 is quite complex. For a preliminary estimation of heat losses, when deciding on the heating method, it is sufficient to use the approximate determination of heat losses according to Tab. 7.14. The table gives the heat loss per 1 m^3 of heated space. The total heat loss of the building is then equal to the sum of the heat losses of the individual rooms [10].

Method of cooling rooms	Heat loss (W)
Middle room (both sides of the heated room):	
a) above an unheated cellar and protected from above by a heated room	34 - 47
b) above the heated room and above the heated room	30 - 40
c) above the heated room and cooled from above by the soil	37 - 53
Corner room with windows in both walls:	
a) above an unheated cellar and protected from above by a heated room	40 - 58
b) above the heated room and protected from above by the heated room	35 - 49
c) above the heated room and cooled from above by the soil	44 - 65
d) above an unheated cellar and cooled from above by the soil	47 - 73
Bathroom	40 - 80
Lobby	15 - 30
Staircase	18 - 35
Average heat loss in 1 m^3 of heated space of a family house	35 - 60

Tab. 7.14: Approximate determination of heat losses

❑ Calculation of heat losses - Standard EN 12831

Standard [12] sets out the procedure for calculating the heat supply required for heating and achieving the required internal temperature. A new element is the inclusion of thermal bridges, whereas the standard does not consider any heat gains. This can be a problem in the calculation for low-energy to passive houses.

$$\Phi_i = \Phi_{T,i} + \Phi_{V,i} \tag{7.75}$$

where Φ_i is the heat loss through penetration and ventilation (W), $\Phi_{T,i}$ is the proposed heat loss through construction (W), $\Phi_{V,i}$ is the proposed heat loss through ventilation (W).

Heat loss through penetration and thermal bridges

The design heat loss through the penetration is determined by the relationship

$$\Phi_{T,i} = (H_{T,ie} + H_{T,iue} + H_{T,ig} + H_{T,ij}) \cdot (\vartheta_{int,i} - \vartheta_e) \tag{7.76}$$

where $H_{T,ie}$ is the heat loss through penetration directly to the outdoor environment (W-K^{-1}), $H_{T,iue}$ is the heat loss through the unheated space (W-K^{-1}), $H_{T,ig}$ is the heat loss through penetration to the soil (W-K^{-1}), $H_{T,ij}$ is the heat loss through a space heated to a significantly different temperature (W-K^{-1}), $\vartheta_{int,i}$ is the design indoor temperature (°C), ϑ_e is the design outdoor temperature (°C).

The term thermal bridge is the main new feature of the new standard and characterises the heat loss through the wall at the point of contact between two different structures. The thermal bridge is characterised by the linear heat transfer coefficient (W·m^{-2}·K^{-1}) and also by its length (m).

$$H_{\mathrm{T,ie}} = \sum_k S_k \cdot U_k \cdot e_k + \sum_l \Psi_l \cdot l_l \cdot e_l \qquad (7.77)$$

where S_k is the area of the building part in m^2, e_k, e_l are the weathering correction factors (-), U_k is the heat transfer coefficient of the building part in W·m^{-2}·K^{-1}, l_l is the length of the thermal bridge in m, ψ_l is the heat transfer coefficient of the thermal bridge in W·m^{-1}·K^{-1}.

Heat loss by ventilation

To determine the heat loss through ventilation, we should base our considerations on the following equation:

$$\Phi_{\mathrm{V,i}} = H_{\mathrm{V,i}} \cdot (\vartheta_{\mathrm{int,i}} - \vartheta_{\mathrm{e}}) \qquad (7.78)$$

where V_i is the air exchange in the heated space (m^3 ·h^{-1}).

For the determination of V_i it is particularly important whether the ventilation is natural or forced. In natural ventilation, sufficient air exchange is determined by infiltration through the building envelope and the hygienic amount of air that must be exchanged.

$$V_{\mathrm{min,i}} = n_{\mathrm{min}} \cdot V_{\mathrm{i}} \qquad (7.79)$$

where n_{min} is the minimum outdoor air exchange rate per hour (h^{-1}), V_i is the volume of the heated room (m^3).

The minimum air exchange rate is 0.5 for the basic living room and 1.5 h^{-1} for the bathroom.

Proposed thermal power

$$\Phi_{\mathrm{HL,i}} = \Phi_{\mathrm{T,i}} + \Phi_{\mathrm{V,i}} + \Phi_{\mathrm{RH,i}} \qquad (7.80)$$

where $\Phi_{HL,i}$ is the design heat output (W), $\Phi_{T,i}$ is the heat loss through the structure (W), $\Phi_{V,i}$ is the heat loss through ventilation (W), $\Phi_{RH,i}$ is the flood power required during intermittent heating (W).

Evaluation of the comparison of standards CSN 06 0210 and CSN EN 12831

The biggest difference in both standards is the heat loss through the structure, which is mainly distinguished by the presence or absence of thermal bridges. Another element that differentiates the standards is the absence of heat gains in the calculation in EN 12831, either permanent (presence of humans) or variable (solar radiation).

It is therefore necessary to approach the calculation in great detail to ensure the correct design of the heat source to maintain the optimal ratio of investment to operating costs, because under dimensioning will result in investment savings at the expense of higher operating costs and vice versa.

Calculation of heating input

For the calculation of the heat source input power, the chosen method of electric heating, the heating mode at nominal or damped temperature, and the method of forced ventilation are decisive. The actual installed electrical input of the heaters may be higher than the calculated total input maximum:

- 20 % for power input up to 50 kW,
- 10 % for power inputs higher than 50 kW.

If the calculated input power of the electric heater is within the first third of the difference in input power of the heater type series, the type with the lower input power shall be selected. The calculation of the heating input has its specifics for each type of electric heating. In the following we will discuss the calculation of heating input separately for direct, storage and mixed (hybrid) electric heating systems.

Direct electric heating

The input power of a convection or radiant heater P_k is determined from the relationship

$$P_k = \Phi_c \cdot K \qquad (7.81)$$

where P_k is the input power of the convection or radiant heater (W), Φ_c is the total heat loss of the building (W), K is the heating process coefficient, a value of 1.0 is selected for continuous operation, 1.1 for heating breaks up to 4 hours, 1.2 for breaks longer than 4 hours, 1.4 for intermittent use.

Storage electric heating

This heating method uses electricity consumption during selected, usually low tariff hours (charging from 10 pm to 6 am) and in justified cases during selected daytime hours (charging after 2 hours or more). The input of the storage heat source can be determined from the total daily heat demand Φ_d , which depends on the total heat loss per hour Φ_c , the required heating time to full temperature t_v and the damped heating time t_t . The heating time t_v includes the ramp-up time to the required temperature. The electrical input power is the same for continuous and staggered charging time t_n = 8 hours.

The heating operating modes for the calculation of the heat source input are determined from the full heating time t_v at ϑ_i = 20 °C. The accumulate heating is designed for the operating mode given by the time t_v (h) kitchen 10 h, kitchen with dining room 12 h, living rooms 14 h, children's rooms 14 h, other rooms 12 h. The sizing of accumulate heaters is carried out according to the relation

$$P_a = \Phi_d \cdot k_v \qquad (7.82)$$

where P_a is the power input of the accumulate heater (stove) (W), k_v is the coefficient of operation (h^{-1}) see. Tab. 7.15

Heating break t_s (h)	Traffic coefficient k_v (h^{-1})		
	Dynamic with fan III.	Static with control damper II.	Static without control damper I.
0	0,14	0,18	0,20
2	0,15	0,23	---
4	0,17	0,31	---
6	0,19	(0,50)	---
8	0,22	(1,25)	---

Tab. 7.15 Operating coefficient value

The daily heat demand is then

$$\Phi_d = \Phi_c \cdot t_v \quad (7.83)$$

Electric central accumulate heating is proposed for full heating for 12 hours. The remaining daytime operation is either dimmed or intermittent. The total daily heat demand Φ_d for hot water systems shall be determined according to the following formula

$$\Phi_d = \Phi_{dd} + \Phi_{dn} \quad (7.84)$$

$$\Phi_{dd} = \frac{\Phi_c}{\eta} \cdot (t_{vd} + t_{td} \cdot f) \quad (7.85)$$

$$\Phi_{dn} = \frac{\Phi_c}{\eta} \cdot (t_{vn} + t_{tn} \cdot f) \quad (7.86)$$

where Φ_{dd} is the daytime heat demand (Wh), Φ_{dn} is the low tariff heat demand (Wh), t_{vd} is the required heating time to full temperature in daytime (h), t_{vn} is the required heating time to full temperature in low tariff (h), t_{td} is the required damped heating time in daytime (h), t_{tn} is the required damped heating time in night time (h), f is the building structure influence coefficient, considered equal to 0.3 for heavy, 0.4 for medium and 0.5 for light structure, η is the heating system efficiency of 0.95.

The required input power is then determined by the formula

$$P_a = \frac{\Phi_d}{t_n} \quad (7.87)$$

Mixed (hybrid) electric heating

Mixed heating consists of a storage part and a direct heating part. The accumulate heating system draws electricity for a maximum of 8 hours per day during night time hours set by the electricity supplier. Direct heating operates at lower outdoor temperatures during off-peak times of the day (e.g. 11am to 5pm).

Mixed heating makes it possible to connect more electric heating equipment to the existing grid, as the consumption rate is lower than for pure accumulate heating. It is also important to reduce the size of the equipment and thus the purchase costs.

The design of the electric hybrid heater is carried out separately for the storage part and for the direct heating part.

$$P_{\mathrm{h}} = 0{,}6 \cdot P_{\mathrm{a}} \tag{7.88}$$

where P_h is the power input of the hybrid heater (W), P_a is the power input of the accumulate heater calculated according to the relation for accumulate heaters and for the charging time T_n = 8 hours (W).

The direct heating part of the hybrid heater shall be determined according to

$$P_{\mathrm{ph}} = 0{,}4 \cdot P_{\mathrm{a}} \tag{7.89}$$

However, the input of the direct heating part must cover at least 90 % of the heat loss of the room. The central accumulate heat source for mixed heating shall be sized at 60 % of the input of a pure accumulate central heating system with an eight-hour charging time. The input power of the direct heating part of the hybrid system shall be at least 10 % higher than the heat loss of the room and shall be about half the input power of a pure accumulate source with an eight-hour charging period.

Electric heating systems

The irregularity of daily consumption, resulting from the normal rhythm of human life, has led to an attempt to use the available power plant capacity during off-peak periods. This made possible the introduction of accumulate appliances for heating or hot water, which were switched on only at night. However, further developments have shown that with only storage heat, the possibilities of the electricity system would soon be exhausted, which is why today the electricity industry also offers direct heating and hybrid systems.

Storage electric heating

This heating method uses electricity consumption during selected, usually low tariff hours (charging from 10 pm to 6 am) and in justified cases during selected daytime hours (charging after 2 hours or more).

The electrical energy is converted into heat in resistance heating cells or cables that are stored in the accumulate material. This takes the form of a heater, boiler or is a concrete part of a building structure, usually a floor. Heating requires a reliable knowledge of the heating time t_v to the calculated internal temperature ϑ_i , which includes the so called ramp-up time to full temperature and the damped heating time t_t .

There are several possible ways of electric accumulate heating.

Storage heaters

Magnesite and fireclay are generally used as the accumulation material. Three types of accumulate heaters are distinguished according to their design and the way the heat is shared during room heating (discharge of the heater), as shown in Fig. 7.64.

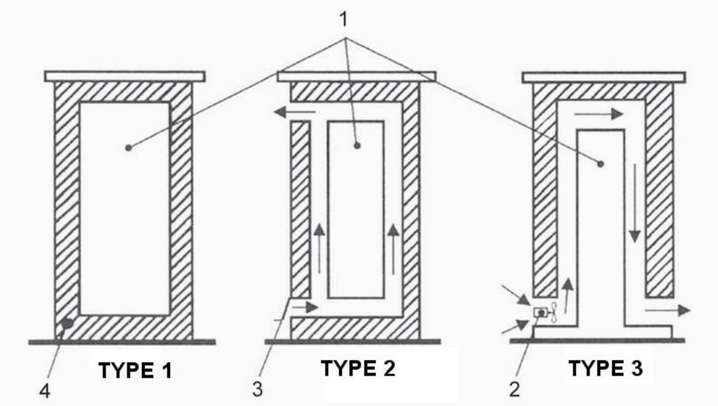


Fig. 7.64 Three types of accumulate heaters

1 - accumulation substance, 2 - fan, 3 - control damper, 4 - thermal insulation

Electric accumulate central heating consists of a traditional hot water heating system - an electric, usually resistive heat source and a water accumulator. The heat is transported from the accumulator to the heated room. This suppresses the basic principle of electric heating, which is to bring the energy up to the heated room with maximum controllability of its conversion.

Another possible type of accumulate heating is the so-called large-area underfloor accumulate heating. The heat source is heating cables laid in the concrete screed of the floor construction. The surface temperature of the floor shall not exceed 25 °C. Long service life and a guarantee are prerequisites for the application of the heating system.

A purely accumulate system of electric underfloor heating, charged exclusively by the night current for 8 hours, is particularly suitable for new and renovated buildings used only in the morning, at most in the early afternoon. It is not suitable for rooms heated all day. It is characterised by good thermal insulation underneath (combination of polystyrene foam and mineral fibre insulation) and, in particular, by the large thickness of the accumulation plate (90 to 150 mm). The heating plane with heating cables is placed in the lower half of the accumulation plate Fig. 7.65.

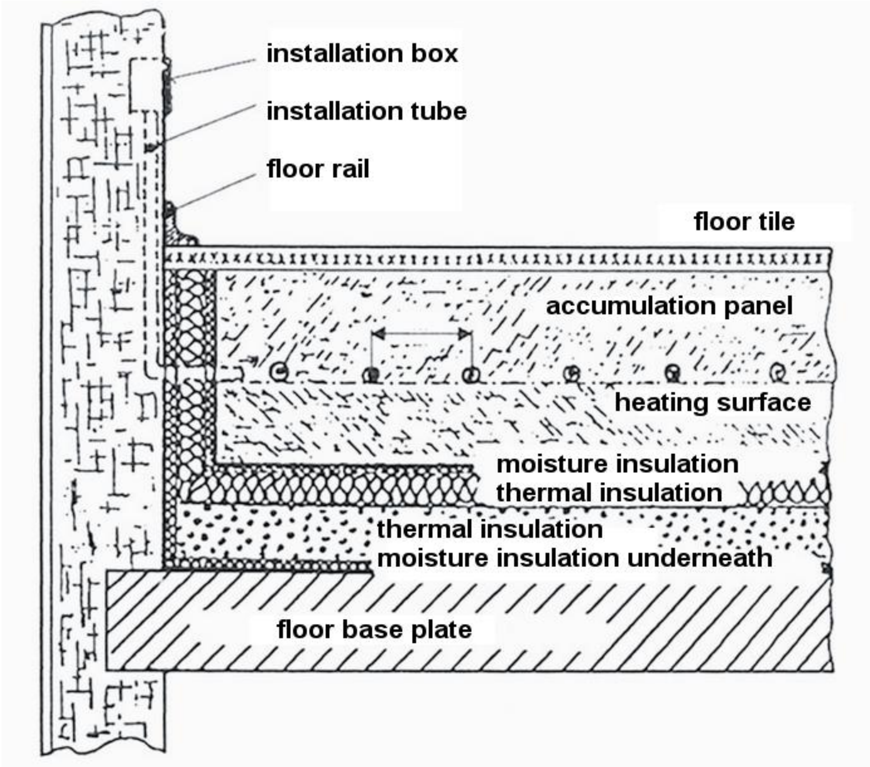


Fig. 7.65 Storage electric underfloor heating

Direct electric heating

It consists of a distribution system, direct-fired heaters with heating elements or electrodes and a control circuit to ensure the optimum heating cycle. Depending on the location of the heat source and the method of heat sharing, electric direct heating systems can be classified as follows:

Local

- convectors and hot air heaters,
- electric underfloor heating cables,
- radiant heating systems.

Central

- hot water electric boilers.

Convection electric heating

Convector heaters are electric heaters that convert all the electricity supplied into heat. Cold air enters the convector from the bottom and heated air leaves from the top, which then heats the whole room by natural circulation Fig. 7.66.

Natural convection heaters are mobile, portable or designed for fixed installation on the wall. They are either radiators with a heated cartridge, usually oil, or convector heaters with heating resistance. These are usually tubular stainless steel heating elements with pressed aluminium fins, adapted for quiet operation. The ambient air is heated by natural convection around the heating element. Modern convector heaters are equipped with a high quality control system with the possibility of central control of their operation. Forced convection heaters are portable or wall-mounted direct-heating appliances in which the air is blown past the heating resistors by means of a fan.

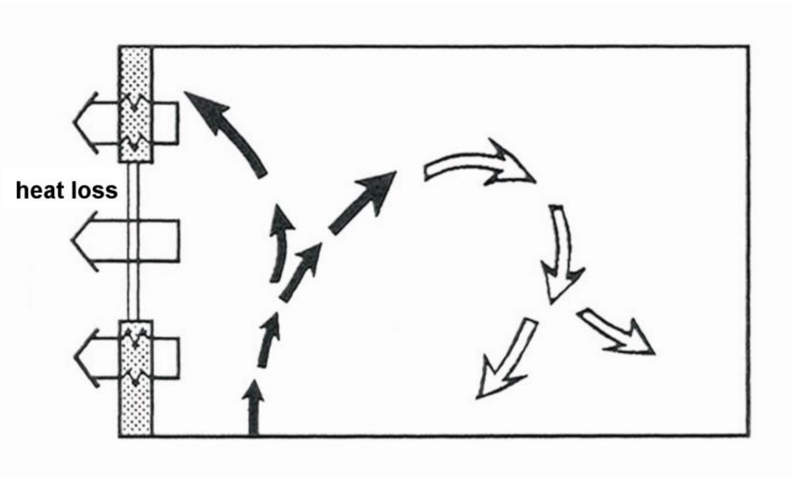


Fig. 7.66 Air circulation in the room

Underfloor heating with heating cables

Large-scale floor systems, made by pouring special electric heating cables into the concrete floor, are Fig. 7.67, are popular mainly because of their high efficiency, even heat distribution over the whole area, excellent use of the heated space, relatively easy implementation and the creation of thermal comfort at a lower air temperature than e.g. convectors.

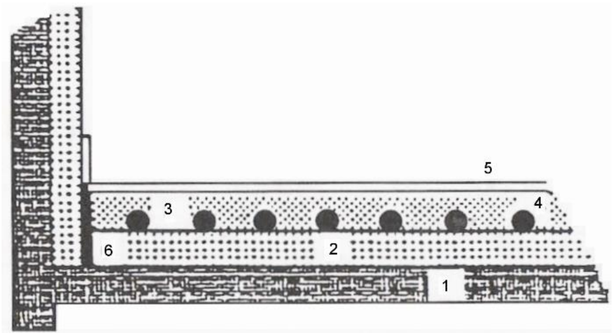


Fig. 7.67 Underfloor heating with heating cables

1-base concrete, 2-polystyrene (about 40 mm), 3-concrete layer (30-50 mm), 4-heating cables, 5-paving, 6-insulation connection

Radiant electric heating

While in convection heating the body is heated mainly by air, which transfers heat by flowing over the surface of the heated object, in radiant heating the heat is transferred mainly by radiation Fig. 7.67. Each body radiates electromagnetic energy into its surroundings. Of the wide range of wavelengths, we are interested only in those that can be absorbed by objects and converted into thermal energy.

Radiant heaters may be infrared radiant heaters where the heating element has a surface temperature greater than 250 °C and the radiation is directed by a reflector in a specified direction.

Low-temperature radiant heating is provided by radiating the surface of surfaces heated to 25 to 40 °C. Special foils or panels are usually fixed to the ceiling and walls. In a room heated in this way, the air temperature and relative humidity are lower than with convection heating. The energy consumption is also lower, mainly due to heating to a lower desired room temperature. The energy savings compared to convection heating are roughly between 18 and 24 %.

The use of radiant panels is very wide. They are intended for creating thermal comfort of workshops with clearance heights up to 3.2 m, for breeding of blooded animals, tempering of greenhouses, etc. Panels with lower power ratings are intended for heating residential premises.

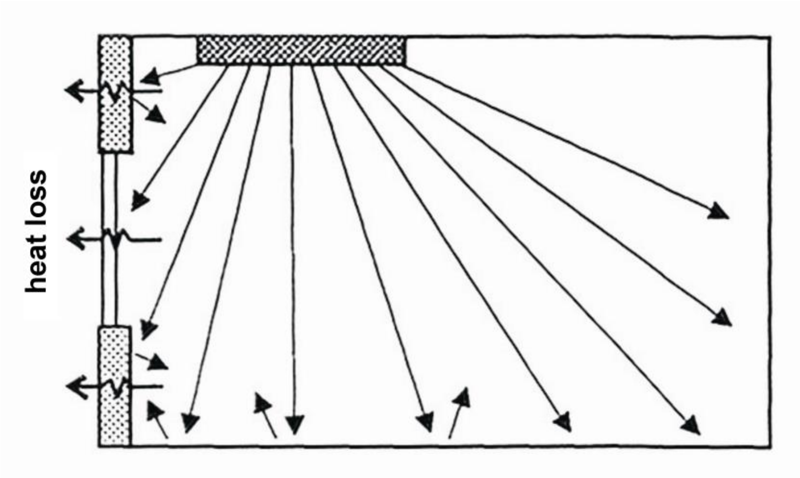


Fig. 7.68 Radiant electric heating

Heating with hot water electric boilers

Electric boilers can be used for heating new buildings, but they are also very suitable as a replacement for solid fuel boilers in central heating systems of family houses and terraced houses.

Hot-water electric boilers - the heating medium is water, which is heated in a closed vessel, the boiler, from which it is then piped to radiators or similar equipment in individual rooms. The heating of the water in the boiler is provided either by heating elements based on the resistive principle, i.e. a classical resistance boiler, or by electrodes, i.e. an electrode boiler, in which heat is generated by the passage of an electric current through the water (electrolyte) between the electrodes.

❑ Mixed (hybrid) electric heating

Mixed heating consists of a storage part and a direct heating part. The storage heating system draws electricity for a maximum of 8 hours per day during night time hours set by the electricity supplier. The direct part of the heating system operates at lower outdoor temperatures during off-peak hours of the day. It can be assumed that in future years this type of electric heating will find many more users than it has done so far.

Mixed heating systems can be designed as follows:

- electric hybrid heater,
- combination of central storage heating with direct heaters,
- combination of large area underfloor storage heating with direct heaters.

Mixed heating allows more electric heating equipment to be connected to the existing grid, as the consumption rate is lower than for pure storage heating. It is also important to reduce the size of the equipment and thus the purchase costs.

The central storage heat source for mixed heating shall be sized at 60% of the input power of pure storage central heating with an eight-hour charging time. The input power of the direct heating part shall be at least 10 % higher than the heat loss of the room and shall be about half of the input power of a pure storage source with eight hours charging.

Issues of automatic heating control

The purpose of automatic control is to maintain a physical variable that is subject to change at a desired value without human intervention. In room heating, this variable is usually the internal temperature of the room. Maintaining the quantity at the desired value can be achieved by:

- by measuring the actual value of the controlled variable (in this case temperature),
- by comparing the measured actual value with the desired (set) value,
- by acting on the regulated variable (temperature or water flow) to reduce the detected difference.

For the design of the control device it is necessary to know:

- user requirements,
- basic characteristics of the building structure and heating system,
- applicable regulations.

The requirements of the flat user are generally expressed in terms of the indoor temperature required in the whole or part of the house or flat or in individual rooms whose use is known. The basic characteristics of a building include knowledge of the magnitudes of heat loss expressed by the thermal performance of the building and knowledge of the storage properties of the structure.

The type of heating system is selected according to the heat loss of the building. The storage properties will influence the design of the heating system with regard to the selection of the control device so that the temperature control is stable and accurate. The characteristics of the heating system make it possible to specify:

- the required heat output of the heating surface to cover the heat losses,
- the response time of the heating system when the internal temperature changes, allowing the selection of the control device.

Selected response times of the heating system:

- cast iron heating 20 min to 1 hour,
- steel heating 10 min to 20 min,
- convector 5 min to 10 min,
- large floor heating area 2 to 5 hours.

In all heating systems, with the exception of large-area heating, it is possible to use control according to the indoor air temperature. In some cases, the output of the heating system is controlled according to the outside temperature. The control is based on a predetermined dependence of the output on the outdoor temperature and is not controlled by the indoor temperature. Therefore, outdoor temperature control should be supplemented by indoor temperature control.

Control circuits

The control device consists of the following parts:

- a sensor that measures the actual value of the regulated variable, usually temperature, and converts it into a physical quantity (electric current or voltage) that can be easily and conveniently processed in the controller,
- a controller, in which the actual value of the regulated variable (temperature) is compared with the desired setpoint, can be built into the control part or sensor,
- the control part that carries out the control (e.g. electrically operated mixing valve or contactor that disconnects the electric heating appliance from the mains).

Closed control circuit

In a control circuit, there are three basic variables: the controlled, control and fault variables. The controlled variable is the internal temperature. The disturbance variables affect the controlled variable (heat loss, heat gain, wind).

The controller evaluates the actual value of the regulated variable (setpoint) and the value of the control variable. The resulting control deviation is processed in the controller, which sends a signal to the controlling authority. The change in the output of the body is reflected by a change in the internal air temperature and the sensor registers the changed temperature value. The circuit is closed.

Closed feedback control circuit

The added feedback makes it possible to predict the response and thus accelerate the action of the regulation. For example, the heating water supply temperature (auxiliary value) is sensed and fed into the controller. This feedback control circuit is used for individual indoor air temperature control. Simple and inexpensive ways of controlling the indoor temperature with a room thermostat with feedback are used for flats.

Open control circuit

It is mainly used in central heating, if we know sufficiently the response of the regulated circuit to changes in outdoor temperature, which is the main fault variable. The auxiliary variable is the heating water temperature. It is therefore a circuit that is used in controlling according to the outdoor temperature. This simplification of the control process is conditional on the knowledge of the dependence of the outdoor temperature and the heating water temperature for a given indoor temperature in the rooms of the building. The circuit is used in central control of several rooms in one building. The change of each disturbance variable (temperature, wind, and glare) is sensed by a sensor and the information obtained is transmitted to the controller. The controller controls the control part according to the set dependencies of the disturbance variables on the controlled variable.

The whole control process is carried out according to the determined dependencies set in the controller and the accuracy and stability of the control depends on how accurately the dependencies have been determined and set. This control is also called equithermic control. For a given room, a set of so-called equithermic curves can be determined (also called "heating curves"), which describe the interdependence of the heating water temperature, the room temperature and the outside temperature. Based on the desired room temperature, a specific curve can be selected and the heating water temperature can be regulated according to the outside temperature.

Note

Throughout the chapter 7 uses verbatim quotations, figures and tables from the literature [13]. Additional information on the issues addressed in this chapter can be found in this book.

Summary of terms 7.5.

Heating, thermal comfort, thermal state of the environment, effective ambient temperature, heat loss, direct heating, storage heating, hybrid heating, heating control, equithermic control.

Questions 7.5.

1. Explain the concept of thermal comfort.
2. Write a relationship for the thermal equilibrium of a person.
3. What is the thermal state of the environment?
4. Draw the ideal vertical temperature distribution in the room.
5. What is the effective ambient temperature? Give the relationship for the calculation.
6. Write a relationship for the resulting ambient room temperature.
7. Draw what the thermal comfort zone looks like.
8. State the relationship for the total heat loss of a room Q_c .
9. List the basic types of electric heating.
10. List the possibilities of direct electric heating.
11. Describe the options for controlling electric heating.
12. What are equithermic curves?

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8. LIGHTING TECHNOLOGY

8.1. Fundamentals of lighting technology

TIME TO STUDY:

4 hours

TARGET:

After studying this paragraph, you will be able to

- define the basic concepts of lighting technology
- define the basic quantitative and qualitative parameters of light sources
- solve simple examples of lighting technology

EXPLANATION

Light is electromagnetic radiation that is able to build up visual perception through the visual organ. Radiation can be characterized by frequency or wavelength. Wavelengths of visible radiation are in the range λ = 380 ÷ 780 nm. Visible radiation is the part of optical radiation that follows ultraviolet radiation at shorter wavelengths and passes into infrared radiation at the longer wavelengths.

Seeing or visual perception is the process of cognition of the surrounding environment. It is the process of receiving visual information by distinguishing the difference in brightness (contrast) of colours and shapes. On the basis of the distinction, identification and analysis, which is the recognition of objects and the relationships between them, occurs and is classified in our consciousness, either for immediate use for a given activity or for storage in memory. The goal of vision is thus recognition.

Information power

The amount of information obtained by sight and transmitted to the human brain can be characterized by information output. Its magnitude increases with increasing illuminance and therefore brightness of the observed objects.

Information power increases with increasing illuminance, but its increase is limited by the maximum transmission capacity of the information channel. The increase in information or visual power is therefore much more influenced by an increase in illuminance in the relatively low level region around 50 lx than by an increase in relatively high illuminances in the region above 500 lx. These facts should be taken into account when designing artificial lighting systems in terms of maximum efficiency of energy use. That is, it is the transformation of electrical energy into the amount of information transmitted that must be considered, not the direct transformation of electrical energy into light. In fact, the curve of the dependence of the amount of transmitted power shows that designing lighting systems for illuminance higher than 5 000 lx only makes sense in justified cases (e.g. operating theatres, etc.).

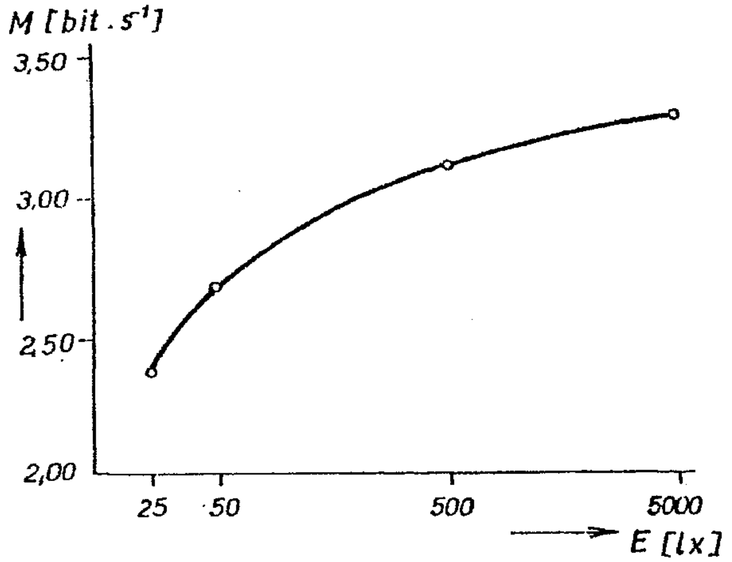

Fig. 8.1 Dependence of the amount of information transmitted on the illuminance

The Essence of Light

Light causes not only visual perception but also colour sensation. The colour properties of primary light sources are referred to as chromaticity or are described by the general colour rendering index R_a, the colour properties of secondary light sources are referred to as chromaticity. Radiation of each wavelength of visible light excites a colour counter. Each colour counter corresponds to a spectral colour, which is described by a colour tone. The composition of visible light is described and illustrated in Tab. 8.1 at Fig. 8.2 [1].

Wavelength λ(nm)	Colour tone of spectral colour
380 ÷ 420	purple
420 ÷ 440	blue-violet
440 ÷ 460	blue
460 ÷ 510	blue-green
510 ÷ 560	green
560 ÷ 590	yellow
590 ÷ 650	orange
650 ÷ 780	red

Tab. 8.1 Colour tones of visible light

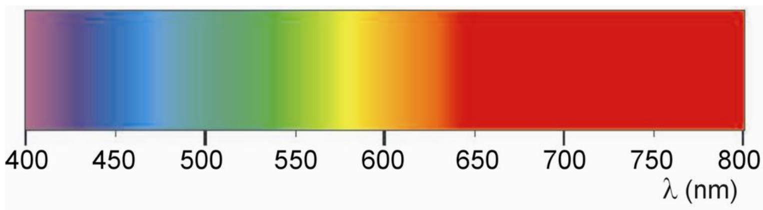

Fig. 8.2 Colour distribution in the spectral region of visible radiation

❑ Concepts, symbols, quantities, units

Luminous flux

The luminous flux Φ represents the radiant flux Φ_e , which is judged from the sensitivity of the human eye. It tells us how much light energy a source emits into its surroundings. The unit of luminous flux is the lumen (lm). Radiant flux represents the amount of power that radiation transmits, emits or receives.

Luminous intensity

Luminance is a luminous technical quantity that describes the distribution of light radiation in space. It indicates how much luminous flux is emitted by a source at a spatial angle in a certain direction. The unit of luminous intensity is the candela (cd). Candela is one of the basic physical units of the SI system. Since 1979, the candela is defined as the luminous intensity of a source that emits monochromatic radiation at a certain angle with an intensity of 1/683 $W \cdot sr^{-1}$ and a frequency of $540 \cdot 10^{12}$ Hz. The mean value of the luminous intensity is then determined from the luminous flux Φ emitted at a unit solid angle Ω.

$$I = \frac{\Phi}{\Omega} \tag{8.1}$$

where I - luminous intensity (cd); $d\Phi$ - luminous flux (lm); Ω - solid angle to which the luminous flux is emitted (sr).

The luminous intensity is determined for a point source, that is, the source has negligible dimensions and relative to the distance of the point r to which the check measurement is made.

Illuminance

Illuminance, or illuminance intensity, is another of the derived photometric quantities. It indicates the value of the luminous flux fall on a unit area (1 m^2)

$$E = \frac{\Phi}{A} \tag{8.2}$$

where E - illuminance (lx); Φ - luminous flux (lm); A - area covered by the luminous flux (m^2).

Luminous exitance

Luminous exitance is a photometric quantity defining the areal density of the luminous flux Φ emitted from area A. It therefore defines the magnitude of the luminous flux emanating from this surface A.

$$M = \frac{\Phi}{A} \tag{8.3}$$

where M - illuminance ($lm \cdot m^{-2}$); Φ - luminous flux (lm); A - area on which the luminous flux falls (m^2).

Luminance (brightness)

The luminance is calculated from the ratio of the luminance I and the projection of the illuminating area A_p, which the observer can see. If the area is seen at a certain angle, the projection of this area will be smaller than the actual area.

$$L = \frac{I}{S_{\mathrm{p}}} \tag{8.4}$$

where L - luminance (cd·m^{-2}); I – luminous intensity (cd); A_{p} - projection of the illuminating surface

Solid angle

Solid angle is an important quantity used in light engineering calculations. It represents the portion of space that is bounded by a conical surface that forms an area A on a sphere of radius r. The vertex of such a cone is at the centre of the sphere (Fig. 8.3). The size of the solid angle at which the area A can be seen from the centre of the sphere is calculated by relation (8.5).

$$\Omega = \frac{A}{r^2} \tag{8.5}$$

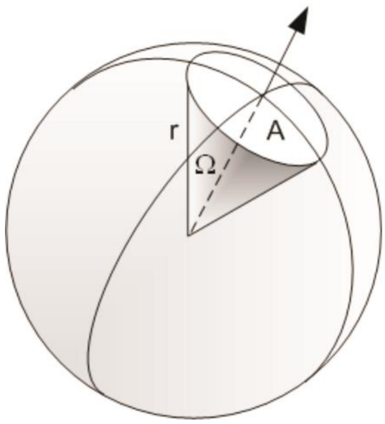

Fig. 8.3 Definition of the solid angle

where Ω - solid angle in steradians (sr); A - area formed by the cone representing the given solid angle (m^2); r - radius (m).

The unit of solid angle is the steradian (sr). The maximum value of the solid angle is obtained by considering the surface of the whole sphere as A ($A = 4 \cdot \pi \cdot r^2$, $\Omega = 4\pi$).

Luminous efficacy of light sources

For electric light sources, we check the level of conversion of electrical energy into light energy. The luminous efficacy is given by the ratio of the luminous flux Φ and the electrical power P. The luminous efficacy thus determines what value of luminous flux can be obtained from one watt. However, care must be taken when calculating light sources that have a ballast, such as fluorescent lamps or discharge lamps. While for sources without ballasts (conventional incandescent lamps) the indicated wattage is the same as the wattage of the light source. In the case of light sources with ballast, the specific power input must be defined. This is equal to the specific power increased by the power consumed by the ballast [1], [2].

$$\eta_{\mathrm{p}} = \frac{\Phi}{P} \tag{8.6}$$

where η_{p} - luminous efficacy (lm·W^{-1}); Φ - luminous flux (lm); P - electrical power (W).

An overview of the specific power of different types of light sources is in Tab. 8.2.

Type of light source	**Power (W)**	**Luminous efficacy (lm·W^{-1})**
Bulb	15 - 200	6 - 15
halogen bulb	10 - 2000	14 - 26
compact fluorescent lamp	5 - 60	56 - 88
linear fluorescent lamp T8	10 - 58	65 - 90
linear fluorescent lamp T5	14 - 80	70 - 104
induction discharge lamps	50 - 400	70 - 93
mercury vapour lamp	50 - 1 000	50 - 80
high pressure sodium discharge lamp	50 - 1 000	88 - 150
halide lamp	35 - 3 500	94 - 103
low pressure sodium lamp	18 - 180	130 - 200
light-emitting diodes	1 - 20	up to 140
xenon lamp	25 - 10 000	up to 95
plasma light source	up to 250	up to 85

Tab. 8.2 Overview of the specific power of commonly manufactured light sources

Colour temperature

The colour temperature of a source is the equivalent temperature in Kelvin (K) of the so-called black Planck radiator at which the spectral composition of the radiation of the two sources is close. If the temperature of the absolute blackbody increases, the blue part of the emitted spectrum increases and the red part decreases. For example, an incandescent lamp with continuous spectrum light has a chromaticity temperature of 2700 K, while a fluorescent lamp with daylight-like light has a colour temperature of 6000 K.

This quantity has a significant influence on the suitability of the light source for specific visual activities. As the colour temperature of a particular type of light source increases, its luminous flux, and therefore its specific light output, decreases due to the spectral sensitivity curve of the human eye, and vice versa.

Fig. 8.4 Colour temperature

Correlated colour temperature T_C (K)

It is used to describe the colour properties of light; in the case of thermal light sources (incandescent lamps) it corresponds to the filament temperature, in the case of discharge light sources the term substitute colour temperature is used, which corresponds to an equivalent temperature source with a similar spectral composition to the discharge light source. An overview of the colour temperatures for different types of light sources is given in Tab. 8.3.

Type of light source	T_C (K)
fluorescent lamp cold daylight	6 500 and more
fluorescent daylight lamp	5 400
blue sky	6 500
sun in summer at noon	5 500
fluorescent lamp cold white	4 000
sun at sunset	3 500 ÷ 4 000
bulb, fluorescent lamp warm white	2 700
candle flame	1 800

Tab. 8.3 Colour temperature and correlated colour temperature of different light sources

For light sources, there are three basic categories of light colour depending on the correlated colour temperature:

- warm white < 3 300 K,
- white 3 300 ÷ 5 000 K,
- daily > 5 000 K.

Even though light sources may have the same colour of light, they may exhibit different colour rendering depending on the spectral composition of the light from these sources. We describe these properties using a colour rendering index.

Colour rendering index CRI, R_a (-)

Each light source should render the colours of the surroundings with its luminous flux in a true-to-life manner, as we know them from natural light or incandescent light.

The measure of this property is the general colour rendering index CRI given by the range 100 ÷ 0. Colour rendering index (CRI) of 100 is given by light sources that display colours faithfully, i.e. in the same way as daylight. In contrast, a colour rendering index of 0 is given to light sources which emit all the light flux at one wavelength, so that colours cannot be distinguished because they are not present in the spectrum. For example, a colour rendering index of more than 80 is prescribed for indoor workplaces with permanent occupants.

Lifetime of the light source (h)

The lifetime of light sources is a very important parameter that tells us how long a given light source will last economically. In the case of light bulbs, the lifetime is determined by the limit state - filament burn-in. However, for other sources, such as discharge lamps or LEDs, this definition is not sufficient. During the working life of a fluorescent lamp, discharge lamp or LED, the luminous flux will naturally decrease. After a certain period of time, even if the source is still functioning, it becomes uneconomical and requires replacement. We therefore distinguish here between two definitions of lifetime:

- Average lifetime - the average of the lifetimes of individual light sources of a lighting system operated under predetermined conditions. The period is given by the time it takes for exactly half of the monitored number of lamps to be lit, i.e. the failure rate reaches 50 %. During the duration, there is a gradual decline in the number of working lamps, as expressed by the mortality curve.
- Useful (economic) lifetime is defined with respect to the gradual decrease of the luminous flux of the sources during their lifetime. The end of useful life is reached when the luminous flux of the source is at 80 % of the initial luminous flux value (for LEDs 70 % is often considered).

Type of light source	Average lifetime (h)	Useful life (h)
ordinary light bulbs	1 000	1 000
halogen bulbs	2 000 - 3 000	2 000 - 3 000
compact fluorescent lamps	15 000	6 000 - 15 000
linear fluorescent lamps	20 000	10 000 - 18 000
high pressure mercury	16 000 - 24 000	10 000 - 20 000
high pressure sodium	32 000	20 000
low pressure sodium lamps	16 000	16 000
metal halide lamps	10 000	4 000
induction lamps	60 000	20 000
power LEDs	50 000 - 100 000	25 000 - 50 000
plasma light sources	50 000	50 000
xenon lamps	1 000 - 3 000	1 000 - 3 000

Tab. 8.4 Approximate lifetimes for various types of light sources

❑ Light-technical properties of materials

The luminous flux of light Φ that falls on the surface of a body is partly reflected Φ_ρ from that surface, partly transmitted Φ_τ , and part of that flux is absorbed Φ_α by the body. The factors of reflection ρ , transmittance τ , and absorption α are given relations:

$$\rho = \frac{\Phi_\rho}{\Phi} \tag{8.7}$$

$$\tau = \frac{\Phi_\tau}{\Phi} \tag{8.8}$$

$$\alpha = \frac{\Phi_\alpha}{\Phi} \tag{8.9}$$

There is a correlation between these factors, which can be understood as the law of conservation of energy (equation (8.10), Fig. 8.5).

$$\rho + \tau + \alpha = 1 \tag{8.10}$$

The distribution of the light flux reflected from the surface of a substance can vary. The simplest case is the so-called **specular reflection**, where light rays are reflected from a given surface at the same angle as they strike the surface. Another simple case is when the light flux reflected from an element of a surface is split so that the brightness of that element of the surface under consideration is the same in all directions. This is a uniformly diffuse or **diffuse reflection.** The luminosity of such an ideal diffuser is maximum in the perpendicular direction. At other angles the luminosity is calculated according to the cosine law.

$$I_\gamma = I_0 \cdot \cos\gamma \tag{8.11}$$

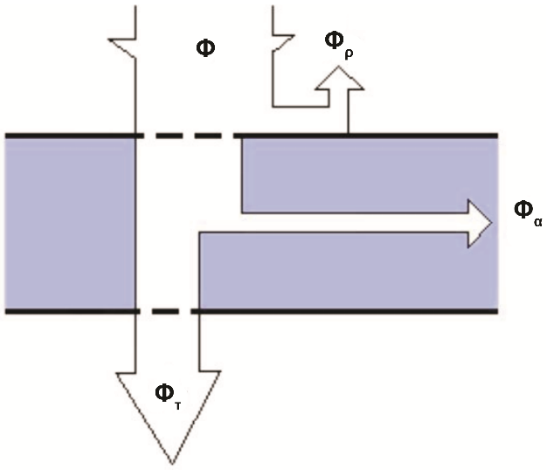

Fig. 8.5 Distribution of luminous flux as a function of reflection, transmission and absorption factors

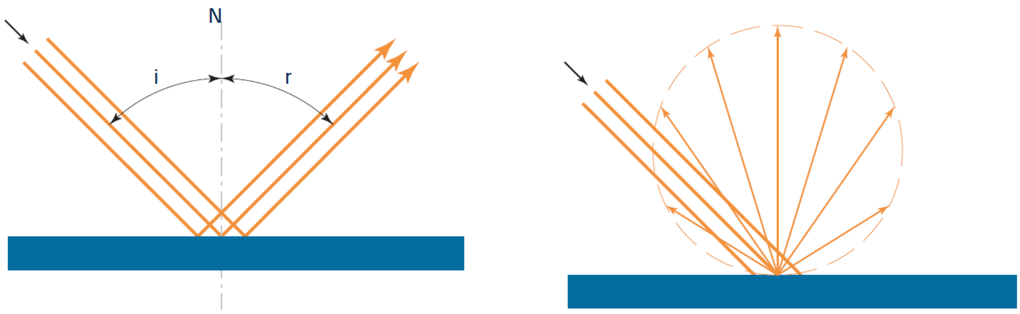

Fig. 8.6 Ideal (specular) reflection on the left and diffuse reflection (Lambert emitter) on the right side [3]

For diffuse surfaces, the relationship between their illuminance *E*, luminance *L* and surface reflectance ρ is important.

$$\pi \cdot L = \rho \cdot E \qquad (8.12)$$

If we examine the transmission of light through a material, we find that in some substances that are clear or perfectly transparent (e.g. optical glasses, thin layers of water, etc.) there is a direct transmission, where the rays passing through the substance come out in the original, though parallel shifted, direction. However, many substances partially or completely scatter the light flux passing through them. In the case of ideal uniformly scattered light transmission, the luminous intensity distribution is also governed by the cosine law. This means that the light-technical properties of such a surface are then the same as those of a diffuse reflecting surface.

In practice, however, there are neither ideal mirrors nor ideal diffusers. Mirrors in varying degrees also scatter light somewhat, and conversely, dull, faint or rough surfaces used to diffuse light have a certain mirroring effect.

The reflective and transmissive properties of fabrics have a significant effect on the total power consumption of lighting systems, especially in small indoor spaces where the reflectivity of surfaces results in an increase in illuminance on the comparison plane due to multiple reflections.

Summary of terms 8.1.

Luminance, luminous flux, illuminance, luminosity, brightness, solid angle, colour temperature, general colour rendering index, lifetime of the light source, specular reflection, diffuse reflection.

Questions 8.1.

1. Draw the dependence of information power on illuminance.
2. How is a candela defined? What is it a unit of?
3. How to calculate the luminous flux, luminous intensity?
4. Write the relations for calculating illuminance and luminous exitance.
5. What is luminous efficacy, what is its unit?
6. What is a solid angle?
7. Explain the concept of colour temperature.
8. What is the colour rendering index?
9. Explain the concept of lifetime of a light source.
10. Explain what specular reflection and diffuse reflection are.

8.2. Parameters and characteristics of luminaires and light sources

TIME TO STUDY:

3 hours

TARGET:

After studying this paragraph, you will be able to

- define the basic parameters and properties of luminaires
- define the basic parameters and properties of light sources

EXPLANATION

Luminaires

Luminaires are devices which distribute, filter or alter the light emitted by one or more light sources and contain, in addition to the light sources themselves, all the parts necessary for mounting and protecting the sources and, where necessary, auxiliary circuits, including the means of connecting them to the network.

The luminous active parts of luminaires serve to change the distribution, direction or dispersion of the luminous flux of sources, glare limitation - limitation of the luminaire brightness in the angle at which the luminaire can be perceived by the observer and filtration - removal of the unwanted part of the spectrum emitted by the light source.

The structural parts of the luminaire are used to fix the source, to fix the light-active parts, to protect the source and the light-active parts from the intrusion of foreign objects and water. The luminaires shall meet the conditions of simple and easy installation, easy maintenance, long service life and reliability and shall not be dangerous to their surroundings in terms of temperature.

Types and classification of luminaires

Luminaires can be classified according to different aspects, e.g. according to:

- use and purpose - Fig. 8.7,
- mounting type - Fig. 8.8,
- distribution of luminous flux - Tab. 8.5, Fig. 8.9.

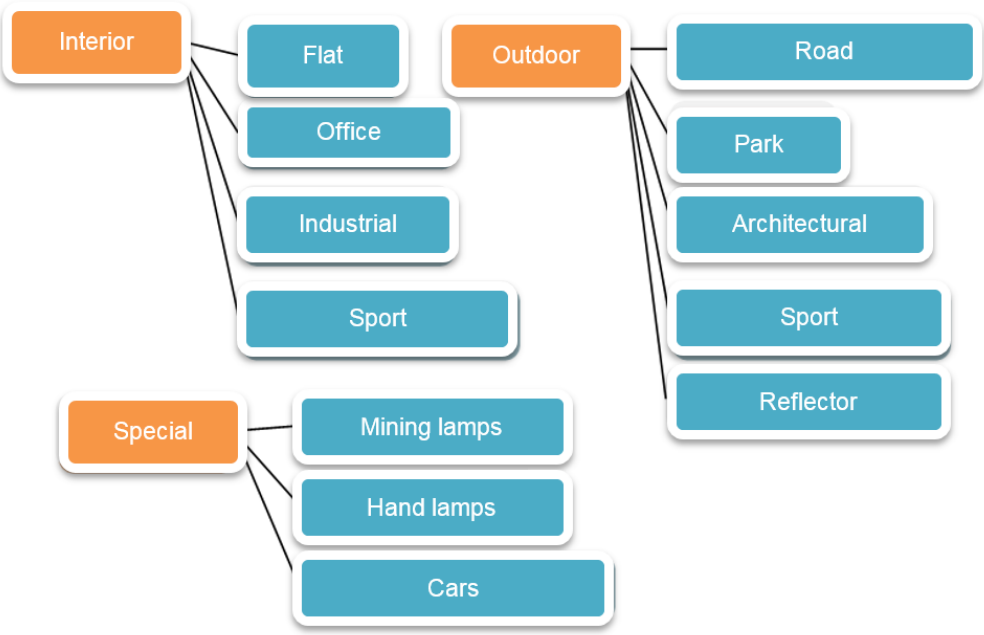

Fig. 8.7 Basic dividing of luminaires according to use and purpose

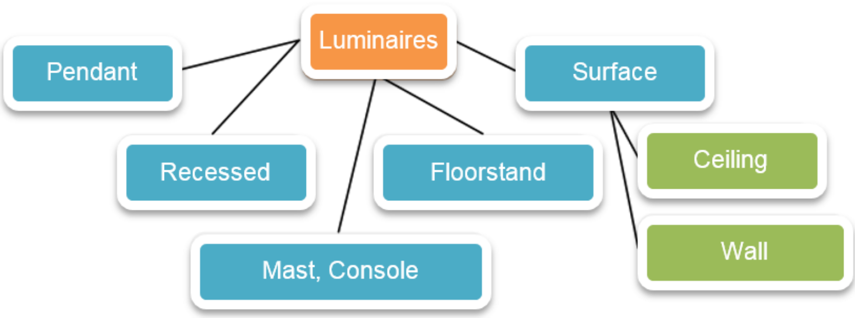

Fig. 8.8 Dividing of luminaires according to mounting type

Luminous flux distribution class	Name	Φ_{direct} / $\Phi_{overall}$
I	Direct	80 - 100 %
II	Semi direct	60 - 80 %
III	General diffused	40 - 60 %
IV	Semi indirect	20 - 40 %
V	Indirect	0 - 20 %

Tab. 8.5 Classification of luminaires according to luminous flux distribution

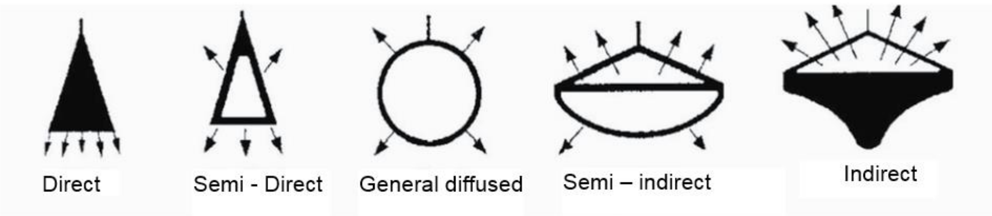

Fig. 8.9 Pictograms of luminous flux distribution

❑ Basic parameters of luminaires

Luminous flux of the luminaire

The luminous flux Φ_{SV} , which is optically treated by the luminaire, is given by the difference of the luminous flux of all light sources Φ_Z placed in the luminaire and the luminous flux lost Φ_{ZTR} , which is lost in the optical treatment.

Luminaire efficiency

The luminaire efficiency η_{SV} characterizes the luminaire's economy and its value is given by the ratio of the luminous flux of the luminaire Φ_{SV} to the luminous flux of the light sources Φ_Z according to the relation

$$\eta_{SV} = \frac{\Phi_{SV}}{\Phi_Z} \qquad (8.13)$$

The maximum efficiency in this respect should be a bare light source in a socket. However, it is not possible to use this because of glare, inappropriate direction of the emitted luminous flux and inadequate protection from environmental influences and dangerous contact. In order to maximise the use of the electricity supplied, it is necessary to achieve high values of this quantity. For conventional luminaires, the efficiency ranges from 0.5 to 0.8. For LED luminaires and high quality headlamps, it can be over 0.95.

Luminance of the luminaire

The luminance of a luminaire is defined as the ratio of the luminance in a given direction and the size of the projection of the illuminating surface in a plane perpendicular to the direction under consideration.

$$L_\gamma = \frac{I_\gamma}{A \cdot \cos\gamma} \qquad (8.14)$$

where L_γ - the luminous intensity of the beam of light (illuminating surface) (cd); A - the size of the illuminating surface visible to the observer (m^2); γ - the angle by which the visible surface is rotated from the perpendicular to the axis of view.

Shading angle

The shading angle δ indicates the degree of shading of the light source by the luminaire. It is the smallest acute angle between the horizontal plane and the line joining the edge of the luminaire to the light source. For a clear bulb it is its filament, for an opal fluorescent or discharge lamp it is the surface of the bulb.

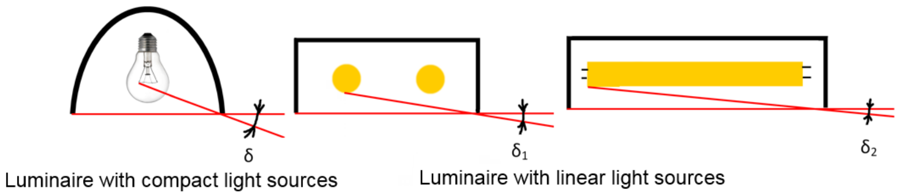

Fig. 8.10 Shading angle of the luminaire

Luminance intensity distribution curves

Luminance represents the amount of luminous flux Φ emitted into a given oriented solid angle Ω . When this angle is very small, we speak of luminance "in a given direction". For luminaires, luminance curves, which are graphs of luminance in each direction, are given. The luminous intensity is calculated according to the relationship

$$I = \frac{\Phi}{\Omega} \tag{8.15}$$

The luminance curves can be found in the luminaire catalogue sheets and provide an illustrative idea of the way the light flux spreads in the space. From the luminous flux curves it is possible to read e.g. the angle of the aperture, the direction of the maximum luminous flux, etc.

The luminosities are most often given using the C-γ photometric system. For luminaires with a rotationally symmetrical luminance surface, a curve in one photometric plane is sufficient. For fluorescent luminaires, two curves are usually given, in the C_0 and C_{90} planes. For outdoor luminaires, maximum luminance values are prescribed for given glare levels for glare prevention reasons, for certain directions in selected planes in the C-γ system. The luminance distribution of a given luminaire can also be represented by an isocandel diagram.

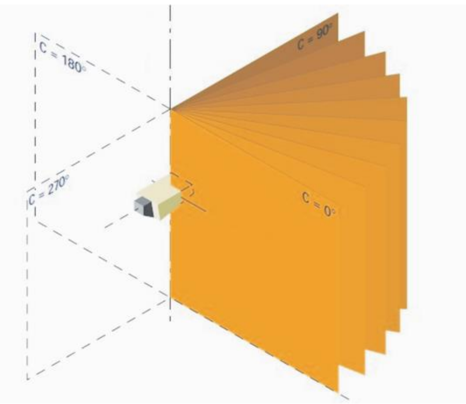

Fig. 8.11 C-γ system of measurement planes (A-α, B-β system)

Protection classes of luminaires

In terms of electrical safety, luminaires are classified into the following three classes according to Tab. 8.6.

Protection class I	Marking where the protective conductor is connected to the terminal , used for all low voltage metal luminaires
Protection class II	Marking , protection by double or reinforced insulation. Used not only for all-plastic luminaires.
Protection class III	Marking . Connection only to SELV or PELV sources, typically halogen bulbs at 12V or LED.

Tab. 8.6 Protection classes of luminaires

Construction components of luminaires

In addition to their own functions, the construction components and materials used for all types of luminaires have to meet additional requirements:

- luminous stability,
- temperature stability,
- corrosion resistance,
- mechanical strength.

Light fastness is an important variable that determines the lifetime of many materials. Permanent changes such as yellowing, whitening, embrittlement, cracking or crazing occur through constant exposure to light and ultraviolet radiation, amplified by heat and moisture.

The thermal stability of the components is of particular importance because the operating temperatures at the luminaire are often at the limits of permissibility. If these values are exceeded, permanent changes occur, e.g. deformation, embrittlement, charring and cracking.

The corrosion resistance of metals must be ensured by effective surface protection, which also affects the appearance and light-technical properties of the material. In order to meet the permissible conditions of use, the required light-technical parameters and aesthetic requirements, the following surface treatments are used: painting, nickel plating, chrome plating, enamelling, galvanising, cadmium plating, plastic coating, polishing and anodising. The corrosion resistance of plastics is guaranteed and therefore does not require additional measures.

Mechanical strength is a measure of the stability of structural components, especially in plastics and quartz glass. Radiation, heat, cold and humidity can change the mechanical strength and thus the reliability of the luminaire.

The structural elements are divided into three groups:

- light-technical (light-active),
- electrical engineering,
- mechanical.

The reflective materials used for the light-emitting parts are:

- glass mirrors,
- painted surface areas,
- opal light-scattering glass,
- plastics or fabrics.

For permeable materials in the light-emitting parts of luminaires the following are used:

- quartz glass (clear glass, cathedral glass, opal glass, frosted glass, refractor glass),
- light-transmitting plastics,
- light-transmitting fabrics.

Luminous active parts serve to direct the light flux coming from the luminaire, i.e. to adjust the luminous intensity curve, to reduce glare and to filter the light flux. The quality of the optical system determines the parameters of the whole luminaire, especially its efficiency.

Electrical parts luminaires are used for connection, fixing and operation of light sources and luminaires. These include: bulb sockets, switches, sockets and forks, internal wire leads, external leads, connecting and interconnecting terminals, luminaire boxes, ballasts, igniters and capacitors. The individual parts shall correspond to the light sources used. The use of different light sources changes the connection conditions.

Mechanical parts of luminaires serve as protective or supporting parts of light sources and light-technical and electrical construction elements. The essential structural parts of luminaires which are counted among the mechanical structural elements are: protective glass, protective grille, support structure, focusing devices, hinges, fixing parts, forks, joints and stands for luminaires for local lighting. As the different parts have very different meanings and are subject to different loads, different materials are used. The luminaires must have the necessary mechanical strength and be corrosion-resistant, meet the prescribed temperature tests and be electromagnetically compatible.

❑ Options for increasing the efficiency of luminaires

The efficiency of luminaires can be increased in two ways:

- by increasing the efficiency of the optical parts,
- by reducing losses in electrical parts.

Basic principles of luminous flux direction

In most luminaires, the principles used to direct the luminous flux of light sources are according to Fig. 8.12.

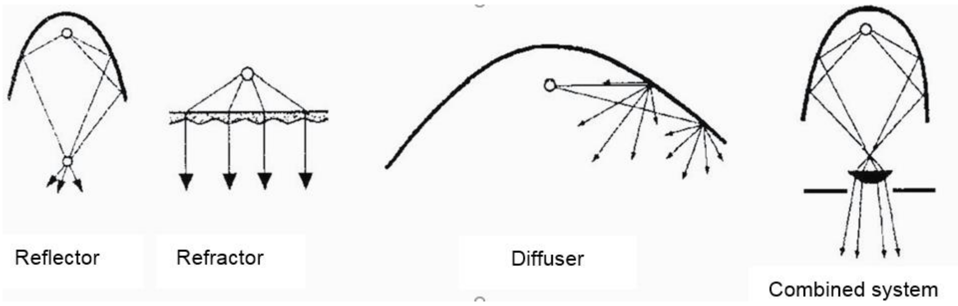

Fig. 8.12 Basic types of light-active surfaces

Reflector changes the distribution of the light flux by means of mainly mirror reflections. Aluminium alloys coated with metals with a silver admixture with a mirror finish are used for the production of reflectors. Such reflectors are the best choice in terms of achieving superior luminaire performance because they achieve efficiencies of up to 95 %.

Refractor changes the distribution of light flux according to the optical law of refraction. Refractors for luminaires are most often made of glass, PMMA (polymetalacrylate), polystyrene or other plastics.

Diffuser diffuses the light flux by reflection or transmission and emits the light flux as a uniformly diffusing surface; diffusers with diffuse reflection and diffuse transmission are distinguished.

❑ Light sources

Light sources are an essential element of lighting systems. Of the artificial light sources, the most important are those powered by electricity, i.e. electric light sources. The quality and cost-effectiveness of the lighting system depends largely on the correct choice of light source.

The parameters of light sources can be divided into **quantitative** and **qualitative**:

- The basic quantitative parameters that describe the characteristics of light sources are luminous flux, power input and specific power, see chapter 8.1. In addition to these, the geometrical dimensions, the type of socket used, the permissible operating position of the light source, the voltage, the operating temperature of the source, etc. are also important.
- The quality of light sources is assessed by lifetime, replacement colour temperature, colour rendering index and stability of light technical parameters.

Important properties include geometric dimensions, shape, weight, distribution and adjustability of luminous flux, acquisition and operating costs.

The stability of light technical parameters is related to the operating characteristics of light sources. It is a time dependence that can be defined as fast or slow:

Rapid changes are changes in parameters such as luminous flux depending on the supply voltage at a frequency of 50 Hz. The luminous flux fluctuates at twice the frequency and the depth of fluctuation depends on the inertial properties of the light source. This phenomenon can cause a stroboscopic effect, which becomes a dangerous issue in some operations, especially those with rotating machinery. Other rapid changes include changes in luminous flux as a function of fluctuations in the effective voltage value. This fluctuation is caused by the operation of some appliances such as electric arc furnaces. In particular, fluctuations in the light flux in the frequency range of 8 to 12 Hz have a disturbing effect on visual perception. Incandescent lamps are the most sensitive to voltage fluctuations. Rapid changes also include changes in parameters related to the light source's start-up after switching on to the mains. Incandescent lamps charge almost instantaneously, whereas the parameters of discharge lamps settle down after a few minutes.

Slow changes mean the dependence of the light source parameters on static voltage changes, which is expressed by cross characteristics. Slow changes also include parameter changes due to ageing of the light sources. During their lifetime, the luminous flux decreases. For example, for incandescent lamps the luminous flux decreases to 90 % after 1000 hours of operation. Discharge lamps are required not to drop below 70 % of their rated luminous flux after their lifetime.

In general, electric light sources can be divided into three basic groups (Fig. 8.13), namely:

- thermal (incandescent and halogen lamps),
- discharge (fluorescent or discharge lamps),
- light emitting diodes (LEDs).

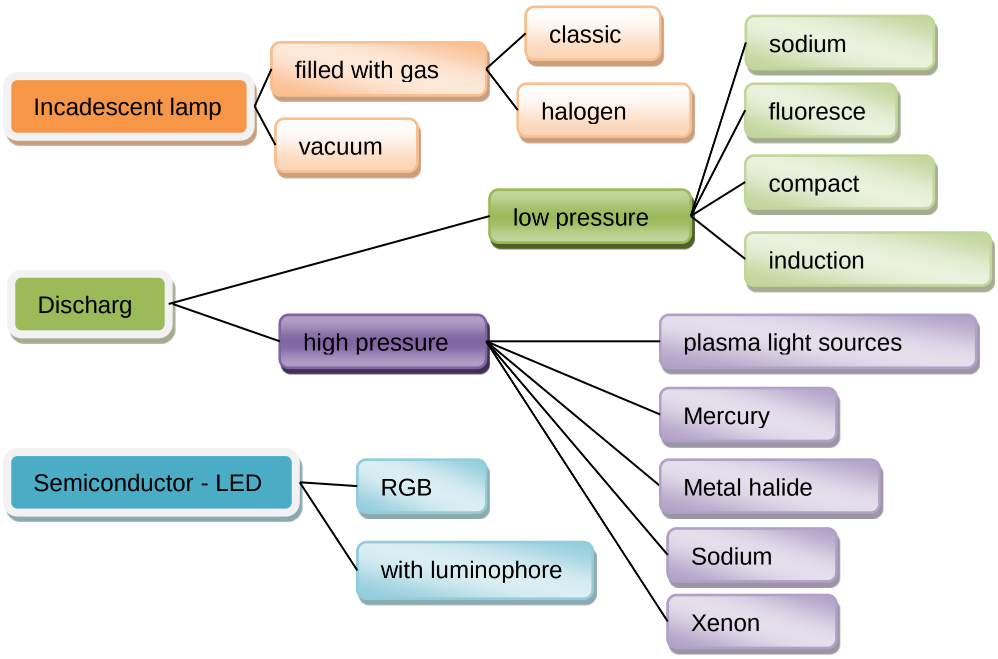

Fig. 8.13 Electric light sources

In **incandescent lamp**, a conductive substance (metal) is heated to a high temperature by the passage of an electric current and this substance emits optical radiation as a result of thermal motion.

Discharge light sources are based on the principle of electrical discharges in gases and vapours of various metals and use the conversion of electrical energy into kinetic energy of electrons, which is converted into optical radiation when they collide with gas atoms.

Light emitting diodes (LEDs) work on the principle of emitting energy in the form of photons when electrons spontaneously return from the excited state to the ground energy state.

Fig. 8.14 shows the luminous efficacy of the sources. These dependencies show a very important property of light sources, namely the rate of conversion of the electrical energy consumed into the luminous flux emitted. For each type of light source, the luminous efficacy are shown from the time of beginning of production to the present day.

Bulbs

The advantages of incandescent lamps include their simple design, small size and weight, simple power supply, low cost, instant start, stable illumination during their entire lifetime, continuous spectrum, colour rendering index CRI = 100, wide range of wattages and voltages, independence of ambient temperature and the fact that they do not contain substances that would place an enormous burden on the environment. The disadvantages of incandescent bulbs are their low lifetime, low specific power and the significant dependence of the parameters on the stability of the power supply - a 1 % change in voltage results in a 3.6 % change in specific power.

An electric current passes through the resistance filament of a tungsten bulb, losses occur and the electrical energy is first converted into heat - the filament heats up. The filament heated to a high temperature becomes a source of radiation. The principle of incandescent lamps shows that up to 95 % of the electrical energy supplied is converted into heat (dissipated by radiation in the infrared part of the spectrum, by conduction and convection) and only the remaining 5 % is converted into visible light radiation. Although incandescent bulbs are very wasteful, they are still popular and have applications especially where the light is short.

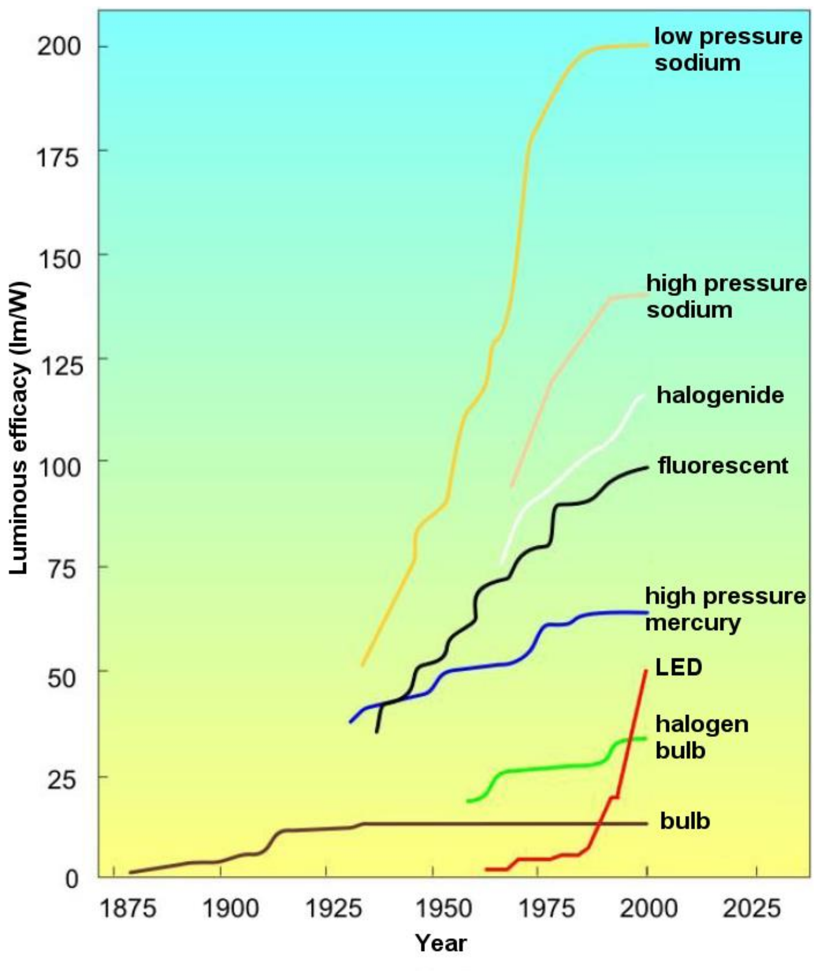

Fig. 8.14 Evolution of the luminous efficacy of light sources

The bulbs are produced in different variations of bulb shape (plain, candle, spherical, shaped, linear), bulb surface treatment (clear, matt, opal, reflector, coloured) and the value of the supply voltage or the type of socket.

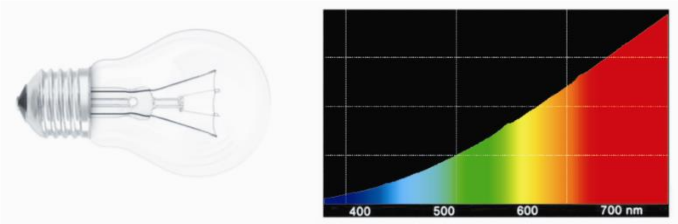

Fig. 8.15 Bulb and its spectrum

Halogen bulbs

The principle of operation of halogen lamps is similar to that of ordinary incandescent lamps. The improvement is the filling with an admixture of halo elements (J, Br, Xe) in the internal environment of the bulb. In an ordinary bulb, tungsten gradually evaporates from the heated filament and deposits on the inner surface of the bulb. The bulb gradually turns black and transmits less light. When the tungsten evaporates above a critical point, the too-thin filament burns out.

Vaporization of tungsten helps to prevent the pressure of the filling gas. The longer life is also due to the halogen cycle running in the bulb. The vaporized tungsten combines with the halogen at a lower temperature at the bulb wall to form halide, which chaotically returns to the filament due to the temperature field, where it decomposes due to the filament temperature. The tungsten deposits on the filament and the halogen returns to the surface of the flask and the cycle repeats.

Advantages of halogen bulbs over conventional bulbs:

- the bulb does not blacken and has a stable luminous flux throughout its lifetime,
- higher specific output, up to 26 $lm \cdot W^{-1}$,
- longer service life,
- high resistance to temperature changes,
- higher colour temperature,
- small flask diameter (higher gas pressure, lower tungsten evaporation rate).

The bulbs of modern halogen lamps are covered with a selective filter (IRC technology) that returns part of the infrared radiation back to the filament. The specific power is thus increased by up to 25 %.

In practice, halogen bulbs are most often used for low voltage, often already as a complete set with a small reflector.

Fluorescent lamps

Fluorescent lamps are low-pressure mercury lamps that emit mainly in the ultraviolet region. This is transformed into visible radiation by a phosphor. The principle of fluorescent lamps is as follows. In a glass tube, mercury vapour is excited by the electric field between the electrodes, in which invisible UV radiation is emitted. A special substance, the luminophoredeposited luminophore on the inner surface of the glass tube, converts the invisible UV radiation into visible light. By choosing the luminophore, it is possible to influence the spectrum of light emitted by the fluorescent lamp.

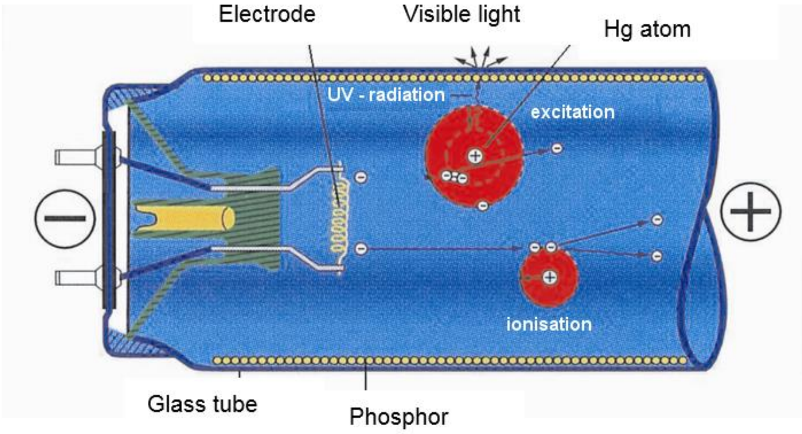

Fig. 8.16 Principle of fluorescent lamp function

Like all lamps, fluorescent lamps cannot do without ballasts. When the discharge is lit, the voltage at the fluorescent lamp is lower than the mains voltage. If a magnetic ballast is used, a voltage drop is created on the ballast which limits the current flowing through the fluorescent lamp; if an electronic ballast is used, the fluorescent lamp current is controlled by electronic circuits.

T5 type fluorescent tubes have a tube diameter of 16 mm and are shorter than the standard T8 tube with a diameter of 26 mm. They offer a higher specific output, up to 104 $lm \cdot W^{-1}$ and, are designed for operation with electronic ballasts only. T5 fluorescent tubes achieve savings over T8 fluorescent tubes in the following areas:

- higher specific output of T5 fluorescent lamps with electronic ballast,
- higher luminaire efficiency due to 40% lower shading of the slimmer fluorescent lamp,
- with T5 fluorescent lamps it is possible to construct more subtle luminaires, which results in further material savings.

The lifetime of fluorescent lamps is strongly influenced by the number of times they are switched on. Therefore, they are not suitable where frequent switching on and off occurs. The lifetime of fluorescent lamps also varies according to the mode of operation. When operated with a conventional ballast, the lifetime of the fluorescent lamp is around 10 000 h, while when operated with an electronic ballast it is around 18 000 h.

Fluorescent lamps are produced in a wide range of replacement colour temperatures from 2 700 to 8 000 K and with a colour rendering index of 60 - 98. There are also special fluorescent lamps with extended service life up to 75 000 h or with a modified spectrum for plant cultivation, animal husbandry and others.

Fig. 8.17 T8 linear fluorescent lamp and its spectrum

Compact fluorescent lamps

Compact fluorescent lamps are identical in principle to linear fluorescent lamps. However, their tubes are bent or curved to achieve more compact dimensions. Compact fluorescent lamps are available with or without an integrated electronic ballast (which is built into the luminaire). There are also dimmable 12 V versions for use in low voltage island systems and caravans. The specific output of compact fluorescent lamps is lower (maximum approx. 88 $lm \cdot W^{-1}$) and this is due to the inherent shielding of the tubes and socket etc.

Unlike incandescent lamps, where the luminous flux reaches its rated value almost immediately, fluorescent lamps reach their rated value after about 3 minutes of operation. Fluorescent lamps are also very temperature dependent and therefore not suitable for outdoor lighting.

Electronic ballast for compact fluorescent lamps provides:

- instant start without flashing,
- resistance to frequent switching,
- longer lifetime,
- elimination of strobe effect and fluctuation of light flux.

Induction lamps

Induction lamps, like fluorescent lamps, are low-pressure mercury lamps. Unlike fluorescent lamps, they have no electrodes and use a high-frequency electromagnetic field produced by the coil(s) to ignite and burn the discharge. They are used exclusively with an electronic ballast.

Advantages of induction lamps:

- long service life, more than 60 000 h (no electrode burn),
- small loss of luminous flux during the illumination period,
- fast luminous flux rise after switching on or restarting and, unlike high-pressure discharge lamps, the possibility of immediate reignition,
- High luminous efficacy up to 93 $lm \cdot W^{-1}$.

Induction lamps are used in areas with high demand for replacement of light sources (lighting of tunnels, industrial halls, bridges, etc.). As the dimensions of most induction lamps are relatively large, the efficiency of luminaires changing the spatial distribution of the luminous flux is low due to the absorption of part of the luminous flux by the light source.

Fig. 8.18 Osram Endura (coils around the perimeter) and Philips QL (coil inside the bulb)

High pressure mercury lamps

The visible radiation is produced by arc discharge in mercury vapour at a pressure of 0.1 MPa in a quartz glass discharge tube. High-pressure mercury lamps emit directly in the visible region about 15 % of the energy input and their light is blue-white to blue-green. The UV radiation, mainly at 365 nm, has to be transformed into the visible region using a phosphor. The main electrodes consist of a tungsten wire covered with an emissive layer of barium oxide, strontium and calcium.

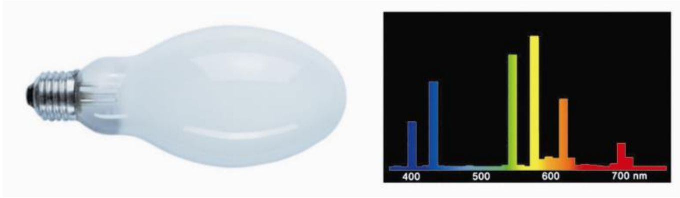

Fig. 8.19 Mercury lamp and its spectrum

The red component of the light is missing and for this reason an orthophosphate phosphor is applied to the inner wall of the outdoor flask to ensure the transformation of the remaining UV radiation into the red region of the spectrum. It takes 3-5 minutes for the mercury discharge to stabilise. After the discharge is interrupted, re-ignition occurs after 7 minutes. The advantage of these lamps is a small decrease in luminous flux during lifetime, resistance to temperature changes and shocks. Lifetime is 12 000 to 15 000 h, colour rendering index CRI = 60, specific output 50 to 80 $lm \cdot W^{-1}$. Discharge lamps are not suitable for indoor lighting due to low R_a and longer re-fire times. High pressure sodium lamps with higher specific power have displaced them from lighting industrial areas, streets and sports grounds. De facto, they have already been replaced in all areas of their use by other light sources (better quality, more efficient) and are no longer installed in new lighting systems. Mixed discharge lamps, light sources combining an incandescent lamp with a mercury vapour lamp that do not need a ballast, are still in use today.

Low pressure sodium lamps

In low-pressure sodium discharge lamps, the primary discharge occurs in a discharge tube made of boron glass, in argon gas and neon. The discharge has a classic neon colour. Only after a certain period of time, when the sodium is in the gaseous state at a sodium vapour pressure of 0.5 Pa and a discharge tube wall temperature of about 300 °C, is monochromatic radiation emitted in the 589 and 589.6 nm wavelength bands - in the yellow part of the spectrum. The radiation of the sodium lamp is close to the maximum spectral sensitivity of the human eye, which is why its specific power is 130 to 200 $lm \cdot W^{-1}$. In their light it is not possible to distinguish colours (CRI = 0), the lifetime of the discharge tube reaches up to 24 000 h. The discharge tube of sodium lamps has a circular cross-section and bends into the shape of the letter U or W. The outer bulb thermally insulates the discharge tube, is simple and exhausted to a high vacuum.

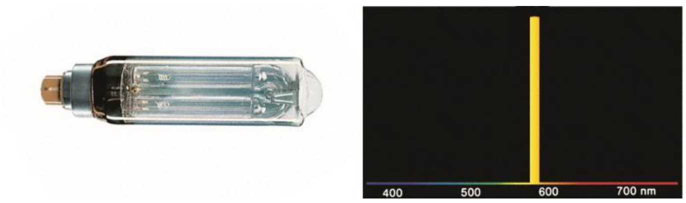

Fig. 8.20 Low pressure sodium lamp and its spectrum

Despite considerable progress and improvements in their performance, their use has been limited to road and highway lighting due to very poor colour rendering. Today they are mainly used in the Benelux countries and in the UK. In our country, with rare exceptions, low-pressure sodium discharge lamps have not found much use and, given the ever-improving parameters of high-pressure sodium discharge lamps, their further spread is not envisaged.

High pressure sodium lamps

The discharge in sodium vapour is characterised by an intense resonant doublet as in a low pressure sodium vapour discharge in the yellow part of the visible spectrum with wavelengths of 589.0 and 589.6 nm. These characteristics have been used since the 1930s in the design of low-pressure sodium lamps. As the volume of the discharge space decreases, the pressure of sodium vapour increases, reaching a maximum at a pressure of about 27 kPa and depending on other parameters (composition of the sodium amalgam, type and pressure of the filling gas, geometrical parameters of the burner, input power of the discharge lamp, etc.) luminous efficacy can reach up to 150 $lm \cdot W^{-1}$. The discharge space of this source must be made of polycrystalline or monocrystalline alumina (synthetic corundum). As the sodium vapour pressure increases, the spectral emission is significantly broadened and strong continuous radiation is produced, while at the same time resonant radiation is absorbed. As the pressure increases, the radiation in the long-wave part of the spectrum increases and the spectrum of radiation becomes richer, resulting in better colour rendering of the illuminated objects. This type of discharge is used in modern high-pressure sodium lamps, which have made a significant impact especially in public lighting.

The range of high-pressure sodium lamps is very wide, with wattages ranging from 50 to 1000 W. The colour rendering index of these lamps is around 25. The discharge lamp does not allow a warm re-ignition and can only be lit after it has cooled down. It takes about 5 minutes to reach its rated luminous flux. There is no fluctuation in luminous flux over the outdoor temperature range.

High pressure sodium lamps must be operated in a circuit with a choke and suitable ignition device. When the operating conditions are observed (permitted voltage fluctuations of less than 5%, properly sized chokes), lamps from leading manufacturers achieve a lifetime of up to 30 000 h. The end of life is due to a gradual increase in discharge voltage. When this voltage exceeds a certain ratio to the mains supply voltage, the discharge goes out. After cooling, the discharge is reignited and the cycle repeats. Periodic extinction of the discharge lamp is a sign of end of life and the lamp must be replaced.

Fig. 8.21 High pressure sodium lamp and its spectrum

High-pressure sodium lamps have brought significant electricity savings to lighting practice, which is why the share of high-pressure sodium lamps in public lighting is dominant. High-pressure sodium lamps have universal use in public lighting: they are suitable for illuminating all roads, pedestrian areas and the facades of buildings. A certain disadvantage of these sources is the inferior colour rendering of the illuminated objects. Sodium high-pressure discharge lamps of low wattage are used for VO, 50-70 W in villages, up to 150 W in towns, 150-250 W, on large roads (250 - 1 000 W).

Halide lamps

Visible radiation is produced here both in mercury vapour, but mainly by the radiation of halide products (90 % of the radiation), i.e. compounds of halide elements with e.g. gallium, thallium, sodium, etc. This leads to an increase in colour rendering index up to CRI = 90 and luminous efficacy up to 130 $lm \cdot W^{-1}$.

In a quartz or ceramic burner, a cycle similar to the regeneration cycle of halogen bulbs is created. The outer bulb is made of borosilicate glass. Halogen lamps operate at an outdoor temperature of -20 to 60 °C. The lifetime of these lamps is up to 15 000 h.

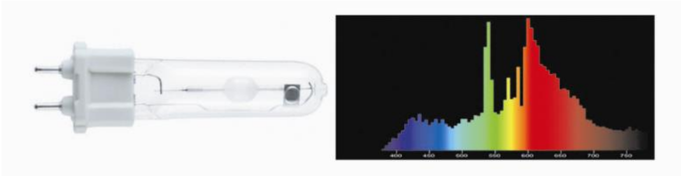

Fig. 8.22 Halide lamp and its spectrum

Halogen lamps require a lighter. The power range starts at 35 W and ends at 3,500 W, the lamps are produced with different bulb shapes and socket types. The lamp takes about 10 minutes to charge to its rated parameters, depending on size and wattage. Despite the high price, halogen lamps are becoming popular especially where there are high requirements for colour rendering. Halogen lamps of smaller wattages are used in the illumination of shop windows and commercial premises, museums and exhibition halls. Larger wattages are used in the lighting of exhibition centres, sports grounds, transport hubs and in industry.

Xenon lamps

Xenon lamps are high-pressure lamps used today mainly in automotive headlights or in projection and lighting technology. Xenon lamps need a high voltage pulse (over 20 kV) to ignite the discharge The operating voltage at the discharge is about 85 V / 100 Hz for most types of automotive lamps, so a special inverter is needed to connect them. Discharge lamps for lighting in lighting technology are usually tubular, can have an input power of up to 10 kW and are cooled by air or water. The replacement colour temperature is most often in the range of 4 000 - 12 000 K and the emission spectrum is similar to daylight, the luminous efficacy is up to 95 $lm \cdot W^{-1}$ and lifetime about 2 500 h.

Light emitting diodes - LEDs

In recent years, LEDs have been increasingly used in all areas of lighting technology. Their widespread use is mainly due to their increasing luminous efficacy. LEDs are an electronic ballast that generates light radiation when a current passes through a semiconductor junction. It therefore uses a different physical principle than incandescent or discharge lamps and has many characteristics that distinguish it from previous conventional light sources. The semiconductor junction emits a very narrow spectrum. The primary radiation is essentially monochromatic. LEDs are already a highly efficient light source that is gaining ground in place of conventional light sources. LED technology has great potential for future development.

LEDs can be divided into 3 categories:

- SMD LED (indication) - computers, cars, mobile phones, orientation lighting
- Classic LED (signalling) - indicator lights, third brake lights of automotive, advertising, orientation lighting
- Power LED (lighting) - traffic signalling, illumination, entertainment industry

Generate white light using LEDs is possible in principle in two ways:

- **mixing monochromatic LEDs** - white light can be obtained by mixing several complementary wavelengths of a certain power ratio. Mixing can be done depending on the light quality requirements. Mixing two wavelengths will produce a dichromatic source. Mixing three monochromatic LED emitters (e.g. RGB) produces a trichromatic light source. Increasing the number of monochromatic components increases the colour quality of the resulting white light.
- **wavelength converter** - when primary radiation is emitted at a shorter wavelength (most often in the blue range), part of the light is absorbed in the converter material

and re-radiated as light radiation with a longer wavelength. The most commonly used wavelength converters are phosphor-based.

A typical representative is a white LED based on a blue LED chip (GaInN/GaN) and a phosphor converter. The radiation in the visible range that is emitted from the semiconductor is blue. Part of the light is distributed directly to the observer and part of the short-wavelength photons are absorbed in the encapsulation space (phosphor layer) and re-emitted with longer wavelengths in the yellow spectrum. The emitted spectrum consists of luminescence of blue light and phosphorescence of yellow light. By adjusting the relative ratio of luminescence and phosphorescence, not only the replacement colour temperature but also the specific power (decreases with increasing T_C) and the colour rendering index (increases with decreasing T_C) can be optimised.

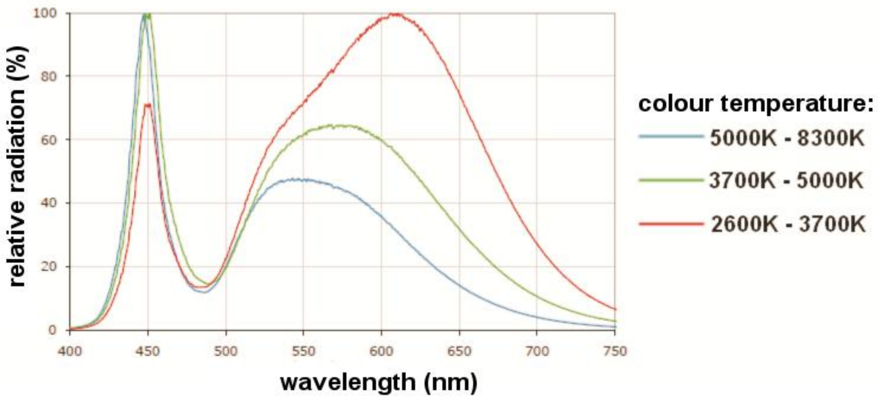

Fig. 8.23 White LED and typical spectra of LEDs with phosphor luminophore

At Fig. 8.23 shows typical spectra of white LEDs. LEDs are currently still under development and their luminous efficacy is still increasing. When development is complete, the luminous efficacy of these lamps is expected to be above the 200 $lm \cdot W^{-1}$ level (Fig. 8.24). Due to the minimal occurrence of red in the emitted spectrum, achieving a high colour rendering index appears to be one of the main challenges for LEDs. However, current technologies make it possible to achieve CRI better than 90.

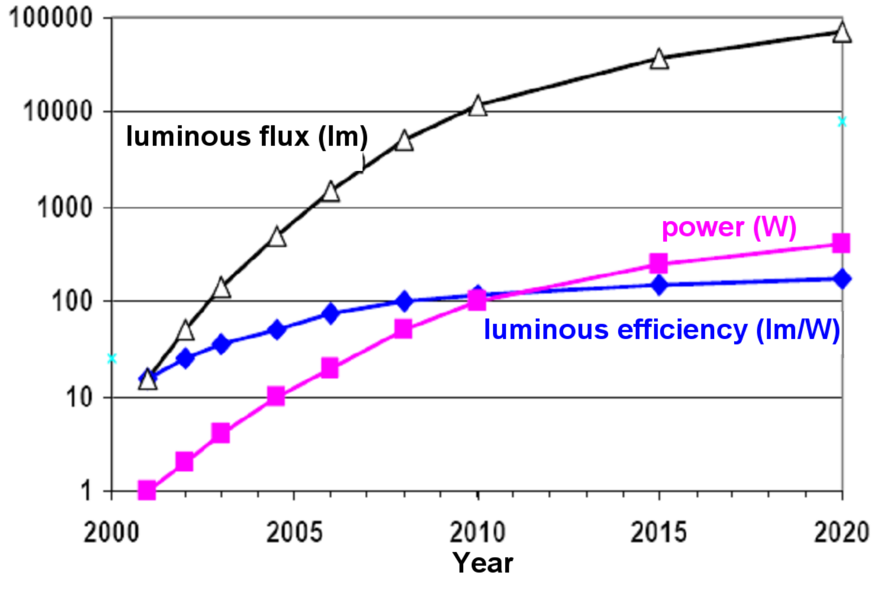

Fig. 8.24 Graph showing the evolution of LED parameters in the time

The biggest problem with LEDs at the moment is heat dissipation from the PN junction area. For this reason, individual sources are in the wattage range. Another problem associated with heat dissipation from the PN junction is the reduction in luminous flux and lifetime with increasing junction temperature. In contrast, LEDs have significant advantages over conventional light sources in terms of easier routing and faster luminous flux rise, mechanical robustness and lifetime independence from switching and dimming. A small DC voltage is used for power supply. LEDs are current controlled due to their volt-ampere characteristic.

Note

Throughout the chapter 8 uses verbatim quotations, figures and tables from the literature [4]. Additional information on the issues addressed in this chapter can be found in this book.

Summary of terms 8.2.

Luminaire, light source, shading angle, luminance curves, reflector, refractor, diffuser.

Questions 8.2.

1. What is the efficiency of the luminaire, in what range is it?
2. How do we sort luminaires according to their luminous flux distribution?
3. What are the possibilities to increase the efficiency of luminaires?
4. List the basic principles of light flux direction.
5. Explain the principle of increasing the luminous flux of a halogen bulb compared to a conventional bulb.
6. Explain the principle of light in a linear fluorescent lamp.
7. How does a compact fluorescent lamp differ from a linear fluorescent lamp?
8. Explain the function of the electronic ballast of a compact fluorescent lamp, what does it provide?
9. What does the spectrum and specific power of a low and high pressure sodium lamp look like?
10. What spectrum do LEDs emit?
11. Can LEDs emit across the entire visible spectrum? Explain.
12. What limits the maximum power consumption of LED luminaires?

ADDITIONAL RESOURCES 8

[1] Sokanský K. et al.: Rationalization in outdoor lighting, CSO RS Ostrava , 2005

[2] Habel, J. et al.: Lighting technology and illumination. Prague: FCC PUBLIC, 1995. p. 37. ISBN 800-901985-0-3

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[6] EN 12665. Light and lighting - Basic terms and criteria for determining lighting requirements. 2003

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9. PROJECT

TIME TO STUDY:

3 hours

TARGET:

After working on this project you will be able to

- calculate the cost of electricity consumed by your household
- suggest the most advantageous electricity provider

EXPLANATION

Project assignment

Make a proposal to the electricity provider or change it. Base this on your invoice for the previous period. Your task is to compare:

a) this year with last year,

b) different providers (minimum 2).

In both cases, assuming that consumption in the periods compared is the same. A list of providers can be found here https://www.elektrina.cz/dodavatele-elektriny/. Of course, you can choose any provider, but you will fulfill the assignment if you consider only the dominant ones: ČEZ, E.ON, PRE, innogy, MND energie, Ltd., Centropol.

For comparative calculations use the Price Calculator of the tzb-info portal or the ERO:

https://kalkulator.tzb-info.cz/

https://eru.gov.cz/srovnavace-kalkulatory

The project will include tables from the "Price Calculator" and an evaluation. If you will be submitting the project electronically, please title the document VueeRok_Login_Surname. Enter the completed project into the LMS system.

Which part of the final invoice is affected by the change of supplier and which part is affected at all?

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[1] https://www.kalkulator.cz/energie

[2] https://www.srovnejto.cz/energie

SOLUTION KEY

Using the Solution Key

The correct answers can be accessed by:

- press Ctrl + click on page number, figure, table, equation - go to the beginning of the answer to the question
- by opening the bookmark list Shift+Ctrl+F5, selecting a specific question in the list and pressing the **Go To** button. Unlike using the cross-reference in the previous point, the entire answer is highlighted in the text at the same time.

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SOLUTION KEY 2.4.

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Transformation of the structure and content of higher education at VŠB-TUO

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