Power Plants (part 1)

Radomír Goňo

VŠB - Technical University of Ostrava

Faculty of Electrical Engineering and Computer Science

Ostrava 2014

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

This study material was created within the framework of the project

Central European Energy Institute - CZ.1.07/2.2.00/28.0256

1. BASIC POWER PLANT CONCEPTS, THERMAL CYCLES

Study Objectives

- **To get acquainted with the basic concepts of power plants**
- **Understanding fundamental thermal cycles**

Keywords

Power, reserve, own use consumption of power plant, energy efficiency, daily load diagram, Carnot cycle , Brayton cycle, Clausius-Rankine cycle, steam-gas cycle

Required study time

120 minutes

Text to Be Studied

Introduction

Energy is, to put it very simply, a fundamental quantity of the physical world. Societal development is subject to quantitative and qualitative chronological changes of energy flows, which man tries to regulate. The acquisition, transformation and transport of energy, especially electrical and thermal energy, is the subject of inquiry of the scientific field of Energetics. This introductory chapter serves as the "initiation" of the reader into the basic concepts of this field of study and the understanding of the fundamental energy cycles that are used in energetics.

1.1 Basic power plant concepts

Power – time-independent concept [kW], [MW]

Load – varies from 0 - P_{max}

P_N* – *rated power – the greatest power that can be permanently supplied while in compliance with the nominal values of its parameters. Machines are designed for it, but the best parameters, e.g. efficiency, are not necessarily achieved with it.

P_{max}* – *the maximum power output that the equipment can be burdened (overloaded) with for a certain period of time.

- *Optimal power* – power at which the equipment achieves the highest efficiency.

- *Technical minimum* – the smallest power output which will still not damage the equipment.

P_i – ***installed*** – is equal to the sum of the rated power of all equipment.

P_d – ***achievable*** – power output when all machines are running.

P_p – ***ready*** – Highest achievable active power based on the operating conditions and is given by the current conditions – on technical grounds.

- *Quarter-hour power* – the arithmetic average in 15 minutes.

- *Medium load*
$$P_{stř} = \frac{1}{T_0}\int_0^T P(t)dt = \frac{A_{SV}}{T_0} \text{ [W]} \tag{1.1}$$

A_{SV} ….. Gross power output including own consumption

T_0 ……. Load duration

$P_{stř}$ …….. permanent constant load for the duration T_0 as during variable load

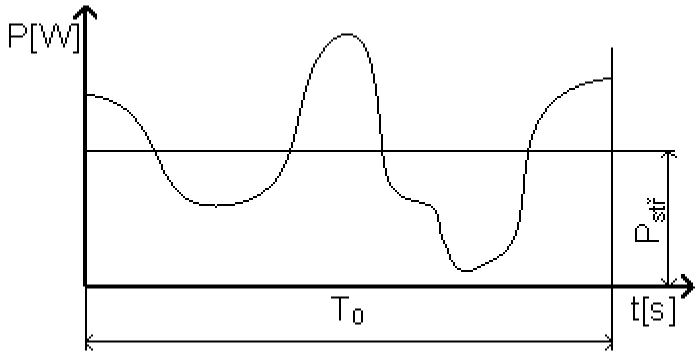


Fig. 1.1 Medium load determined from immediate load in a giving time interval

Reserve:

- ***spinning (immediate)*** – it is the sum of the differences between immediate and a rated power of all equipment. Reaction in 5 to 30 seconds, it is activated in primary regulation
- ***warm (minute)*** – the boiler in operation Reaction within 15 minutes
- ***cold (hour)*** – the machines at rest Reaction in 1 to 5 hours

Own use consumption of power plant

- The quantity of electric energy consumed by a power plant during the technological process without considering losses

- ***Coefficient of own use consumption***

$$k_{VS} = \frac{A_{VS}}{A_{SV}} \cdot 100 \qquad [\%] \tag{1.2}$$

- Nuclear 15%
- Thermal 10%
- Water (at least)

Duration of installed power utilization (per year or T_0) – has an impact on the production costs of electricity

$$T_i = \frac{A_{SV}}{P_i} \qquad [h/T_0; kWh/T_0; kW] \tag{1.3}$$

Energy efficiency – the basic balance for power equipment

$$\sum P_{vstup} = \sum P_{využ} + \sum P_{ztrát} \tag{1.4}$$

$$1 = \frac{\sum P_{využ}}{\sum P_{vstup}} + \frac{\sum P_{ztrát}}{\sum P_{vstup}} \tag{1.5}$$

$$1 = \eta - \sum \xi \quad \Rightarrow \quad \eta = 1 - \sum \xi \tag{1.6}$$

η ….. Efficiency of the energy system

$\Sigma\xi$ ... The sum of the relative energy losses of the system

Daily load diagram

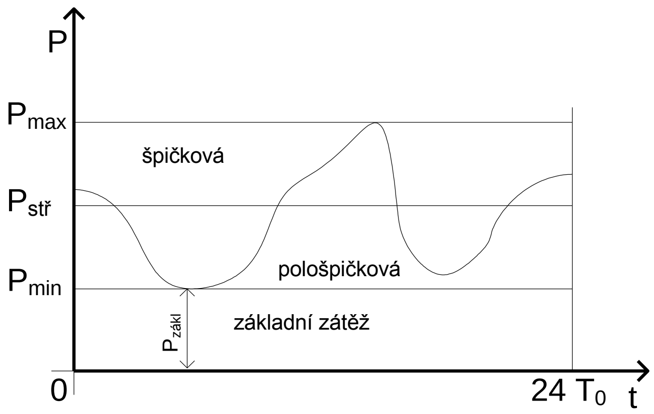


Fig*. *1.2 Daily load diagram

Load duration diagram

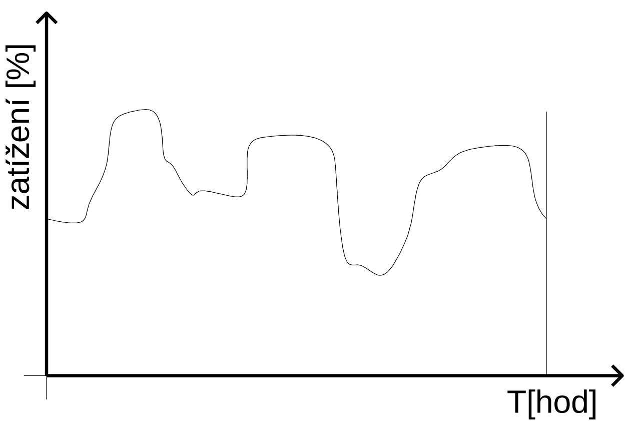


Fig*. *1.3 Load duration diagram

1.2 Thermal Cycles

The thermal cycle is formed by a number of changes in a certain system, after which the system gets to its original state. These changes are represented by a closed curve in a p-v diagram. If all the changes are reversible, the cycle is illustrated by a closed curve also in the diagram T-s and the reversibility of changes requires:

- That the second law of thermodynamics $dQ = T \cdot ds$ applies to the changes
- That changes proceed infinitely slowly
- That changes proceed during stationary flow without resistance

Irreversibility of changes arises by changing the speed of the flow, changing the mass of the working substances through irreversible changes in the physical state, etc. Real cycles are always irreversible. A return cycle can be assigned to each actual cycle, arising from the actual cycle while ignoring all losses, the so-called comparison cycle. The comparison cycle coefficient expresses the ratio of thermal efficiencies of a real cycle η_{t0} and the comparison cycle η_{tp}:

$$\nu = \frac{\eta_{t0}}{\eta_{tp}} \tag{1.7}$$

Carnot cycle

The Carnot cycle is made up of four reversible changes of the working substance:

- 2-3 By isothermal expansion when the heating body temperature is T_1
- 3-4 By adiabatic expansion when the temperature drops from T_1 to T_2
- 4-1 By isothermal compression when cooling body temperature is T_2
- 1-2 By adiabatic compression between temperatures T_2 and T_1

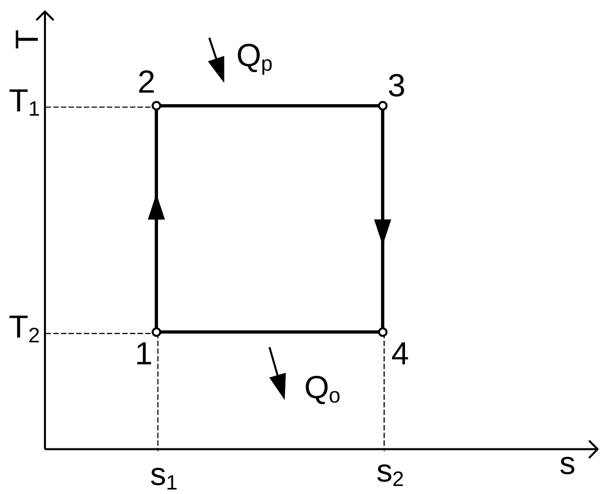


Fig. 1.4 The Carnot cycle

Heat Q_p is fed into the system during isothermal expansion and heat Q_o is discharged during isothermal compression.

$$\eta_c = \frac{Q_p - Q_o}{Q_p} = 1 - \frac{T_2}{T_1}$$ - Thermal efficiency of cycle (1.8)

The Carnot cycle cannot be realized in practice. It can be only be realized approximately in the area of wet steam. It has the highest efficiency of all possible cycles.

Brayton gas cycle

It is indicated in the T-s diagram in Fig. 1.5

Heat dissipation differs depending on whether the cycle is closed or open. A closed cycle dissipates heat through a heat exchanger, while an open cycle is concluded through the atmosphere. Sometimes an open cycle may have a heat exchanger. This is in cases where the exhaust gases reach very high temperatures, and a part of their heat is utilized for heating compressed air in the B state.

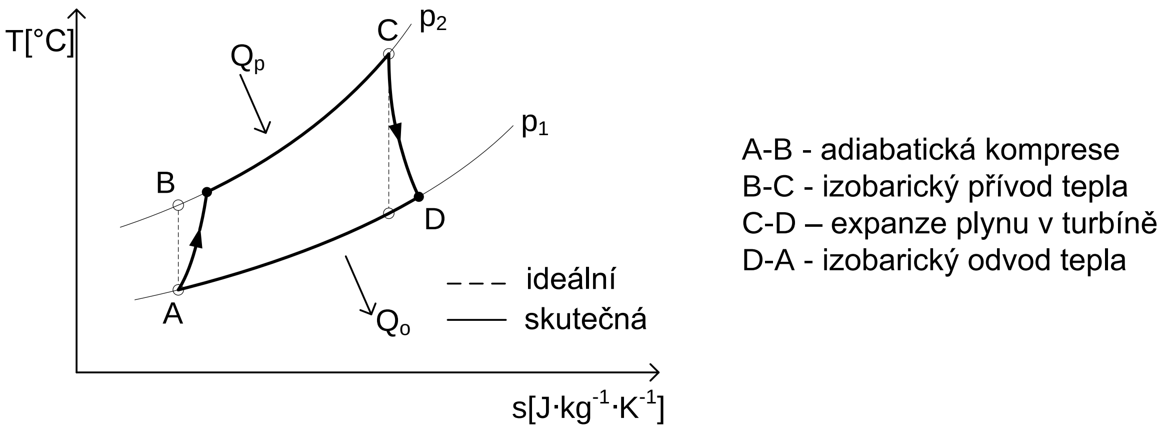


Fig. 1.5 Brayton gas cycle

For the calculation of the cycle with an ideal gas holds:

- input heat $q_p = i_C - i_B$ [kJ/kg] (1.9)
- output heat $q_o = i_D - i_A$ [kJ/kg] (1.10)
- specific work $l = (i_C - i_B) - (i_D - i_A)$ [kJ/kg] (1.11)

The technical efficiency of the cycle is: $$\eta_J = 1 - \frac{T_D}{T_C} = 1 - \left(\frac{p_{AD}}{p_{BC}}\right)^{\frac{\kappa - 1}{\kappa}} \quad [-]$$ (1.12)

Clausius-Rankine (steam) cycle

Utilizes the phase changes between liquid and vapor. The condensed liquid "1" is compressed using a pump to working pressure, whereby it isobarically supplies heat $q_{p.}$. The liquid meanwhile heats up to the boiling point, isothermally evaporates, and overheats. Adiabatic expansion then occurs in the steam turbine from the state "2" to the state of wet steam "3". This steam isothermally condenses and expels the heat q_o.

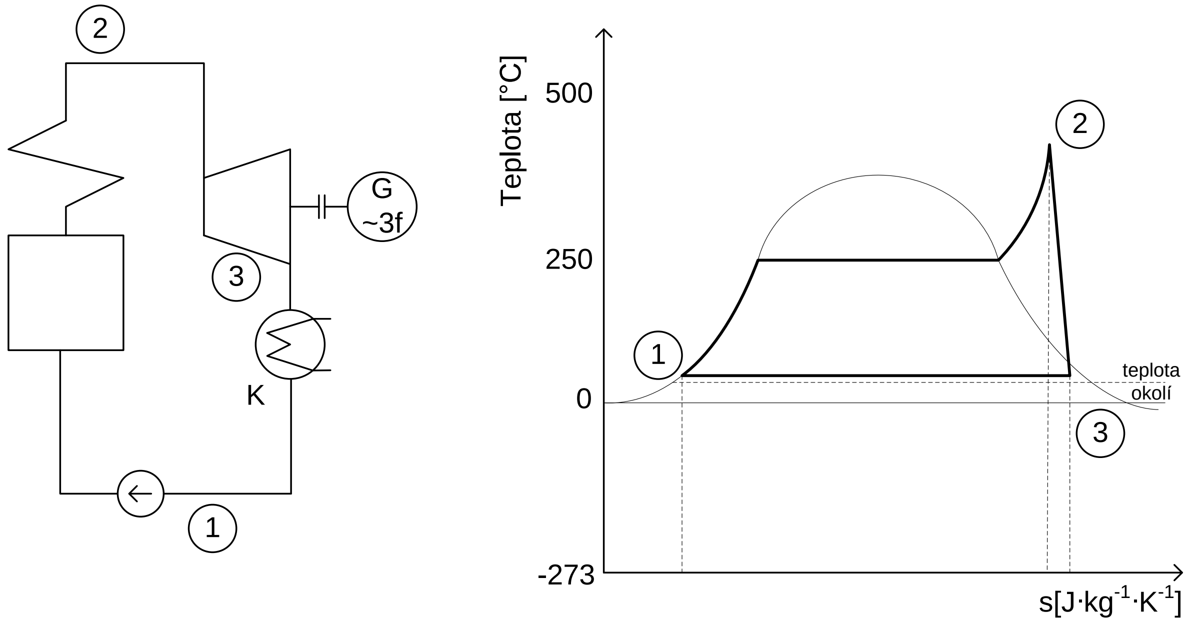


Fig. 1.6 Schematic diagram of the steam cycle and a T-s diagram of the steam cycle

- input heat $q_p = i_2 - i_1$ [kJ/kg] (1.13)
- output heat $q_0 = i_3 - i_1$ [kJ/kg] (1.14)
- pump work: $l_C = \dfrac{p_1 - p_2}{\rho}$ [kJ/kg] (1.15)
- Thus the thermal efficiency of the pump is: $\eta_{CR} = \dfrac{i_2 - i_3 - \dfrac{p_1 - p_2}{\rho}}{i_2 - i_1 - \dfrac{p_1 - p_2}{\rho}}$ [−]

(1.16)

The efficiency of the cycle can be increased:

By *reheating the steam*, when the steam partially expands in the high-pressure part of the turbine, then is reheated in the reheater and the expansion is completed in the low-pressure part of the turbine. See fig. 1.7. *By regenerative feedwater heating*, when a portion of the steam heats the condensate and the feed water.

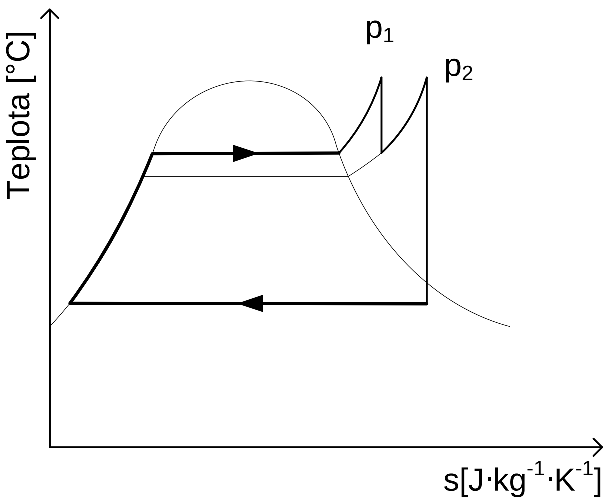


Fig. 1.7 T-s diagram of steam reheating

Combined gas and steam cycle

With realized gas cycles, relatively high middle temperatures of inlet heat t_c = 600-800 °C are attained, and with stationary gas turbines as high as 1350 °C. Whereas in steam cycles, the temperature of the inlet heat is relative low, with t_2 most often being at 540 °C, 650 °C at maximum. Temperature of the outlet heat is low, $t_3 = t_1$ =30 °C, which is an advantage. By combining the two types of cycles, their disadvantages are eliminated and the advantages are utilized: high temperature of the heat inlet, low temperature of the heat outlet, thereby enabling the achievement of higher efficiency than with separate cycles.

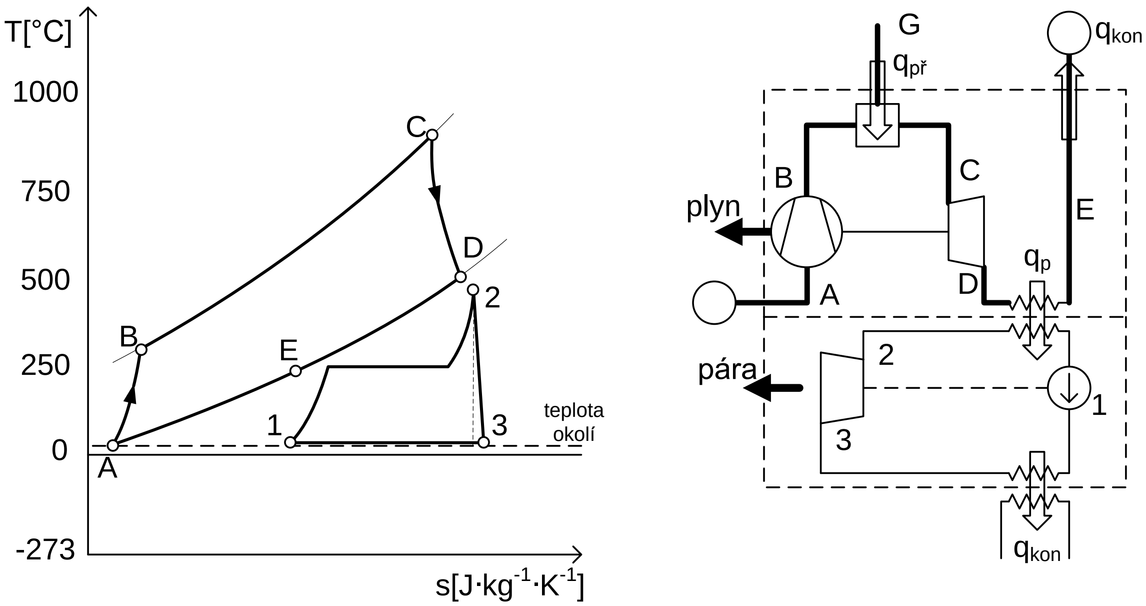


Fig. 1.8 T-s diagram and schematic diagram of a steam-gas cycle (combined cycle)

The simplified relation of the overall efficiency of a steam-gas power plant:

$$\eta_{el} = \eta_t \eta_{kt} \eta_{sk} \eta_{tdsv} \eta_{vs} = 0.42 \text{ up to } 0.58 \qquad (1.17)$$

- η_t (up to 0.58) – thermal efficiency of a combined cycle
- η_{kt} (up to 0.93) – boiler efficiency
- η_{sk} (up to 0.98) – combustion chamber efficiency
- η_{tdsv} (up to 0.84) – thermodynamic efficiency of the turbo-generator at the terminals
- η_{vs} (up to 0.94) – efficiency of own consumption

Power plants today achieve these efficiencies:

- η_{el} = 0.28-0.38 in large blocks with a purely gas cycle
- η_{el} = 0.28-0.42 with a steam cycle
- η_{el} = 0.42-0.58 with a steam-gas cycle

The disadvantage of steam-gas cycles is the necessity of burning quality fuels in the gas part (gas, oil). During the combustion of fuels with a high content of ash (coal), it is necessary to incinerate or gasify the fuel under pressure. It is also necessary to clean the created gas under pressure and high temperature. This technology is still very expensive.

? *Review Questions*

1) **Define the terms medium load, own use consumption of power plant and energy efficiency of equipment!** (3 points)

2) **How do we classify the electrical power reserve in the electricity grid? Specify the types of power plants contributing to the various types of reserves.** (2 points)

3) **Draw a T – s diagram of the Carnot cycle, and describe its individual parts and its principle!** (2 points)

4) **Compare the Brayton and the Clausius-Rankine cycles (circulation)!** (1 point)

5) **Describe the steam-gas cycle (circulation), draw its T – s diagram and state the advantages and disadvantages of this cycle!** (2 points)

Summary

New findings and concepts:

- Knowledge of basic power plant concepts
- Knowledge of basic thermal cycles

Key to questions

1) **Define the terms medium load, own use consumption of power plant and energy efficiency of equipment!** (3 points)

Medium load $$P_{stř} = \frac{1}{T_0}\int_0^T P(t)dt = \frac{A_{SV}}{T_0} \text{ [W]} \qquad (1.1)$$

A_{SV} ….. Gross power output including own consumption,

T_0 ……. Load duration,

$P_{stř}$ …….. permanent constant load for the duration T_0 as during variable load.

Own use consumption of power plant

- The quantity of electric energy consumed by a power plant during the technological process without considering losses

- ***Coefficient of own use consumption*** $$k_{VS} = \frac{A_{VS}}{A_{SV}} \cdot 100 \qquad [\%] \qquad (1.2)$$

- Nuclear 15%
- Thermal 10%
- Water (at least)

Energy efficiency – the basic balance for power equipment

$$\sum P_{vstup} = \sum P_{využ} + \sum P_{ztrát} \qquad (1.4)$$

$$1 = \frac{\sum P_{využ}}{\sum P_{vstup}} + \frac{\sum P_{ztrát}}{\sum P_{vstup}} \tag{1.5}$$

$$1 = \eta - \sum \xi \quad \Rightarrow \quad \eta = 1 - \sum \xi \tag{1.6}$$

η ….. Efficiency of the energy system

$\Sigma\xi$ ... The sum of the relative energy losses of the system

2) How do we classify the electrical power reserve in the electricity grid? Specify the types of power plants contributing to the various types of reserves. (2 points)

Reserve:

- ***Rotating (immediate)*** - it is the sum of the differences between immediate and a rated power of all equipment. Reaction in 5 to 30 seconds by all the sources working into to the electricity grid. Thermal, nuclear, hydroelectric power plants, renewable energy sources (RES)

- ***Warm (minute)*** - boiler in operation Reaction within 15 minutes Hydroelectric, pumped storage and wind power plants, electrochemical cells, gas power plants

- ***Cold (hour)*** - the machines at rest Reaction in 1 to 5 hours Thermal, nuclear and steam-gas power plants

3) Draw and describe the individual parts and the principle of the Carnot cycle (circulation). (2 points)

The Carnot cycle is made up of four reversible changes of the working substance:

- 2-3 By isothermal expansion when the heating body temperature is T_1
- 3-4 By adiabatic expansion when the temperature drops from T_1 to T_2
- 4-1 By isothermal compression when cooling body temperature is T_2
- 1-2 By adiabatic compression between temperatures T_2 and T_1

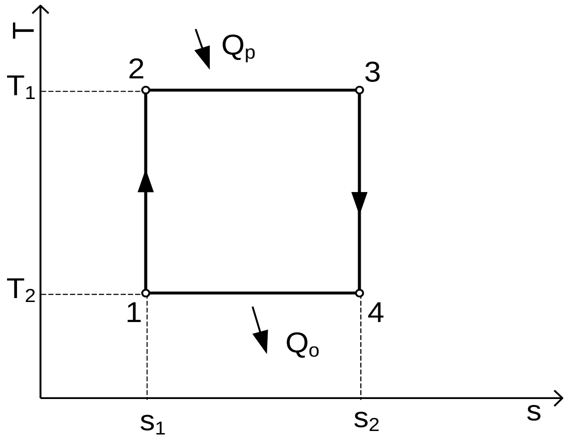


Fig*. *1.4 The Carnot cycle

Heat Q_p is fed into the system during isothermal expansion and heat Q_o is discharged during isothermal compression.

$$\eta_c = \frac{Q_p - Q_o}{Q_p} = 1 - \frac{T_2}{T_1} \text{ - Thermal efficiency of cycle} \qquad (1.8)$$

The Carnot cycle cannot be realized in practice. It can be only be realized approximately in the area of wet steam. It has the highest efficiency of all possible cycles.

4) Compare the Brayton and the Clausius-Rankine cycles (circulation)! (1 point)

See page 6 and 7 of this chapter.

5) Describe the steam-gas cycle (circulation) and state its advantages and disadvantages! (2 points)

See page 8 of this chapter.

2. THERMAL POWER PLANTS - THERMAL POWER PLANT EQUIPMENT

Study Objectives

- **To become acquainted with the equipment and operation of thermal power plants**
- **The physical properties of water and the relations between them utilized in power plants**
- **The impact of thermal power plants on the environment**

Keywords

Condensing power plant, expansion turbine, back pressure turbine, extraction turbine, the fuel circuit the power plant, boiler, pipelines, condenser, feedwater, dryness, deaerator, feedwater pump, reheater, emissions, immisions

Required study time

300 minutes

Text to Be Studied

Introduction

At the present time, the energy industry cannot do without the production of electric power by using power plants working on the principle of burning fossil fuels. These fuels include the brown and black coal, natural gas, crude oil and petroleum products. The accessibility of brown and black coal takes precedence over the purchase of crude oil and natural gas from abroad. As a result, coal is the most important source for the production of electrical energy in the Czech Republic for the first half of the 21st century.

2.1 Condensing power plant

Fuel is fed into the steam boiler K and its combustion releases the heat needed to produce steam. The resulting steam is dried in the superheater and then expands in the turbine T up to the very low output pressure of 2.5-7 kPa. After the condensation of the steam in the condenser K by means of water cooling, the condensate is transported through a low pressure regeneration heater NTO, the supply tank NN and high pressure regeneration heaters VTO back to the boiler.

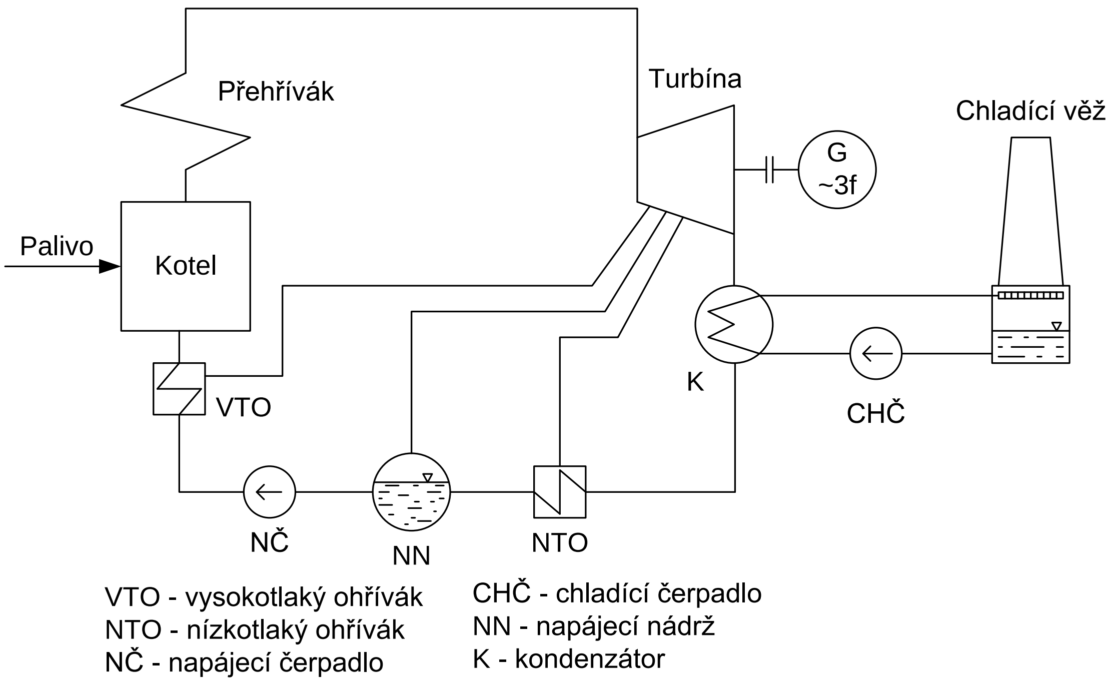


Fig. 2.1 Schematic diagram of a condenser power plant

To achieve the highest possible efficiency, we strive to achieve the maximum inlet pressure and temperature of the input steam. Tiered regenerative heating of steam is used, and the reheating of steam is often also employed. Conversely, the lowest possible pressure is chosen in the condenser.

- Pressure of input steam p_0 = 10 – 24 MPa
- temperature of input steam t_0 = 450 - 565 °C
- pressure in the condenser p = 2.5 - 7 kPa.

2.2 Cogeneration units with gas internal combustion units

Cogeneration - the common production of electricity and heat in diesel or gas combustion engines

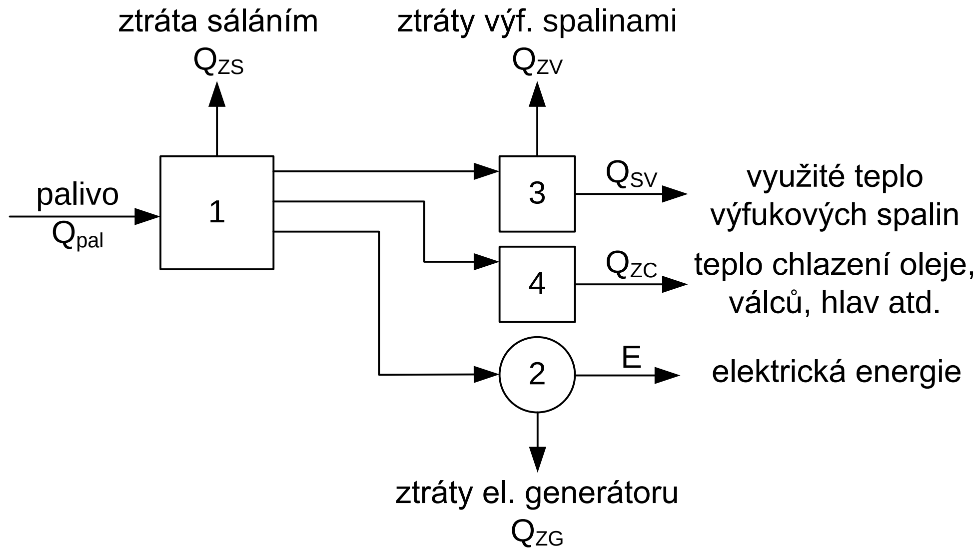


Fig. 2.2 Utilized heat and losses during cogeneration

The use of internal combustion engines for the combined production of electricity and heat enables the reduction of consumption of primary energy sources and significantly reduces harmful emissions. The efficiency achieved in heating applications reaches up to 90%.

The units manufactured have a power output of a magnitude of tens of kW up to several MW. In addition to engines running on natural gas, there are engines available that run on biogas, landfill gas, etc.

Experience shows that the greatest influence on the economy of operation of cogeneration units with combustion engines is the price of the electricity sold to the network (if it is not consumed on site) and the duration of utilization of the installed power source.

The fundamental equation describing the cogeneration can written as follows:

Electrical efficiency $$\eta_e = \frac{E}{Q_{pal}} \quad [-] \tag{2.1}$$

Thermal efficiency $$\eta_t = \frac{Q_{ZC} + Q_{SV}}{Q_{pal}} \quad [-] \tag{2.2}$$

Overall thermal efficiency $$\eta_{tc} = \frac{E + Q_{ZC} + Q_{SV}}{Q_{pal}} \quad [-] \tag{2.3}$$

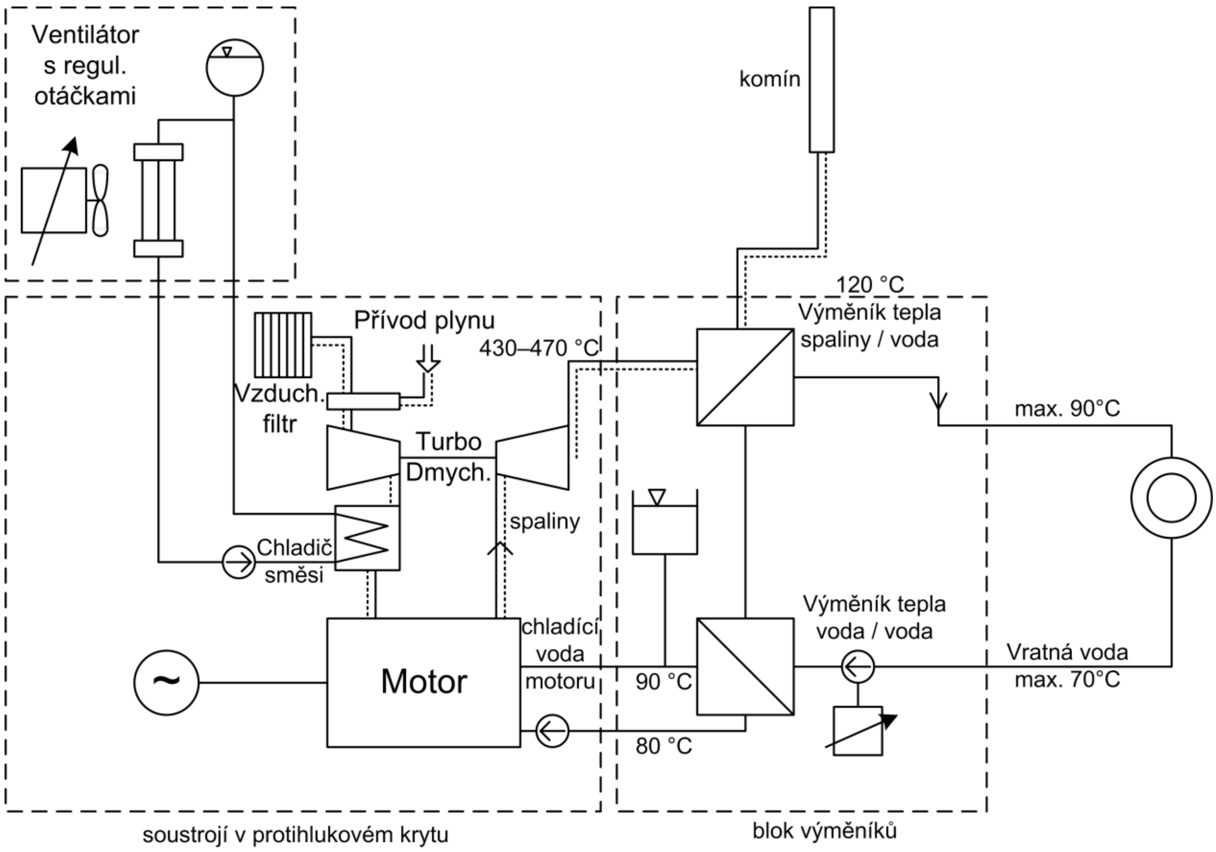


Fig. 2.3 Schematic diagram of a cogeneration unit

2.3 Trigeneration

Trigeneration is basically a cogeneration unit equipped with cooling equipment, so that it can have adequate cooling power available for technological or air conditioning purposes.

The cooling equipment is usually of the compressor type (driven by an electric motor powered from a cogeneration unit) or absorption (the drive provided by utilizing the waste heat of the cogeneration unit). Larger units are equipped with both types, which allows for more flexible adaptation to the requirements of the subscribers of electricity and heat.

The economic advantageousness of trigeneration is conditioned by a large enough subscription to the cold output. If power output is designed optimally, the supply of cold output can improve the economic characteristics in two ways:

- in the case of compressor cooling, electricity costs are lower than in its purchase from the network,
- in the case of absorption cooling, the fuel needed for attaining heat is also used to produce a more expensive form of energy – electricity, so that overall costs are reduced.

2.4 Types of boilers, the power plant fuel circuit

Types of boilers

1. Drum
   - With natural circulation
   - With forced circulation
2. Flow-through
3. Fluid – the fuel burns in suspension and burns through better =higher efficiency

A critical component is the evaporator, in which the depositing of salt occurs after water evaporation.

Boiler water is distilled, without organic substances and mechanical impurities. Degassed O_2, SiO_2, CO_2 and without Ca, Mg. Losses of about 5% occur, which are replenished with soft water.

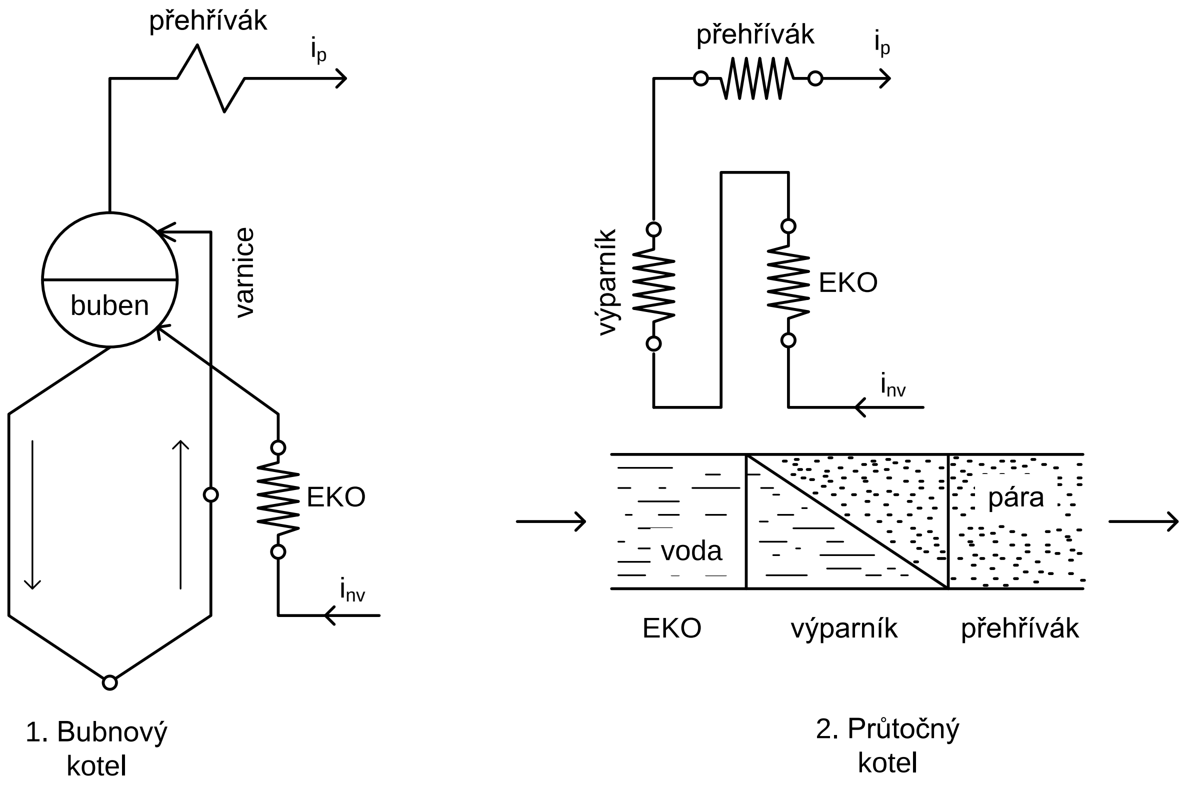


Fig. 2.4 Drum and flow-through boiler

Surface blowdown - removal of salts at the surface of the boiling water

Bottom blowdown - draining of deposits at the lowest point of the boiler, either constantly or intermittently

Boiler parameters:

q_k = 15 MJ/kWh – specific heat of boiler

m_u = 1 kg/kWh – specific fuel amount

m = 4 kg/kWh – specific steam consumption of for turbine

Boiler efficiency
$$\eta_k = \frac{Q_k}{M_u \cdot k_v} \qquad (2.4)$$

Q_k ……… Heat produced

k_v ………. Fuel calorific value [MJ/kg]

M_u ……… Fuel amount

Power plant fuel circuit

The power plant fuel circuit includes machinery and equipment necessary for the transport and storage of fuel supplied to the power plant.

Coal is transported to the plant in wagons by rail, by river shipping or directly from the coal mine by conveyor belt.

It is unloaded by unloaders at the place of need, or from Hopper wagons into slotted trays. From here it travels through propeller rollers and belts to the boiler room or to the coal stockyard. The stockyard has equipment for the distribution of coal, collection and transport of coal to the boiler room. This equipment is all electric. In special cases, equipment is used for homogenization of coal.

In the power plant, the coal is transported horizontal and inclined belts. Inclined belts have safety equipment preventing the belt from spinning in the opposite direction during an electric motor failure or loss of voltage in order to avoid clogging of the hoppers and the area around the belt.

2.5 Types of turbines

Thermal turbines are classified according to several criteria

a) The working substance

i. *Gas turbines*, their working substance is usually the combustion products of gaseous or liquid fuels with an input temperature into the turbine of 600 to 1400 °C and the output temperature of 450 to 600 °C, with an electricity production efficiency of 28 to 38%

ii. *Superheated* s*team turbines* The input steam temperature is 400 to 650 °C, with the overall efficiency of electricity production (including the steam boiler) being 28 to 42%

iii. *Saturated or wet* s*team turbines* They are used mainly in nuclear power stations.

b) Output steam pressure

i. *Back-pressure turbines* The output pressure is relatively high (0.11 up to 0.6 MPa), so that the steam can be used for heating and technological purposes.

ii. *Condensing turbines* The steam expands into a vacuum to the pressure of 0.002 up to 0.01 MPa. The condensing heat of this (emission) steam is lost and dissipates into the environment through a cooling system.

c) Extractions of the steam from the turbine

i. *Turbine with unregulated extractions* Steam is extracted at several places in the turbine and heats the feedwater of the boiler, so that the efficiency of the heat cycle is increased.

ii. *Turbine with the regulated extractions* Steam is extracted through one or at most three extraction points with the appropriate pressure, which supply heat to consumers. The extraction of steam is regulated according to the requirements of consumption.

d) The number of bodies

i. *Single-body turbines* for smaller power outputs

ii. *Multi-body turbines* with a high pressure part, low pressure part and possibly middle pressure part for greater power outputs.

e) The number of stages

i. *Single-stage turbines* for small power outputs

ii. *Multi-stage turbines*, with up to 20 stages in one body

f) The operating principle

i. *Balanced pressure turbines* The enthalpic drop of the stage is entirely transformed into speed in the distribution (guide) vanes, so that the pressure before and behind the circulating blades is the same.

ii. *Overpressure turbines* Part of the enthalpic is transformed into speed even in the circulation blades

g) The flow of the working substance

i. *Axial turbines* The most common type today. Steam flows parallel to the axis of the shaft.

ii. *Radial turbines* Steam flows perpendicular to the axis of the shaft; today practically not being built anymore.

iii. *Centripetal turbines* The steam enters the turbine radially and exits axially. The principle is used for small turbines (superchargers, expanders in oxygen generation plants, etc.).

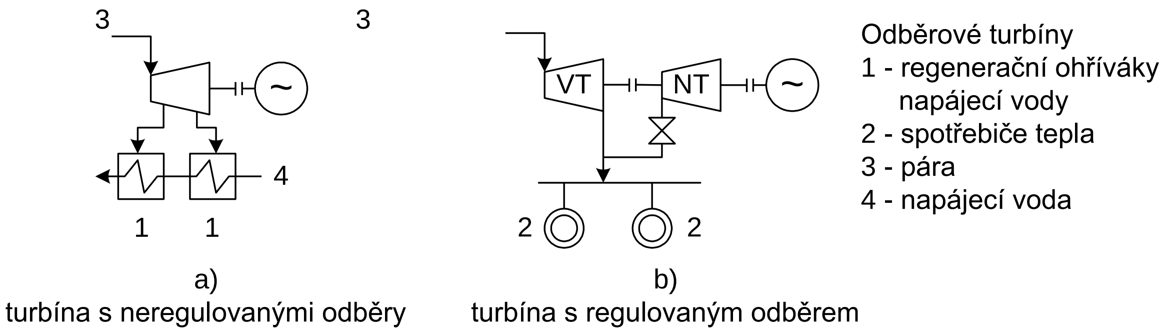


Fig. 2.5 Illustration of extraction turbines

Operating principle

Each stage of the turbine is made up of a fixed distribution blade grill (wicket gate) and a circulating blade cascade placed on the rotor. The distribution blades consist of a series of parallel jets, whose purpose is to convert the jetted mass pressure to speed with minimal losses.

The working substance exiting from the jets of the distribution blades enters the blade cascade of the runner, where its kinetic energy is converted to torque. Through the change in momentum, circumferential force arises in the circulating blades.

In a balanced pressure stage, the entire enthalpic drop of the stage is converted in the guide vanes into speed, while in an overpressure stage only a part, with the rest of the enthalpic drop converted into speed in the revolving blade cascade, and subsequently, in the rotor, the kinetic energy is converted into mechanical work. The ratio of the enthalpic drop converted in the circulating blades to the entire enthalpic drop of the stage is called the degree of reaction r. In the balanced pressure stage $r = 0$ and in the overpressure stage $r = 0.5$.

Gas turbines

The working substance of gas turbines used in the power industry are usually combustion gases of gaseous or liquid fuels. The biggest advantages of gas turbines include:

- Compact configuration of the machine and small enclosed space
- Small material consumption
- Low specific investment costs as a result
- Small water consumption
- High operational reliability
- Power output flexibility

The disadvantages of gas turbines:

- Necessity of using expensive liquid or gaseous fuels
- Large amount of compression work, which equals 2/3 of the mechanical energy produced by the turbine
- High demands on manufacture and the materials used
- High exhaust gas temperature, which reduces thermal efficiency of the cycle, if the heat of the exhaust gases is not utilized = > steam-gas cycle

Cooling systems of condensing turbines

- *Flow-through cooling* It is the simplest and cheapest cooling system. It consists of a tubing condenser, a pumping station and pipeline system. The condensation heat is led out by river, lake or sea water. Only mechanical impurities are removed from the water. This system achieves the lowest pressure in the condenser and thus a high thermal efficiency of the steam cycle. The disadvantage is the high fees for the use of river water, a shortage of water and possibly inadmissible heating of river water.
- *Circulatory cooling* In this case the cooling water circulates between the turbine condenser and a cooler, where heat is passed into the air. The movement of the water is ensured by a circulating cooling pump.

Types of coolers

- *Wet cooling tower with natural draft* – the cooling water is sprayed out into the air, which flows through the water shower due to the chimney effect

- *Wet cooling tower with artificial draft* – the chimney effect is substituted by fans

- *Dry cooling tower* – with artificial or natural draft. Cooling is not carried out with sprayed water, but with flowing air. A minimum of water consumption.

- *Hybrid cooling tower* – a combination of wet and dry tower

- *The Heller system* – the turbine condenser provides mixing, whereby the condensation of steam is reached by spraying its own condensate into steam. The condensate is cooled in a dry cooling tower.

- *Air condenser* – emission steam from the turbine is fed directly into a cooling system of ribbed tubes, in which it condenses. The air has forced circulation.

2.6 Thermodynamics – steam

In changes of substances between solid, liquid and gaseous states, the following terms are used:

Latent heat – is the heat energy required to bring to a substance to change its state from solid to liquid or liquid to gas. In the opposite process, latent heat is removed from the substance.

Evaporation – the process in which vapor is formed on the surface of a liquid spontaneously at every temperature, if there is free space above the surface

Boiling – when the liquid to which heat is brought achieves such a temperature that vapor forms throughout its volume

Vaporization – conversion of liquid by any means

Wet vapor – a mixture of boiling (rich) liquid (mass m ´) and saturated vapor (mass m")

Saturated vapor – in a given space there is only the vapor at the temperature and pressure of the boiling point

Superheated vapor – vapor with a temperature higher than the boiling point at a given pressure

Critical point – is the highest temperature that the liquid phase can reach. At a higher temperature, the substance exists only in the gas phase.

Dryness of wet vapor x – expresses the quantity of saturated vapor m´´ [kg] in one kg of wet vapor m ´.

$$x = \frac{m''}{m' + m''} \quad [kg/kg] \tag{2.5}$$

The moisture of wet vapor 1-x is determined by the ratio of saturated liquid and wet vapor in the given space, and expresses the quantity of saturated liquid kg in one kg of wet vapor.

$$1 - x = \frac{m'}{m' + m''} \quad [kg/kg] \tag{2.6}$$

Steam diagrams

In technical practice, steam diagrams *i – p, T – s, i – s* are used for the illustration of thermal processes, from which the values of needed quantities for the given state quantities can be deducted, most often *p, t* or with wet steam *p, x*, continuously throughout the entire range.

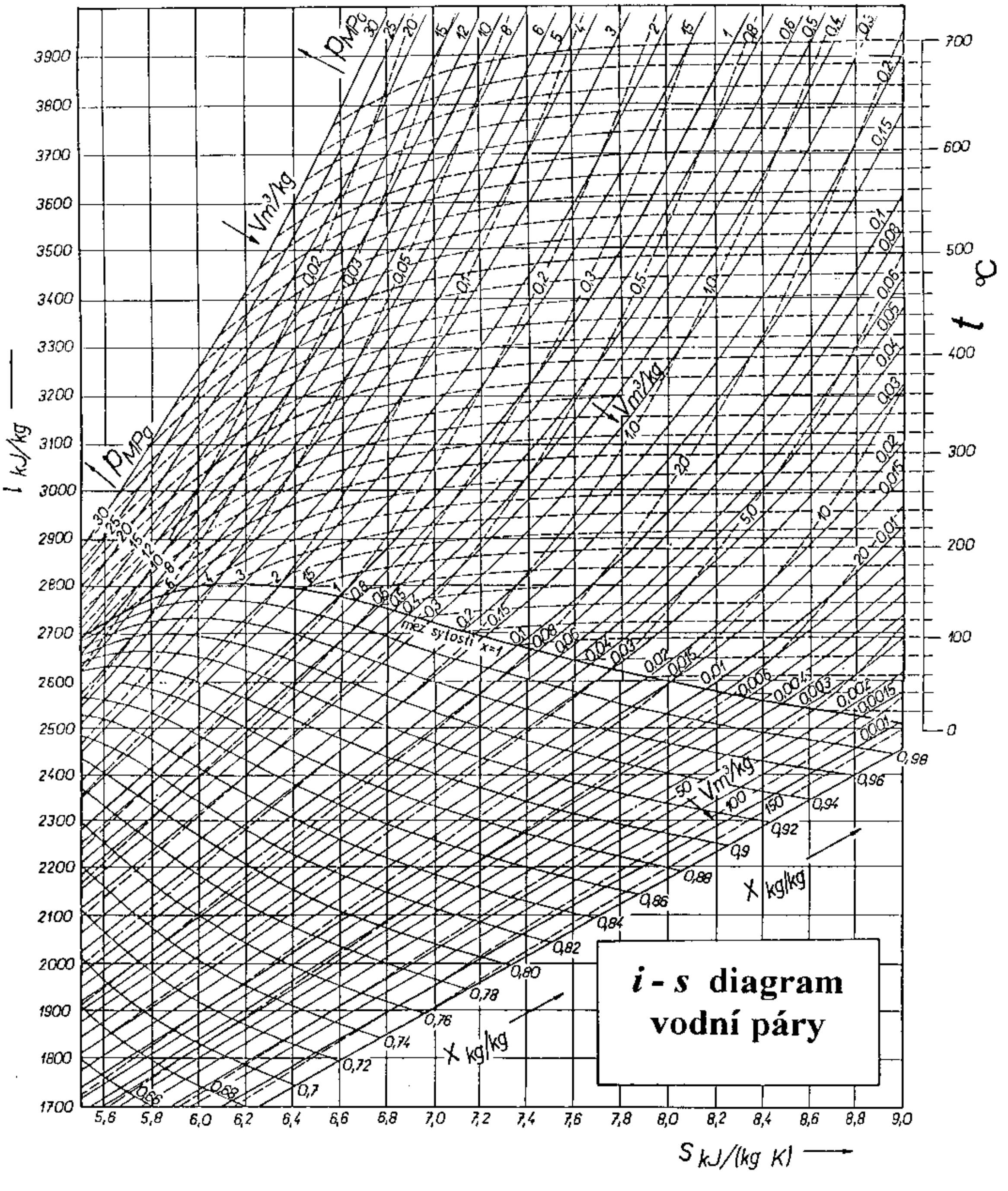


Fig. 2.6 i – s diagram of steam (Mollier diagram)

For the determination of the enthalpy of the steam it is necessary to know these quantities:

- ***Saturated steam*** – without moisture one quantity, *t* or *p*, possibly *v* (on the limit curve for *x* = 1).

- ***Wet steam*** – two quantities, *t – x* or *p – x*, possibly *v – x, v – p, v – t*.

- ***Superheated steam*** – two quantities, *p – t* or *v – t, v – p*.

The accuracy of the reading depends on the size of the diagram and is smaller than when using steam tables. For this reason the initial conditions of steam are usually determined more accurately from tables.

Example: Enthalpy of feedwater for p_{nv} = 10 MPa, $\boldsymbol{t_{nv}}$ = 220 °C is *(i – 4.2t)=21.7 kJ/kg, of which* $i_{nv} = 4.2 \cdot 220 + 21.7 = 945.7$ *kJ/kg.*

Tables of properties of the saturated liquid and the saturated vapor of water

Uspořádání podle teplot

t	p	v'	v''	ρ"	i'	i''	l_{23}	s'	s''
°C	MPa	$m^3.kg^{-1}$		$kg.m^{-3}$	$kJ.kg^{-1}$			$kJ.kg^{-1}.K^{-1}$	
0,01	0,0006108	0,0010002	206,3	0,004847	0	2501	2501	0	9,1544
5	0,0008719	0,0010001	147,2	0,006793	21,05	2510	2489	0,0762	9,0241
10	0,0012277	0,0010004	106,42	0,009398	42,04	2519	2477	0,1510	8,8994
15	0,0017041	0,0010010	77,97	0,01282	62,97	2528	2465	0,2244	8,7806
20	0,002337	0,0010018	57,84	0,01729	83,90	2537	2454	0,2964	8,6665
25	0,003166	0,0010030	43,40	0,02304	104,81	2547	2442	0,3672	8,5570
30	0,004241	0,0010044	32,93	0,03037	125,71	2556	2430	0,4366	8,4523
35	0,005622	0,0010061	25,24	0,03962	146,60	2565	2418	0,5049	8,3519
40	0,007375	0,0010079	19,55	0,05115	167,50	2574	2406	0,5723	8,2559
45	0,009584	0,0010099	15,28	0,06544	188,40	2582	2394	0,6384	8,1638
50	0,012335	0,0010121	12,04	0,08306	209,3	2592	2383	0,7038	8,0753
60	0,019917	0,0010171	7,678	0,1302	251,1	2609	2358	0,8311	7,9084
70	0,03117	0,0010228	5,045	0,1982	293,0	2626	2333	0,9549	7,7544
80	0,04736	0,0010290	3,408	0,2934	334,9	2643	2308	1,0753	7,6116
90	0,07011	0,0010359	2,361	0,4235	377,0	2659	2282	1,1925	7,4787
100	0,10131	0,0010435	1,673	0,5977	419,1	2676	2257	1,3071	7,3547
110	0,14326	0,0010515	1,210	0,8264	461,3	2691	2230	1,4184	7,2387
120	0,19854	0,0010603	0,8917	1,121	503,7	2706	2202	1,5277	7,1298
130	0,27011	0,0010697	0,6683	1,496	546,3	2721	2174	1,6345	7,0272
140	0,3614	0,0010798	0,5087	1,966	589,0	2734	2145	1,7392	6,9304
150	0,4760	0,0010906	0,3926	2,547	632,2	2746	2114	1,8418	6,8383
160	0,6180	0,0011021	0,3068	3,258	675,5	2758	2082	1,9427	6,7508
170	0,7920	0,0011144	0,2426	4,122	719,2	2769	2050	2,0417	6,6666
180	1,0027	0,0011275	0,1939	5,157	763,1	2778	2015	2,1395	6,5858
190	1,2553	0,0011415	0,1564	6,394	807,5	2786	1979	2,2357	6,5074
200	1,5551	0,0011565	0,1272	7,862	852,4	2793	1941	2,3308	6,4318
210	1,9080	0,0011726	0,1043	9,588	897,7	2798	1900	2,4246	6,3577
220	2,3201	0,0011900	0,08606	11,62	943,7	2802	1858	2,5179	6,2849
230	2,7979	0,0012087	0,07147	13,99	990,4	2803	1813	2,6101	6,2133
240	3,3480	0,0012291	0,05967	16,76	1037,5	2803	1766	2,7021	6,1425
250	3,9776	0,0012512	0,05006	19,98	1085,7	2801	1715	2,7934	6,0721
260	4,694	0,0012755	0,04215	23,72	1135,1	2796	1661	2,8851	6,0013
270	5,505	0,0013023	0,03560	28,09	1185,3	2790	1605	2,9764	5,9297
280	6,419	0,0013321	0,03013	33,19	1236,9	2780	1542,9	3,0681	5,8573
290	7,445	0,0013655	0,02554	39,15	1290,0	2766	1476,3	3,1611	5,7827
300	8,592	0,0014036	0,02164	46,21	1344,9	2749	1404,2	3,2548	5,7049
320	11,290	0,001499	0,01545	64,72	1462,1	2700	1237,8	3,4495	5,5353
340	14,608	0,001639	0,01078	92,76	1594,7	2622	1027,0	3,6605	5,3361
360	18,674	0,001894	0,006943	144,00	1762,0	2481	719,30	3,9162	5,0530
374	22,087	0,002800	0,00347	288,00	2032,0	2147	114,70	4,3258	4,5029

The one-line symbol belongs to boiling (rich) liquid and the double-line to saturated steam. The latent heat of vaporization is determined from the relation: $l_r = i'' - i'$ [kJ/kg] (2.7)

Uspořádání podle tlaků

p	t	v’	v’’	ρ’’	i’	i’’	l_{23}	s’	s’’
MPa	°C	$m^3.kg^{-1}$		$kg.m^{-3}$	$kJ.kg^{-1}$			$kJ.kg^{-1}.K^{-1}$	
0,001	6,92	0,0010001	129,9	0,00770	29,32	2513	2484	0,1054	8,975
0,002	17,514	0,0010014	66,97	0,01493	73,52	2533	2459	0,2609	8,722
0,003	24,097	0,0010028	45,66	0,02190	101,04	2545	2444	0,3546	8,576
0,004	28,979	0,0010041	34,81	0,02873	121,42	2554	2433	0,4225	8,473
0,005	32,88	0,0010053	28,19	0,03547	137,83	2561	2423	0,4761	8,393
0,006	36,18	0,0010064	23,74	0,04212	151,50	2567	2415	0,5207	8,328
0,007	39,03	0,0010075	20,53	0,04871	163,43	2572	2409	0,5591	8,274
0,008	41,54	0,0010085	18,10	0,05525	173,9	2576	2402	0,5927	8,227
0,009	43,79	0,0010094	16,20	0,06172	183,3	2580	2397	0,6225	8,186
0,010	45,84	0,0010103	14,68	0,06812	191,9	2584	2392	0,6492	8,149
0,02	60,08	0,0010171	7,647	0,1308	251,4	2609	2358	0,8321	7,907
0,03	69,12	0,0010222	5,226	0,1913	289,3	2625	2336	0,9441	7,769
0,04	75,88	0,0010264	3,994	0,2504	317,7	2636	2318	1,0261	7,670
0,05	81,35	0,0010299	3,239	0,3087	340,6	2645	2204	1,0910	7,593
0,06	85,95	0,0010330	2,732	0,3661	360,0	2653	2293	1,1453	7,531
0,07	89,97	0,0010359	2,364	0,4230	376,8	2660	2283	1,1918	7,479
0,08	93,52	0,0010385	2,087	0,4792	391,8	2665	2273	1,2330	7,434
0,09	96,72	0,0010409	1,869	0,5350	405,3	2670	2265	1,2696	7,394
0,10	99,64	0,0010432	1,694	0,5903	417,4	2675	2258	1,3026	7,360
0,15	111,38	0,0010527	1,159	0,8627	467,2	2693	2226	1,4336	7,223
0,2	120,23	0,0010605	0,8854	1,129	504,8	2707	2202	1,5302	7,127
0,3	133,54	0,0010733	0,6057	1,651	561,4	2725	2164	1,672	6,992
0,4	143,62	0,0010836	0,4624	2,163	604,7	2738	2133	1,777	6,897
0,5	151,84	0,0010927	0,3747	2,669	640,1	2749	2109	1,860	6,822
0,6	158,84	0,0011007	0,3156	3,169	670,5	2757	2086	1,931	6,761
0,7	164,96	0,0011081	0,2728	3,666	697,2	2764	2067	1,992	6,709
0,8	170,42	0,0011149	0,2403	4,161	720,9	2769	2048	2,046	6,663
0,9	175,35	0,0011213	0,2149	4,654	742,8	2774	2031	2,094	6,623
1,0	179,88	0,0011273	0,1946	5,139	762,7	2778	2015	2,138	6,587
1,2	187,95	0,0011385	0,1633	6,124	798,3	2785	1987	2,216	6,523
1,4	195,04	0,0011490	0,1408	7,103	830,0	2790	1960	2,284	6,469
1,6	201,36	0,0011586	0,1238	8,080	858,3	2793	1935	2,344	6,422
1,8	207,10	0,0011678	0,1104	9,058	884,4	2796	1912	2,397	6,379
2,0	212,37	0,0011766	0,09958	10,041	908,5	2799	1891	2,447	6,340
2,2	217,24	0,0011851	0,09068	11,03	930,9	2801	1870	2,492	6,305
2,4	221,77	0,0011932	0,08324	12,01	951,8	2802	1850	2,534	6,272
2,6	226,03	0,0012012	0,07688	13,01	971,7	2803	1831	2,573	6,242
2,8	230,04	0,0012088	0,07141	14,00	990,4	2803	1813	2,611	6,213
3,0	233,83	0,0012163	0,06665	15,00	1008,3	2804	1796	2,646	6,186
3,5	242,54	0,0012345	0,05704	17,53	1049,8	2803	1753	2,725	6,125
4,0	250,33	0,0012520	0,04977	20,09	1087,5	2801	1713	2,796	6,070
5,0	263,91	0,0012857	0,03944	25,35	1154,4	2794	1640	2,921	5,973
6,0	275,56	0,0013185	0,03243	30,84	1213,9	2785	1570,8	3,027	5,890
7,0	285,80	0,0013510	0,02737	36,54	1267,4	2772	1504,9	3,122	5,814
8,0	294,98	0,0013838	0,02352	42,52	1317,0	2758	1441,1	3,208	5,745
9,0	303,32	0,0014174	0,02048	48,83	1363,7	2743	1379,3	3,287	5,678
10,0	310,96	0,0014521	0,01803	55,46	1407,7	2725	1317,0	3,360	5,615
11,0	318,04	0,001489	0,01598	62,58	1450,2	2705	1255,4	3,430	5,553
12,0	324,63	0,001527	0,01426	70,13	1491,1	2685	1193,5	3,496	5,492
13,0	330,81	0,001567	0,01277	78,30	1531,5	2662	1130,8	3,561	5,432
14,0	336,63	0,001611	0,01149	87,03	1570,8	2638	1066,9	3,623	5,372
16,0	347,32	0,001710	0,009318	107,3	1650	2582	932,0	3,746	5,247
18,0	356,96	0,001837	0,007504	133,2	1732	2510	778,2	3,871	5,107
20,0	365,71	0,00204	0,00585	170,9	1827	2410	583	4,015	4,928
22,0	373,7	0,00273	0,00367	272,5	2016	2168	152	4,303	4,591

Critical values:

1. Temperature 374.15 °C
2. Pressure 22.129 MPa
3. Specific volume 0.00326 $m^3.kg^{-1}$
4. Specific enthalpy 2100 $kJ.kg^{-1}$
5. Specific entropy 4.430 $kJ.kg^{-1}.K^{-1}$

2.7 Emissions, desulphurization, and reducing NO_x

Emissions resulting from the combustion of fossil fuels are involved in the formation of the greenhouse effect. They can be further oxidized in the atmosphere, or descend back to the surface of the Earth via water. Gaseous chemical compounds in flu gas together with particulate dust primarily cause the formation of acid rain , thereby increasing the acidity of the soil and water resources. They also cause direct and indirect damage to the human body.

Formation of sulfur oxides – sulfur dioxide SO_2 is formed in the burning of fossil fuels through the oxidation of sulfur by the oxygen in the air.

$$S \text{ (fuel)} + O_2 \text{ (air)} \rightarrow SO_2 \text{ (flu gas)} \quad (2.8)$$

About 1-2% of the SO_2 undergoes further oxidation in a boiler to SO_3, sulfur trioxide, which is also formed, however, by oxidation in the atmosphere:

$$2\ SO_2 \text{ (combustion products)} + O_2 \text{ (air)} \rightarrow 2\ SO_3 \text{ (flu gas)} \quad (2.9)$$

$$SO_3 \text{ (atmosphere)} + H_2O \rightarrow H_2SO_4 \text{ (sulphuric acid)} \quad (2.10)$$

Formation of nitrogen oxides – flu gas from a boiler consists of about 95% of nitrous oxide NO and 5% of nitrogen dioxide NO_2.

$$N \text{ (fuel)} + \tfrac{1}{2}\ O_2 \text{ (air)} \rightarrow NO \text{ (flu gas)} \quad (2.11)$$

Oxides NO_x can form through the oxidation of:

- Nitrogen in the air entering into the boiler fireplace
- Nitrogen that is chemically bound in the fuel
- Nitrogenous intermediates in gas phase (e.g. fluidized-bed boilers)

Formation of CO_2 and CO – is the essence of the combustion of fossil fuels while releasing heat energy

$$C\ (fuel) + O_2\ (air) \rightarrow CO_2\ (flu\ gas) \qquad (2.12)$$

$$C\ (fuel) + \tfrac{1}{2}\ O_2\ (air) \rightarrow CO\ (flu\ gas) \qquad (2.13)$$

CO_2 is involved in the creation of the greenhouse effect, while CO is toxic and damaging to the respiratory and circulatory system of organisms.

Fly ash – solid residues of combustion, which are transported by chimney discharge to various distances, where they cause the pollution of air and the environment. Together with absorbed SO_2 it can accumulate in the respiratory tract and damage it.

Radioactivity – neither in the Czech Republic nor in other countries are there statutory limits for emissions of radioactive nuclides from power plants burning fossil fuels. If measurement of radioactive nuclides occurs at these power stations, the measured values are usually compared with the observed and allowed values of radioactivity escaped from nuclear power plants. The permissible boundary for the escape of the radionuclides of inert gases from nuclear power plants with a power output of 1000 MW is $5.9 \cdot 10^{14}$ Bq/year or their maximum permissible concentration of $1,1 \cdot 10^{4}$ Bq/m^3. Results of measurements of the leakage of radioactivity at more than 400 nuclear power plant blocks did not exceed the value of $1 \cdot 10^{13}$ Bq/year.

Measurements carried out in the Czech Republic indicate that the total emission of radioactivity in comparison with radioactive leaks from nuclear power plants was several orders of magnitude less than the maximum permissible levels for these leaks. The measurements showed that the radioactive nuclides concentrate during the combustion process on the solid residues of burning, and do so all the more the greater the surface area of the residue. From this point of view, the most dangerous is fine fly ash and the least dangerous is crude fuel. It is therefore desirable to attain the highest possible efficiency of separation of the solid residues after the combustion of fossil fuels.

Desulfurization

The formation and concentration of sulfur oxides in the flu gas of boilers depends on the sulfur content in the fuel. The essence of flu gas desulfurization is chemically binding the sulfur oxide SO_2 resulting from the combustion of sulfur in the fuel to solid calcium sulfate $CaSO_4$ (gypsum). This applies only to some methods.

Desulfurization can be dealt with as follows:

- Before combustion – fuel modification, coal gasification, selection and mixing of fuels
- In the course of combustion – dosing of additives into the fuel or the combustion chamber, combustion in a fluidized bed, so-called direct desulfurization
- After combustion – desulfurization of flu gas

Desulfurization processes are classified according to the manner of capturing the SO_2 into those that are regenerative, cyclic (with regeneration of the active substance) and those that are irreversible, non-cyclic or one-off, i.e., without regeneration of the active substance. Another classification is according to the phase at which the SO_2 is captured, i.e.. processes that are wet, semi-dry or dry.

Methods:

Dry limestone methods – desulfurization of flu gas with finely ground limestone in boilers and desulfurization of flu gas in the fluidized layer The necessary high fineness of the grind, problems with using and storing waste, low efficiency of desulfurization

Wet limestone wash – it is essentially washing out SO_2 and other acidic ingredients (HCl, HF) from the flu gas with a limestone suspension and their subsequent neutralization and creation of the final product – energogypsum – through oxidation and crystallization. Energogypsum is used in the manufacture of gypsum plaster, gypsum board, gypsum foam, etc.

Semi-dry desulfurization method – the principle consists in spraying a water suspension of sorbent into the flue gas stream. This causes a reaction to occur between the water suspension and the acid components of the flu gas (SO_2, SO_3, HCl, HF). The sorbent is most often burnt lime or calcium hydroxide.

In the case of dry and semi-dry methods the output basically power plant fly ash, from which gypsum cannot be separated. Toxic substances are bound in the fly ash which may escape into the groundwater or return back into the river. Stabilization by adding lime and water, thus forming a solid product that does not release toxic substances. Usage as mine fill, road substrate, etc.

Reduction Of NO_x

Nitrogen oxides resulting from the combustion of fossil fuels are irritating to both plant and animal tissue, participate in the formation of acid rain and under adverse conditions co-create smog.

Primary measures to reduce the production of NO_x

Primary measures are supposed to reduce the formation of NO_x during the combustion process. This can be achieved by:

- Decreasing the combustion temperature
- Reducing the O_2 concentration in the flame
- Shortening the period of that reactive substances remain in areas with favorable conditions for the formation of NO.

Secondary measures for reduction of NO_x production

Secondary measures consist of the removal of already formed NO_x from the flue gas. It is used mainly in countries that use fuels with a high calorific value. In the Czech Republic secondary measures are less significant, with some exceptions. This is due mainly to the technology of preparation and the combustion of lower quality brown coal, which positively affects the lower formation of NO_x.

Selective non-catalytic reduction – Reduction of NO_x with ammonia or urea - low efficiency. For temperatures of 900 to 1050 °C.

Selective catalytic reduction – by using a catalyst the reactions proceed at the lower temperatures of 300 to 400 °C.

Simultaneous methods – the removal of both SO_x and NO_x is possible. They can be divided into dry and wet washings. Their development is ongoing and they are highly effective.

? *Review Questions*

2) Draw a basic schematic diagram of a condensing power plant and describe each of its elements! (3 points)

2) What types of boilers are used in thermal power plants? Draw and briefly describe the the different types! (2 points)

3) Describe the principle of cogeneration and write the efficiency equation! (2 points)

4) Define the term dryness of wet steam. (1 point)

5) List the impurities (in various states of matter) accompanying the production of electrical energy in thermal power plants and list the methods of their elimination! (2 points)

Summary

New findings and concepts:

- the principle of cogeneration
- The principle of operation of a thermal (steam) power plant
- The significance of individual equipment in thermal power plants
- The impact of thermal power plants on the environment

Key to questions

1) Draw a basic schematic diagram of a condensing power plant and describe each of its elements! (3 points)

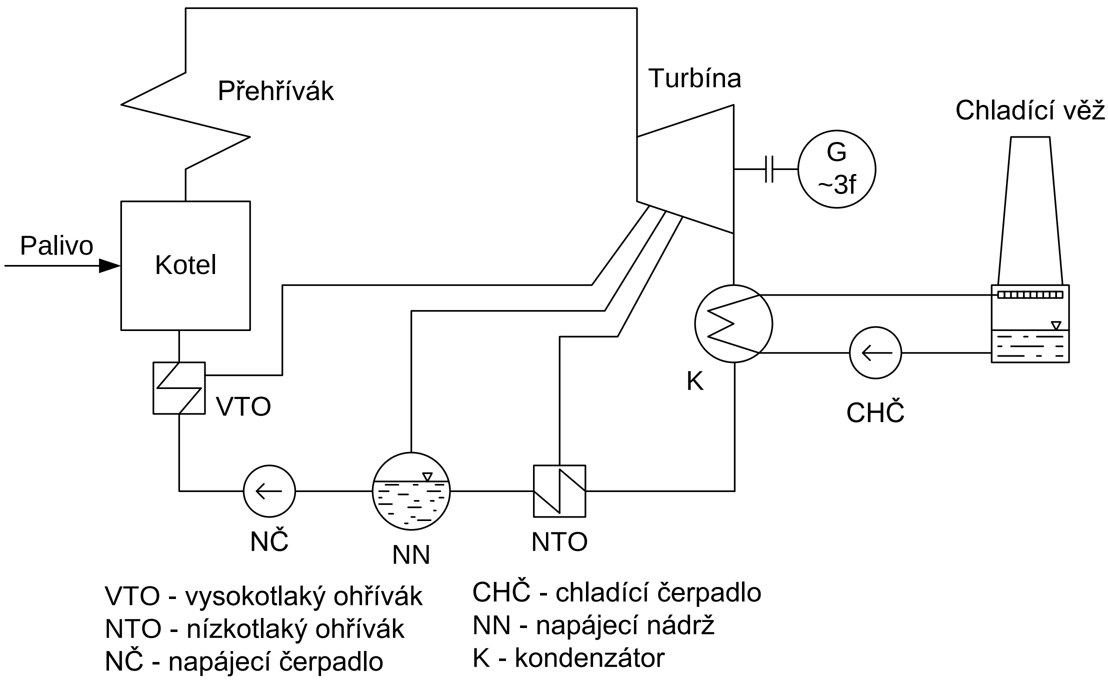


Fig. 2.1 Schematic diagram of a condenser power plant

2) What types of boilers are used in thermal power plants? Draw and briefly describe the the different types! (2 points)

See page 5.

3) Describe the principle of cogeneration and write the efficiency equation! (2 points)

Cogeneration **-** the common production of electricity and heat in diesel or gas combustion engines

The use of internal combustion engines for the combined production of electricity and heat enables the reduction of consumption of primary energy sources and significantly reduces harmful emissions. The efficiency achieved in heating applications reaches up to 90%. In addition to engines running on natural gas, there are engines available that run on biogas, landfill gas, etc.

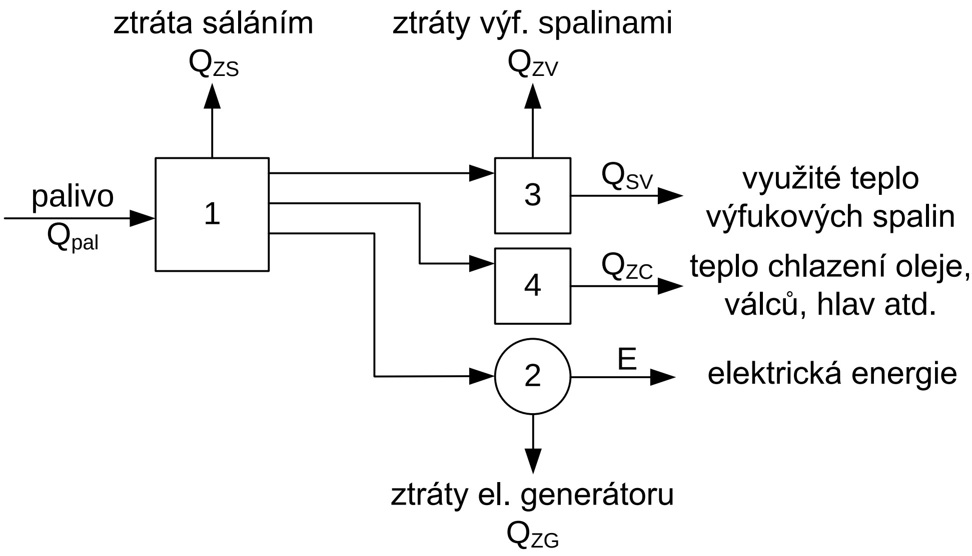


Fig. 2.2 Utilized heat and losses during cogeneration

Experience shows that the greatest influence on the economy of operation of cogeneration units with combustion engines is the price of the electricity sold to the network (if it is not consumed on site) and the duration of utilization of the installed power source.

The fundamental equation describing the cogeneration can written as follows:

Electrical efficiency $$\eta_e = \frac{E}{Q_{pal}} \quad [-] \tag{2.1}$$

Thermal efficiency $$\eta_t = \frac{Q_{ZC} + Q_{SV}}{Q_{pal}} \quad [-] \tag{2.2}$$

Overall thermal efficiency $$\eta_{tc} = \frac{E + Q_{ZC} + Q_{SV}}{Q_{pal}} \quad [-] \tag{2.3}$$

4) Define the term dryness of wet steam. (1 point)

Dryness of wet vapor x – expresses the quantity of saturated vapor m´´ [kg] in one kg of wet vapor m ´.

$$x = \frac{m''}{m' + m''} \quad [kg/kg] \tag{2.5}$$

5) List the impurities (in various states of matter) accompanying the production of electrical energy in thermal power plants and list the methods of their elimination! (2 points)

NO_x, SO_x, CO_2, CO, fly ash and radioactivity

The elimination of these impurities is set out on page 29.

3. NUCLEAR POWER PLANTS

Study Objectives

- **Understanding the basic principles of the fission of atomic nuclei**
- **Knowledge of the structure and the principle of operation of nuclear power plants**
- **Knowledge of the principles of nuclear safety**

Keywords

Atomic core, uranium, fission chain reaction, reactor, radioactive radiation, nuclear fuel, radioactive waste

Required study time

300 minutes

Text to Be Studied

Introduction

Nuclear power today produces around 17% of world electricity production. Nuclear energy is used for the production of electricity in 31 countries. Currently in operation are about 440 nuclear power blocks, which annually produce 2,300 TWh of electricity. Another 40 blocks are in the process of construction, and permanent growth can be counted on according to the scenario of the International Atomic Agency IAEA. One of the most important benefits of the use of nuclear energy in the production of electrical energy is the reduction of emissions of carbon dioxide, which to a great extent contribute to the greenhouse effect. In 1996, global production of CO_2 was 22,700 Mt. Nuclear energy currently reduces this amount by more than 700 Mt of CO_2 per year. In addition, the production of electricity from the nucleus helps to limit other harmful atmospheric emissions, not only of gases such as sulfur dioxide, nitrogen oxide, and others, but also solid substances and radioactive elements contained in fuel.

Nuclear power is clean – it does not produce CO_2, SO_2, NO_x or fly ash, it does not consume oxygen.

Nuclear power is compact – it produces stably in any weather.

Nuclear energy consumes a minimum amount of fuel – one gram of uranium gives out as much energy as a ton of coal or crude oil. In addition, recycling is well mastered.

Nuclear power is stable – the price of nuclear fuel is not subject to sudden price fluctuations.

Nuclear energy produces minimum waste – approximately a million times less than the waste from the combustion of crude oil, coal, or natural gas. In addition, the waste can be used again.

Nuclear energy is cheap – high investment costs, low operating costs and long service life.

Nuclear power is responsible – as the sole source of energy that also counts into the costs of its product the fees for future liquidation of waste and equipment.

Nuclear energy is safe – two accidents over more than a half-century of operation of nuclear power plants with a total loss of 4,000 lives.

Nuclear power plants (NPP) reduce air pollution, small amount of fuel - small demands on transport - location close to consumption - improved transmission ratios.

Thermal energy from NPP, unlike conventional thermal power plants where it is gained through combustion, may be released in the course of a nuclear reaction in two ways:

- By splitting the atoms of certain heavy elements (U, Pu) - **fission reaction**.
- By fusion-synthesis of certain light elements (atoms of heavy hydrogen) at an extremely high-temperature - **thermonuclear reaction**.

Another difference is the problem of nuclear safety and the transportation and storage of nuclear fuel (Pool 6-7 years, buffer stock 20-30 years, permanent storage).

Gross electricity production in 2005 versus 2004 was approximately 2% lower (82,578.5 GWh). Of this total, 63.1% was produced at steam power plants, 29.9% at nuclear power plants (the installed capacity of NPP is 21.6%), 3.7% at hydroelectric power plants and 3.2% at steam-gas and gas power plants.

Tab. 3.1 Gross electricity production in 2005 (Note: SPP – Steam power plants, SGPP – Steam-gas power plants, GCPP – Gas and combustion power plants, HPP – Hydroelectric power plants, NPP – Nuclear power plants, WPP – Wind power plants, SPP – Solar power plants)

	Výroba elektřiny brutto [GWh]	Instalovaný výkon [MW]
PE		
spalováním černého uhlí	*6 382,0*	
spalováním hnědého uhlí	*43 480,4*	
spalováním biomasy	*552,3*	
spalováním olejů	*236,4*	
spalováním zemního plynu	*313,1*	
spalováním ostatních plynů	*1 053,9*	
ostatní	*119,1*	
Celkem PE	**52 137,2**	**10 663,8**
PPE + PSE		
spalováním zemního plynu	*784,0*	
spalováním bioplynu	*85,4*	
spalováním ostatních plynů	*1 779,1*	
ostatní	*16,6*	
Celkem PPE + PSE	**2 665,1**	**800,4**
VE	**3 027,0**	**2 166,0**
JE	**24 727,6**	**3 760,0**
VTE	**21,3**	**22,0**
SLE	**0,1**	**0,1**
Celkem	**82 578,5**	**17 412,2**

3.1 Brief Historical Overview

1895 German physicist Wilhelm Conrad Röntgen (1845-1923) discovered x-rays, for which in 1901 he received the first Nobel Prize in physics ever awarded.

1896 French physicist Antoine Henry Becquerel (1852-1908) discovered the natural radioactivity of uranium ore (pitchblende). In 1903 he received the Nobel Prize in physics for this discovery of natural radioactivity.

1897 British physicist of New Zealand origin Ernest Rutherford (baron Rutherford of Nelson, 1871-1937) differentiated, on the basis of various penetration, alpha and beta rays. In 1908, he received the Nobel Prize in Physics for research in the field of radioactive transformation of the elements and the chemistry of radioactive substances.
J. J. Thomson discovered electrons and found that they are parts of the atoms.

1898 Marie Curie – Skłodovská (1867-1934), French physicist and chemist of Polish origin, and her husband Pierre Curie (1859-1906), French physicist and chemist, discovered the radioactive elements polonium and radium. In 1903, they together received the Nobel Prize in Physics for research on natural radioactivity. Marie also received the Nobel Prize for Chemistry (1911) for the discovery of radium and polonium, the isolation of radium, research of its properties and compounds.

1903 Ernest Rutherford with Frederick Soddym (1877-1956), developed the theory and formulated the law of radioactive transmutation of elements.

1910 Marie Curie – Skłodowská and her husband made pure metal radium from Jáchymov pitchblende.

1911 Ernest Rutherford proposed the planetary model of the atom.

1919 Ernest Rutherford realized the first artificial radioactive transmutation of an element by bombarding the nuclei of an isotope of nitrogen with alpha particles.

1942 The first controlled chain reaction took place in an experimental nuclear reactor, which was located under the university stadium Stagg Field in Chicago. The construction of the reactor and the experiment were led by the Italian physicist Enrico Fermi (1901-1954), who started the controlled chain reaction with his own hand. Men stood all around on the reactor and in their hands held buckets with a solution of cadmium salts in case that the reaction got out of control. The egg-shaped reactor with a diameter of 4 meters with 6 tons of fuel ran for 20 minutes.

1954 The first nuclear power plant was put into operation. The power output of the NPP, which was located in Obninsk in the former USSR, amounted to 5 MW.

3.2 Basic concepts from nuclear physics

- **Atom** - a particle consisting of a positively charged nucleus and negatively charged electrons that circulate around, so that the atom as a whole is neutral. An atom has a diameter measuring in the order of 10^{-10} m.
- **Atom nucleus** -is the central part of an atom, with dimensions in the order of 10^{-14} m, which concentrates in itself almost all of the mass of the whole atom. It consists of positively charged protons (*Z*) and neutral neutrons (*N*), which are collectively referred to by the term nucleon ($A = Z + N$). These particles are bound to each other by strong attractive nuclear forces.
- **Electron cloud** - contains electrons in different shells (orbitals). The number of electrons in the last shell determines the chemical properties of the elements.
- **Electron** - (e) is a particle of the electron cloud with the mass of 0.00062 m_u and carrying an electric charge of $-1.609 \cdot 10^{-19}$ C.
- **Neutron** - (n) is a particle of the atomic nucleus without a charge with the mass of 1.00897 m_u ($1.6747 \cdot 10^{-27}$ kg).
- **Proton** - (p) is a positively charged particle of the atomic nucleus with the mass of 1.00751 m_u ($1.6729 \cdot 10^{-27}$ kg). The number of protons in the nucleus equals the number of electrons in the electron cloud, so the atom is outwardly neutral.
- **Nucleons** - the particles contained in the nucleus, i.e., p i n.
- **Atomic (proton) number *Z*** - is the number of protons p in the nucleus of an atom.
- **Mass number *A*** - is the number of nucleons (protons and neutrons) in the nucleus and at the same time is the atomic weight rounded off to nearest whole number. The number of neutrons in the atomic nucleus is A - Z.
- **Nuclide** - A set of atoms that are the same, which have a clearly determined same 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 that have the same atomic number Z, but various masses A. For example, hydrogen ${}_1H^1$ - light hydrogen (protium), ${}_1H^2$ - heavy hydrogen (deuterium, D), ${}_1H^3$ – (tritium, T); uranium ${}_{92}U^{238}$, ${}_{92}U^{235}$, ${}_{92}U^{234}$.
- **Radioactive substance activity -** is a quantity determined by the number of radioactive transmutation ongoing in a substance per unit of time. If 1 transmutation occurs in a

substance in 1 second, it has the activity of 1 Becquerel (Bq). Due to the fact that this unit is very small, we are more likely in practice to meet up with units kBq, GBq, MBq, etc.

- **Radioactivity** - is the property of some atoms to spontaneously decay (transmute) into simpler atoms while simultaneously emitting electromagnetic radiation or particles.
- **Ionizing radiation** – this term covers radiation emitted by radioactive substances, x-ray radiation (X rays), radiation created in particle accelerators and neutron radiation. It is called "ionizing" because during its passage through material it ionizes the surrounding atoms, either directly, if the radiation is made up of electrically charged particles, or indirectly, in the case of neutral particles. Sources of ionizing radiation are either natural or artificial.
- **Radionuclide** - is an unstable nuclide subject to spontaneous radioactive transmutation.
- **Radioisotope** - is an unstable isotope subject to spontaneous radioactive transmutation.
- **Radioactive radiator** – is a substance (solid, liquid or gaseous), which is radioactive, thus almost all substances. Radioactive radiators are characterized by their activity. We classify them into open and closed, according to radiation into its surroundings.
- **Labeling of atoms -** e.g. $_{92}U^{238}$, $_{Z}U^{A}$.
- **Atomová mass unit** (amu) m_u - is equal to 1/16 of the mass of the main isotope of carbon C^{16} ($m_u = 1.66044 \cdot 10^{-27}$ kg).

3.3 Binding energy

Exact measurements on mass spectrographs showed 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 amount of the **mass defect** (deficit). During the formation of the nucleus from free nucleons, they are affected by mutual attractive nuclear forces and in their convergence they perform work, which will be reflected in a decline in the total energy of the set of nucleons. We must supply the same amount of energy while splitting the nucleus. The amount of energy needed to split the nucleus 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 constant of the equivalence of mass and energy.

The energy corresponding to the mass defect 1 m_u:

$E = 1.66044 \cdot 10^{-27} \cdot (2.99792456 \cdot 10^{8})^{2} = 1.492329 \cdot 10^{-10}$ J

1 eV = $1.602 \cdot 10^{-19}$ J (energy acquired by the electron when it passes between two places of an electric field with a voltage of 1 V)

$E = 931.48 \cdot 10^{6}$ eV = 931 MeV

At a mass deficit equaling 1 a.j.h. the energy released was 931 MeV.

For the possibility of utilizing at least part of the binding energy of nuclei, the total binding energy is not decisive, but above all the binding energy per nucleon $e_j = E/A$. In releasing energy through nuclear synthesis, the nuclei that are fused have small energy e_j, while in fission, nuclei with great energy e_j are utilized.

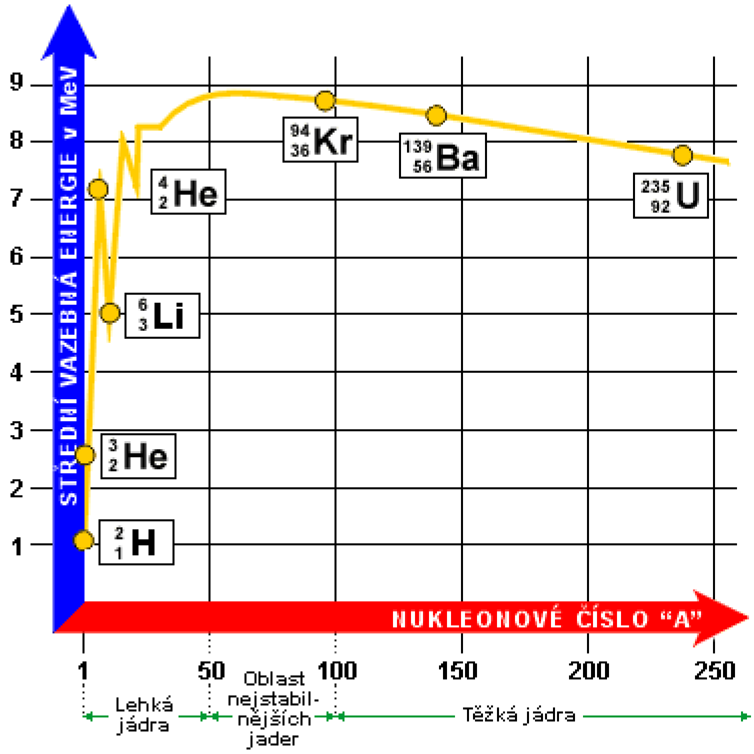


Fig. 3.1 The dependence of the average binding energy of nucleons on the number of nucleons

3.4 Radioactivity

3.4.1 Natural Radioactivity

Spontaneous decay of nuclei is a form of radioactivity in which a heavy nucleus breaks up into two or three lighter fragments (splinters). At the same, one or more neutrons fly out. It is the manifestation of an intra-nuclear force instability, which is the result of an excess of protons or neutrons in the nucleus, or the mass and complexity of the nuclei of atoms, wherein this state does not allow them to remain stable.

Manifestations of radioactivity include α decay, β decay, K capture, photon radiation γ, spontaneous fission of heavy atomic nuclei and the emission of neutrons or photons from the nucleus. Radioactivity is not dependent on temperature and pressure.

The impermanence of radioactive substances is characterized by the **half life** T - the period in which will have decayed one half of the radioactive nuclei present at the beginning of the decay. It is a characteristic constant for a given radionuclide.

There exists a theory that all substances in the world are radioactive. Only their half-life is so long that we are not able to measure it. The radioactivity of every radionuclide therefore decreases over time. We say that the radionuclide "is dying out".

3.4.2 Types of Decay

- **α-decay** – occurs in heavier atoms. Escaping from the radioactive substance are particles α, or the nuclei of helium atoms ${}_2He^4$ with a half life of T = 10^{-4} s - 10^{17} years. Radiation is emitted by most of the natural radioactive elements.
- **β decay** - T = 10^{-2} s - 10^{15} years
    - Negatron emission (electrons) β^-, a transmutation of a neutron into a proton occurs inside the nucleus, in which an electron is emitted,
    - a positron emission β^+, while inside the nucleus the transmutation of the proton into a neutron occurs.
- **Electron capture** - the capture of electrons from the inner electron spheres by the nucleus.
- **Radiation of particles γ** (photon**)** - in the decay of α and β there also occur emissions of electromagnetic radiation with a very short wavelength, whereby the radiation equalizes the energy differences between the various energy states of the atom nucleus.

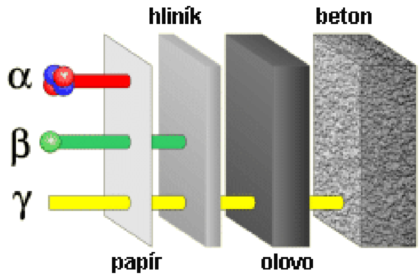


Fig. 3.2 The penetration of particles through different materials

3.4.3 Artificial radioactivity

Artificial radioactive substances are formed by the action of external particles (mostly neutrons) on isotopes of natural elements - creating radioactive elements not existing in nature.

3.5 Nuclear reaction

During the fission reaction of an atom nucleus, an average of two to three neutrons are released, which may cause the splitting of further nuclei. This is how a fission "chain"reaction forms.

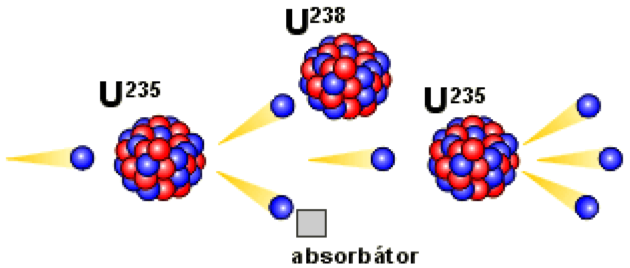


Fig. 3.3 Nuclear fission of uranium

To invoke a reaction of nuclei with other nuclei or particles, the energy of the particles falling upon the nucleus of the target substance must be great enough to overcome the Coulomb forces between the particles and nucleons in the nucleus.

Invoking reactions:

- **Bombarding** of various substances with light nuclei, i.e., protons, neutrons, or particles α accelerated in cyclotrons, experimentally even e, γ and x.

- **Increasing temperature** to 10^7 - 10^8 °C - the particles have sufficient energy to overcome mutual electrostatic repulsion. This is the thermonuclear reaction taking place inside stars and the source of their enormous energy.

Practically, however, only the interaction of neutrons with atomic nuclei is used in nuclear reactors. A neutron has no electrical charge so that while approaching the atomic nucleus it does not need to overcome repulsive electrostatic forces, and therefore even neutrons with low kinetic energy can be used.

The following interactions occur in a nuclear reactor between the neutron and the nucleus of the atom:

- **Neutron scattering** - after impact with the nucleus, the neutron bounces off and flies ahead in a different direction. If the total kinetic energy of both particles remains unchanged, we are talking about elastic scattering, which causes the slowing down of neutrons (slow, thermal neutrons). The energy of slow neutrons at 20 °C is 0.025 eV, while the energy of fast neutrons is greater than 1.1 MeV. If, however, a part of the energy changes into the excitation energy of the nucleus, we are talking about inelastic scattering. Part of the energy of the nucleus is emitted by radiation γ and the nucleus goes back to its original state.
- **Neutron capture** (uptake, absorption) - with the emission of a charged particle or photon. The neutron is absorbed by the target nucleus which emits the particle γ. For example, the impact of a neutron on the nucleus of U in the fuel:

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

The resulting isotope $_{92}U^{239}$ decays with a half life of 23 minutes (it emits an electron) into an isotope of neptunium and this with T = 2.3 days into plutonium, which is a valuable secondary nuclear fuel.

- **Nuclear fission** is the most important reaction - the heat energy from the reaction is transferred at the heat exchanger. The neutron is absorbed by the nucleus, which then splits into 2 parts - fragments, and then neutrons are released. The progress is accompanied by the emission of photons and particles β. Nuclei are fissionable only by neutrons of certain energies - effective cross-section.

Many more other reactions also occur in the reactor, but only the reliably operated and controlled fission can be utilized for energy production.

3.5.1 Effective cross-section

The effective area of the nucleus for the relevant reaction. The probability of reaction of a neutron with the nucleus depends on the area of the atom, the number and type of target nuclei and also on the speed of neutrons (seeFig. 3.4).

$$\sigma = \frac{C}{Na \cdot I} \ (m^2)$$

Where C - the number of nuclei hit by neutrons

Na - number of atoms on 1 m^2

I - The number of neutrons

σ is called the **microscopic** effective cross-section for the given reaction (σ_e - elastic scattering, σ_i - inelastic scattering, σ_r - absorption, σ_f - fission). Indicated are the specific speed (energy) of a neutron in m or, as the case may be, in barns, where 1 bn = 10^{-28} m^2.
For fast neutrons σ is small and for slow neutrons σ is large.

Increasing the effective cross-sectional area decreases the required amount of fissionable material.

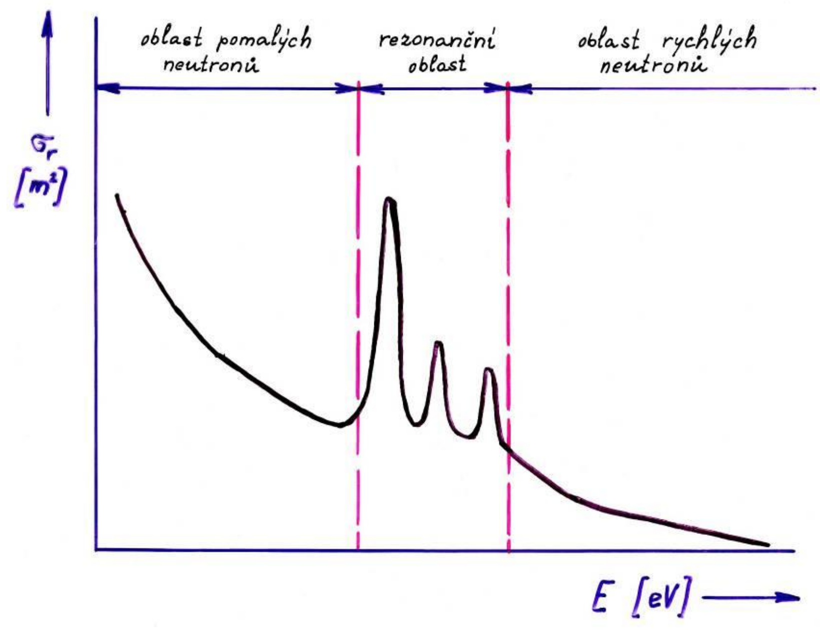


Fig. 3.4 The dependence of neutron absorption by isotopes on the energy of neutrons

Tab. 3.2 The effective cross-section of uranium nuclei for thermal neutrons (bn)

	σ_f	σ_r	σ_e
Natural uranium	3.92	3.5	8.2
U^{235}	590	108	8.2
U^{238}	0	2.8	8.2

In a practical determination, the weakening of the flow of neutrons in the passage through a substance layer is also considered.

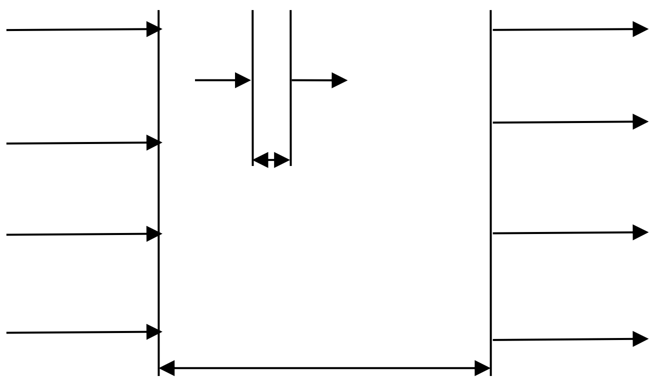


Fig. 3.5 Weakening of the neutron flow

Onto the surface of a layer of substance with the thickness x falls I_0 neutrons. If the number of nuclei of atoms is N in m^3, then in the layer dx there will be N · dx neutrons per m^2, which corresponds to the level of the considered amount of Na, and therefore N · dx will be the number of nuclei in this layer that will participate in the reaction. Then the relative loss of neutrons passing through a layer dx will be:

$$\frac{dI}{I} = N \cdot dx \cdot \sigma$$

$$I_x = I_0 \cdot e^{-N \cdot \sigma \cdot x}$$

Where I_0 - number of impacting neutrons

I_x - Number of exiting neutrons

$N \cdot \sigma = \sum$ (m^{-1})is the effective **macroscopic** cross-section, N - number of nuclei in m^3.

$N \cdot dx \cdot \sigma$ indicates the probability of neutron absorption by layer x.

3.5.2 Fission of the nuclei of uranium atoms - released energy

The neutron transfer energy to the nucleus of the atom and the nucleus goes into an excited state -the nucleus has an ellipsoidal shape and begins to pulse, if the energy is sufficiently great, the firmness of the nucleus is compromised, the Coulomb forces increase, splitting of the nucleus occurs - 2.5 ± 0.1 neutrons and radiation particles are released.

$${}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{92}U^{236} \rightarrow {}_{Z1}F^{A1} + {}_{Z2}F^{A2} + 2\ {}_{0}n^{1}$$

for example

$${}_{92}U^{235} \rightarrow {}_{38}Sr^{95} + {}_{54}Xe^{139} + 2\ {}_{0}n^{1}$$

The relative atomic mass of Sr, Xe and 2 n is 235.918 m_u, from which follows the mass defect $\Delta m = 236.133 - 235.918 = 0.215\ m_u$.

Energy of the splitting of 1 uranium nucleus:

$$E = 931.48 \cdot \Delta m = 931.48 \cdot 0.215 = 200\ \text{MeV}$$

The energy needed for the splitting of 1 nucleus U is 200 MeV smaller than the energy needed for the splitting of both of the resulting fission products.

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

The energy released by fission:

-Kinetic energy of a light fragment	100 MeV
-Kinetic energy of a heavy fragment	70 MeV

- Energy of fissile neutrons	5 MeV
- Energy of instant radiation γ	5 MeV
-Energy of the radioactive radiation of fragments β and γ	12 MeV
- Energy of neutrinos	8 MeV
Total	200 MeV

The kinetic energy of fragments is manifested as heat, the energy of γ radiation is quickly dissipated and the energy of the particles β from fissile waste products is gradually released in the course of their radioactive decay. The energy of neutrinos cannot be used.

Reactor thermal power is determined by the average number of thermal neutrons which pass through the area of 1 cm^2/s of the active zone. The amount is called the neutron flow and is approximately 10^{12} - 10^{14} neutrons cm^2/s.

The number of atoms in 1 kg of U^{235}:

$$N_{235} = \frac{6{,}0225 \cdot 10^{26}}{235} = \frac{1}{m_{235}} = \frac{1}{235 \cdot 1{,}66 \cdot 10^{-27}} = 2{,}563 \cdot 10^{24} \quad (\text{atomů} \cdot kg^{-1})$$

The energy released in the fission of 1 kg U^{235}:

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

$E = 22.81 \cdot 10^{6}$ kWh

The thermal power generated in the fission of 1 kg in 24 h:

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

We can get approximately 1 MWd (megawattday) from 1 g of U^{235}.

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

3.5.3 Controlled chain reaction

A fission reaction proceeds in the fuel of a nuclear reactor, which tends to be uranium oxide, a mixture of oxides of uranium and plutonium, or plutonium. The nucleus of the atom of a fissile element (uranium, thorium, plutonium) may, after an impact from a flying neutron under favorable circumstances, split apart. Created are two new nuclei, fission products, and two to three new neutrons. Fission products have very high kinetic energy, collide with the neighboring nuclei and thus heat the surroundings. This creates a high temperature, which we can use for power generation. The new neutrons fly further and may split other nuclei. A chain reaction starts up, the basis of nuclear power generation.
The isotope uranium 235 spontaneously splits even in nature into two lighter nuclei and one or more free neutrons. Neutrons from spontaneous fission, however, would not be sufficient to start a chain reaction in a reactor. An external neutron source is used to start up a reactor. A neutron has a high level of energy. The likelihood that during its flight it will split the nucleus of isotope uranium 235 is small, and in its collision with it will probably just bounce off like a ball bouncing off a wall. The neutron bounces off the nuclei without transferring a part of its great energy to them, and merely changes its direction of flight. For it to be able to split nuclei, we have to slow it down. The best way to slow down the neutron is a collision with a nucleus of approximately the same size, for example with the nucleus of the hydrogen atom, which consists of a single proton. A substance that slows down neutrons is called a moderator. A fast neutron was changed into a slow neutron. It again collides with the nucleus of uranium 235. This time, however, it does not bounce off. With a high probability it will split the nucleus apart and a fission chain reaction will be initiated. In order to prevent the reaction from developing in an unrestrained and uncontrolled manner, an absorber is present in the reactor which absorbs excess neutrons.

The fissile material in the fuel of so-called slow reactors, which are the most widespread in the world, is the isotope uranium 235. The reason is that this isotope is characterized by a rising probability of fission as the speed (energy) of the neutrons decreases.

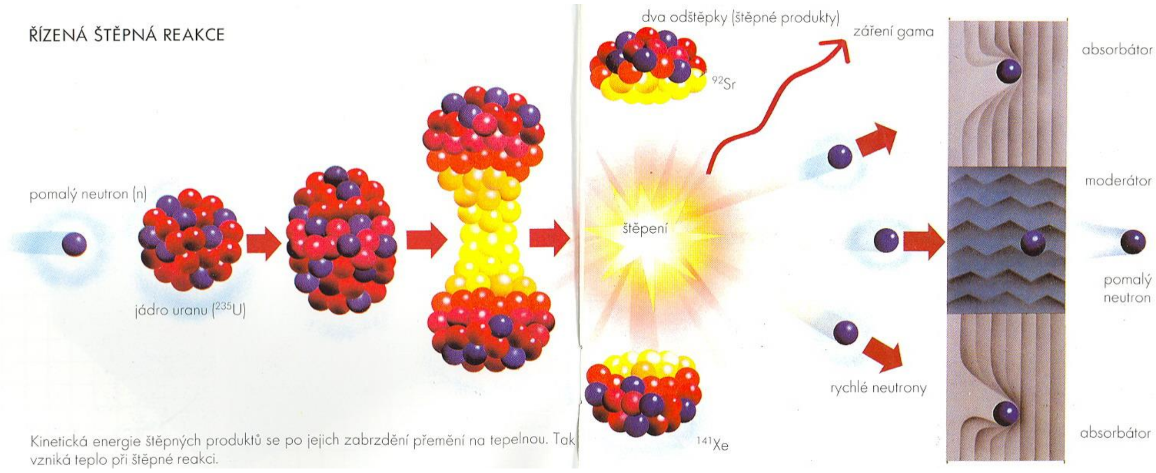


Fig. 3.6 Controlled fission reaction

According to the course of the fission chain reaction, we distinguish three basic states in the reactor:

1. In the subcritical state, the density of the absorber is so high that the neutrons generated in the fission reaction are fully absorbed and cannot cause the fission of any more nuclei. The chain of the fission reaction is severed and the reaction ceases. In practice, such a state in the nuclear reactor is created through the introduction of control and emergency rods with the absorber into the active zone of the reactor. This is done in cases where we want to reduce the power of the reactor or to decommission it from operation.
2. In critical condition, the density (the number of inserted rods) of the absorber and fuel is such that from the two to three neutrons resulting from the fission of the fuel, always just one initiates another fission reaction. In such a case, the chain reaction still continues - it does not grow, nor is it extinguished. This condition corresponds to the normal operation of the reactor at constant power output.
3. If a supercritical state occurs, the fission nuclear reaction grows, because the number of neutrons splitting nuclei is also growing. Such a condition is necessary for increasing the power of the reactor.

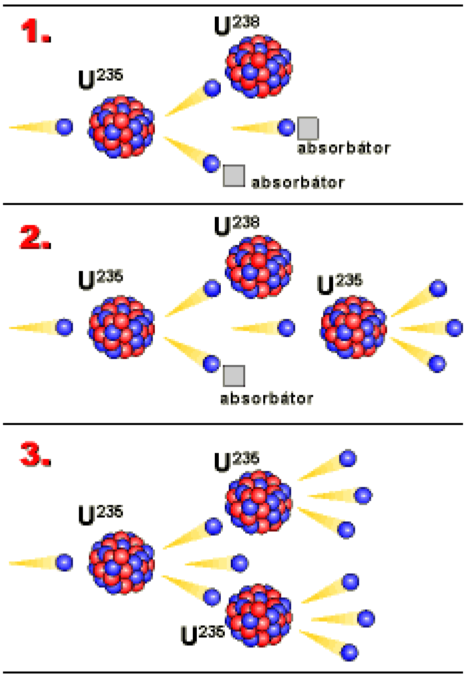


Fig. 3.7 Basic states of a reactor

For practical utilization of nuclear energy, we have to maintain the chain reaction so that after its commencement at a small number of nuclei it spreads to the whole of the active zone of reactor, continues in it constantly and without any external intervention is not extinguished, i.e., so that the number of newly formed neutrons will not be smaller that the number of neutrons in the previous generation. The ratio of the number of neutrons in one generation to the number of the previous generation is called the **multiplication factor K**. For self-sustaining maintenance of the chain reaction, K must be ≥ 1. If K < 1, the reaction ceases, at K > 1 the power output of the reactor grows.

If K > 1, the number of neutrons for each neutron increases by (K - 1) neutrons in each generation. So that if there were n neutrons, their number increases in 1 generation to n · (K-1). The increase over a specific period of time is determined by the equation:

$$\frac{dn}{dt} = \frac{n \cdot (K-1)}{\tau} = \frac{n \cdot K_{ex}}{\tau}$$

$K_{ex} = K - 1$ ... Excess reactivity

τ ... the mean value of the time interval between two successive generations of neutrons.

After integration we get:

$$n = n_0 \cdot e^{\frac{tK_{ex}}{\tau}}$$

n_0 ... the number of neutrons at the beginning of the reaction

n ... the number of neutrons over time t

If K > 1, the number of neutrons grows exponentially over time. After achieving the desired power output, we decrease the multiplication factor to K = 1 in order for the chain reaction to continue at constant power, which is realized by lowering the control rods in the active zone (the control rod is made from a substance with a large absorbent effective cross section, e.g., from cadmium, hafnium or boron steel. During the full immersion of the control rods, K_{ex} is negative and the number of neutrons will exponentially decrease until the reaction stops. The state at K = 1 is called the **critical state of the reactor**, at K > 1 the state of the reactor is **supercritical** and at K < 1 **subcritical.**

We will illustrate the determination of the conditions for achieving the multiplication factor value of K ≥ 1 in an example of a reactor for thermal neutrons with the use natural uranium. For simplicity, we will ignore the escape of neutrons from the reactor, which assumes a reactor with infinitely large dimensions.

In the splitting of U235 by a thermal neutron, the number fast neutrons formed is υ = 2.5, and because not all of the neutrons caught in the fuel will cause fission, the median number of fast neutrons released in fission will be less than υ:

$$\eta = \upsilon \frac{\sigma_f}{\sigma_r}$$

σ_f ... the effective cross-section of fission with slow neutrons

σr ... the effective cross-section of the absorption of slow neutrons

During the capture of n slow neutrons, there are n· η fast neurons released. Before a portion of the fast neutrons slows down, the others cause fission in U235 and mainly in U238, which increases the number of fast neutrons somewhat to the number n· η· ε

ε > 1 is the **multiplication factor of fast neutrons**.

$$\varepsilon = \frac{\text{celkový počet rychlých neutronů vzniklých působením neutronů různých energií}}{\text{počet rychlých neutronů vzniklých působením pomalých neutronů}}$$

The fast neutrons created in this manner slow down through collisions with the moderator, but a portion of them are absorbed without fission in the U238. Factor p < 1 indicates the number of slowed down neutrons - **the probability of failure to capture**:

$$p = \frac{\text{počet rychlých neutronů, které při zpomalování nebyly zachyceny}}{\text{celkový počet rychlých neutronů}}$$

A portion of the rest of the thermal neutrons will be captured in the nuclear fuel, and the remaining portion will be absorbed by the moderator, the coolant, structural materials, etc. The portion of utilized neutrons is indicated by the thermal utilization factor f:

$$f = \frac{\text{počet tepelných neutronů zachycených jaderným palivem}}{\text{celkový počet zachycených a pohlcených tepelných neutronů}}$$

The number of thermal neutrons captured in the nuclear fuel (in the next generation) will then be equal to the product of $n \cdot \eta \cdot \varepsilon \cdot p \cdot f$. The multiplication factor for a reactor of an infinitely large size will K_∞ be:

$$K_\infty = \frac{n \cdot \eta \cdot p \cdot f}{n} = \eta \cdot p \cdot f$$

We obtain the so-called 4 factor formula. To sustain a chain reaction in a system with natural uranium, the following applies:

$$\eta \cdot \varepsilon \cdot p \cdot f = 1$$

Factors η and ε depend on the type of fuel used, η increases through the enrichment of uranium 235 fuel. Factors p and f depend on the ratio of the amount of fuel and moderator and on their arrangement in the active zone of the reactor.

When considering the reactor with final dimensions, a part of the neutrons will escape from the reactor and factors ε and p will also change somewhat. Therefore, when thinking about the conditions of the chain reaction in a system with an active zone of final dimensions, we must take into account the correction for the escape of fast and thermal neutrons. The multiplication factor of the system with final dimensions then is:

$$K_{ef} = K_\infty \cdot u_r \cdot u_p = K_\infty \cdot u$$

u_r ... Fast neutron leakage factor

u_p ... Slow neutron leakage factor

3.5.3.1 The critical size and critical mass of the reactor

The amount of freed neutrons is dependent for the given fuel on its quantity, i.e., on the volume of the reactor. The escape of neutrons from the reactor, however, is dependent on the size of its surface, and so designers strive to create a reactor with the smallest ratio of surface to volume (ball). This can be achieved by increasing the dimensions and choosing an appropriate reactor shape. At certain dimensions and shape we will attain an automatic chain reaction, i.e., $K_{ef} = K_{\infty} \cdot u = 1$. Such a reactor size is called a critical dimension or the critical mass of the reactor. If the active zone is surrounded by a reflector, the amount of escaping neutrons is reduced and the size, i.e., the critical dimension of the reactor is reduced.

The operation of a nuclear reactor is not constant even at a constant heat load, as the composition of its active zone changes during the course of the burning down of the fuel, through the impact of the formation of new fissile isotopes, the formation of fission waste products and the influence of radioactive decay. With a change in the composition of the active zone also comes a change in the multiplication factor. In theory, one could achieve constant burning of the active zone through continuous replenishment of nuclear fuel and removal of burnt out waste products. This is hard to carry out in a heterogeneous reactor, however, and constant reactor power is therefore maintained through control rods.

Fissile waste products and the waste products of their decay have various effect on the working of the reactor. Isotopes with large effective cross-sections of absorption for thermal neutrons, for example Xenon Xe135 formed as a fissile waste product, or those forming from fragments of iodine J135, cause so-called **reactor poisoning** by actively absorbing thermal neutrons, and with a half-life of 6-7 h then transmute into the isotope Xe136 with a low absorption cross section. The poisoning of the reactor reaches steady state after a certain time. Another group of waste products called slag has a smaller absorption cross-section, but the concentration of these waste products in the active zone almost never reaches steady state. The poisoning and slagging of the reactor absorbs a part of the neutrons and manifests itself by reducing reactivity, which must be compensated for by the creation of the compensation rods that are a part of the control rods.

The poisoning of the reactor and its course (it continues even after the shutdown of the reactor and after reaching maximum gradually declines to zero in about 30 h), slagging, fissile waste products and the waste products of their decay are constantly changing in the active zone and complicate the determination of the kinetics of the reactor. The value of the **multiplication factor also changes along with the temperature of the fuel and the moderator** (changes occur in the nuclear properties, the density of material in the active zone, and also the effective cross-sections). We can express the dependence on temperature with the following equation:

$$K_{ef} = K_{ef0} \cdot (1 + \alpha \cdot T)$$

We are trying to achieve a negative temperature coefficient α, so that the multiplication factor would fall with rising temperature. We thereby prevent a sudden power increase, possibly even a reactor failure. In some cases, self-regulating abilities of the reactor are achieved, which then during an increase in temperature reaches a stable state without the intervention of automatic control.

3.5.3.2 Reactor power control

The flow of neutrons and the power output of the reactor is controlled by changing the multiplication factor, in other words by changing the neutron total. We can achieve this in following basic ways:

a) By a change the amount of fuel in the active zone (homogeneous reactors)
b) By a change in the amount of the absorbing substance in the active zone
c) By a change in the escape of neutrons through relocating a part of the reflector
d) By a change in the amount of moderator in the active zone

In all these cases, the balance is dynamic in nature and must be maintained through continuous control, using an actuator based on the measurement of the flow of neutrons in the ionization chambers. To control the power output of the reactor, three groups of control rods are used:

1) Control (management) rods serve to start up, shut down and maintain constant reactor power output (they also compensate for the effect of the temperature coefficient).
2) Compensating rods compensate for the negative reactivity resulting from the burning out of fuel, reactor poisoning and slagging.
3) Emergency rods, which automatically intervene in case of a sudden increase in the reactor and in other reactor malfunctions.

The total number of control rods for large reactors is about 40, of which 2-4 are compensating and emergency rods. The depth of rod immersion into the active zone indicates the instantaneous reactivity of the reactor, and thus we can express the NPP reserve of reactivity in m.

As already mentioned, a portion of the neutrons (about 0.75%) is irradiated by decay products with considerable delay. If the average lifespan of instant neutrons is ~ 0.001 s, then in 6 groups of delayed neutrons it varies from 0.07 to 80 s. This implies a mean value of the lifespan of delayed neutrons during the fission of U235 of 12.24 s. The mean lifespan of all neutrons, including those delayed, is:

$$\tau = 12.24 \cdot 0.0075 + 0.001 \cdot 0.9925 \approx 0.1 \text{ s}$$

Assuming the K_{ef} = 0.005, then in 1 s the final number of neutrons without considering delayed neutrons will be:

$$n = n_0 \cdot e^{\frac{tK_{ex}}{\tau}} = n_0 \cdot e^{\frac{1 \cdot 0,005}{0.001}} = 150 \cdot n_0$$

and when considering the delayed neutrons:

$$n = n_0 \cdot e^{\frac{1 \cdot 0,005}{0.1}} = 1,05 \cdot n_0$$

So instead of the original 150 multiplied increase, the number of neutrons increases only by 5%, and thus the **presence of delayed neutrons significantly simplifies the control of the reactor**.

3.5.3.3 Reproduction of nuclear fuel

Besides being a source of thermal energy, a reactor can also be a source of new fissile substance, i.e. a regeneration reactor. In a thermal reactor with U238 and U235, the nuclear fuel U235 is burned while the absorption of neutrons by U238 creates plutonium Pu239 according to the equation:

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

poločas rozpadu: 23 min, 2,3 dne, 24 tis. let

Similarly, in a reactor with U235 and Th232 during the burning of U235 and the absorption of neutrons by thorium, a new nuclear fuel U233 is created according to the equation:

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

By absorbing a neutron, the atom of the isotope of thorium Th233 is created, which with the emission of particle β^- (electron) changes to palladium Pa233 and from it again by the emission of particle β^- arises uranium U233.

The ratio of the number of atoms of the newly created fissile substance to the number of atoms of consumed nuclear fuel is called the **conversion ratio** or **coefficient of reproduction** Cr. This coefficient is equal to the number of thermal neutrons captured in U238 or Th232 per 1 thermal neutron:

The fission of 1 atom releases 2.5 neutrons, of which 1 falls to the splitting and 0.4 to non-fission capture in U235. 1.1. neutrons remain, so that Cr can be a maximum of 1.1. In reality it is less than 1 in view of the absorption of neutrons outside of the fuel and the escape of neutrons.

$$Sr = \frac{\text{neutrony zachycené v } ^{238}_{92}\text{U}}{\text{neutrony zachycené v } ^{235}_{92}\text{U}}$$

Apart from the reactors mentioned, there are breeder reactors for fast neutrons with fuel Pu239 and U238, in which Pu239 is burned and a new fuel is created through the absorption of neutrons by U238. In this case we are not talking about a coefficient of reproduction, but a **breeding ratio**. Contains values of 1.2 - 1.6. Breeder reactors have the advantage that they utilize U238 as a nuclear raw material for the production of secondary nuclear fuel.

3.6 Description of a Nuclear Power Plant

Nuclear power plants are basically thermal power plants, but the heat needed for the conversion of water to steam is not acquired by the combustion of fuel, but by nuclear fission. Starting with the turbine driving the generator, a nuclear power plant is actually the same as the classic coal power plant. The only difference - of course a fundamental one - is in the heat source.

The **primary** (first) circuit serves for the transfer of thermal energy from the active zone to the steam generator.

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

The **Secondary** (second) circuit is used to transport the steam and to transform its internal energy into the rotary movement of the turbine. The basic parts of the secondary circuit include: the secondary part of the steam generator, the secondary circuit piping systems, the turbo-generator, condenser and pumps. Just like the primary circuit, it is a closed system to prevent possible leakage of radioactivity.

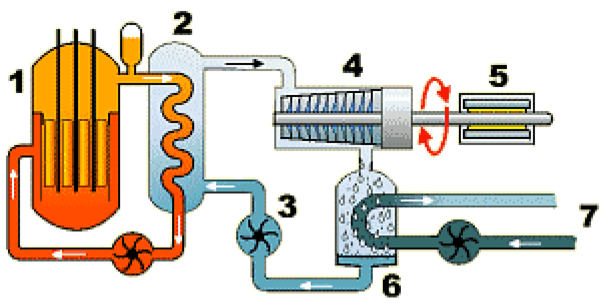


Fig. 3.8 Schematic diagram of a nuclear power plant - 1 Reactor, 2. Steam generator, 3. Pump, 4. Turbine, 5. Generator, 6. Condenser, 7. Inlet and outlet of cooling water

3.6.1 Nuclear power plant efficiency

Since the price of fuel is not a substantial component in the price per kWh generated as it is in classic power plants , the specific consumption of fuel is not a fundamental indicator of the economical management of a HPP. Generally, we distinguish between gross efficiency, the efficiency of the conversion of heat into electrical energy, and net efficiency, which also includes the own consumption of the NPP. Own consumption of the NPP amounts to 15-20% of the total electrical power output (the circulation pumps take the main share). The net efficiency ranges between 25-33%. Fuel consumption also depends on burnout depth of the fuel assemblies.

The efficiency of each type of NPP is given in chapter 3.6.5.

3.6.2 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. Nuclear reactions taking place in the reactor are also a source of a radioactive radiation.

The mean value of the energy of the neutrons released during fission is approximately 2 MeV. They are fast neutrons, and to convert them to thermal (slow) neutrons it is necessary to reduce their speed, for which a moderator is used. Materials utilized as a moderator have low atomic mass and low neutron absorption capability. Through multiple collisions of neutrons with the particles of the moderator, the energy of fast neutrons is reduced to the level of thermal neutrons. From the energy industry point of view, the nuclear reactor is a generator of heat which is released during the fission or thermonuclear chain reaction.

In order for the reactor to operate successfully, we must provide it with fuel, a moderator, an absorber and coolant that will carry away the heat arisen during fission. Reactors are classified into many different types according to the type and configuration (assembly) of these components.

The fuel is made up of fuel rods. Small pellets of fuel are stacked on top of each other, creating a rod about 9 mm in diameter. A bundle of these rods makes up a fuel cassette. In a reactor of the VVER 1000 type, for example, over 47 thousand rods are inserted into hexagonal fuel cassettes, with each cassette containing 317 of them. The part of the reactor into which fuel is placed and where the fission reaction also proceeds is called the active zone. The fuel rods are protected with coating of a special alloy, usually based on zirconium, which guarantees the transfer of heat from the fuel to the coolant and at the same time does allow radioactive fission products to pass through. In some types of reactors the fuel is in the form of spheres, which are freely released into the active zone.

In reactors where the fission is carried out by slow neutrons the moderator is most often water, but graphite or heavy water (D_2O) is also used. In reactors that operate on the basis of fast neutrons (i.e. the fissile isotope is uranium 238 or plutonium), the moderator is missing.

The absorber is also inserted into the active zone in the form of rods, similarly to fuel. Fuel cassettes sometimes have two parts - the fuel is in the bottom part, the absorber in the top. The power of the reactor is then controlled by pulling out or pushing in the cassettes into the active zone. Emergency rods are prepared in case of the need for immediate cessation of the power output of the reactor. They contain a much higher concentration of absorber than control rods contain.

The emergency bars are pulled out to extend above the active zone, where they are held in place with the aid of electromagnets. If necessary, an emergency signal will switch off the electromagnets and the rods will free fall into the active zone, thereby stopping the fission reaction. In some reactors the rods are actually shot out, making their intervention even faster.

The coolant is a medium that carries the heat away. During the splitting of nuclei new nuclei fly out (fission fragments) into the surrounding nuclei and their kinetic energy causes heating of the surrounding area. The heat transfer medium carries the heat to where we can utilize it. The material undergoing fission needs to be cooled continuously to prevent the melting of the coating on the fuel rod and the escape of fission products. Proving to work best as coolant are plain water, heavy water, carbon dioxide, helium, sodium and certain salts or alloys. Reactors tend to have one or more cooling circuits.

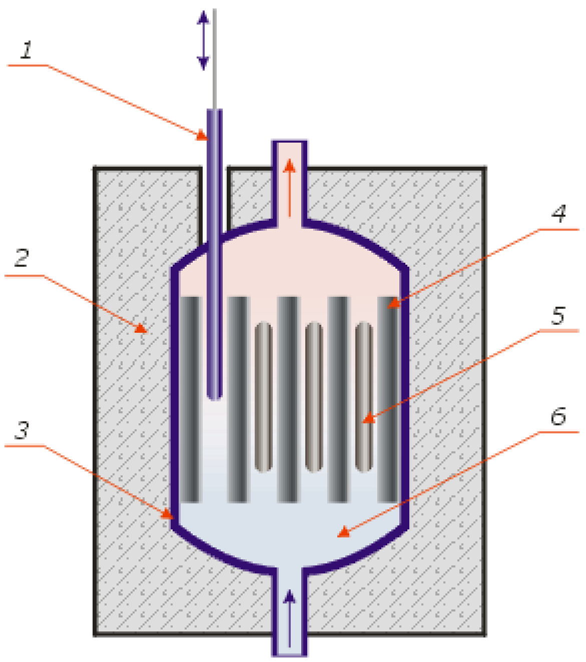


Fig. 3.9 The basic parts of a nuclear reactor (1 – control and protection rods, 2 – biological protection, 3 – thermal protection, 4 – moderator, 5 – fuel assemblies, 6 – cooling medium)

3.6.2.1 Nuclear reactor materials

The correct selection of materials has an effect on the price of the equipment, its simplicity, reliability, safety and durability, including its design technology. The most important properties include:

- Mechanical (strength during thermal stress, fracture toughness)
- Corrosion resistance
- Thermal (direct and fast heat outlet)
- Low effective cross-section for neutron capture (except absorbents)
- Radiation stability (the main radiation damage is caused by the interaction of neutrons with the materials)
- High purity (small impurities lead to changes in the mechanical, corrosive and nuclear properties)
- Availability and price
- Technological design (easy processing, weldability)

3.6.2.2 Types of fissile and fertile materials and their preparation

The active materials of the fuel assemblies are classified according to purpose:

a) Ensuring the fission reaction - fissile materials
b) Ensuring the creation of new fuel - fertile materials

The a) group includes materials containing any of the isotopes $^{235}_{92}U$, $^{233}_{92}U$, $^{239}_{94}Pu$ for thermal reactors, or $^{238}_{92}U$ for fast reactors. Of these isotopes, only $^{235}_{92}U$ (0.712% in natural uranium) is present in nature, and is therefore called a **primary fissile material**. $^{239}_{94}Pu$ is an accompanying isotope of uranium ore, but with an presence of only $5 \cdot 10^{-12}$ %. It is therefore attained as $^{233}_{92}U$ in an artificial way through irradiation in a reactor. Thus, both are **secondary fissile materials**. Isotopes $^{238}_{92}U$ (in natural uranium 99.282%) and $^{232}_{90}Th$ (occurrence of natural thorium 100%) are among fertile materials that are the raw material for the production of fissile materials.

The economy of reactors requires the campaign to be as long as possible in order that the burnout be as complete as possible. Also required is the stability of the cells and tightness against the leakage of fission products into the primary circuit - the radiation resilience of the encasement.

Metal nuclear fuels

Advantages - high density (high macroscopic cross-section), thermal conductivity

Disadvantages - high radiation and volume growth

Usage up to 500 °C with burnout 5,000 - 25,000 MWd/t.

Ceramic nuclear fuel

- Oxides of U, Pu, and Th, most commonly UO_2 (uranium dioxide)
- non-oxide - C, S, P, N, Si, most commonly UC (uranium carbide)
- Dispersion phase in a matrix of non-fissile metal (Al, stainless steel) or graphite

Advantages - high temperature, high burn-out at low volume growth

Disadvantages - worse thermal conductivity and thus the occurrence of large thermal differences on the surface and inside

Use for higher power output and temperature - PWR, BWR, HTGR and fast reactors

Uranium

Pitchblende ore containing 30 - 60 % U_3O_8 is crushed, mechanically enriched and chemically processed until we get the powder UO_2, which is then further enriched. Uranium exposed to air is covered by a protective layer of oxides, at temperatures of around 700 °C it changes its crystalline structure and with it its mechanical properties, so that its thermal conductivity is improved.

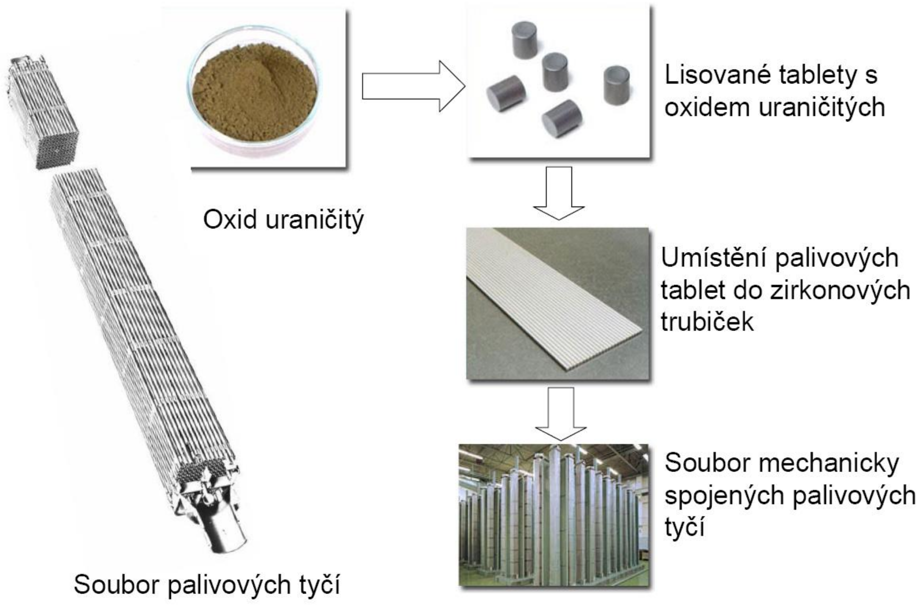


Fig. 3.10 Production of uranium fuel

Thorium

Natural $^{232}_{90}Th$ is the raw material for the production of $^{233}_{92}U$. The source of Th are monazite sands and silicates, which are dissolved in nitric or sulfuric acid. It has better physical properties than U - high thermal conductivity and a lower thermal expansion.

Plutonium

Produced by the capture of neutrons by $^{238}_{92}U$. It is counted on for fast fertile reactors.

3.6.2.3 Materials for the covers of fuel cells

Protection of fuel from direct contact with the working environment, prevents the escape of fission products and can be used as a structural element. Must maintain good properties while flowing and must have low effective cross-section for neutron absorption.

Aluminum and its alloys

Poor mechanical properties and low corrosion resistance, they are used for UO_2 to 480 °C

Magnesium and its alloys

For reactors cooled by CO_2, for temperatures to 530 °C, they corrode in moist conditions

Zirconium and its alloys

The best material, for higher temperatures, good corrosive resistance, low absorption cross-section

Beryllium

The lowest absorption cross-section, suitable also as a moderator and reflector. Disadvantages - price, difficult technology and toxicity

Austenitic steel and nickel alloys

For higher temperatures up to 750 °C

3.6.2.4 Moderators and reflectors

Moderators are substances that with small losses slow down fast neutrons. A neutron loses the greater amount of kinetic energy, the **lighter** the nucleus of the moderator. (elements with low atomic number). A collision should cause a great loss of energy by a neutron, and should have a low effective cross-section for absorption.

Water, heavy water D_20

D_20 is the best moderator. Disadvantages - corrosive aggressiveness, radiolysis of water by irradiation and low boiling point.

Graphite

Advantages - low price, strength, heat resistance, easy workability and good thermal conductivity. Properties are improved by radiation. Must be artificially produced from coke due to purity.

Beryllium

Advantages - excellent moderator and construction material. Disadvantages - expensive, fragile and toxic.

Polyphenols

Advantages - liquids, so that they better ensure the exchange of heat, non-aggressive. For temperatures to 400 °C.

3.6.2.5 Coolants

Takes heat away from the active zone. We require:

- High thermal conductivity and specific heat
- Small energy consumption in ensuring circulation
- High boiling point with low melting temperature
- Thermal stability
- Resistance to radiation
- Low corrosive aggressiveness
- Low absorption cross-section
- Low tendency to induced radioactivity
- Low price

Gaseous

Disadvantage - poor ability to take heat away, so that high pressures and large volumes are worked with

Air - readily available, poor thermal conductivity, corrosive, radioactivity after irradiation and large absorption cross-section for thermal neutrons

CO_2 - small absorption cross-section for thermal neutrons, cheap and available

Helium - small absorption cross-section for thermal neutrons, thermally and chemically stable, non-radioactive and non-corrosive Disadvantages - price, unavailability and sealing

Liquid

Higher ability to lead heat away, worse corrosive properties

Molten salts

Fluorides, high thermal and radiation stability, suitable for higher temperatures

Liquid metals

Good at transferring heat away, high boiling point and they do not decay with radiation. The disadvantage is corrosiveness,necessity of high purity - equipment fouling. Sodium, bismuth, and mercury are used.

3.6.2.6 Absorbent materials

They are used in the system of control and protection of reactors - high absorption cross-section. We also require radiation stability, stability of mechanical and corrosive properties, thermal conductivity, and low density. Materials containing boron are used, but the material is brittle and machining it is difficult. Also a rod filled with powdered B_4C.

In use are materials from dispersion solutions in zirconium or titanium.

Cadmium - low melting point and low strength.

3.6.2.7 Materials for pressure vessels

Steels - we require strength, toughness, corrosive resilience, and good weldability. For light-water reactors low-alloy steels are used, for fast reactors high alloy 18/8 with a low carbon content.

Concretes - based on Portland cement, which has good resistance to radiation. For shielding reactors, heavy concretes are used containing substances with a high mass number, e.g., boron binders and the mineral filler colemanite. Iron balls and cuttings are added for capturing high energy neutrons.

3.6.3 Containment

Containment - the protective cover of reinforced concrete around the reactor and primary circuit. Containment prevents the "free" spread of radioactive substances into the environment during accidents with damage of the primary circuit.

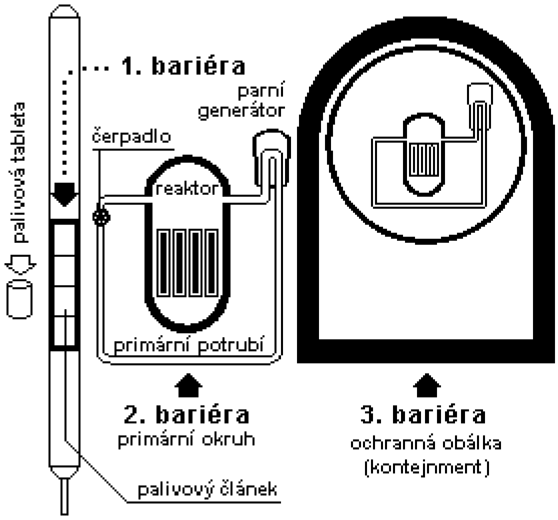


Fig. 3.11 Protective barriers

3.6.4 Volume compensator

Volume compensator - is one of the important components of the primary circuit of a nuclear power plant. A change in the power output of the reactor is accompanied by a temporary or permanent change of the mean temperature of the coolant, and in a closed circuit also by a change in the coolant pressure. Big pressure changes are undesirable in terms of the reliable operation of a nuclear power plant, and therefore to restrict them a volume compensator is used, which most often is a separate container with sealed auxiliary volume and with a gas or steam cushion above the coolant surface.

Tab. 3.3 The parameters of a volume compensator of the primary circuit with reactor VVER-440

Volume of compensator	44 m^3
Height	10,800 mm
Interior diameter	2,400 mm
Electroheater power	1 620 kW

3.6.5 Classification of Nuclear Reactors

Types of reactors are distinguished by the various combinations of:

- Fuel-uranium-235, uranium-233 and plutonium 239
- Coolant - water, heavy water, carbon dioxide, helium and sodium
- Moderator - water, heavy water, graphite or without moderator

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

Fast reactors - fission of nuclear fuel foremost by fast neutrons (above 0.1 MeV), new fissile material is created - breeder reactors.

Tab. 3.4 Designation of individual types of reactors

Type designation	Full meaning in English	Czech term
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

The share of individual types of nuclear reactors in the world energy industry:

- Light water (LWR) - the moderator and coolant is plain water (85 %)
  - Pressurized water (PWR, another designation is VVER) - pressurized water cooled and moderated reactor (Dukovany, Temelín) (63 %)

    - Boiling (BWR) - cooled and moderated with a mixture of water and steam (22%)
- Graphite - the moderator is graphite (9%)
    - Gas cooled MAGNOX (CGR) - the coolant is CO_2, the fuel is natural uranium (1.5%)
    - Advanced gas cooled (AGR)-the coolant is CO_2, the fuel is low-enriched uranium (2.5%)
    - Water cooled (LWGR, other designation BWGR and RBMK) - boiling water cooled (Russia-Chernobyl, Obinsk) (5%)
    - High temperature (HTGR) - helium-cooled, enriched uranium, which can withstand high temperatures of approx. 900 °C
- Heavy water (HWR, the most known being CANDU) - heavy water moderator, CO_2 coolant or water (5%)
- Fast breeder (FBR) - fission is initiated by neutrons that were not decelerated, without moderator, the coolant is sodium (1%)

3.6.5.1 PWR

Basic characteristics

Thermal, pressure reactor, moderated and cooled by plain water. PWR (Pressurized Water Reactor), VVER (vodo-vodjanoj energetičeskij reactor). It is the most common type of nuclear reactor today. Reactors of this type are operating in the Temelín and Dukovany power plants as well.

The composition of the active zone

Small cylinders of UO_2 stacked and hermetically sealed in a tube cladding of zirconium alloy form a fuel rod. Bundles of about three hundred (for reactors with power output of around 1000 MW) regularly arranged fuel rods form fuel assemblies, from which the active zone inside the pressure vessel of the reactor is composed. The replacement the spent fuel is done once a year to a year and a half while the reactor is shut down. Usually 1/3 of the fuel assemblies are replaced.

Heat transfer and production of electricity

Water under high pressure flows through the active zone around fuel rods, where it is heated and channeled through piping into steam generators, in which it brings the water of the secondary circuit of the block to a boil. The resulting steam drives the turbine connected to the generator of electric current. The secondary circuit is further cooled by the so-called tertiary circuit, whose dominant feature is often its high cooling towers.

Basic parameters of a 1000 MW reactor:

Fuel - enriched uranium in the form of uranium dioxide (UO_2) Enriched with isotope ^{235}U to from 3.1% up to 4.4%

The dimensions of the active zone are 3 m in diameter x 3.5 m in height

Water pressure in the reactor is 15.7 MPa

Water temperature at the outlet of the reactor is 324 °C

The efficiency of the power plant is 32.7%

The amount of fuel in the reactor is 60 to 80 tons of UO_2

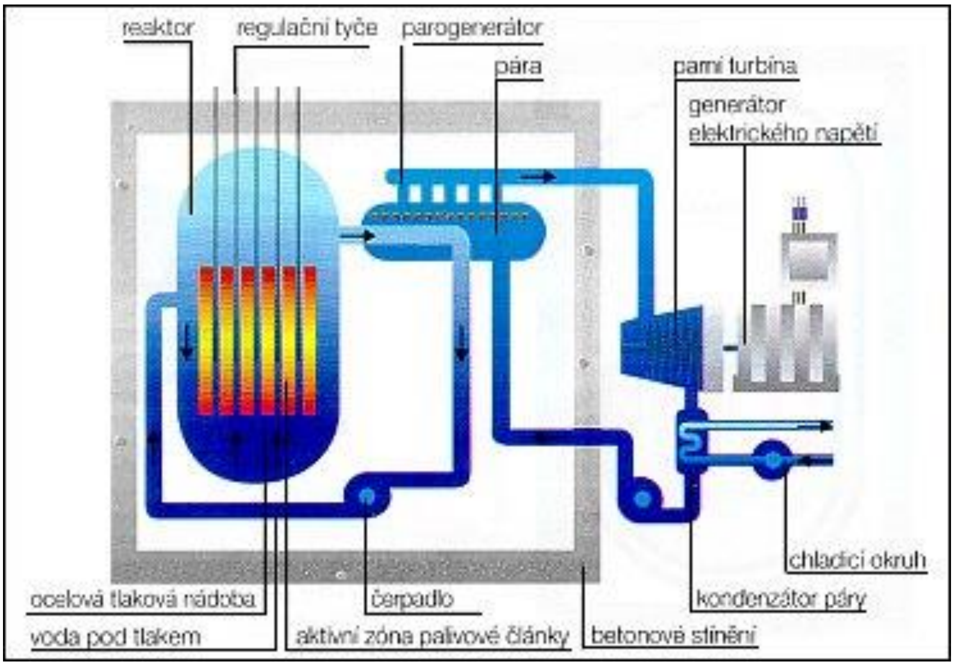


Fig. 3.12 PWR reactor

3.6.5.2 BWR

Basic characteristics

Thermal, boiler reactor, moderated and cooled by plain water BWR (Boiling Water Reactor) This is currently the second most common type of nuclear reactor (after PWR).

The composition of the active zone

Small cylinders of UO_2 stacked and hermetically sealed in a tube cladding of zirconium alloy form a fuel rod. Bundles of about three hundred regularly arranged fuel rods form fuel assemblies, from which the active zone inside the pressure vessel of the reactor is composed. The replacement the spent fuel is done once a year to a year and a half while the reactor is shut down. The active zone of the BWR reactor resembles classic pressurized water reactors in its design.

Heat transfer and production of electricity

The water is heated in the active zone up to the boiling point and the steam forms directly in the pressure vessel of the reactor. This steam is stripped of drops in the upper part of the reactor and from there goes directly to the turbine, which is connected to a generator of electric current. This simplification compared to the pressurized water reactor PWR brings with it the disadvantage that the steam driving the turbine is radioactive.

Basic parameters of a 1000 MW reactor:

Fuel - slightly enriched uranium in the form of uranium dioxide (UO_2) Enriched with isotope ^{235}U to 2.1%

The dimensions of the active zone are 4,5 m in diameter x 3.7 m in height

Water pressure in the reactor is 7 MPa

Water temperature at the outlet of the reactor is 286 °C

The efficiency of the power plant is 33.3%

The amount of fuel in the reactor 122.3 tons of UO_2

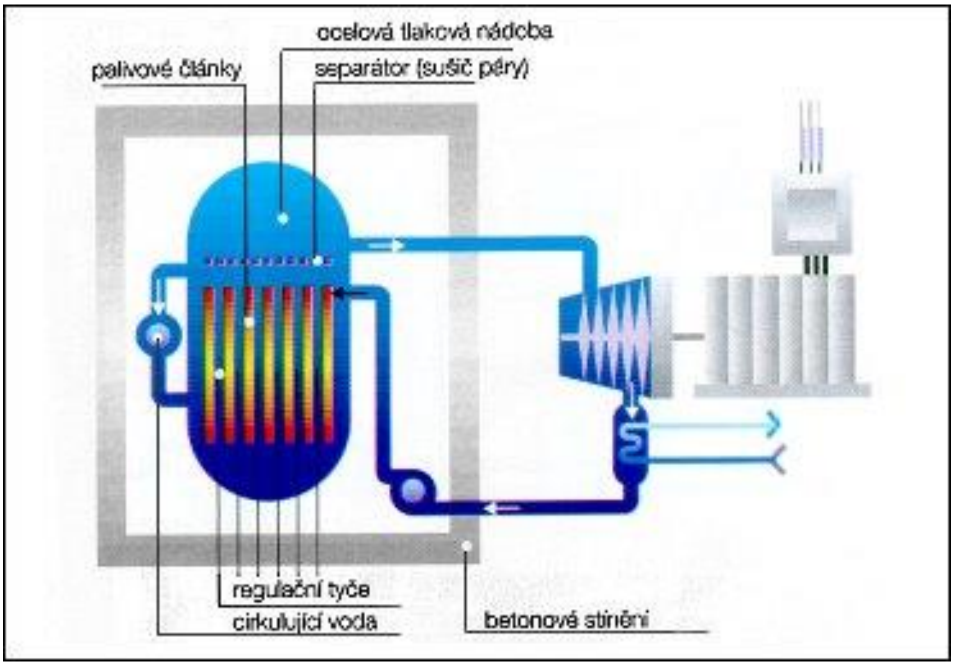


Fig. 3.13 Reactor BWR

3.6.5.3 GCR, Magnox

Basic characteristics

Thermal, gas cooled, graphite moderated reactor. GCR (Gas Cooled Reactor), usually cooled by carbon dioxide CO_2. Today, it is not an widely used reactor. The United Kingdom advanced furthest in its development, but these type of blocks are no longer built today and they are more or less serving out their time. Even the first British nuclear power plant at Calder Hall was equipped with this type of reactor.

The composition of the active zone

Compact fuel assemblies consist of rods of natural metal uranium covered with an oxide of magnesium (magnesium oxide = Magnox). The active zone in the shape of a vertical cylinder consists of graphite blocks through which pass through several thousand vertical channels - several fuel rods are placed into each of these, stacked on top of each other. The whole of the active zone is enclosed in a spherical steel pressure vessel, which itself is enclosed by thick concrete shielding. The reactor design allows for exchange of fuel while in operation.

Heat transfer and production of electricity

Cooling gas circulates through the channels around the fuel rods, heats up and is channeled into the steam generators, in which it passes its heat to the water of the secondary circuit. The cooled gas is forced back into the reactor by blowers, steam formed in the steam generator drives the turbine connected to the generator of electric voltage.

Basic parameters of a 600 MW reactor:

Fuel - natural metallic uranium

The dimensions of the active zone are 17.4 m in diameter x 9.1 m in height

The gas pressure in the reactor is 2.75 MPa

The temperature of the gas at the outlet of the reactor is 360 °C

The efficiency of the power plant is 25.8%

The amount of fuel in the reactor is 595 tons

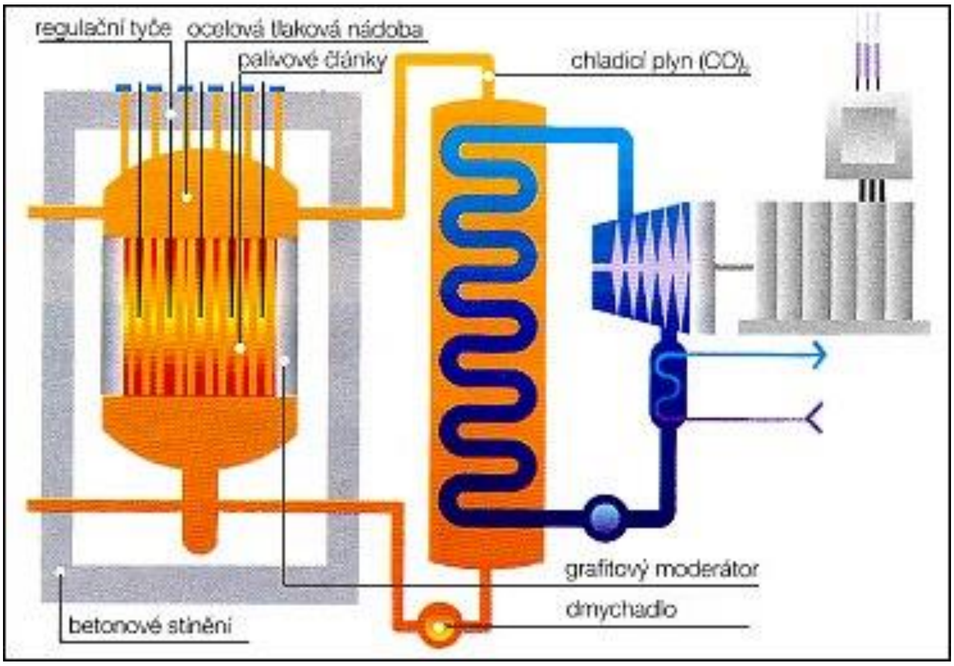


Fig. 3.14 GCR reactor, Magnox

3.6.5.4 AGR

The advanced gas cooled reactor AGR (Advanced Gas Cooled, Graphite Moderated Reactor)is so far used exclusively in the United Kingdom, where 14 such reactors are in operation. The fuel is uranium enriched by the isotope U235 in uranium dioxide form, the moderator is graphite, the coolant carbon dioxide. The power plant is dual circuited.

Typical parameters of an AGR reactor with a power output of 600 MW:

Uranium enriched to 2.3% of isotope U235

The dimensions of the active zone are 9.1 m in diameter and 8.5 m height

The CO_2 pressure is 5.5 MPa

The temperature of CO_2 at the reactor outlet is 450 °C

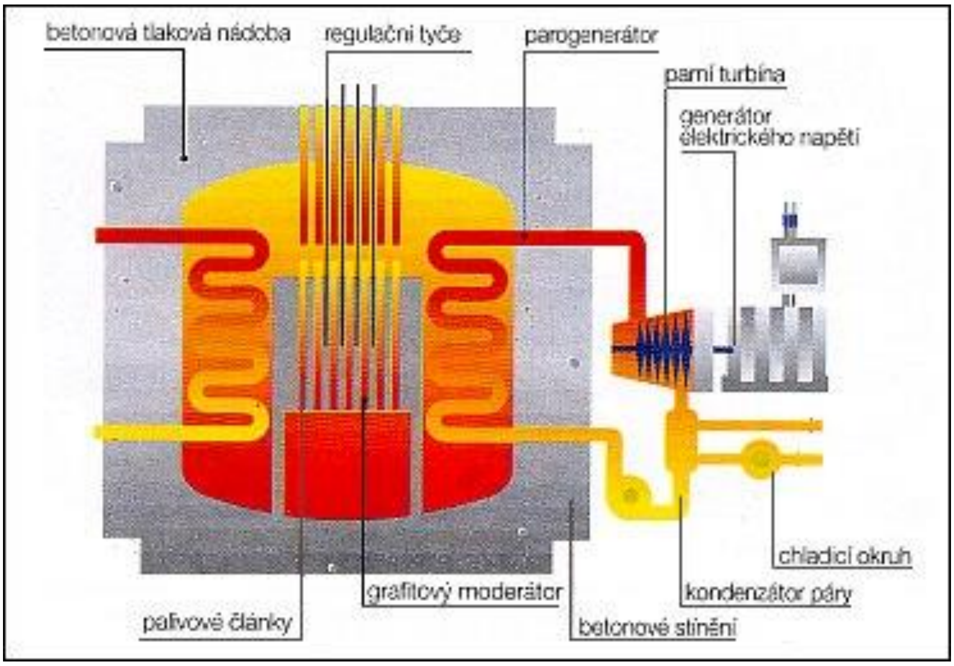


Fig. 3.15 AGR reactor

3.6.5.5 LWGR, RBMK

Basic characteristics

Thermal, plain water cooled, graphite moderated reactor of great power outputs. RBMK (Reactor Bolshoy moščnosti kanalnyj). Sadly renowned Chernobyl reactor type. The first nuclear power plant in the world already used this type of reactor. Their construction was suspended after the Chernobyl accident, and there are only a few of these reactors in operation today.

The composition of the active zone

The fuel rods are slender tubes made of an alloy of zirconium and niobium, into which pellets of UO_2 are stacked. The active zone of the 1000 MW reactor consists of 1693 vertical pressure channels evenly spaced in a cylindrical block of graphite. Each pressure channel is filled with 36 fuel rods.

Heat transfer and production of electricity

Water is driven by pumps into each pressure channel, which heats up in the sewers to the boiling point, so that a mixture of water and steam flows out of the channels. This mixture goes into the so-called separators, which separate the remaining water, and the saturated steam is conducted onto a turbine coupled with a generator of electric current. The plant is therefore single circuit - radioactive steam flows in the turbines and it is necessary to shield them.

Basic parameters of a 1000 MW reactor:

Fuel - slightly enriched uranium in the form of uranium dioxide (UO_2) Enriched with isotope 235U to 1.8% up to 2.4%

The dimensions of the active zone are 11.8 m in diameter x 7 m in height

The pressure of the saturated steam in the separators is 6.9 MPa

Water temperature at the outlet of the reactor is 284 °C

The efficiency of the power plant is 31.3%

The amount of fuel in the reactor is 192 tons of UO_2

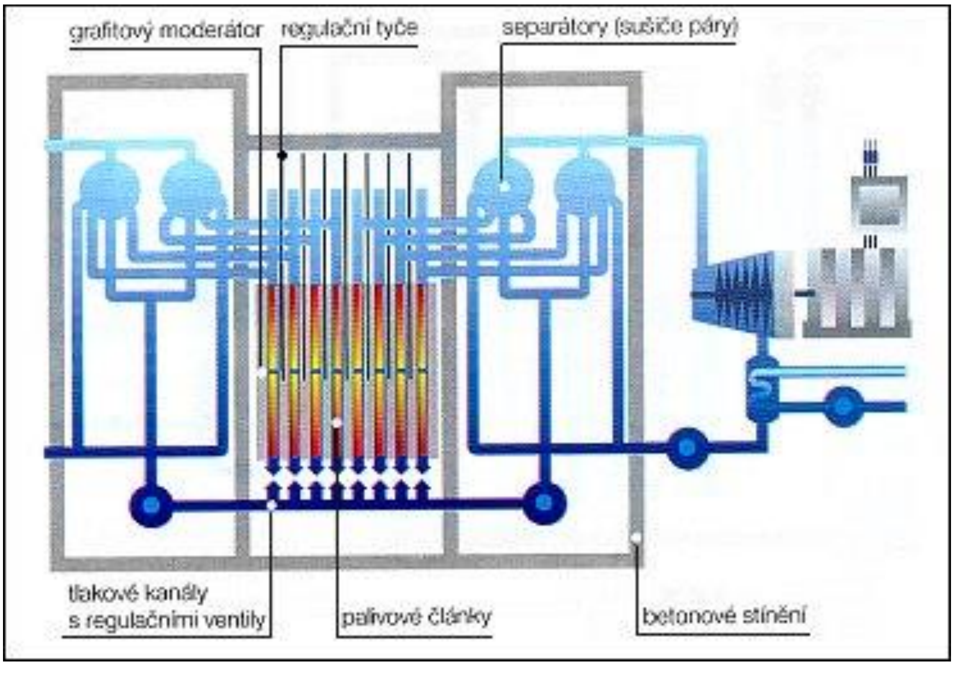


Fig. 3.16 The LWGR, RBMK reactor

3.6.5.6 HTGR

Basic characteristics

A thermal, gas cooled, graphite moderated, high temperature reactor. HTGR (High Temperature Gas Cooled Reactor). Due to their excellent thermal characteristics, high-temperature reactors are one of the more promising kinds of nuclear reactors. The United Kingdom, Germany and the United States have all engaged in building them. The possibility of attaining high temperatures is given mainly by the fact that it is not necessary to be so wary of deformation of the fuel assemblies through the effect of temperature.

The composition of the active zone

Microspheres of fuel are coated with three layers of silicon carbide and carbon, so the total diameter of the micro assembly reaches about 0.9 mm. Roughly 20,000 microspheres of coated fuel are evenly dispersed in a sphere of graphite about as large as a tennis ball. The fuel balls are freely scattered into a cylindrical active zone. They are then gradually removed at its bottom. This process is constantly repeated, and any fuel spent in the meantime is replaced by new. In the United States, hexagonal blocks are used instead of balls and the active zone is a compact cylinder composed of these blocks.

Heat transfer and production of electricity

The heat transfer is mediated by helium. The helium is driven with a blower through the active zone, from which it flows heated up into the steam generator, where it transmits its heat to boiling water. Steam with a high pressure and temperature is created, which drives a steam turbine coupled to a generator of electric current. Hot helium can also serve as a source of heat energy for other than power generation purposes, such as the production of hydrogen.

Basic parameters of a 1000 MW reactor:

Fuel - highly enriched uranium in the form of uranium dioxide (UO_2) Enriched with isotope 235U to 93%

The dimensions of the active zone are 5.6 m in diameter x 6 m in height

The pressure of the helium in the reactor is 4 MPa

The temperature of the helium at the outlet of the reactor is 750 °C

The efficiency of the power plant is 39%

The amount of fuel in the reactor is 0.33 tonnes of UO_2 and 6.6 tons of ThO_2

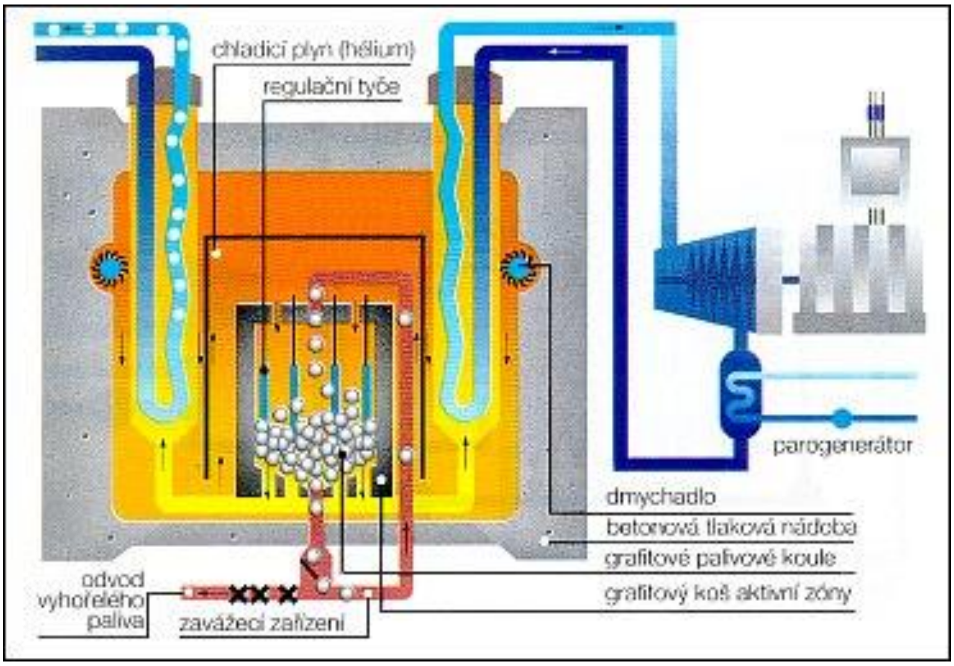


Fig. 3.17 HTGR reactor

3.6.5.7 HWR, CANDU

Basic characteristics

Thermal, heavy water moderated reactor. CANDU (CANada Deuterium Uranium) reactor of Canadian design developed for the fission of natural uranium. With it, Canada wanted to avoid the need for enrichment, which was demanding both technologically and energy-wise. The reactor gradually also spread outside of Canada.

The composition of the active zone

Small cylinders of UO_2 enclosed in short tubes made of zirconium alloys form the fuel rods from which the fuel assembly is assembled. The basis for the design of the active zone is the vessel in the shape of a lying cylinder (the so-called Calandria), which has horizontal vents for the placement of pressure tubes of zirconium alloy. The vessel is filled with a heavy water moderator, which must be cooled in a special circuit in order for its temperature to remain low (moderation ability decreases with temperature). Fuel assemblies are inserted in the pressure tubes, and cooling heavy water flows around them.

Heat transfer and production of electricity

Cooling gas circulates through the channels around the fuel rods, heats up and is channeled into the steam generators, in which it passes its heat to the water of the secondary circuit. The cooled gas is forced back into the reactor by blowers, steam formed in the steam generator drives the turbine connected to the generator of electric voltage.

Basic parameters of a 900 MW reactor:

Fuel - natural metallic uranium

The dimensions of the active zone are 7 m in diameter x 5.9 m in length

The pressure of the heavy water coolant at the outlet from the reactor is 9.3 MPa

The temperature of the heavy water coolant at the outlet from the reactor is 305 °C

The efficiency of the power plant is 30.1%

The amount of fuel in the reactor is 117 tons of UO_2

The temperature of the heavy water moderator is 30 °C

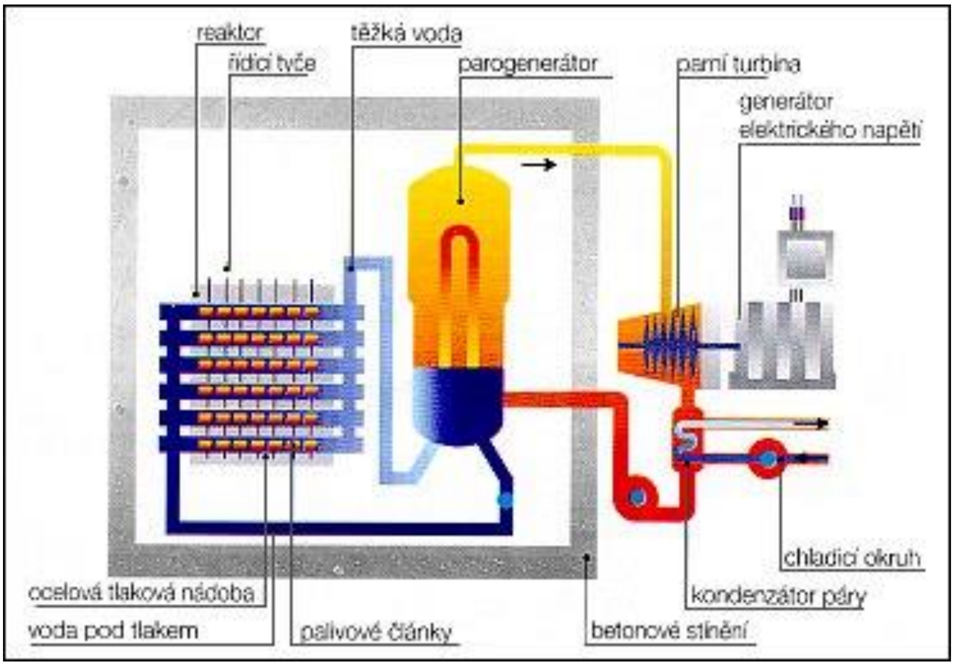


Fig. 3.18 HWR, CANDU reactor

3.6.5.8 FBR

Basic characteristics

Non-moderated fast breeder reactor. The FBR (Fast-Breeder Reactor) enables better utilization of fuel, because during its operation it produces mores plutonium then it burns itself. In the present period of cheap uranium, however, it is not able to compete economically with other types of reactors. France has advanced the most in the development of these reactors, having put into operation a commercial power plant of 1200 MW, and the Soviet Union. The United Kingdom and Germany have also been engaged in this field.

The composition of the active zone

The fuel rods are consists of fuel pellets enclosed in a stainless steel tube cover. The active zone is composed of bundles of these fuel rods, and in addition is surrounded by a breeder cover, which contains uranium in the form of UO_2, again in pipes made of stainless steel.

Heat transfer and production of electricity

The active zone is sunk in a wide steel container filled with sodium. Hot sodium heated in the active zone is drawn into the heat exchanger, which is also inside the reactor vessel. In this heat exchanger, heat is transferred to the secondary circuit, where sodium also circulates. This already non-radioactive sodium flows into the steam generator, which produces steam that drives a turbine connected to a generator of electric voltage.

Basic parameters of a 1200 MW reactor:

Fuel - plutonium dioxide (PuO_2) and uranium dioxide (UO_2). Enrichment of fuel with plutonium to 16.6%

The dimensions of the active zone are 3.7 m in diameter x 1 m in height

The pressure of sodium in the reactor is 0.25 MPa

The temperature of sodium at the outlet of the reactor is 545 °C

The efficiency of the power plant is 42%

The amount of fuel in the reactor is 31.5 tons of PuO_2/UO_2 mixture

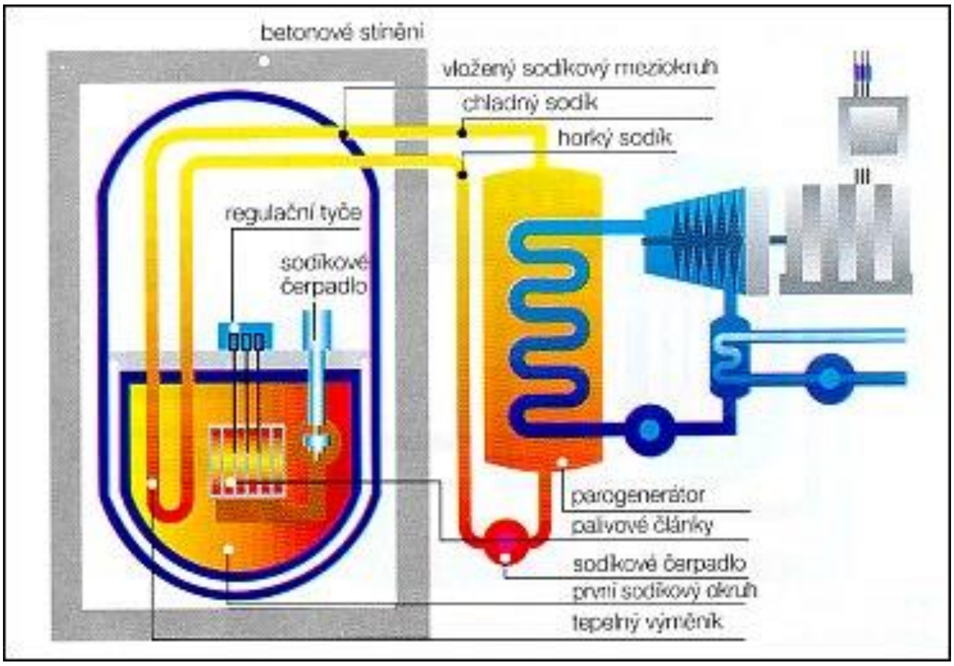


Fig. 3.19 FBR reactor

3.6.6 The basic thermal scheme of nuclear power plants

The simplest scheme of a nuclear power is **single-circuit.** Directly in the reactor, boiling water creates steam, which is channeled to the turbine. There it performs useful work, and after cooling down in condensers it returns back do the reactor. The whole cycle is continuously repeated. It is a very simple procedure, but it has one disadvantage: the water from the reactor may be radioactive and may carry trace amounts of activated corrosive products. This water comes into contact with a large part of the machinery of the power plant, mainly the turbine, condensers and pumps. This is why this method is no longer used in new power plant generations. (the BWR reactor).

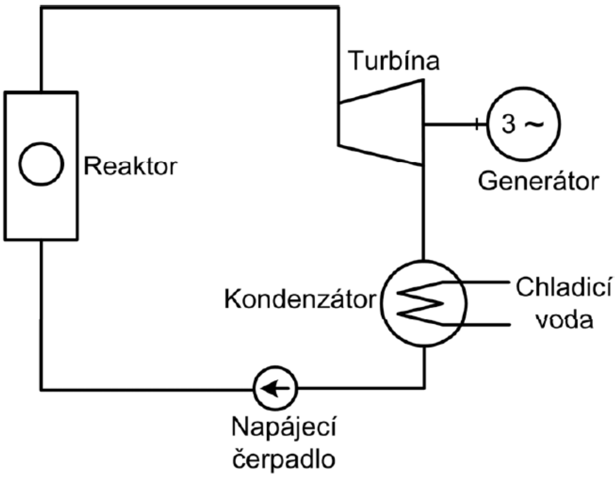


Fig. 3.20 Single-circuit with steam turbine

In most countries, including the Czech Republic, **dual circuit** power plants are operated. The water from the reactor circulates in the so-called primary circuit. The pipes of the primary circuit pass through the heat exchanger, the so-called steam generator, where they heat the water in the secondary circuit. Only there does steam form, which is channeled to the turbine and into the condensers. The secondary cooling circuit does not at all come into contact with reactor (PWR).

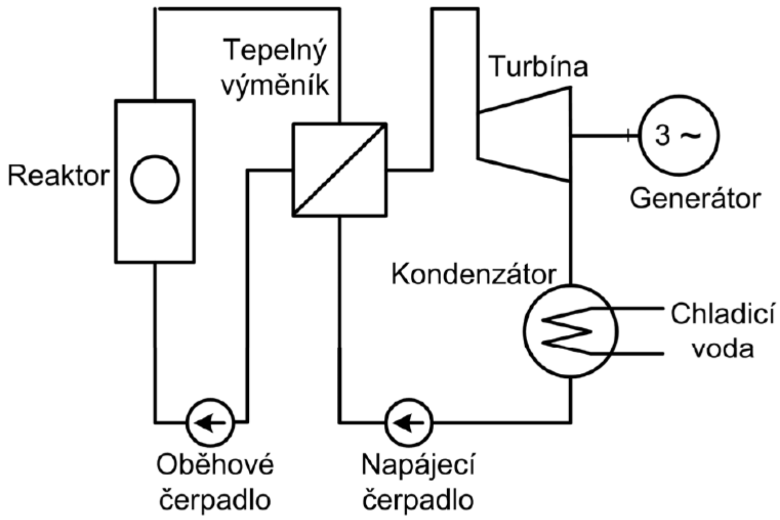


Fig. 3.21 Dual circuit with steam turbine

Some power plants with special types of reactors even use a **three-circuit** scheme of operation. These are, for example, fast breeder reactors, which as coolant

in the primary circuit utilize liquid metal (FBR reactor).

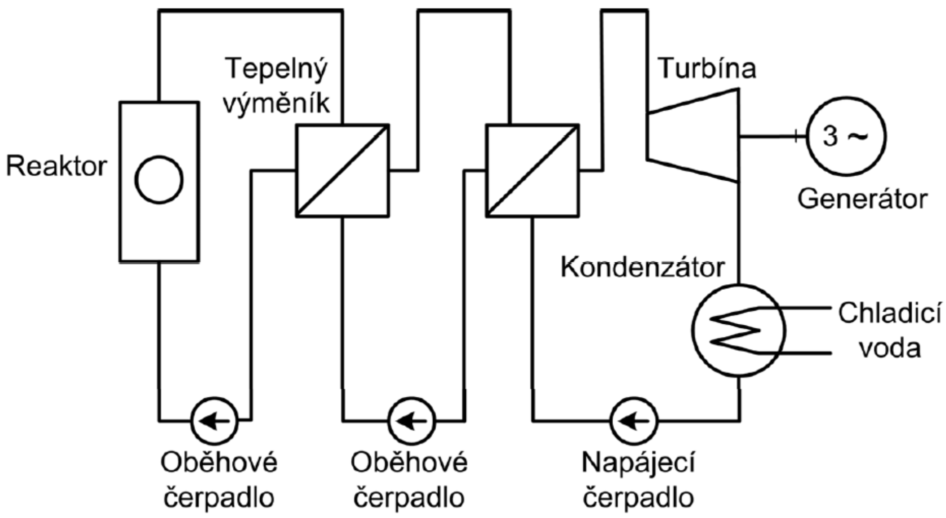


Fig. 3.22 Three circuit with coolant in the form of liquid metal

3.6.7 Requirements for electrical equipment

The importance of nuclear power as an energy source is huge. They are used to cover the basic parts of the diagram of power consumption, because their power is harder to control. In addition, the investment costs for the construction of nuclear power plants are high and the operational costs low, so they should be utilized as much as possible. They also play an important role in reducing emissions.

Own consumption of NPP requires, in particular:

- Ensuring consistent and absolutely reliable electricity supply of the entire equipment of the reactor during operation, emergency states and after reactor shutdown.
- Securing routine maintenance of the reactor during operation, with regard to the long operating period of the reactor.

The peculiarity of the operation of a reactor is the additional creation of heat after the shutdown of the reactor due to the energy of nuclear fuel fragments, which it is necessary to transfer out with the coolant. For these reasons, own consumption must be secured with power supply from at least two independent power sources and accumulator batteries. In addition, the power plant has an emergency source of power (diesel generator) in case there is no voltage in the network or on the terminals of the generator. Some power plants take advantage of a direct power line to another power plant, preferably hydroelectric, to ensure its own consumption.

3.6.8 Description of a VVER 440 block

FUEL: Enriched uranium in the form of uranium dioxide (UO_2) MODERATOR: Light (ordinary) water COOLANT: Light (ordinary) water ACTIVE ZONE: Small tablets of UO2 hermetically sealed in a zirconium casing form the fuel rods. Dozens of the fuels rods are assembled into so-called fuel cassettes. Power control is carried out using emergency and control rods that are slid into the active zone or pulled out from it.

Basic technical data:

Thermal power: 1375 MW

Electric power output: 440 MW

The height of the active zone: 2.5 m

The diameter of the active zone: 2.88 m

Number of fuel cassettes: 349 pieces

Weight of the fuel in the reactor: 42 t

Enrichment of fresh fuel: 3.3 %

Number of fuel rods in a cassette: 126 pieces

Fuel rod diameter: 9.1 mm

Coolant pressure: 12.3 MPa

Coolant temperature at the inlet: 265 °C

Coolant temperature at the outlet: 295 °C

Number of loops in the I circuit: 6 pieces

Turbo-generators: 2 x 220 MW

Net efficiency of the block: 27.67 %

Utilization - 7,000 h/year

Economic life of the power plant - 25 years

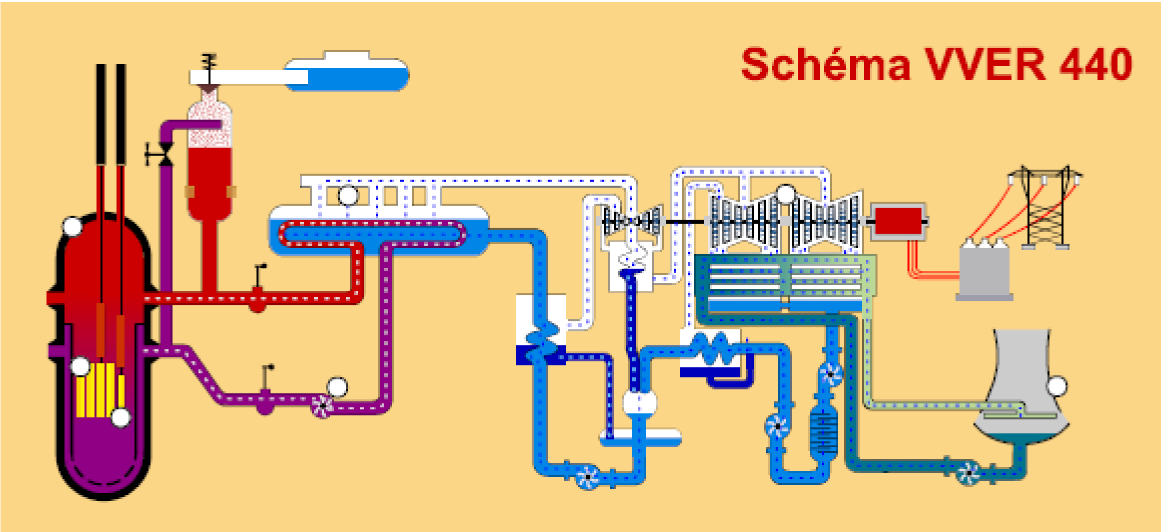


Fig. 3.23 Schematic diagram of a VVER 440 block

3.7 Measurement of Radioactive Radiation

Definition of fundamental quantities

Radionuclide activity is a quantity that indicates the number of radioactive nuclei that disintegrate in 1 second. The unit is 1 *Bq* (Becquerel).

The effect of ionizing radiation is determined not only by the activity of the source, but it also depends on the energy the radiation carries and how efficiently it transfers it to the environment through which it passes. The measure of the effect of radiation is the so-called ***dose***. A dose is a physical quantity that indicates how much of the energy of ionizing radiation is absorbed by 1 kg of a substance. The unit is 1 *Gy* (Gray), which corresponds to the energy of ionized radiation 1 (J) absorbed in 1 kg of a substance.

The effect of radiation on the living organism must be adjusted according to the type of radiation. The ***dose equivalent*** is a quantity that expresses the biological effectiveness of individual types of radiation. Each type of radiation has a so-called ***quality factor q***. The dose equivalent is calculated as the product of the radiation dose and the quality factor. The unit of dose equivalent is 1 *Sv* (Sievert), more often *mSv*.

Note:

The value of the quality factor for the individual types of ionizing radiation are specified empirically:

Beta radiation, gamma and x-ray radiation: $q = 1$

neutron radiation - slow neutrons: $q = 3$

Alpha and neutron (fast neutrons) radiation: $q = 10$

3.7.1 Measurement of Radioactivity

Due to its wavelength, the radiation of radioactive substances is invisible to the human eye. Neither can any other sensory organ of a human being detect the presence of the radioactive radiation. We must therefore rely on a variety of physical methods.

In some methods, the resulting signal is proportional to the type and energy of radiation. Such detectors are called proportional counters. In other detectors, the signal does not depend on the initial energy of the radiation, e.g.: Geiger – Müller tube.

There are methods which are able to register a single particle and monitor its tracks. An example is the Wilson cloud chamber, based on making the path of a particle visible using miniature droplets. A bubble chamber with liquid hydrogen or a thick layer of photographic emulsion is another example of detection methods. Using an external magnetic field, it is possible to track particles, analyze their traces, and identify exactly the type of particle.

The measurement of radioactivity utilizes a number of different effects of ionizing radiation:

- The measurement of ionization caused by the passage of a photon or a particle through the environment.

Film dosimetry is a method based on the principle of blackening of the photographic emulsion. It is used to identify small doses of radiation. The measurement of high doses of radiation is carried out by utilizing changes in the optical properties of substances (colors), the quantity of heat liberated (so-called calorimetry) or changes in the electrical properties of semiconductor components.

- Measurement of the faults that have arisen in a solid substance.

The measurements are performed as either relative, comparing to a standard under the same conditions, or as absolute, which due to the need of correction of the result for the different effects of the environment that affect the result (geometric arrangement, the absorption of ambient radiation, the ambient noise,the reflection of radiation from the underlay, etc.) are much more complex. An example of an absolute measurement is the manganese sulphate bath method.

Radiation detectors - devices for determining the presence of radiation and its intensity.

Dosimeters - devices for measurement the size of the dose (the amount of energy that radiation transferred to a substance.)

Gas detectors - are the most commonly used radiation detectors. They are based on the ionization and excitation of the atoms of gas. The gas is enclosed in a metal shell with an electrode in the center. Voltage is introduced between the shell and the electrode. As soon as radiation enter the detector, it causes ionization, which manifests itself as an ionization current between the electrode and the shell. Different types of detectors are distinguished according to the size of the current for the voltage, e.g.: ionization chamber, proportional counter and Geiger-Müller counter.

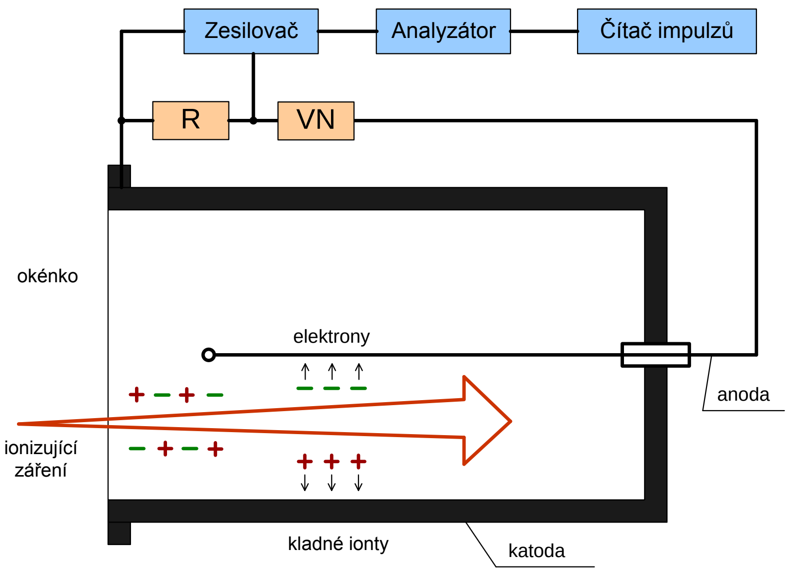


Fig. 3.24 Wiring diagram of a gas detector

Moderation detectors - are used to detect neutrons and to determine their energy. They are made of a substance that effectively slows down (moderates) neutrons. Usually it is a substance with a high content of hydrogen, e.g.: paraffin wax, polyethylene, etc.

Scintillation detectors - are based on the excitation of electrons in the scintillator to a higher energy state through radiation. The return of the electrons to the basic state is manifested as light flashes, which are measured by a photomultiplier. A scintillator may be solid organic (e.g., anthracene) or inorganic (e.g., sodium iodide) crystals, and solutions or suspensions of organic scintillators in an organic solvent, e.g., toluene.

Semiconductor detectors - radiation causes the electrons in the semiconductor to vault into the so-called conduction zone of the semiconductor. If magnetic field acts on the semiconductor, this vault manifests itself as a sudden increase in electrical conductivity. A suitable electronic device registers the electric impulse. The foundation of semiconductor detectors are mostly monocrystals of silicon or germanium with trace quantities of lithium, or super-pure germanium. For their proper operation, they must be cooled to the temperature of liquid nitrogen.

Film dosimeter - is made up of a special photographic emulsion. The intensity of its blackening is proportional to the dose of radiation. Film dosimeters are most often used to determine low doses in personal dosimetry.

Thermoluminescent dosimeter - is also used as a personal dosimeter in the form of a ring. It enables determination of the dose received by the worker's hands. A thermoluminescent substance has the property that radiation excites its electrons into a higher energy state. When the irradiated substance is subsequently heated (approx. 200 °C), the electrons return to their base state and the surplus of their energy radiates in the form of light flashes. Using a photomultiplier, the light flashes are converted to voltage pulses and measured.

Analytical methods

Nuclear spectrometry – deals with the measurement of the energy of nuclear radiation. The frequency distribution of emitted particles depending on their energy is called the nuclear spectrum, and according to the type of radiation it is divided into the alpha, beta and gamma spectrum. The beta spectrum is continuous with a specific maximum value of energy, while the alpha and gamma spectra are discrete. The nuclear spectrum is characteristic for every radionuclide and is the main source of information about the structure of the atomic nucleus. Nuclear spectroscopy is widely used for qualitative chemical analysis (the energy of emitted particles and half-life) and quantitative analysis (radiation intensity).

Autoradiography – utilizes the effects of ionizing radiation on photographic materials. By placing an activated object on a sensitive layer of photographic material (chromatographic plates), we obtain an imagine - an autoradiogram, which informs us not only about the distribution of radioactive atoms in a sample, but also about their quantity. We measure the density of the blackening on the autoradiogram with a photometer.

Activation analysis - used to determine the elemental composition of an unknown sample. The sample is irradiated, most often with neutrons in a nuclear reactor. Atoms of elements present in the sample are activated and the resulting radionuclides are then determined by gamma-spectrometry. It is one of the most sensitive analytical methods, enabling the detection of even 10^{-12} g of an element in 1 gram of the sample. This method is called the neutron activation method. In addition to neutrons, protons or highly energetic photons are also utilized for activation.

X-ray fluorescence analysis (XRFA) - this method is based on the measurement of the fluorescence excited in the examined sample using an x-ray lamp (classic XRFA) or the radiation of an appropriate radionuclide (radionuclide XRFA). According to the wavelength of the resulting fluorescent radiation, a determination of which elements are present in the sample (qualitative analysis) can be made, and according to the intensity of the fluorescent radiation, the amount of the element in the sample (quantitative analysis) can be determined. Semiconductor or scintillation detectors are used for detection. This method is used for the elemental analysis of samples. Although not being as accurate as activation analysis, it does not cause damage to the examined material and above all, no artificial radioactivity is generated.

a)

b)

Fig. 3.25 a) A personal film dosimeter, whole and disassembled into components b) Measurement by X-Ray fluorescence analysis

Marked compounds – are those kinds of chemical compounds in whose molecules one of the original nuclides is substituted by a radionuclide, e.g.: stable ^{1}H, ^{12}C, ^{31}P, ^{32}S are substituted by radionuclides ^{2}H, ^{14}C, ^{32}P, ^{35}S. Compounds chemically marked in this way behave exactly the same as the original compounds, but thanks to different physical characteristics it is possible to determine their presence everywhere where they were they were introduced. This has significance in their use as indicators, or "tracers" (chemical and biochemical reactions used especially in medicine and biochemical research, technological processes). The incorporation of a radionuclide atom into the molecule of an organic compound is done most commonly by chemical synthesis, photosynthesis and biosynthesis (e.g., the cultivation of lower biological organisms in an environment of radioactive carbon dioxide).

Some nuclear analytical methods need strong sources of radiation. For neutron activation analysis, neutron radiation from a nuclear reactor is used, for analysis by means of charged particles, accelerators are used. Special irradiation facilities are being built with strong radionuclide sources of gamma radiation, most often ^{60}Co or ^{137}Cs, with activities of as much as 10^{16} Bq and more, and accelerators of electrons with energies from about 0.1 to 10 MeV. A strong emitter is placed in water shielding in a tank, from which it is extended out into working position. In the presence of a strong emitter, and interesting effect occurs in the water - Cherenkov radiation. It is a blue light, which arises during the passage of charged particles through an environment at a speed greater than the speed of light in this environment. It is one of the few opportunities available to us to "watch" outer manifestations of radioactivity.

Tracer analysis (radioindicator method) – uses appropriately selected compounds for the study of the movement, behavior and transformation of chemical substances in physical, chemical and biological processes. These compounds are called radioindicators. It is a simple, quick and very sensitive method.

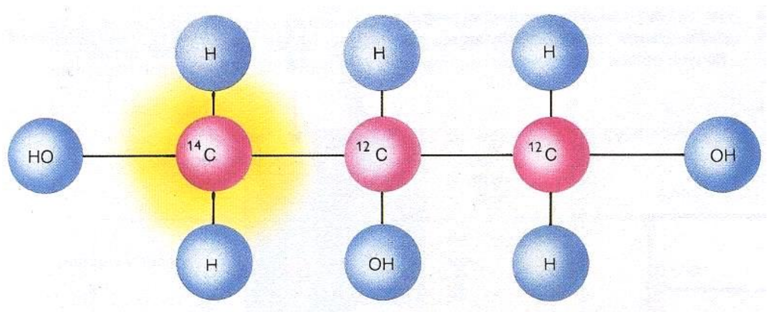


Fig. 3.26 Glycerol marked with carbon ^{14}C

Dilution analysis (method of isotopic dilution) - the specific activity of the radioindicator is diluted by a specified substance, chemically identical but non-radioactive. After the addition the specific radioactivity drops, but the overall activity remains unchanged. The quantity of the specified substance can be calculated from the mutual ratio of the original activity and the activity after the dilution.

Radioimmunoanalysis *and* ***radioenzyme analysis*** - these methods again utilize marked compounds. They are used for tracking biologically important compounds (e.g. hormones) in samples of body fluids. Both methods are rapid, specific and very sensitive (they detect the presence of a substance in concentrations as low as of 1 pg/l). Radioimmunoanalysis (RIA) is based on the immune response. Radioenzyme analysis (REA) uses a specific enzyme to transfer a radioactive indicator to the analyzed ensemble. After separation, the measured activity determines the concentration of the substance in the sample. Both analyses proceed in test tubes (in vitro), so that the patient's body does not come into contact with radionuclides.

Particle accelerator U120-M is the only cyclotron for research purposes in the Czech Republic and has been used since 1977. It produces protons, deuterons and alpha particles (helium ions $^{3}He^{++}$) with speeds of up to a quarter of the speed of light and energies of 38 MeV, 19 MeV and 53 MeV, respectively.

The cyclotron (Golem) is hid behind a 2.5 m thick concrete wall. The device itself is 3 m high, weighs more than 120 tons and its power consumption can reach as much as 120 kW. The magnetic field in the center of the cyclotron may, depending on the type and energy of the particles accelerated, reach up to 1.8 T.

In addition to utilization for basic research, the cyclotron is used for the manufacture of radiopharmaceuticals for the detection of radioactive isotopes in the body or for targeted tumor diseases treatment. In addition, it is also used to manufacture substances for Positron Emission Tomography (PET).

Particle accelerators can generally be used to study the brittleness of materials under stress, mimic the changes caused by aging, test the chambers and reactors of nuclear and fusion reactors, or for accelerator-driven transmutations in which particles produced by the accelerator "shot apart" the radioactive isotopes in the fuel used and even produced energy in the process.

3.8 Nuclear Safety

3.8.1 The international scale for the evaluation of nuclear events

In the Czech Republic, state administration and supervision of the use of nuclear energy and ionizing radiation in the area of radiation protection and in the areas of nuclear, chemical and biological protection is provided by the **State Office for Nuclear Safety** (SÚJB).

For the assessment of events in a nuclear power plant, the International Atomic Energy Agency established the INES scale (International Nuclear Event Scale). It basically distinguishes incidents (1-3) and accidents (4-7). All member countries and nuclear facilities are to inform according to this

scale of all events in which changes or deviations arise in the area of nuclear safety.

0 - Event without safety significance (the most routine operational malfunctions, normally manageable)

1 - Deviation from normal operation (malfunctions that do not present a risk, but reveal inadequacies in security measures)

2 - Incident (technical failures that do not affect the safety of the plant directly, but may lead to a reassessment of security measures).

3 - Serious incident (irradiation of plant operating staff above the standard, smaller leak of radioactivity into the surrounding area - fractions of the limit).

4 - Accident with effects in the nuclear facility (partial damage to the active zone, radiation exposure of the plant operating staff, radiation exposure of inhabitants of the surrounding area beyond the limit).

5 - Accident with impact on the surroundings (more serious damage to the active zone, leakage of 100 to 1000 Tbg of biologically significant radioisotopes, the need for a partial evacuation of the surrounding area.)

6 - Serious accident (a large leakage of radioactive substances outside the object, the necessity of using emergency plans to protect the surrounding area).

7 - Major accident (a major leak of radioactive substances into a large territory, immediate health consequences, long-term threat to the environment).

In the hitherto course of the nuclear era, there have been only a few incidents that fall into categories 4-7 of the INES scale (NPP A-1 Jaslovské Bohunice, level 4, 1977; NPP Three Mile in the USA, level 5, 1979; NPP Chernobyl, level 7, 1986).

3.8.2 Protection against ionizing radiation

Protection against ionizing radiation is an important condition of work with radioactive materials. This is because radiation causes the creation of chemically very reactive radicals in the irradiated tissue, leading to the damage or extinction of the cell. At higher doses, irreparable damage of certain organs sensitive to radiation may occur (e.g., the eye, blood-forming tissue, genital organs, etc.); these effects engender so-called radiation sickness, and at extremely high doses can lead to the death of the irradiated individual. In general, we can say that the more complicated an organism is, the more sensitive it is radiation and the lower is the dose sufficient to destroy it. For a human being, a dose of 5 Gy is a dose at which half of the irradiated die.

Besides this, damage to the genetic information stored in the cells occurs, which result in adverse mutation that may not appear until subsequent generations, even at very low doses of radiation. This effect has no threshold dose.

Protection against ionizing radiation is based on several principles:

- Increasing the distance of the operating staff from radiation sources - the intensity of radiation decreases with the square of the distance
- Shortening of the time spent in the vicinity of radioactive substances to a minimum
- Work with the minimal activity of the radiation sources for a given task
- Effective absorption (shielding) of the radioactive radiation (shielding) by appropriate materials – alpha (α) radiation is completely absorbed in thin layers of paper, beta (β) in metal, glass, etc. The shielding of gamma radiation (γ) and neutrons is more difficult. Layers of heavy metals (Pb, W, U) are used For the absorption of gamma radiation, and heavy concrete with an additive of barite is used in construction work. Conversely, the best for neutron shielding are substances with a high content of light elements, in particular hydrogen (polyethylene, water, etc.). The operating staff monitors tasks through the shielding by using a mirror, a periscope or a peephole of leaded glass. The handling of the source of radiation is carried out using a manipulator.

For protection while working with open emitters, the toughest requirements of safety at work must be fulfilled. We must be careful to avoid capture on the surface of the body or the inhalation of dust particles containing material from the emitter (use of respirators, protective gloves and clothing, etc.) In the event of internal contamination, the radioactive substances creating the biggest problem are those which remain in the body for a long time and emit alpha and beta radiation, because all the energy of this radiation is absorbed in a small volume of tissue.

A measure of the effects of ionizing radiation is given by the dose equivalent. It is the product of the dose and the quality factor of individual types of radiation, which expresses the influence of the radiation on the biological effect. For radiation protection purposes, limits of the dose equivalent are specified, i.e., its maximum value to which an individual can be exposed.

Tab. 3.5 Dose equivalent limits

Organs and tissues	The highest permissible dose equivalents for workers		Dose equivalent limits for individuals from the population/year (mSv)
	Quarterly (mSv)	Annual (mSv)	
Gonads, active bone marrow, uniform exposure of the whole body	30	50	5
Skin, thyroid gland and bone	150	300	30
Hands and forearms, feet and ankles	400	750	75
Any other organ or tissue	80	150	15

Note: The dose from one routine lung x-ray, 0.02 mSv, is accumulated by a human being from the natural environment in three days. During a CT (computer tomography) scan of the chest, the dose reaches the value of 8 mSv, corresponding to 3.6 years of accumulation from a natural background. Positron Emission Tomography (PET) of the head "transmits" a dose of 5 mSv.

Monitoring the doses (or dose equivalents) from external sources of ionizing radiation to which the individual is exposed is dealt with by personal dosimetry. These dosimeters are most commonly based on film (the blackening of a sensitive film layer), thermoluminescent (irradiation of aluminophosphate glass containing traces of manganese), or neutron (a pair of plates of fissile material, between which is polyester Mylar foil) dosimetry.

To ensure the safety of the operating staff against radioactive radiation, the reactor is surrounded by protective layers. These are usually two protective insulations: **thermal** insulation, which directly relates to the reflector and reduces the flow of neutrons. This thermal protection heats up during the absorption of neutrons and γ rays and must therefore be cooled. Its thickness depends on the material, for example with steel it is 10-25 cm. Directly following up on thermal protection is **biological** protection, which also limits the flow of neutrons and γ rays to the allowed value. Usually it is a layer of concrete with a thickness of approximately 2.5 m. The protection of the operating staff and the area surrounding the power plant against radiation is on Fig. 3.27.

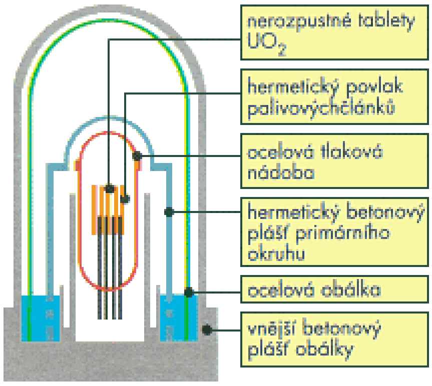


Fig. 3.27 The security features of a reactor

Another important element in guaranteeing the safety of a nuclear power plant is the principle of self-regulation of the reactor. Self-regulation is the ability of the reactor to limit sudden changes in power output automatically, even without the use of regulatory bodies. If there is an unexpected increase in the power output of the reactor, self-regulation returns the output to original operating values. The development of reactors is directed precisely to these types, with so-called inherent (internal) security.

3.8.3 The Chernobyl accident

Two massive explosions shortly after each other on the night of April 26, 1986 destroyed the fourth block of the Chernobyl nuclear power plant, near Kiev in the former USSR, and the radioactive fumes of the resulting fire spread by the wind threatened not only its surrounding area, but also a number of neighboring countries. The cooling systems of the Soviet graphite channel reactor type RBMK-1000, in whose more than sixteen hundred individually cooled channels boiling water turns directly to steam, are themselves extremely complicated. The physically considerably unstable active zone of the reactor, which is moreover surrounded by combustible graphite, lacks a protective envelope (see containment), and even the reactor control system did not meet the safety requirements of the IAEA. The so-called inherent instability of these reactors lies in the fact that if a rise in temperature occurs, and within the channels the number of bubbles in the steam rises, then the reactivity and thus the power output have a tendency to rise, unlike water-water reactors, where the reaction would on the contrary be mediated. That fateful night the operators were supposed to carry out an improperly prepared attempt to use the electrical power of a coasting down turbine-generator unit for short-term emergency cooling of the reactor. With the consent of superiors the shift supervisor disabled the safety automatics preventing the admittance of a riskily low reactor power output value. Control rods were lifted in such numbers and so high that, when at 1 h 23 min 40 sec it was indicated that as a result of the above-mentioned positive coefficient of reactivity the power output lowered to only 200 MW_t was starting to rise stormily with the growth of the steam in the channels, they were unable to drop back fast enough into the active zone. Only 4 seconds later, thermal power rose at least a hundredfold and there was a steam explosion that threw the thousand ton reactor lid aside. Air entered into the hot masses of the torn apart block, and through its reaction with hydrogen created by the contact of water vapor and searing hot graphite there immediately followed a second explosion, which tore to pieces a part of the active zone. Flying hot debris lit the asphalt coating of the roof. When the roof caved in, a cloud of smoke along with 5 tons of radioactive substances were ejected into the air. Powerful leaks of radioactivity managed to be subdued after a ten day heroic fight by poorly equipped rescue workers and soldiers, to whose lives and health in the first few days was given absolutely no regard. Variable winds took the radioactive cloud and at least two million TBq of radioactive substances (particularly iodine and cesium) in several moves over Scandinavia, Central Europe and the Balkans.

The disaster immediately sought 31 dead from among the employees of the power plant and the firemen, and 237 people became acutely ill from exposure to radiation. Thousands of rescuers and helpers received dose equivalents from 300 to 500 mSv. A 30 km diameter region around the power plant is still closed to the public, and the damage to the land, the economy and property was later estimated at more than 10 billion US dollars. Over half a million people helped in the later expanded evacuation, a quarter of which who were affected by more powerful substances are still under medical supervision. During the dramatic rescue operation, the ruins of the reactor were buried under thousand tons of clay, dolomite, and lead, and with the help of remote-controlled heavy machinery the destroyed reactor hall was enclosed by a complicated concrete sarcophagus weighing 3/4 million tons. It is under constant scrutiny, but must now be reconstructed because of the threat of its "perforation".

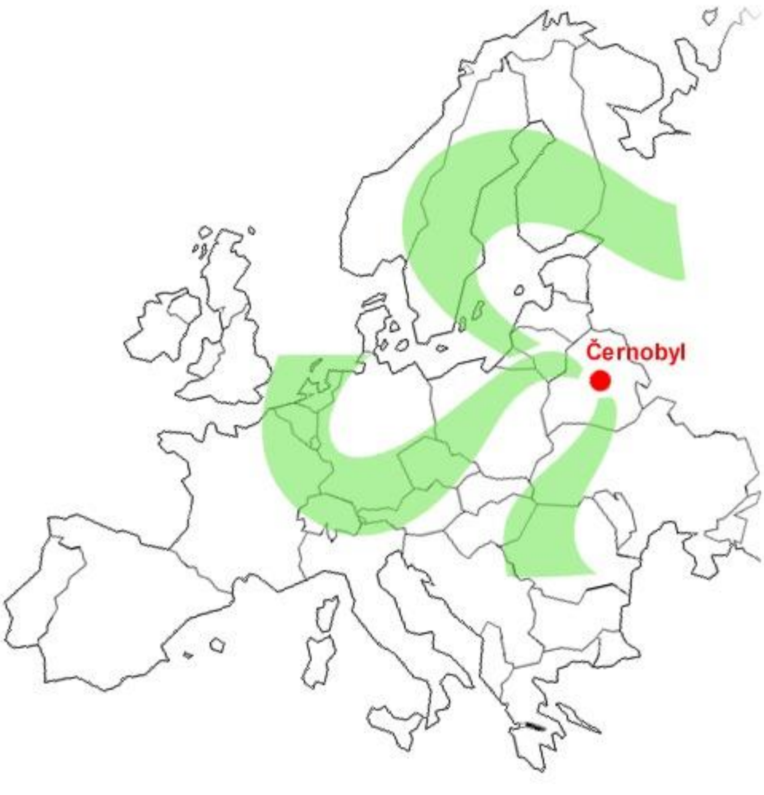


Fig. 3.28 Area of radioactive dust dissemination

3.9 Management of radioactive waste (RAO)

3.9.1 Storage of radioactive waste

Radioactive waste comes into existence through the use of radionuclides in human activity. Radioactive waste can be stored in specially prepared sites, repositories, which can be divided into:

- ***Surface*** ("near surface") - low and medium active waste, worldwide there are more than 80 such duly approved repositories.
- ***Underground*** - so far only one is licensed also for storing transuranic radioactive waste (RAW) of high activities, the "WIPP"(**W**aste **I**solation **P**ilot **P**lant) in New Mexico, USA, which is operated since 1999. In six years of operation, it accepted 3,500 shipments of RAO with a volume of almost 30,000 m^3. The repository is located in a 200 million year old stable salt basin in uninhabited desert at a depth of more than 300 m below the surface. In plan are also repositories in the Yucca Mountains in Nevada, USA; in Japan, Finland, Sweden, Canada, the United Kingdom, China, Hungary, Belgium, ...

The trend in the area of disposal of radioactive waste is the specialization of storage:
The most well-known type are landfills of ***very low active RAW*** ("VLLW" – **V**ery **L**ow **L**evel **W**aste) due to the large savings in investment costs.

Another example are repositories with ***long-term RAW*** (elements with a half-life longer than 30 years with a content of alpha emitters higher than 4 000 kBq/kg). These are further divided into long-term RAW with *low and intermediate activity*, e.g., type "BOREHOLE" (a vertical borehole in high quality stable rock with a depth of 10-50 m), and *highly active* (natural radioactive reaction is accompanied by the generation of heat) *long-term RAW.*

Repositories utilize materials which when in contact with water become impermeable rock themselves. They are placed in high-quality rock at a distance of tens or hundreds of meters from a source of drinking water or the earth surface.

a) b) c)

Fig. 3.29 a) Scheme of a surface repository of RAW, b) Repository in the storage in the Richard mine near Litoměřice, c) Scheme of deep repository of RAW

3.9.2 Transmutation of elements

Beyond the storing of RAW, there are some transmutation technologies capable of deliberately transmuting an element into another element or other radionuclide with more favorable characteristics (the utilization of plutonium from decommissioned nuclear weapons, the recycling of spent fuel in a new mixed fuel (MOX), the transmutation of thorium, etc.).

THORP (**T**hermal **O**xide **R**eprocessing **P**lant) - is a designation for an industrial plant for the processing of used nuclear fuel operated by the British Nuclear Group (BNG) and owned by the Nuclear Decommission Authority (NDA) on the west coast of Great Britain. The service was introduced in 1999.

After pulling out the spent fuel rods from reactor (after approx. 4 years), they contain approximately 3% of waste products, which are eliminated by a chemical, “reprocessing” procedure. The remaining 97% is unused uranium and newly created plutonium.

Reprocessing procedure - spent fuel rods are transferred to a THORP facility pool, where they are still in the process of being cooled. The rods are subsequently put into hot chambers, where they are cut into approximately five- centimeter pieces that fall into stainless steel baskets submerged in hot nitric acid (HNO_3). After several hours the fuel and dissolves and only the empty metal covers remain in the basket. This acidic solution goes to the centrifuge, where the liquid is separated from the smallest remnants of solid parts. Radioactivity is carefully remeasured throughout the process to avoid leakage and misuse of the radioactive material. The nitric acid with the dissolved fuel then proceeds to the chemical separation. First, by using a solvent based on paraffin, the uranium and plutonium are separated from the remnants of fission products, which remain in the nitric acid. The plutonium is separated from the uranium by using the aqueous phase and employing so-called pulsed columns (mechanical vibrations are substituted by pulses of compressed air) containing many perforated plates of stainless steel with which the solution is stirred. The uranium and plutonium are subsequently used in a fuel production plant to make fresh fuel cassettes.

Spent nuclear fuel is processed in the THORP plant for the United Kingdom, Japan, Switzerland, Sweden and Germany.

3.10 Use of Radioactive Radiation Outside the Energy Sector

3.10.1 Applications in industry

Industrial defectoscopy - is used to search for surface and internal defects in metallurgical products or to check the quality of welds. The product or weld is irradiated by a radionuclide emitter and a cassette of photographic film is placed on its opposite or outer side. Any defects can be identified on the basis of an evaluation of the photographic film.

Radiation thickness gauges - by using beta radiation, the thickness of material being produced in continuous operation is checked. They are usually used in rolling mills, the plastics industry and in foundries to check the thickness (walls) of a product or the quantity of bulk material fed into a batch.

Radionuclide level-gauge - used when checking and determining the level of a liquid in vessels and tanks where the other methods cannot be used. It is based on the level of the absorption of radiation in its passage through liquid or air.

Tracer methods are used to monitor the movement and distribution of materials in different technological equipment and transport systems on the principle of the radioindicator method. Monitored in this way are flows, mixture mixing, ventilation, filtration, leaks, wear of the material and the progress of corrosion.

Ionization smoke detectors - are based on the different absorption of radiation in various environments. The sensor of an electric fire alarm contains a radioactive emitter, whose alpha radiation creates ionization current between two electrodes. In the presence of smoke the absorption of the environment changes, leading to a change in the ionization current and this change is registered by the fire alarm system.

Control of the purity of raw materials, semi-finished products and resulting materials in those fields where high purity has a critical role. Primarily utilized are neutron activation analysis and X-ray fluorescence analysis. We can usually find this method being used in the manufacture of semiconductors and fibers for optoelectronics, where the prescribed purity of the material is 99.9999%. Additives (dopants) in silicon wafers are controlled by autoradiography.

Ionization caused by a radioactive area emitter is used to ***remove accumulated electrostatic charge*** in the manufacture of insulation materials. This is utilized in the rubber, plastics, paper and textile industry and in the manufacture of magnetic tape.

The production of composite materials, polymer foams, polymer fibers, thin layers and layers of insulation, rubber vulcanization - a suitable porous natural or artificial material (wood, stone, concrete, etc.) is allowed to soak up the monomer and then irradiated with the appropriate radiation dose, which causes polymerization and thus enables us to produce material with completely new properties. This method is used to produce, e.g.: floor coverings, facing bricks, tiles in construction, but also, for example, the neoprene of divers. Polymerization by ionizing radiation has the advantage that the resulting material is not contaminated with chemical initiators, catalysts, etc. Through radiation, we are also able to achieve the grafting of suitable chemical substances onto the surface of the fibers, which then modify the properties of the product in an appropriate way (better dyeability, absorbency, wrinkle resistance, etc.), which is used in the textile industry.

Some types of polyethylene after irradiation "***remember" the shape*** that they had during irradiation. In this way it is possible to make suitable insulating cuffs and couplings for a variety of applications, which after heating shrink back to the original size before irradiation and so ensure a high-quality connection, electrical insulation, adhesive product packaging, etc.

Different colors (yellow, brown to smoky gray) ***of specialty glass*** are produced using irradiation. The color tone and the durability of the coloring (decades) depend on the composition of the glass. A typical example of the use of this method is the New Stage of the National Theater in Prague.

Radioactive ***self-illuminating pigments*** - e.g.: with ^{147}Pm or tritium in the form of paint, they are applied to the numbers and hands of a watch as a permanently glowing mass. Not only are they used in watches, but also for the designation of the scales of measuring instruments and to produce orientation signs used in mines and the like.

3.10.2 Applications in health care

Radionuclides have been applied in healthcare ever since their discovery. At first it was for medicinal purposes and subsequently also for diagnostic purposes. In connection with it are being created new medical disciplines - nuclear medicine, radiology. Besides these, the use of ionizing radiation has penetrated even into other areas (the sterilization of medical supplies, pharmaceuticals, manufacturing, etc.).

Nuclear medicine - uses artificial radionuclides (produced in nuclear reactors or accelerators) for diagnostic or therapeutic purposes. Radionuclides are applied either directly or in the marking of materials intended for application (so-called radiopharmaceuticals).

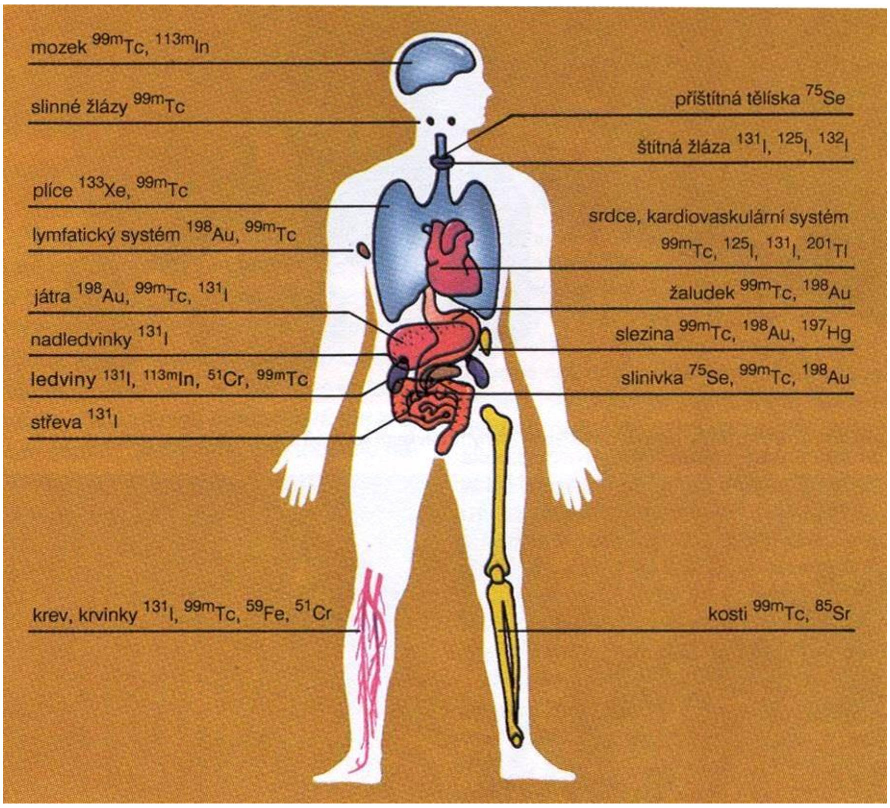


Fig. 3.30 Individual organs of the human body and the radionuclides used for their examination

Detected radiation allows painless and quick assessment of a function or provides information about the placement or shape of the examined organs (so-called "in vivo " examination). The functioning of organs can also be tested "in vitro" in a test of bodily fluids. Nuclear medicine primarily utilizes analytical methods (REA, RIA, NAA, scintigraphy). Radiopharmaceuticals are also used for therapeutic purposes in the treatment of malignant tumors. The advantage is that the emitter gets directly into the focal area that we want to irradiate and the effect of the radiation is precisely bounded within a short distance, as determined by the energy of the radiation of the radionuclide used (e.g.: to a depth of 2.2 mm for ^{131}I or 8 mm for ^{32}P).

Balneology - utilizes baths in which the natural water contains the radioactive gas radon (the Jáchymov Spa). Primarily treated are diseases of the locomotive apparatus and rheumatic diseases. In some cases, treatment is combined with irradiation of affected areas.

Radiotherapy - is a treatment method utilizing the effects of radiation for the treatment of malignant tumors. Tumors are made up of young cells that divide very quickly and are many times more sensitive to radiation than healthy tissue. Most often used for the destruction of tumor tissue are x-rays or the gamma radiation of radionuclides ^{60}Co, ^{137}Cs and ^{226}Ra. Sometimes used for the same purpose is a beam of accelerated electrons from a betatron or a beam of accelerated charged particles from a linear accelerator. The irradiation proceeds by using radiation sources placed outside of the human body (an emitter with ^{60}Co, an electron accelerator, x-ray), or by using needles or tubes temporarily placed in the tumor (the so-called brachytherapeutic emitters with ^{137}Cs and ^{226}Ra). The following illustration shows the different shapes of needles and tubes filled with radioactive emitter.

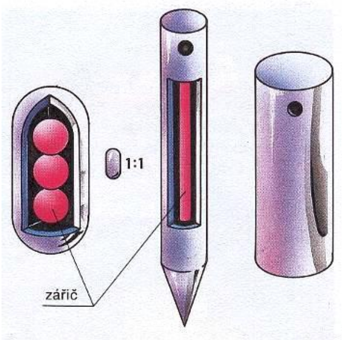


Fig. 3.31 Brachyterapeutic emitters

A separate branch of radiology is rentgenology concerned with the study of the effects of x-ray radiation and its use for therapeutic and diagnostic purposes.

An improved method of x-ray diagnostics is so-called ***tomography***. It utilizes several x-ray sources at once and the subsequent computer processing of the obtained image.

Sterilization of medical supplies (bandages, clothing, surgical gloves and instruments, syringes, endoprostheses, etc.) with radiation technology means the destruction of pathogenic germs with ionizing radiation. Irradiation also makes it possible to attain the sterile food required for the nutrition of some severely ill or injured persons.

Also used in medicine is so-called ***radiation grafting*** - various preparations are grafted onto certain polymeric carriers, which are then released very slowly, thus achieving better therapeutic effects (antibiotics for burns, pharmaceutical preparations, etc.)

3.10.3 Applications in agriculture and the food industry

Agricultural engineering - the efficient use of fertilizers in agriculture plays an important role not only because of their price, or dependence on imports, but also due to the fact that over-fertilizing harms the environment. The aim is for most of the fertilizer to get to the crops with minimum losses (by bad deployment or fertilizing at the wrong time). Optimal fertilization is possible to achieve by modeling through the use of fertilizers marked by appropriate nuclides. To verify the efficiency of fertilizing, artificial fertilizers are marked with the radionuclide ^{32}P or the stable nuclide ^{15}N. In this way, it is possible to track how much nitrogen from the fertilizer is the plant capable of accepting, how much fertilizer bonds with the soil effectively, and how much passes unused into the surrounding environment.

Breeding - through the irradiation of seeds, which causes the mutation, it is possible to change important properties (resistance to disease and bad weather, yields, nutritional value, etc.) of cultured crops or create completely new varieties. The irradiation of seeds has been utilized in agriculture for already 50 years.

Irradiation is also used to ***limit the reproduction*** (male sterilization) of certain species of insects that cause considerable damage in agriculture.

Preparation of feed mixtures - in the preparation of feed mixtures, uniform mixing of the individual components is required. One component of the mixture is marked with a radioactive indicator (tracer) and the progress of stirring of the ingredients is then monitored by a detector.

Livestock farming - radioimmunoanalysis helps to monitor hormone levels, affecting the fertility of the animals (e.g. progesterone). Other kits are used to determine the concentration of carcinogenic of mycotoxins (mold products) in the feed or the bodies of animals.

Food irradiation - according to statistics 25 to 30% of food is wasted to due to decomposition processes or premature germination. If we irradiate them with a source of radiation (e.g.,

^{60}Co), the micro-organisms and pests are destroyed, or germination is suppressed and thus their shelf life is prolonged. Most often irradiated are onions, potatoes, strawberries, tropical fruits, spices, and fish.

Radioactive indicators are used to monitor the influence of trace elements on the ***metabolism of plants***. In ***forestry***, materials from irradiated polypropylene are utilized, which ensures easy degradability of materials and facilitate the planting of trees. Similar materials are applied as so-called geotextiles, firming slopes in large landscaping works.

3.10.4 Application in environmental protection

In view of increasing pollution of the environment, the aim of the efforts of society should be to close production cycles, or at least limit the negative effects to the maximum degree. Ionizing radiation can be used in many cases for the removal of unwanted substances from wastewater and gases.

Tracking the flow and dispersion of polluting emissions - radioindicators are used in the determination of seepage, the interconnection of surface water and groundwater or the ability of watercourses to disperse pollutants.

The presence of poisonous elements in the environment - can be detected by the methods of neutron activation analysis and X-ray fluorescence analysis. Being analyzed are, e.g.: air filters with captured pollutants, fruit along the roads, etc.

Liquidation of the harmful components of flue gas - irradiation with a gamma emitter or an electron accelerator is utilized. Through irradiation of combustion gases, a reaction of sulfur dioxide or nitrogen oxide with added ammonia can be initiated. Solid particles of sulphate or ammonium nitrate are formed, which can then be used as fertilizer or in construction. This method of desulfurization and denitrification of combustion gases has a relatively high efficiency (90%) and its main advantage is that both SO_2 and nitrogen oxides (NO_x) are removed in one stage.

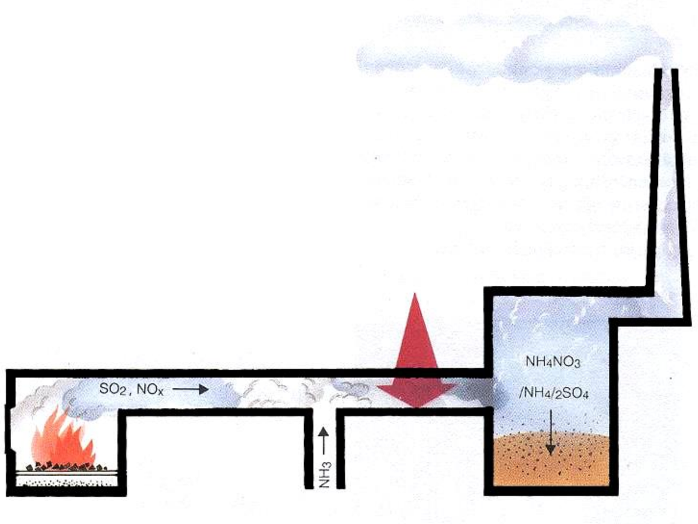


Fig. 3.32 Scheme of the liquidation of oxides of nitrogen and sulfur using irradiation

Curing of varnishes on equipment articles with an electron beam - it is used in particular in hospitals, schools, gyms, etc., to prevent the possible release of toxic solvents contained in varnishes.

Measurement of the activity of natural materials – or the measurement of the dose equivalents of radioactive radiation from materials in the environment.

3.10.5 Applications in archeology and in the protection of monuments

While in archeology are primarily employed measurements of activity and radioanalytic methods, radiation techniques are mainly applied in the protection of monuments.

Dating the age of the objects from dead organisms (wood, bone, ivory, textiles, and iron - if charcoal was used in its production) utilizes the ***radiocarbon method***, involving the measurement of the activity of the remnant of the carbon isotope ^{14}C, which got into them in the form of carbon dioxide (through breathing or photosynthesis, which also contained the radionuclide ^{14}C, resulting from the reaction of cosmic radiation with nitrogen ^{14}N). The amount of radioactive carbon in non-active carbon in the atmosphere is about 1 g of ^{14}C per 10^{12} g. While in a live organism the amount of carbon is maintained in a steady state, after its death the ^{14}C is not replenished and its remnant decays. In view of the fact that the half-life of carbon ^{14}C is 5,730 years, this method gives reliable results for a period of 5,000 - 50 000 years. The disadvantage of the method is the partial destruction of the sample. This is because Carbon ^{14}C is a weak beta emitter with a low energy of emitted by electrons, and is present in samples in extremely low concentrations. For shortening the time of sample measurement, the radiocarbon method is often combined with mass spectroscopy (AMS - Accelerator Mass Spectrometry), which is based on a direct count of the ionized carbon atoms during the flight through a magnetic field after being accelerated in an accelerator. The radiocarbon method was also used for the dating of the Shroud of Turin and to determine the age (authenticity) of the Iron Crown of Charlemagne.

Due to its characteristics, activation analysis is also used. It is used to detect trace amounts of elements in coins, ceramics, marble or in different artistic objects, and provides information on the method of production and, therefore, the development stage of a culture.

Verifying the authenticity or determining the origin of artworks – is based on detecting the presence of trace elements by using neutron activation analysis or X-ray fluorescence analysis. This is a comparative method, which compares the presence of characteristic trace impurities in the original and in the unknown sample.

Protection of monuments - ***the removal of wood-destroying insects, fungi and mold*** through exposure to a radiation source with radionuclide ^{60}Co. The doses selected are low, which ensures that the object, its pigmentation, appearance, etc. is not harmed or changed. A stationary emitter is located in Roztoky u Prahy. In the case that irradiation cannot be technically carried out in a specialized facility, mobile irradiation equipment is used. The saturation of an object with a monomer and subsequent radiation polymerization is used to protect archaeological finds, which can easily succumb to damage after being removed from the place of their discovery (underwater archeology, clay finds, etc.).

3.10.6 Application in geology and water management

Nuclear methods are also used in geological and hydrological surveys for the purpose of obtaining mineral and water resources. Absorption of ionizing radiation indicates the so-called snow water equivalent, i.e. the amount of water in the snow blanket, which is an important piece of information for the estimation of the quantity of water that will be gained from the melting of the snow and the resulting consequences for irrigation in agriculture. Radioindicators monitor the seepage of water through the loose embankments of dams, the mixing of waters and the dispersion of impurities in the watercourses.

Radioindicator methods are used to ***measure flow rates, water seepage, the interconnection of ground water and surface water, the dispersion (scattering) of impurities*** or to monitor ***the effectiveness of treatment plants of drinking and process water***.

Wells with drinking water suffer from the formation iron hydrides, which prevents the access of fresh water into the well. Their creation is the result of the activity of certain micro-organisms. Emitters with ^{60}Co placed around the wells ***prevent the growth of these micro-organisms*** and thus eliminate the problems with this so-called ochring of wells.

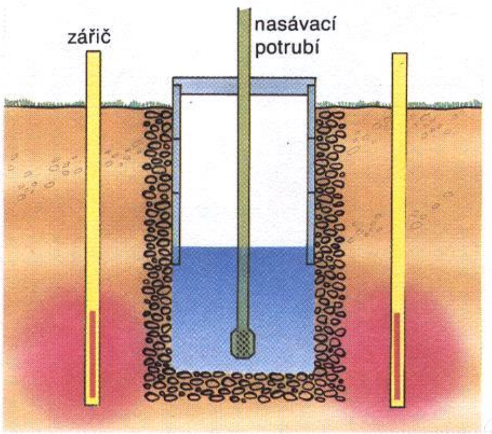
Waste water - containing certain harmful substances (e.g. cyanides, dyes, etc.) can be treated by invoking the breakdown of these compounds using gamma radiation. ***Drinking water*** can also be sterilized by radiation in specialized cases.

Radioactive logging - is a method that is used in the determination of the geological profile of a borehole by measuring the emission of gamma radiation of the various geological layers (gamma logging) or secondary radiation layers after previous irradiation by a stream of neutrons (neutron logging).

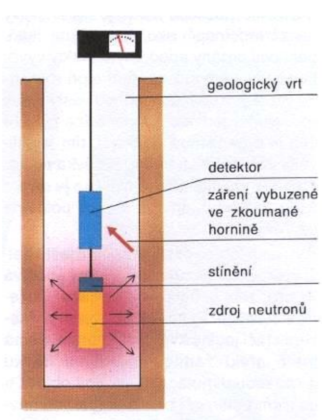
Radioanalytic methods are used in the ***analysis of geological samples***, e.g., X-ray fluorescence analysis is used to determine the presence of S, Ca, F and As in coal.

The scattering of neutrons in their passing through an environment containing atoms of hydrogen (water, crude oil) is used in the measurement of soil moisture and in the search for oil deposits and underground drinking water supplies. The thickness of a layer of ice or snow is measured by the radiographic method using gamma emitters with radionuclides ^{60}Co, ^{137}Cs and ^{241}Am. The method is based on the absorption of radiation by matter.

The principle of dating the age of rocks lies in the measurement of the activity of the radionuclide gas ^{40}Ar, which is released from rocks and is formed through the decay of the radionuclide ^{40}K.



a)



b)

Fig. 3.33 a) Emitters near a well help keep the water healthy and clean, b) Neutron logging

? 4 Review Questions for the Theoretical Section

1) Describe the structure and principle of a nuclear power plant.

(2 points)

2) Name the types of nuclear reactors.

(2 points)

3) Draw the dependency of the absorption of neutrons by isotopes on the energy of the neutrons, and describe each of its parts.

(2 points)

4) Express the relations for the calculation of the energy released from a nuclear reaction.

(2 points)

5) State the basic advantages and disadvantages of nuclear power plants.

(2 points)

? 5 Review Questions for the Practical Section

1) Specify the required amount of natural uranium for the annual operation of a NPP with a power output P_e = 450 MW, if its overall efficiency η_{JE} = 0.275 and the load factor ξ = 0.8 for the case of a theoretical 100% burn-out of U_{235}, without counting the plutonium.

(5 points)

Summary

New findings and concepts:

- Nuclear power stations, their construction and operating principle
- The classification of nuclear power plants according to the materials used
- Ecological effects of nuclear power plants

Answer key to the questions of the theoretical section

Ad 1) Chapter 3.6

Ad 2) Chapter 3.6.5

Ad 3) Chapter 3.5.1

Ad 4) Chapter 3.5.2

Ad 5) Introduction

Answer key to the questions for the practical section

Ad 1)

The energy produced by the plant for the year:

$$W = \frac{8760 \cdot \xi \cdot P_e}{\eta_{JE}} = \frac{8760 \cdot 0{,}8 \cdot 450}{0{,}275} = 11{,}47 \cdot 10^9 \ kWh \cdot rok^{-1}$$

Splitting one nucleus of U_{235} releases the energy E_1 = 200 MeV.

For the probable proportion of U_{235} nuclei which will be split by a slow neutron:

$$\eta_f = \frac{\sigma_{f235}}{\sigma_{a235}} = \frac{582}{694} = 0{,}84$$

and for the number of U_{235} nuclei in 1 kg (Avogadro's number):

$$n_j = \frac{N_A}{m_a} = \frac{6{,}022 \cdot 10^{26}}{235}$$

The usable energy of the fission of one kg of natural uranium (1 kWh = 3.6 · 10^6 J):

$$W_1 = \frac{0{,}714}{100} \cdot E_1 \cdot n_j \cdot \eta_f = \frac{0{,}714}{100} \cdot 2 \cdot 10^8 \cdot 1{,}6 \cdot 10^{-19} \cdot \frac{6{,}022 \cdot 10^{26}}{235} \cdot \frac{0{,}84}{3{,}6 \cdot 10^6} = 1{,}366 \cdot 10^5 \; kWh \cdot kg^{-1}$$

Which represents 137/24 = 5.7 MWd · kg^{-1}

The quantity of natural uranium for the annual production of the plant:

$$M_u = \frac{W}{E} = \frac{11{,}47 \cdot 10^9}{1{,}366 \cdot 10^5} = 84 \; t \cdot rok^{-1}$$

Specific quantity of uranium:

$m_u = M_u / P_e$ = 133 / 450 / 8760 = 33,7 kg · $(GWh)^{-1}$

In the actual operation of a reactor, U_{238} transmutes after the absorption of neutrons and subsequent β^- disintegrations into Pu_{239}, with plutonium itself also being a nuclear fuel. In the course of the campaign, the proportion of Pu_{239} increases and at the end of the campaign its share while in operation may reach 1/3 to 1/2 of the nuclear fuel being burned. Of course, for each reactor and also for each campaign, this ratio may change.

Thus, the Dukovany nuclear power plant for uranium enriched to 3.6% reports actual burnout of 42 MWd· kg^{-1} and without including plutonium that would be, according to the previous calculation, only 3.6/0.714·5.7 = 29 MWd · kg^{-1}.

4. OPERATION OF HYDROELECTRIC POWER PLANTS

Study Objectives

- **To become acquainted with the basic types of hydroelectric power plants**
- **To understanding the principle of their operation**
- **The history of hydroelectric power plants on the territory of the former Czechoslovakia**

Keywords

Flow-through hydroelectric power plant, regulatory hydroelectric power plant, pumped storage hydroelectric power plant, utilizable head, impulse water turbine, reaction water turbine, specific speed, energy equivalent, swallowing capacity of the turbine, permanent reservoir level.

Required study time

20 hours

Text to Be Studied

Introduction

The hydroelectric power plant share of total electricity production in the Czech Republic is only approximately 2.4%. Because this is one of the "easiest" way of producing electrical energy, most of the potential energy of the water on our territory is already being utilized. In addition, the designation of the "roof of Europe" was not received by the Czech Republic in vain. It is located on the headwaters and watersheds of rivers leading into the Black Sea (Morava → Danube), the North Sea (Vltava → Elbe) and the Baltic Sea (Oder). The rivers located in our territory therefore do not have high flow rates. Basic power plant concepts

4.1 Introduction to hydroelectric power plants

The technically usable potential of the rivers in the territory of the Czech Republic is 3,380 GWh/year. Of this amount, the potential of usable in SHPP is 1,570 GWh/year (of which about 30% is being utilized).

With the growth in demand for electricity and the construction of new sources, in particular those transforming chemical energy (thermal and nuclear power plants), the total production share of electricity produced by the transformation of water energy will continue to wane. Hydroelectric power plants, however, have an invaluable role in the stabilization of the electricity grid during sudden power changes and accidents in the grid and in the regulating of loads on interstate transmission lines. An equally important role is played by all our hydroelectric power plants in the coverage of mid-peak and peak parts of the daily load diagram.

In addition to their utilization for energy purposes, the building of hydroelectric power plants is of great importance for the regulation of water years, for irrigation of agricultural land, for the provision of drinking and process water and for recreation. In the supply of the population with drinking water, the share supplied by water reservoirs is approximately 45%, and this share continues to grow [1]. Water consumption in the Czech Republic has already reached 3 billion m^3 per year. 80% of this amount is consumed by industry and the rest by agriculture and the population. In an average year, 55 billion m^3 of rain falls on the territory of the Czech Republic and in a dry year 8.5 billion m^3. Of this, approximately one third flows off from our catchment area.

Already in antiquity, humans understood that running water can make strenuous work easier in many ways. In the countries of the presumed emergence of human culture (Egypt, Mesopotamia, China, Greece, Rome), they knew the value of agricultural land irrigation a long time ago, and they also knew, for example, how to use a water wheel to harness the power of flowing water for lifting water into irrigation canals. They also used the water wheel to power water mills for grain and grinders. The first mention of water wheels is in preserved documents from the 6th century a.d. found in France.

In 1750, Slovak physicist and doctor Ján Andrej Segner constructed a wheel that moved on the basis of the reaction pressure of water. The theoretical principles on which this device worked came from the year 1730, and were derived by Daniel Bernoulli, an important mathematician and physicist originating from the Netherlands.

The foundations of the theory of turbines were laid by Swiss physicist Leonhard Euler in three of his works from the 1750s. The French technician Benoit Fourneyron drew on these insights when engineering the first pressurized water turbine in 1827. In 1847, the also pressurized Francis turbine was constructed, which gradually supplanted the turbines of Fourneyron, because in it the possibility of its gradual improvement was preserved. The Francis turbine was not fully applied in water power plants until the 20th century.

In 1880, American Lester Pelton built a very simple impulse turbine, called the tangential or also the Pelton turbine. This turbine is primarily used for high heads (200 m up to 2,000 m).

For small heads, Viktor Kaplan constructed a type of turbine with very high speed, which first went into production in 1918 in Brno and gradually came to dominate almost the entire world.

The last three mentioned turbine types today comprise essentially the main prerequisite of the transformation of the energy of water flow to energy that is mechanical – rotary. This form of energy has been used for ages to drive various machines in workshops and factories. The biggest drawback, however, was that the workshops and factories had to be in close proximity to a river, in order to make possible the transmission transfer of the driving water wheel to the driven equipment. It was not until the invention of the electric generator and electric motor that this disadvantage was removed.

In the territory of the former Czechoslovakia, we can follow the historical development of water works used for the utilization of hydropower from the year 718, when the first water mill in Central Europe was built on the Ohre River at Žatec. In the year 993, the mills of the Břevnov monastery under the Prague castle were built on the Vltava River. These mills were predominantly for water distribution – water wheels drew water into water towers and fountains. Many water wheels were built in our border regions in the 18th and 19th century for utilizing cheap water power in mills, sawmills, crushing mills, paper factories, and later in starch factories and distilleries. In the period before World War II, many small energy works arose in the Republic which were built from private initiative on smaller and minor watercourses.

Already in 1886 a hydroelectric power plant with a power output of 1,030 kW and head of 10 m was built on the Vltava River in Loučnice. On the same river in 1903, operation was launched at the hydroelectric power plant Pod Čertovou Stěnou (Below the Devil's wall) – Vyšší Brod. Three Francis turbines were installed at the power plant with generators of 1.5 MW in power with voltage of 15 kV. In 1911, another turbine-generator set was installed in the power plant, with a Francis turbine and a generator with a power of 3.5 MW. In the years 1928 to 1929, a reconstruction of the power plant was carried out, with the installation of another Francis turbines (ČKD Blansko) with an 8 MW generator and a rated voltage of 6 kV (42 or 50 Hz). The overall power of the power plant thus reached 16.2 MW, placing this hydroelectric power plant among the largest in Central Europe for many years.

In 1888, electric lighting power by a hydroelectric plant was launched in the town of Písek. In 1891, an air compressor plant of 80 k in power is built for a quarry in Litice na Divoké orlici. In the following period (1913 to 1914 to be exact), power plants also arise in Štvanice (2,350 k), Hradec Králové and others. In 1922 in Slovakia a small underground center was built in Stará Šachta in Kremnice, in 1925 in Dolní Jelenec, in 1927 in Staré Hory and in 1925 in Jasenný with a head of 196 m and Pelton turbines.

Work on the Štěchovice dam started just before the outbreak of World War II. In 1930, the first pumped storage hydroelectric power plant in Czechoslovakia was launched into operation on the Úhlava River, with accumulation in the Black Lake. In 1920, a Kaplan turbine was used for the first time on Czechoslovak territory at the Poděbrady power plant.

The next significant stage of the construction works of hydropower works occurred after1945, when during the following 20 years about 45 large hydroelectric plants were built in Czechoslovakia. These are mainly well known accumulation works on the Vltava River (Slapy, Orlík, Kamýk and Lipno) and almost all the of the Váh River cascade (Liptovská

Mara, Krpeľany, Sučany, Lipovec, Hrušov, Mikešová, Povážská Bystrica, Nosice, Ilava, Dubnica, Skalka, Kotolná, Nové Město nad Váhom, Horná Streda and Madunice).

Until 1945, the view from the era of the Austrian monarchy that the Vltava River is primarily a water navigation route still prevailed. Today, the Vltava River, just as the Váh river, is a hydropower river.

Since 1912, about 90 dams were built on the territory of the Czech Republic. The first large dam was the Vranov dam on the Dyje River. The development of concrete gravity dams culminated in the Orlík water work (1955 to 1965) . The construction of the earth dams developed after 1950.

4.2 Hydroelectric power plants in the Czech Republic

The main share of the production of electrical energy in water power plants is produced by the Vltava cascade. The Vltava River, with its 525 m head from Želnavy to Vrané, is predestined for energy use. Table 4.1 gives an overview of hydroelectric power plants located on the Vltava River.

Power plant	River km	Type of turbine	Power of turbine (MW)	Medium head (m)	Turbine swallowing capacity (m3 · s-1)
ŠP - Lipno I (1959)	329.540	Francis	2 × 60	162	2 × 46
PŠP - Lipno II (1957)	319.120	Kaplan	1 × 1.6	8,5	20
PŠP – Hněvkovice (1992)	210,390	Kaplan	2 × 4,8	-	-
Kořensko (1992)	200,405	Kaplan	2 × 1,9	-	-
ŠP - Orlík (1961)	144,700	Kaplan	4 × 91	70.5 to 44	4 ×150
PŠP-Kamýk (1961)	134,730	Kaplan	4 × 10	15,05	4 × 10
ŠP - Slapy (1955)	91,694	Kaplan	3 × 48	56	3 × 100
PŠP-Štěchovice I (1944)	84,440	Kaplan	2 × 11,25	20	2 × 75
PVE - Štěchovice II (1947)	84,440	Francis	1 × 45	220	2 × 2,5
PR - Vrané (1936)	71,325	Kaplan	2 × 6,94	11	2 × 75

Table 4.1 hydroelectric plant, located on the Vltava River

In addition to the Vltava River Cascade, other important water sources working into the electricity grid of the Czech Republic are the Mohelno hydroelectric power plant and the pumped storage Hydroelectric power plants Dalešice and Dlouhé Stráně. Other hydroelectric plants on the territory of the Czech Republic are SHPP (small hydroelectric power plant) with installed power up to 10 MW.

4.3 Power output of hydroelectric power plant

The type and size of the turbine is chosen on the basis of the known flow rate Q and the utilizable head H (or the specific energy of water Y) of a given water work, see Chapter 4.6. The relation for the power of the turbine P_t is then analogous to the relation for the power of the hydropower source P:

$$P_t = \rho \cdot Q \cdot Y \cdot \eta_t \quad [\mathrm{W; kg \cdot m^{-3}, m^3 \cdot s^{-1}, J \cdot kg^{-1}, -}] \tag{4.1}$$

$$Y = g \cdot H \quad [\mathrm{J \cdot kg^{-1}; m \cdot s^{-2}, m}] \tag{4.2}$$

Where ρ is the density of water, Q represents the volume of water flow through the turbine, Y is the specific energy of water, H is the utilizable head (see page 30) and g is the gravity acceleration in the given geographical conditions. η_t represents the resulting efficiency of the energy conversion of water into the mechanical energy on the shaft of the turbine-generator set in the turbine = overall efficiency of the turbine – see Chapter 4.4.

For preliminary calculations, when it is not yet decided on the type and size of the turbine or the arrangement of the entire works, including water extraction and feeder conduits, it is possible to use for the power on the turbine shaft the simplified relationship in the form of:

$$P_t = k_t \cdot Q \cdot H_b \quad [\mathrm{kW; J \cdot m^{-4}, m^3 \cdot s^{-1}, m}] \tag{4.3}$$

where H_b indicates gross (net) head (m) – the total head given by the difference of the levels (or the pressures of water) before the turbine and behind it, and k_t is the multiplicative coefficient:

- K_t = 6.5 for low pressure unregulated turbines of micro-sources (runner diameter D is 0.3 m),

- K_t = 7 for low pressure turbines of small dimensions (runner diameter D is 0.3 to 0.5 m),
- K_t = 8 for low pressure turbines of larger dimensions (runner diameter D is larger than 0.5 m).

The turbine output shaft power cannot as a rule be fully utilized, however, because the necessary energy transformation was not completed. In hydroelectric power plants, there also still remains the provision of the transformation of the mechanical energy of the rotating shaft to electrical energy, where losses also cannot be avoided. Thus, for the power of the entire machine set, consisting of the turbine, the transfer of the momentum from the shaft of the turbine to the shaft of the generator and the generator itself, it is necessary to use the relation:

$$P_S = g \cdot Q \cdot H \cdot \eta_t \cdot \eta_p \cdot \eta_g \cdot \eta_{tr} \qquad (4.4)$$

Where P_S is the power of the machine set, or the rated power transferred by the power plant at the place of the connection of the power plant to the power grid (kW), η_t is the overall turbine efficiency (-), η_p indicates the efficiency of the transfer of the momentum from the shaft of the turbine to the generator shaft (-), which is given by the transmission design. With gear transmission, this efficiency reaches the value of η_p = 0.94 – 0.97 and in the case of belt drive transmission η_p = 0.92 – 0.98 (MVE). η_g is the electrical efficiency of the generator (-), which moves within the range of η_g = 0.84 – 0.93 with smaller equipment with a power up to 40 kW and η_g = 0.95 – 0.97 with power outputs in the order of magnitude of MW, and η_{tr} is the electrical efficiency of the block transformer (-), Which is dependent on its type and construction.

Assuming that η_t = 0.85, η_g = 0.96, Σh_Z = 0, ρ = 1,000 kg · m^{-3}, η_{tr} = 0.98, g = 9.81 m · s^{-2}, we can also convert the relation 4.4 to the form:

$$P_S = 8 \cdot Q \cdot H_b \qquad (4.5)$$

4.4 Turbine efficiency η_t

The total efficiency of the turbine η_t can be defined as the ratio of the actual utilizable power of the turbine P (measured on the shaft of the turbine) to the theoretical lossless power P_0 corresponding to the water volume flow Q and the relevant head H while deducting losses in other elements of the water path.

$$\eta_t = \frac{P}{P_0} \qquad [-; W, W] \qquad (4.6)$$

This is the efficiency of the transformation of the mechanical energy of water into the mechanical energy of the rotating shaft of the turbine. If we consider that from the efficiency aspect the water turbine is the most perfect mechanical engine of all, we can expect a relatively high efficiency with all types of turbines used.

The values of the highest efficiency and the progress of the values efficiency in their dependence on the changing head and flow are dependent on a number of circumstances and factors. Of these, we can above all name the particular type of the turbine and its absolute dimensions, its production quality and the power size. The greater the power output the turbine is designed for, the larger the dimensions it usually has, the relatively better finished it is, with smoother surfaces, and the greater care is given to the construction and even the lubrication of the bearings. This is also why powerful turbine exhibit higher efficiency, see table 4.4.

P (kW)	30	60	100	200	300	600	1,000
η (%)	82	83	84	85	86	87	88
P (MW)	2	3	6	10	20	30	60
η (%)	89	90	91	92	93	94	95

Table 4.2 Dependence of attainable efficiency on the power of the turbine

The fact that with an increase in power and the dimensions of water turbines also grows their efficiency is documented by formulas for the conversion of the efficiency of model turbines to real turbines, or from a smaller runner diameter to a larger diameter. Of these we can mention, for example, **Moody's formula**, in the form:

$$\eta = 1 - (1 - \eta_M) \cdot \sqrt[4]{\frac{D_M}{D}} \cdot \sqrt[10]{\frac{H_M}{H}} \quad , \qquad (4.7)$$

Where η is the overall efficiency of a larger turbine (-), *D*, *H* indicate the runner diameter and the head of a larger turbine (m), η_M is the overall efficiency of a small model turbine (-), D_M, H_M indicates the runner diameter and the head of a smaller turbine (m), and also **Ackeret's formula**, in the form:

$$\eta = 1 - 0{,}5 \cdot (1 - \eta_M) \cdot \left(1 + \sqrt[5]{\frac{D_M}{D} \cdot \sqrt{\frac{H_M}{H}}} \right), \qquad (4.8)$$

in which each of the Quantities have the same meaning as in equation 4.7.

Included in the overall efficiency of a turbine η_t are all hydraulic losses occurring during the flow of the water through each part of the turbine η_h, as well as volume losses η_v and all mechanical losses η_m arising from the friction in the bearings of the entire machine set. Accounting for the major share of such losses are hydraulic losses, which are given by the hydraulic properties of the turbine. For the mathematical expression of hydraulic losses, it is better to utilize the quantity of hydraulic turbine efficiency η_h, which we can define by using the relation:

$$\eta_h = \frac{H - \sum h_z}{H} \quad \text{[-; m, m]} \qquad (4.9)$$

Where Σh_z are all the hydraulic losses that occur on the route of the water stream through the turbine.

The relation between efficiency and losses of the turbine power can be expressed using the overall ***loss coefficient of turbine*** ξ_t and the ***hydraulic loss coefficient of turbine*** ξ_h. We cab define these coefficients by the dependencies:

$$\xi_t = 1 - \eta_t \quad \text{[-; -]} \qquad (4.10)$$

$$\xi_h = 1 - \eta_h \quad \text{[-; -]} \qquad (4.11)$$

Turbines must be regulated with respect to the existing load fluctuation (or the power needs of the operator) and the variability of working parameters (especially Q and H). Thanks to the ability to regulate the turbine, it can, e.g., at a constant utilizable head, let through larger or smaller water flow rates, and thus provide the desired variability in power. Doing so, however, results in a change the hydraulic efficiency η_h and thus they overall efficiency of the turbine η_t. The dependence of the overall turbine efficiency η_t on utilizable power P is shown graphically in Figure 4.1 in the form of a concave curve with one maximum η_{t0}. Experience shows that this efficiency maximum of water turbines tends to be in the range of 70 to 90% of utilizable power P. The optimal level of overall efficiency η_{t0} is dependent on many circumstances and factors. Of these, we can name for example: the production quality of the turbine, its type and the absolute dimensions of the runner, the size of the installed power of the unit P_i, and generally on the circumstances, .i.e., to what extent the turbine design assumptions agree with the actual operation of the turbine.

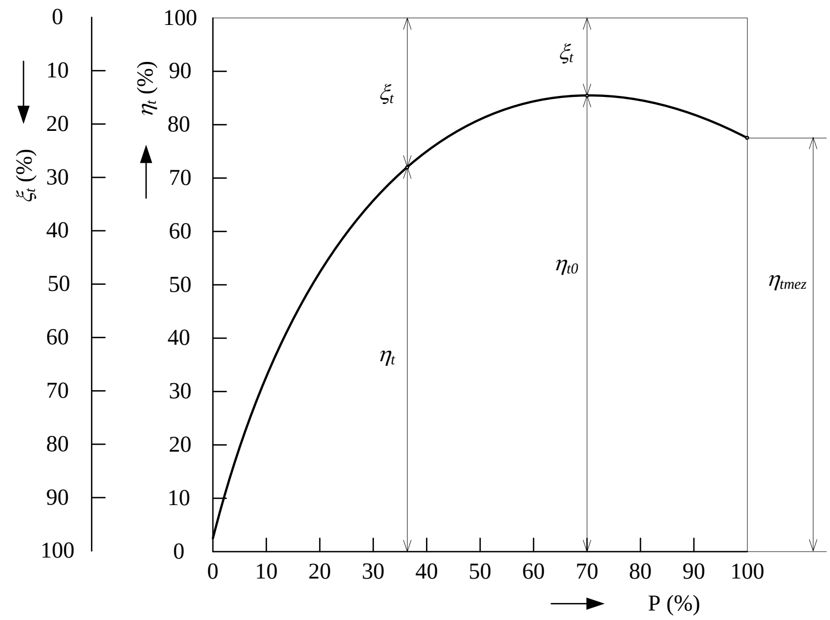


Fig. 4.1 The dependence of overall efficiency η_t and the loss coefficient ξ_t of the turbine on utilizable power *P*

Determining the progress of the overall efficiency of the turbine in its dependence on power in a finished work is very difficult and challenging. It cannot be determined directly, but only through calculation on the basis of current measurement of utilizable heads, flow rates and power outputs of the turbine.

The efficiencies of powerful modern turbines are markedly high, e.g., for the Francis turbine installed in the Lipno I hydroelectric power plant, the efficiency was found to be η_{t0} = 0.94.

Diagonal and Kaplan turbines have the most suitable efficiency curve in dependence on the load. The dependency of turbine efficiency on the flow rate is given in Figure 4.2. Better utilization of a watercourse is provided by a multi-machine arrangement. Its investment costs are higher, however, than a single machine arrangement.

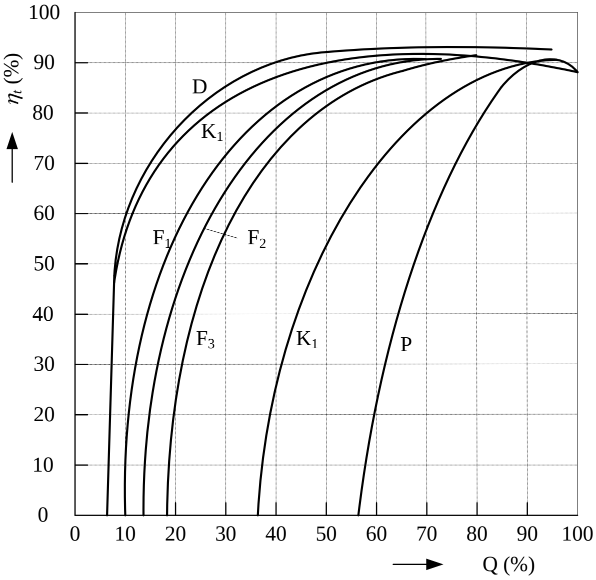


Figure 4.2 Dependency of the efficiency of turbines on the flow rate

D is a diagonal turbine, K_1 is a Kaplan turbine. F_1 is a slow speed Francis turbine,

F_2 is a normal Francis turbine, F_3 is a high speed Francis turbine, K_2 is a Kaplan

turbine – with regulation only by the distributor, P is a Propeller turbine with a fixed blade cascade.

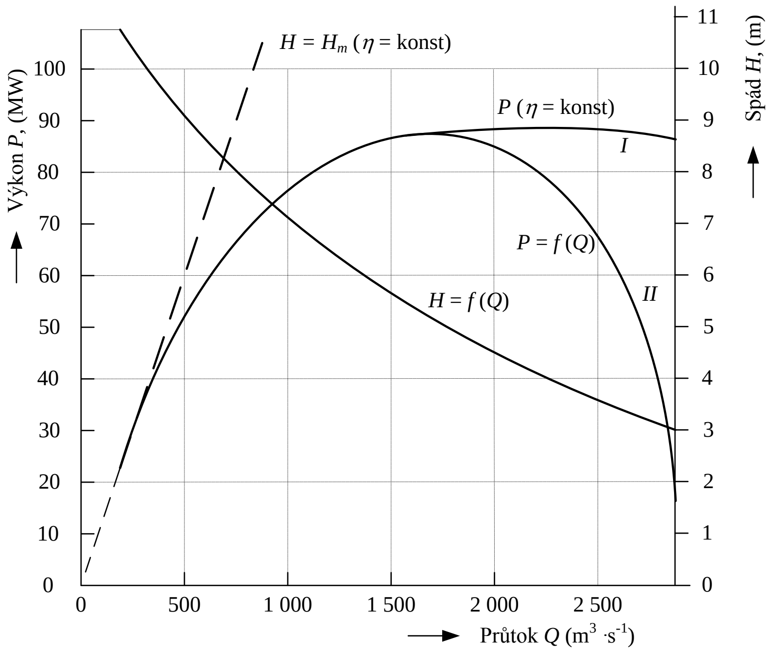


Fig. 4.3 Power of Hydroelectric power plant with variable head

As is clear from relations 4.4 and 4.5, the power of the water works is dependent on the flow rate and the head. If the flow rate changes at a constant head, the dependence of the power on the flow rate is linear, rectilinear. However, this applies only for large works with a large water level difference, where fluctuations in water levels does not affect the total head too much. Figure 4.3 shows the dependence of the power of a hydroelectric power plant on the flow rate when the head is variable. In low-pressure power plants, the head can fluctuate in dependence on the flow rate. It can thus fall to very small values at high flow rates, as follows from Figure 4.3. From the figure, it is evident that the highest power is achieved when the flow rate is optimal. With a maximum flow rate, the head descends to almost a quarter of the original value of small flow rates.

At a constant head and efficiency of turbine, the power of the turbine P_t would be directly proportional to the flow rate Q of the water through the turbine. If we count on a change in head in dependence on the flow rate and on a constant average efficiency $\eta_{stř}$, the course of the power output of the energy works at the flow rate Q will correspond to the curve I. If we consider the actual efficiency of turbines according to their operational characteristics as in Figure 4.2, we get a dependence corresponding to curve II.

4.5 The relations between the basic parameters of the turbine

The relations and links between the basic parameters of turbines are based on hydraulic and geometrical similarity. Turbines are geometrically similar when the ratio of their dimensions is the same in every direction and when they at the same time manifest the identical corresponding angles. These geometrically similar turbine also manifest hydraulic similarity,however, which is given by the fixed relations between the parameters H, Q, n, P, and η. Based on similarity relationships, we can watch not only the behavior of two similar turbines while the parameters are changing, but also the behavior of one turbine when changing parameters. If we label the basis parameters H, Q, n, P, η of one turbine without an index and in a second turbine (smaller) with the index M, i.e., H_M, Q_M, n_M, P_M and η_M, we can extrapolate the relations:

$$n = n_M \cdot \frac{D_M}{D} \cdot \sqrt{\frac{H}{H_M}} \cdot \sqrt{\frac{\eta}{\eta_M}}\,, \qquad (4.7)$$

$$Q = Q_M \cdot \frac{D^2}{D_M^2} \cdot \sqrt{\frac{H}{H_M}} \cdot \sqrt{\frac{\eta}{\eta_M}}\,, \tag{4.8}$$

$$P = P_M \cdot \frac{D^2}{D_M^2} \cdot \sqrt{\frac{H^3}{H_M^3}} \cdot \sqrt{\frac{\eta}{\eta_M}}\,, \tag{4.9}$$

Where n, n_M is the operating speed (min^{-1}), D, D_M is the diameter of the runner (m), H, H_M indicate the net head (m), Q, Q_M indicate the flow rate ($m^3 \cdot s^{-1}$), P, P_M is the power (kW) and η, η_M represent efficiency (-).

The stated similarity relations given by equations 4.7, 4.8 and 4.9, are valid regardless of the kind and type of turbines and regardless of their size. If we ignore the differences in turbine efficiencies, it is only necessary for the differences in runner diameters not to be too large.

4.6 Water Turbines

Types of turbines and specific speed

We will choose the appropriate type of turbine and its specific speed according to the specific energy of the water Y (head H) that the water work has at its disposal. The mutual interrelations are apparent from figure 4.4. These characteristics imply that the choice does not have to be unambiguous, because the individual types of turbine overlap. The basic criteria in the selection of a suitable type turbines are the efficiency of the turbine, the acquisition costs, and the operating costs.

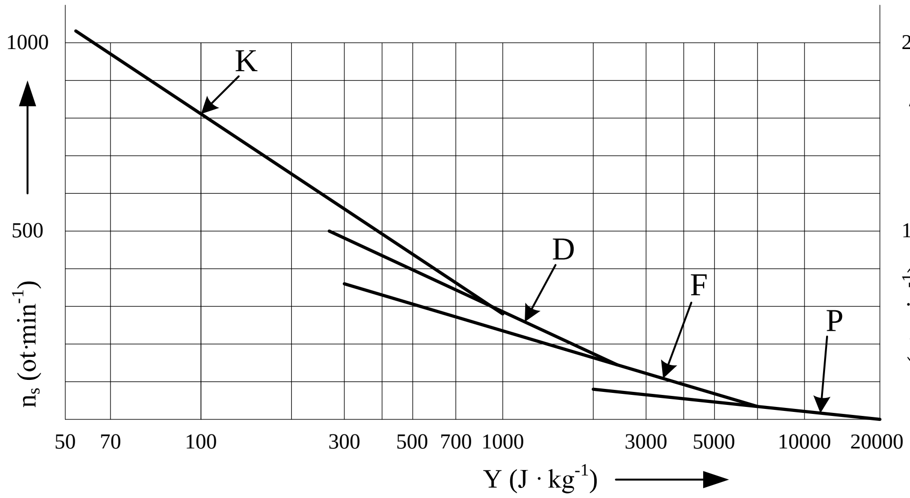


Fig. 4.4 Allocation of turbine type to the given specific energy *Y* (head *H*)

K – Kaplan turbine, D – Deriaz (diagonal) turbine, F – Francis turbine, P – Pelton turbine

Figure 4.5 gives the efficiencies of the most commonly used types of turbines depending on the specific speed n_q (n_s). The basic features of runners are shown in Figure 4.4.

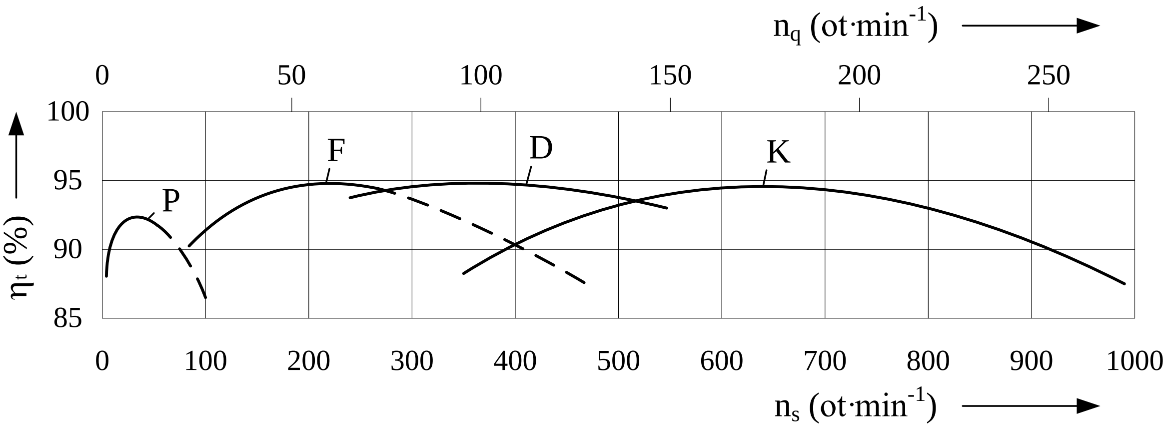


Fig. 4.5 The efficiencies of the most commonly used turbines depending on specific speed n_q (n_s)

K – Kaplan turbine, D – Deriaz (diagonal) turbine, F – Francis turbine, P – Pelton turbine

Foundations of water turbine theory

The foundations of the theory of water turbines are firmly connected with the development of general hydraulics at the start of the 17th century. Only the knowledge of basic hydraulic laws made it possible to describe and theoretically manage the complex process of the transformation of the mechanical energy of water into the mechanical energy of the rotating masses of a water turbine shaft. The following section of this chapter examines two basic directions differing in the essence of the utilized energy:

1. Impulse turbines – utilize exclusively (or predominantly) the kinetic energy of water
2. Reaction turbines – utilize both the kinetic and the pressure energy of water

The boundaries between these types of turbines are generally not altogether clear, and therefore a so-called ***turbine degree of reaction*** $\lambda$was introduced, which we can use as a criterion for deciding, when taking into account the nature of the energy conversion, when to consider a water turbine to be impulsive and when reactive. The degree of reaction of a turbine is defined by the relation:

$$\lambda = 1 - \frac{\alpha \cdot c_0^2}{2 \cdot g} \cdot \frac{1}{H} \qquad [-; -, m \cdot s^{-1}, m \cdot s^{-2}, m] \qquad (4.10)$$

where α is the Coriolis number (factor indicating the unevenness of the distribution of velocity in the flow profile), c_0 is the mean velocity of the water in front of the entrance edge of the revolving blade of the turbine, g is the gravity acceleration and *H* is the utilizable head of the turbine.

If the degree of reaction of a turbine is in the range $\lambda = 0 \div 0.5$ (< 0.5), we consider the turbine to be an impulse turbine, if the degree of reaction is $\lambda \geq 0.5$, we consider it to be a reaction turbine.

Theory of impulse turbines

The working process of an impulse turbine is characterized by channeling the kinetic of water to the runner in the form of a free stream, which after input on the turbine blade passes the bulk of its energy by direct transfer to the shaft of the turbine. The rest of the energy is then used to divert water from the output edges of the orbiting blades of the turbine. We can distinguish two main stages of the work process of the impulse turbine.

First phase - The transfer of the kinetic energy of a free water stream from the output profile of the turbine nozzle to the runner blade.

In hydraulic terms, this phase is associated with the solution of the problems of the efficient spray (throw) of a free water stream through an atmospheric environment. Experimental measurements show that the water jet retains its compactness, integrity and shape only for a limited length of its path from the nozzle of the turbine. The boundary layers of the jet are ripped off by the surrounding air particles. This contact leads to a thermal exchange between the aquatic and atmospheric environments, and thus to a loss of usable water energy. This energy exchange of the boundary layers constantly grows in intensity. A gradual enlargement of the diameter of the jet occurs, until after a certain path length through the air there comes about the complete disintegration into a spray of water particles. Experimental trials focusing on water velocity in the jet show that with the rise in the velocity of the water, the jet begins to disintegrate earlier and the length of the jet is therefore shorter. We achieve a similar and much stronger effect by reducing the diameter of the water jet (decreasing the diameter of the jet ⇒ shortening the integrity of the beam). A certain extension of the length of the path of a unified jet through the air could be achieved by artificial rectifiers, which prevent the creation of a circular movement of the water stream. Rectifiers are associated with the emergence of hydraulic losses, however, due to which this solution is wasteful.

Based on this knowledge, we strive, with impulse turbines, to elect the shortest possible path of the free jet through the air and a large diameter for the turbine nozzles.

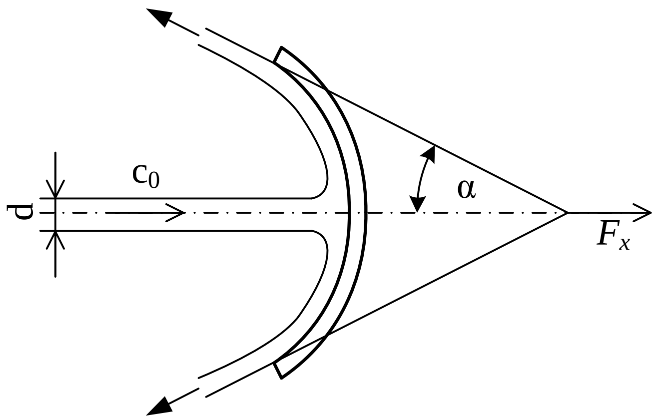


Fig. 4.6 Representation of the vector forces acting on the blade of an impulse turbine

Second phase - The process of the action of the water stream on the orbiting blade of the turbine.

The second phase is in hydraulic terms associated with optimizing the effect of the impact of a free jet on a moving plate. This optimization leads to the use of a concave rotary surface of the blade. If the free jet of water falls on a concave rotary surface, as illustrated in figure 4.6, a Turns out the free Jet on concave surface, a force F_x in the direction of the jet arises, given by the relation:

$$F_x = \frac{\gamma \cdot Q}{g} \cdot c_0 \cdot (1 + \cos\alpha) \quad [\mathrm{N; kg \cdot m^{-2} \cdot s^{-2}, m^3 \cdot s^{-1}, m \cdot s^{-2}, m \cdot s^{-1}}] \tag{4.11}$$

Where $\gamma = \rho \cdot g$ is the specific pressure force of the water volume unit, Q is the volumetric flow rate of the water through the nozzle, g is the gravity acceleration and c_0 is the velocity of the water jet at the point of contact with the blade.

If, in addition, this plate is adjusted so that it enables the deviation of the jet by 180° (i.e. in the opposite direction when $\alpha = 0$), then the force F_x attains its maximum value $F_x = 2 \cdot c_0 \cdot \gamma \cdot Q / g$.

If the plate is moving in the direction of the jet at a constant driving velocity u, the jet acts on it with a relative velocity $w = (c_0 - u)$. By a continuous deviation of the jet on the plate by 180 °, the force drawn will be:

$$F_x = 2 \cdot \frac{\gamma \cdot Q}{g} \cdot (c_0 - u) \quad [\mathrm{N; kg \cdot m^{-2} \cdot s^{-2}, m^3 \cdot s^{-1}, m \cdot s^{-2}, m \cdot s^{-1}}] \tag{4.12}$$

and thus also the power:

$$P = F_x \cdot u = 2 \cdot \frac{\gamma \cdot Q}{g} \cdot (c_0 - u) \cdot u \quad [\mathrm{W; N, m \cdot s^{-1}}] \tag{4.13}$$

We will attain the maximum power value when $u = c_0/2$:

$$P_{\max} = \frac{\gamma \cdot Q}{2 \cdot g} \cdot c_0^2 = P_0 \tag{4.15}$$

Equation 4.15, in which the maximum power is equal to the theoretical power, suggests that under the given circumstances it would be possible to achieve a 100% efficiency of transformation. This efficiency, however, is impossible to achieve in practice. This is due to the emergence of hydraulic losses through the friction of the water on the surface of the blade, and also due to the fact that with the larger number of rotary blades of the impulse turbine, the deviation of the water on the blade by 180 ° would cause the water leaving the working blade to collide with the neighboring blade and act as a brake. On the basis of experience, it is in practice possible for impulse turbines to achieve an efficiency of approximately = η_{max} = 92 to 93 %.

Theory of reaction turbines

The name reaction turbine is derived from the reaction forces between the water stream and the blades of the runner leading to the rotation of the runner. The operating process of a reaction turbine is characterized by channeling the pressure and kinetic energies into the input profile of a spiral, which ensures equal distribution of this energy around the perimeter of the wicket gate of the turbine and further along the perimeter of the input edges of the blades of the runner. It is in the runner that the transformation of most of the energy of the water intake into the mechanical energy of a rotating shaft takes place. The remaining energy of the water from runner leads to the draft tube of the turbine. The modern draft tube can provide an additional conversion of energy into the mechanical energy of the rotating the shaft of the turbine. Only water with the residual energy necessary to ensure the drainage of water from the draft tube leaves its output profile.

To better understand the importance of the used shape of the turbine channel, we will explain the problematic of the action of the water current on the mentioned channels of the turbine. We shall carry out the explanation for the case of a fixed stationary and fixed movable channel.

Fixed stationary channel

We can consider the set of fixed stationary channels to be the spaces between the blades of the turbine runner or the spaces between the support vanes of the turbine spiral.

For the ***volume calculation*** of the action of a water current on the fixed stationary channel of the turbine, we will rely on the schematic diagram in figure 4.7.

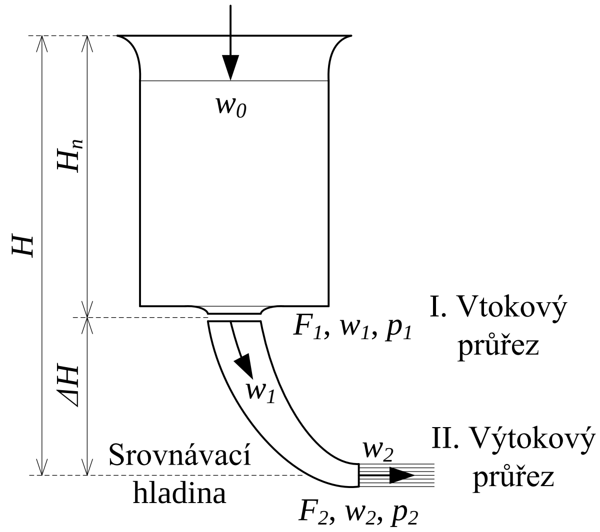


Fig. 4.7 scheme for the volume calculation of a reaction turbine with a fixed stationary channel.

A curved channel is attached to a container in which we maintain a constant water level. The outlet profile (II) with the area S_2 is smaller than the inlet profile (I) with an area of S_1, to prevent the current from detaching from the walls and ensure the channel was completely filled with water. It is therefore obvious, that for the pressure ratios of the inlet and outlet channel it must be true that $p_1 > p_2$.

The composition of the mechanical energy of water in the input profile (I) of the channel and the output profile of the channel (II) will be expressed using Bernoulli's equation — discussed in more detail in the calculation of the utilizable head – see page 30:

$$\frac{p_1}{\gamma} + \frac{w_1^2}{2 \cdot g} + \Delta H = \frac{p_2}{\gamma} + \frac{w_2^2}{2 \cdot g} + h_z \quad [\mathrm{Pa \cdot m^{-3}, kg \cdot m^{-2} \cdot s^{-2}, m \cdot s^{-1}, m \cdot s^{-2}, m}] \quad (4.16)$$

Where h_z are the hydraulic losses in the channel between its outermost cross-sections. We can express the loss level in its dependence on the maximum velocity of the water in the channel (w_2) in the form:

$$h_z = \xi \cdot \frac{w_2^2}{2 \cdot g} \qquad [\mathrm{m; -, m \cdot s^{-1}, m \cdot s^{-2}}] \qquad (4.17)$$

Where ξ is the loss coefficient, whose size is independent of the size of the flow ($\xi = 0.06 – 1.00$).

We can then write the equation 4.16 in the form:

$$\left(1+\xi\right)\cdot\frac{w_2^2}{2\cdot g}=\frac{p_1-p_2}{\gamma}+\frac{w_1^2}{2\cdot g}+\Delta H \tag{4.18}$$

We call equation 4.18 the flow rate equation, since it can be used for the determination of the flow areas of the outermost profiles the channel. For the determination of those areas, however, we must also know the difference in pressure ($p_1 - p_2$) in the input and output profiles of the channel. We will try to displace this pressure differential from equation 4.18.

We will express Bernoulli's equation for the profile of a vessel at the level of the free water surface (*O*) and for the input profile (I) of a turbine channel. Let us assume that the kinetic energy of the water in profile *O* is negligible, therefore the velocity of the water flow through profile *O* w_0 is negligible. We can therefore write the relation:

$$\frac{p_a}{\gamma}+H+0=\frac{p_1}{\gamma}+\frac{w_1^2}{2\cdot g}+\xi_1\cdot\frac{w_1^2}{2\cdot g} \tag{4.19}$$

Where p_a is the atmospheric pressure and ξ_1 is the loss coefficient of the flow into the inlet profile of the turbine channel, which with a rounded inlet edge can be considered to be in the range of ξ_1 = 0.01 to 0.06.

We can further adjust equation 4.19 to the form:

$$\frac{p_1}{\gamma}=H_n+\frac{p_1}{\gamma}-(1+\xi_1)\cdot\frac{w_1^2}{2\cdot g} \tag{4.20}$$

From the continuity equation, we obtain the relationship between the flow rates through the individual profiles and the cross-sections of these profiles:

$$w_1=w_2\cdot\frac{S_2}{S_1}\quad [\mathrm{m\cdot s^{-1}; m\cdot s^{-1}, m^2, m^2}] \tag{4.21}$$

By substituting relation 4.20 into equation 4.18, we obtain the equation:

$$\left(1+\xi+\xi_1\cdot\frac{S_2^2}{S_1^2}\right)\cdot\frac{w_2^2}{2\cdot g}=\Delta H+H_n+\frac{p_a-p_2}{\gamma} \tag{4.22}$$

If the water flows out from the turbine channel into a free environment, then $p_2 = p_a$, and equation 4.20 is transformed into the form:

$$\left(1+\xi+\xi_1\cdot\frac{S_2^2}{S_1^2}\right)\cdot\frac{w_2^2}{2\cdot g}=H \tag{4.23}$$

Equation 4.23 represents the final form of the derived flow equation in the case according to the scheme in Figure 4.7. If we know the shape of the turbine channel (e.g.: the ratio of the cross-sections at the inlet and outlet), and the utilizable head *H*, we can use equation 4.23 to calculate the outlet velocity. With the help of this velocity, we can then for the known flow rate determine the size of the area of the outlet profile S_2 = Q/w_2, and from the continuity equation calculate the other cross-sectional areas of the channel.

In the energy calculation of the impact of a water current on a fixed stationary turbine channel, we will start from Newton's equation, which determines the elemental force d*F* (acting on the tangible element of water *dm*) necessary for the creation of a velocity change d*w* in the time d*t*. We can express this sentence mathematically in general using the relation:

$$dF=dm\cdot\frac{dw}{dt}=\frac{dm}{dt}\cdot dw \qquad [\mathrm{N;\ kg,\ m\cdot s^{-1},\ s}] \tag{4.24}$$

However, equation 4.24 is valid for rectilinear movement. If the movement has a curved track, as in Figure 4.8, then in equation 4.24 we have to merely consider the change of the velocity element w_F in the direction of the action of force *F*. In taking into account the curvature of the track, equation 4.24 is transformed into the form:

$$dF=\frac{dm}{dt}\cdot dw_F \tag{4.25}$$

or also:

$$dF=\frac{Q\cdot\gamma}{g}\cdot dw_F \tag{4.26}$$

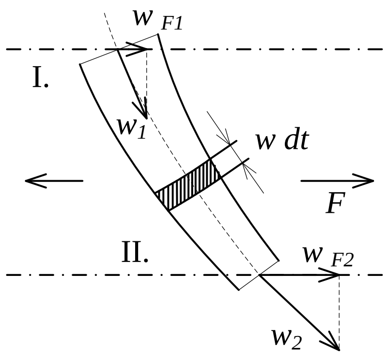


Fig. 4.8 The curvature of the track of a turbine channel

After integration of equation 4.26 from the inlet channel profile (*I*) to the outlet profile (*II*), we get the relation:

$$dF = \frac{Q \cdot \gamma}{g} \cdot \left(w_{F2} - w_{F1}\right) \tag{4.27}$$

Equation 4.26 determines the force we need to change the direction of a water current, i.e., the force with which the channel acts on the water current. The reaction of this force is of the opposite sign, i.e., it acts in the direction in which a free turbine channel would move.

The validity of equation 4.26 is general for any direction of the force *F*, i.e., even for the case indicated in the diagram in Figure 4.9. Therefore, the reaction *F* of the dynamic effect of the water current on the channel can be express in the form of the resultant momentum of water in the outermost cross-sections of the channel:

$$F = \mathrm{Re}\,s\left(\frac{Q \cdot \gamma}{g} \cdot w_1 ; \frac{Q \cdot \gamma}{g} \cdot w_2\right) \tag{4.28}$$

Still remaining to be solved is what moment derives from the resulting reaction *F* to the point selected outside the channel. To determine the moment M derived from the reaction *F* to the selected point, we will use the diagram in Figure 4.10, which shows the turbine channel through which water flows at the velocity of w_1 in the inlet profile (*I*) and the velocity w_2 in the outlet profile (*II*).

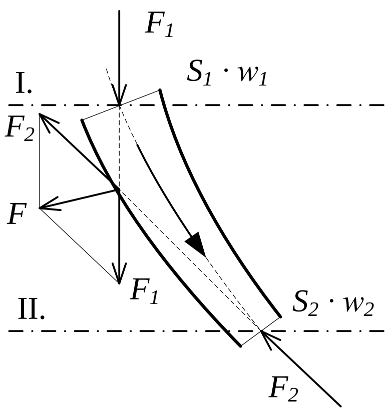


Fig. 4.9 The curvature of the track of a turbine channel – the resultant of forces at the intersection of the concurrent forces

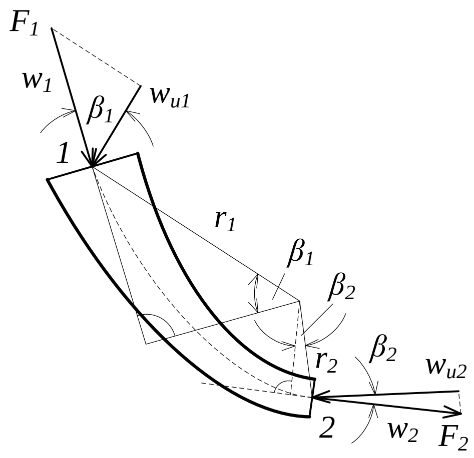


Fig. 4.10 Diagram of a turbine channel for the determination of the resultant moment of force to the selected point

The overall reaction *F* of a channel according to equation 4.28 is the resultant of the forces F_1 and F_2.

$$F_1 = \frac{Q \cdot \gamma}{g} \cdot w_1 \qquad \text{and} \qquad F_2 = \frac{Q \cdot \gamma}{g} \cdot w_2$$

Since the moment of this resultant for the selected point (O) must be equal to the sum of the moments of the components of forces F_1 and F_2, the following relation applies:

$$M_{1,2} = F_1 \cdot r_1 \cdot \cos\beta_1 - F_2 \cdot r_2 \cdot \cos\beta_2 \tag{4.29}$$

or:

$$M_{1,2} = \frac{Q \cdot \gamma}{g} \cdot \left(w_1 \cdot r_1 \cdot \cos\beta_1 - w_2 \cdot r_2 \cdot \cos\beta_2\right) \tag{4.30}$$

For the components of velocity vectors perpendicular to the arms of the moment, we can write:

$$w_{u1} = w_1 \cdot \cos\beta_1 \qquad \text{and} \qquad w_{u2} = w_2 \cdot \cos\beta_2$$

After substituting into equation 2.30 we get the resulting expression for the moment:

$$M_{1,2} = \frac{Q \cdot \gamma}{g} \cdot \left(w_{u1} \cdot r_1 - w_{u2} \cdot r_2\right) \tag{4.31}$$

On the basis of equation of 4.31 can say that the moment of force with which the water acts on the turbine channel is equal to the difference between the angular momentum of the water in the outermost cross-sections of the channel.

Fixed movable channel

Moving turbine channels are represented by the spaces between the blades of the runners of all reaction turbines. Unlike the stationary turbine channels, the channels of the runners of turbines are able to convey the transformation of the energy of water into the mechanical energy of the rotating shaft of the turbine, i.e., to perform work, and so they are the main and hydroenergetically the most significant element of a turbine.

For the solution of the movable turbine channel, is necessary to accurately and comprehensively define the hydraulic quantities that express the movement of the water parts.

In the case of the rotating turbine channel there are a total of three kinds of velocity:

- ***Relative velocity (w)*** – the rate at which water moves relative to the turbine channel
- ***Absolute velocity (c)*** - the speed at which the water flow is moving relative to the stationary space outside the channel
- ***Carrying velocity (u)*** – the speed at which the channel moves in the stationary space

For an easier understanding of the importance of each kind of velocity, we will use a mechanical model of the working process of reaction turbine, as it is indicated in the planar diagram of Figure 4.11.

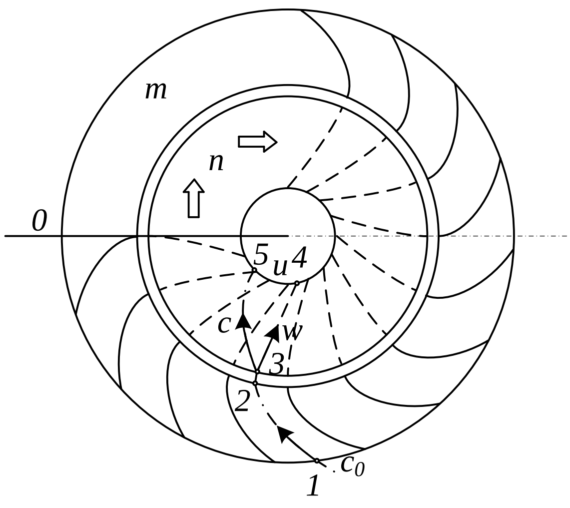


Fig. 4.11 Planar diagram of the mechanical model of a reaction turbine work process

The main part of this model is the rotating circular plate (n) with vertical curved walls in the form of troughs (channels). In the middle of the plate is a trap. Around the rotating plate is a fixed non-rotating plate (m) in the shape of an outer ring, which also has a vertical curved walls in the form of channels.

Let us suppose that the described model is so large that an adult can walk through its fixed movable channels all the way to the trap. In their passage within the model they first complete the absolute path (1 – 2) through the fixed channels (m), enter the rotating plate (n), after which they complete the relative path (3 – 4), and enter into the trap. Because the distance (3 – 4) on the rotating plate is defined by the channel walls partially against the sense of rotation of the plate, the bouncing off during walking would necessarily have to contribute to the acceleration of the plate rotation. An observer outside the model sees the non-rotating plate (m) as well as the absolute path (1 – 2), but on the rotating plate (n) he sees, unlike the person walking on the plate (n), only its absolute path (3 – 5). From the above it follows that on the rotating plate (n) the end point (4) of the relative track was moved to point (5) of the absolute path. Therefore, it is possible to consider path (4 – 5) as the carrying path. To the absolute, relative and carrying paths, we can uniquely assign an absolute (c), relative (w) and carrying velocity (u).

To express the mutual relations and ties of these velocities, we will use the diagram in Figure 4.12, in which the fixed channels and the movable channels are marked on a in a cross-sectional slice of the turbine runner.

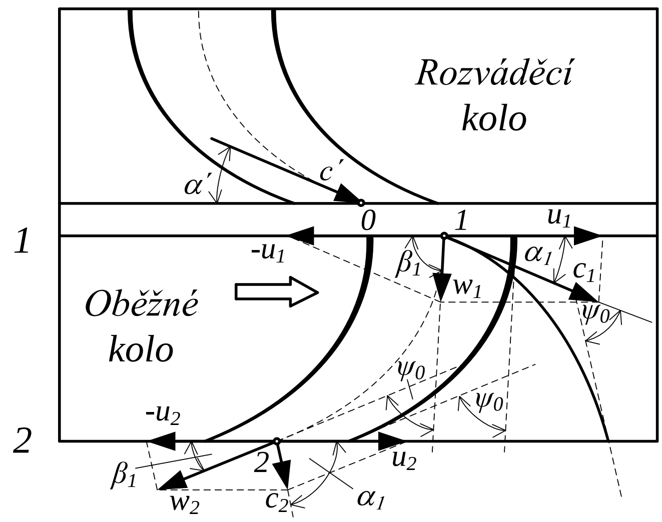


Fig. 4.12 Description of the mutual relations between the individual velocities of a turbine

Water leaves the outlet edge of the wicket gate at the absolute velocity c' and enters into the gap between the wicket gate and the turbine runner. In this relatively narrow blade-less space there must come about, through an increase in the flow area (by the sum of the thicknesses of the blades), a decrease in the absolute velocity to the velocity c_0. Water then enters onto the inlet edge (*1*) of the runner at a velocity of c_1, which must be, given the narrowing of the flow area again by the thickness of the runner blades, greater than the velocity c_0. It can be expected that the velocity c_1 will be equal to the velocity of c', i.e., $c_1 = c'$ will apply. We will characterize the direction of the velocity vectors c', c_0 a c_1 by the angles α', α_0 and α_1, which these vectors form with the carrying velocity vectors u (identical here with the direction of the connecting lines of the inlet and outlet edges of the turbine).

To get the vector of relative velocity w_1 on the inlet edge of the runner blades, it is necessary to add up the absolute velocity vector c_1 with the negative vector of the carrying velocity u_1. For hydraulic reasons, the vector of relative velocity of w_1 must at the same time be parallel to the tangent to the surface of the inlet part of the runner blades. Further along the course through the tapering channel of the runner, the relative velocity must increase up to the velocity w_2, at which the water exits the outlet edge (2) of the turbine runner.

In order to obtain the vector of absolute velocity c_2, we must calculate the vector sum of the relative velocity w_2 and carrying velocity u_2.

Also marked in Figure 4.12 is the absolute path of a water particle. It is obvious that it is deviating from the original direction given by vector c_1 in the direction given by the vector of outlet velocity c_2. We can define the indicated deviation by angle ψ_0, which also defines the absolute curvature of the water flow inducing pressure on the blades of the runner. The size of the angle ψ_0 is determined by the shape of the runner blades of the turbine. We therefore call angle ψ_0 the ***efficient angle of the blades*** or also the ***deviation angle.***

The presented analysis of the paths and vectors of velocities in the reaction turbine runner is valid only for a water stream which perfectly follows the path specified by the shape of the blade. However, this condition is met only with a large number of runner blades. With a small number of these blades, the relative path of the water stream does not fully agree with the shape of the blades.

The analysis of the interaction of velocities c, w and u, expressed in Figure 4.12 in the full range of definition and composition of the vectors of these velocities, is rather demanding and, moreover, lacking in clarity. In practice, therefore, a similar analysis is carried out more effectively and more clearly arranged using so-called ***vector triangles of velocity***, which are illustrated in figures 4.13 a), b) and (c).

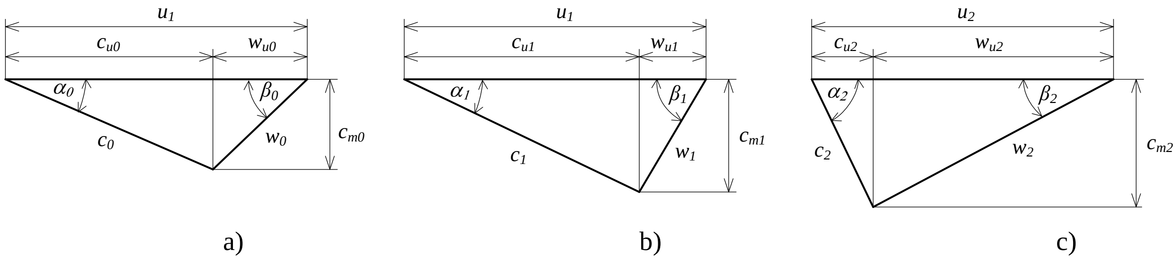


Fig. 4.13 Vector triangles of velocity for water flow in individual parts of the reaction turbine

Figure 4.13 a) shows the vector triangle of the blade-less space (i.e. the gaps between the wicket gate and the runner). Also marked here are the carrying components of velocity, i.e. vectors c_{u0}, w_{u0} and vector c_{0m} in radial (meridional) direction. Similarly handled in figures 4.13 b) and 4.13 c) are the inlet and outlet velocity triangles of the runner.

When calculating the moment of force with which the water stream acts on a rotating channel, we can fully apply the results of the previous solution to the moment of force with which the water stream acts on a non-rotating channel. All that is need is to replace the relative velocity components w_{u1} and w_{u2} with the velocity components c_{u1} and c_{u2}. We get the resulting relationship:

$$M_{1,2} = \frac{Q \cdot \gamma}{g} \cdot \left(c_{u1} \cdot r_1 - c_{u2} \cdot r_2\right) \tag{4.32}$$

In further energy calculation for a moving turbine channel, it will be beneficial if we consider such a flow rate, in which the weight of the water that flows through per time unit is equal to one, i.e. $Q = 1/\gamma$. Equation 4.32 then takes on the form:

$$M = \frac{1}{g} \cdot \left(c_{u1} \cdot r_1 - c_{u2} \cdot r_2\right) \tag{4.33}$$

If we multiply this moment by the angular velocity ω of a rotating channel, we get the expression for the power that the channel ensures in its rotation.

$$M \cdot \omega = \frac{1}{g} \cdot \left(c_{u1} \cdot r_1 - c_{u2} \cdot r_2\right) \cdot \omega \tag{4.34}$$

However, because the product of the angular velocity ω and the arm r is generally equal to the velocity of the carrying velocity u, we can modify equation 4.34 to the form:

$$M \cdot \omega = \frac{1}{g} \cdot \left(c_{u1} \cdot u_1 - c_{u2} \cdot u_2\right) \tag{4.35}$$

The work per unit of time (power) of a rotating channel, expressed by equation 4.35, must be equal to the mechanical energy of the water which is available for energy transformation, i.e. the product of the utilizable head H, and the hydraulic efficiency η_h. This may be formulated by the equation:

$$\frac{1}{g} \cdot \left(c_{u1} \cdot u_1 - c_{u2} \cdot u_2\right) = H \cdot \eta_h \qquad [\mathrm{m \cdot s^{-2}, m \cdot s^{-1}, m \cdot s^{-1}; m, -}] \tag{4.36}$$

We call Equation 4.36, which was already published in somewhat different form in 1754 by Leonard Euler, **Euler's energetics equation (Euler's turbine equation)**. Its validity is general, i.e.. for a rotating channel placed in space in any manner for flow associated with hydraulic losses.

Present in the equation is the hydraulic efficiency of transformation η_h, which is defined on page 7. Nevertheless, we consider it appropriate to specify in more detail here the total hydraulic losses h_z, or the proportion h_z/H, which has a major impact on efficiency. According to experience, while the water flow is working in a reaction turbine, we can distinguish three basic types of component hydraulic losses:

- h_{z1} – Hydraulic losses through friction, changing the curvature of the flow and a change in the flow profiles
- h_{z2} – Losses of kinetic energy by the water stream leaving the outlet edge of the turbine

runner, i.e., $h_{z2} = c_2^2 / 2 \cdot g$ (a part of this energy can be additionally used for transformation in the draft tube of the turbine)

- h_{z3} – hydraulic losses through the incorrect entry of water into the turbine runner (in

a well designed turbine these losses are negligible).

For the overall hydraulic losses in a turbine it is possible to write:

$$\Sigma h_z = h_{z1} + h_{z2} + h_{z3} \qquad \text{[m; m]} \tag{4.37}$$

On the basis of relation 4.37 we can modify the relation for hydraulic efficiency into the form:

$$\eta_h = 1 - \frac{h_{z1}}{H} - \frac{h_{z2}}{H} - \frac{h_{z3}}{H} \tag{4.38}$$

or into the form:

$$\eta_h = 1 - \rho - \alpha - \xi \qquad \text{[-; -]} \tag{4.39}$$

Where ρ is the coefficient of the losses through friction, the change in direction and the flow through areas, α is the coefficient of the turbine outlet loss, and ξ represents the coefficient of the hydraulic losses upon entering the runner of the turbine.

Substituting the relation 4.39 into the Euler energetics equation, we obtain the resultant form:

$$\frac{1}{g} \cdot (c_{u1} \cdot u_1 - c_{u2} \cdot u_2) = H \cdot (1 - \rho - \alpha - \xi) \tag{4.40}$$

For the volumetric calculation of the rotating turbine channel, we use the input and output vector triangles of velocity, as they are shown in Figure 4.13 b) and c). By using a cosine sentence the following relations can be derived:

$$w_1^2 = c_1^2 + u_1^2 + 2 \cdot u_1 \cdot c_1 \cdot \cos \alpha_1 \tag{4.41}$$

$$w_2^2 = c_2^2 + u_2^2 + 2 \cdot u_2 \cdot c_2 \cdot \cos \alpha_2 \tag{4.42}$$

By mutual subtraction of these equations we obtain after modification:

$$u_1 \cdot c_1 - u_2 \cdot c_2 = \frac{1}{2} \cdot (w_2^2 - c_2^2 - u_2^2 - w_1^2 + c_1^2 + u_1^2) \tag{4.43}$$

By substituting equation 4.43 into Euler's energetics equation 4.36, we obtain the relation:

$$\frac{c_1^2 - c_2^2}{2 \cdot g} + \frac{w_2^2 - w_1^2}{2 \cdot g} + \frac{u_1^2 - u_2^2}{2 \cdot g} = H \cdot (1 - \rho - \alpha - \xi) \tag{4.44}$$

We call equation 4.44 the flow equation. Although it is a variation of the energetics equation, it allows us to form a complete idea about the velocity conditions in the runner of a reaction turbine. If we express the turbine outlet loss coefficient α by using the kinetic energy leaving the output edges of the runner blades (c_2^2 / (2 · g)), we can modify equation 4.44 into the form:

$$\frac{c_1^2}{2 \cdot g} + \frac{w_2^2 - w_1^2}{2 \cdot g} + \frac{u_1^2 - u_2^2}{2 \cdot g} = H \cdot (1 - \rho - \xi) \qquad (4.45)$$

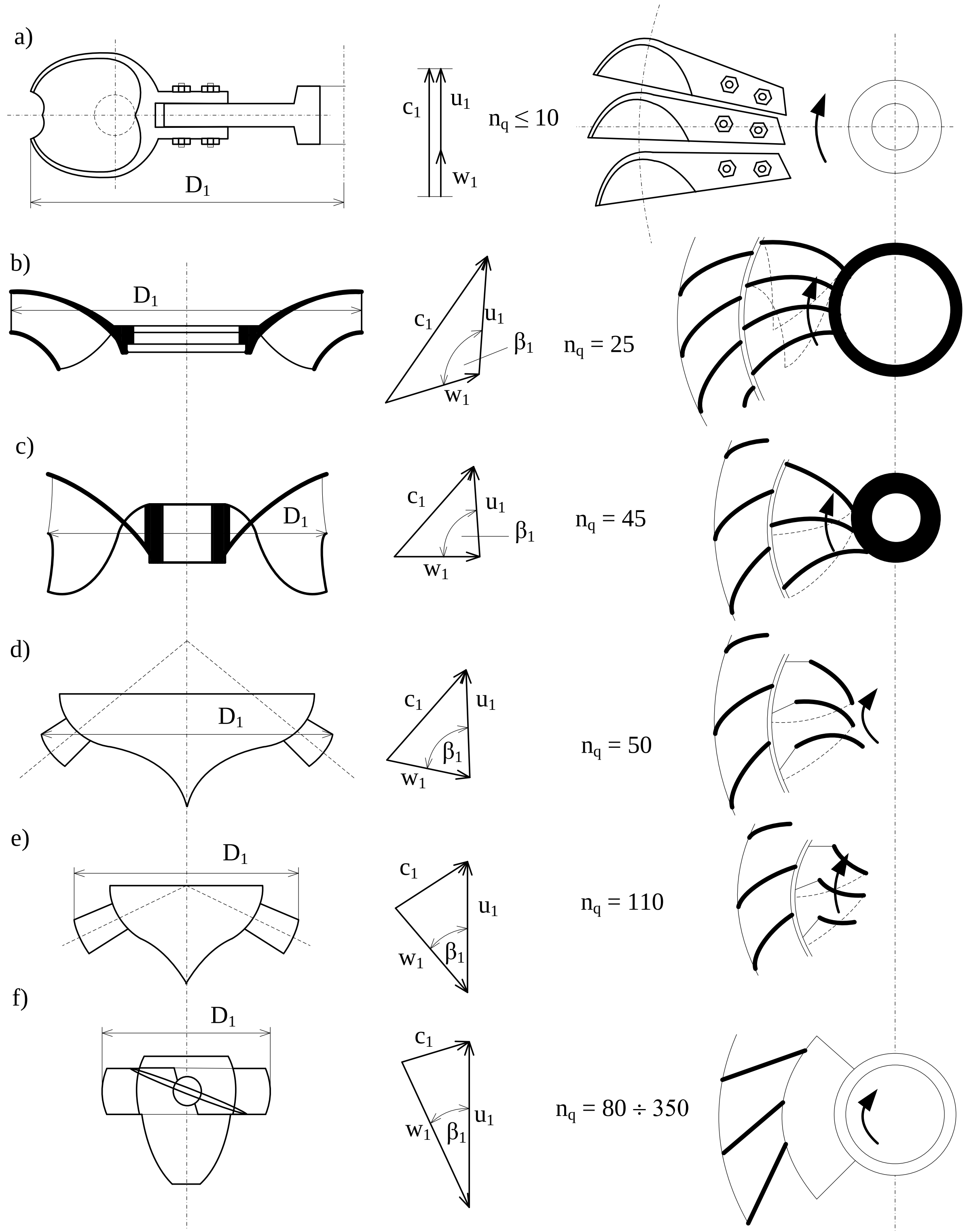


Fig. 4.14 Types of turbine runners sorted according to specific speed n_q

Left part of the image: meridian shapes indicating the form of the runner

Right part of the image: slices perpendicular to the axis of the turbine show blading type

Middle part of the image: triangles of input velocities corresponding to specific rotational speeds

a - Equal pressure Pelton turbine – transforms all the specific energy Y (or the entire head H) into the speed energy of water

b to *f* - Overpressure turbines (Francis, Dériaz, Kaplan) transfer the specific energy of water Y (head H) to the wicket gate (the stator) as well as to the runner.

The character of energy transformation in the runner of the turbine is clearly evident in this equation. The utilizable head, decreased by losses due to friction, curvature of the flow and the change of direction, or possibly the incorrect entry of the water stream into the runner [right side of equation 4.45], is utilized for transformation in three direction, as indicated by the three members of the left side of the equation.

The first member of the left side of equation 4.45 shows that part of the head is utilized for creating the input kinetic energy of the water of the turbine runner. The second part represents the head necessary to increase the kinetic energy of the water flow between the input and output profiles of the runner channels. The third member of the left side of the equation represents the part of the head necessary to overcome the centrifugal force caused by rotation. (As a rule, flows into the turbine runner at a larger external diameter and leaves the runner blades at a smaller internal diameter.)

The basic features of the runners of these turbines are presented in Figure 4.14. On the left are the meridian shapes and on the right are slices led perpendicular to the axis of the turbine. The equal pressure Pelton turbine transfers all the energy of the water to the velocity energy in the nozzle. Overpressure types (b) to (f) convert the total energy to the velocity energy of water in the wicket gate as well as the runner. The middle of the picture depicts the velocity triangles (see page 20).

Turbine specific speed

We shall proceed from Euler's energetics equation (turbine equation):

$$c_{u1} \cdot u_1 - c_{u2} \cdot u_2 = Y \cdot \eta_h \qquad [\mathrm{m \cdot s^{-1}, m \cdot s^{-1}; J \cdot kg^{-1}, -}] \qquad (4.46)$$

For achieving the maximum power, it is necessary that $c_{u2} \rightarrow 0 \Rightarrow \cos\alpha_2 = 0$. If $c_{u2} = 0$, $\eta_h = 1$ a $c_{u1} = c_1$, then equation 4.46 takes on the form:

$$Y = c_{u1} \cdot u_1 = c_1 \cdot u_1 \qquad [\mathrm{J \cdot kg^{-1}}] \qquad (4.47)$$

For Y = constant, equation 4.47 specifies the hyperbolic dependence between u_1 and c_1. Under this assumption, the circumferential speed u_1 rises with the increasing running speed (overpressure) of the turbine runner. The specific speed of the turbine thus rises, which is defined by the relation:

$$n_q = \frac{u^{1,5}}{Y^{0,75}} \qquad (4.48)$$

Specific speed gives us only general information about the characteristics of different types of turbines. In the design and modeling of turbines and in the choice of baseline data, unit speeds and flow rates defined using affinity relationships are applied.

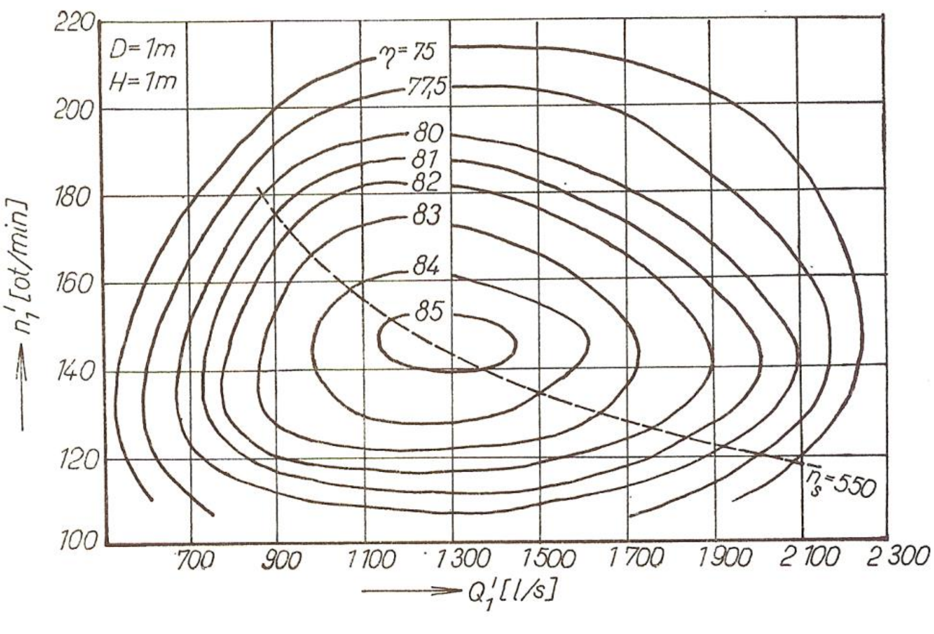


Fig. 4.15 Universal characteristics of a turbine

We obtain the universal characteristics of a turbine from measurements in a model type turbine at a constant head H and runner diameter D and for various openings of the wicket gate "a". We recalculate the results according to the law of similarity to the head H = 1 and the runner diameter D = 1 m, while the curve η = 0 corresponds to the overspeed of the turbine.

For specific energy it applies that $Y \sim u^2 \sim n^2 \cdot D^2$. For D = 1 m and Y = 1 ($J \cdot kg^{-1}$) we obtain $1 \sim n_{11}^2$ (s^{-2}). Using these proportions we obtain the definitional relation of unit speeds:

$$Y = \frac{n^2 \cdot D^2}{n_{11}^2} \quad [J \cdot kg^{-1}] \quad \Rightarrow \quad n_{11} = \frac{n \cdot D}{Y^{0,5}} \quad [s^{-1}] \tag{4.49}$$

For the flow rate, it applies that:

$$Q \approx D^2 \cdot Y^{0,5} \quad [m^3 \cdot s^{-1}] \tag{4.50}$$

For D = 1 m and Y = 1 kg^{-1} the unit flow rate is $Q_{11} \sim 1$ (4.51)

For the unit flow rate we can thus write:

$$\frac{Q}{Q_{11}} = D^2 \cdot Y^{0,5} \quad \Rightarrow \quad Q_{11} = \frac{Q}{D^2 \cdot Y^{0,5}} \quad [m^3 \cdot s^{-1}] \tag{4.52}$$

We define the operational state and specific speed of a turbine on the basis of the unit speed n_{11} and unit flow rate Q_{11} as follows:

$$n_{11} \cdot Q_{11}^{0,5} = \frac{n \cdot D}{Y^{0,5}} \cdot \left(\frac{Q}{D^2 \cdot Y^{0,5}} \right)^{0,5} \quad \Rightarrow \quad n_q = 333 \frac{n \cdot Q^{0,5}}{Y^{0,75}} \quad [s^{-1}] \tag{4.53}$$

The unit quantities of a turbine chosen in practice are $Y = g$ (i.e. head H = 1 m) and speed n (min^{-1}). Then for the unit speed we obtain:

$$n_1' = 60 \cdot n_{11} \cdot g^{0,5} = \frac{n \cdot D}{H^{0,5}} \quad (min^{-1})$$

$$Q_1' = Q_{11} \cdot g^{0,5} = \frac{Q}{D^2 \cdot H^{0,5}} \quad [m^3 \cdot s^{-1}] \tag{4.54}$$

The speed of the turbine and the machinery set, specific speed

The operating rotational speed of water turbines, at which high efficiency of energy conversion is ensured, is spread over a wide range according to the individual turbines and their parameters, ranging from 53 to around 1500 min^{-1}. Low speeds are disadvantageous because they require sophisticated overdrive gears (with regard to electric machines). High operating speeds, on the other hand, are a source of danger during generator failure, when the turbine accelerates to a multiple times higher speed, the so-called ***overspeed***.

The determination of the appropriate operating rated speed of a turbine is relatively challenging, and cannot be done without cooperation with the manufacturer. It is a very serious decision, considering that the turbine is connected directly (or through a transmission) with the generator, whose operation requires constancy of rotation speed. For the preliminary determination of the rated speed of the turbine, experience has shown the following relation can be applied:

$$n = \frac{n_s \cdot H \cdot \sqrt[4]{H}}{\sqrt{P_t}} \cdot 1{,}166 \qquad (4.55)$$

Where n is the rated operating speed of the turbine (min^{-1}), n_s indicates the ***specific speed of a geometrically similar turbine*** (min^{-1}), defined as the operating speed of a turbine with such a runner diameter, that with a head H = 1 m it provides the power of 0.7336 kW (i.e. precisely the power of one horsepower); the specific speed represents a characteristic mark that represents the properties of a turbine regardless on its type – turbines can be compared and evaluated on the basis of this characteristic; H is the net head (m), P_t indicates the turbine output shaft power (kW).

To be able to present the appropriate operating speed of the proposed turbine according to equation 4.55, it is necessary to know the specific speed of turbines which are under consideration. Table 4.3 lists the specific speed of some turbines.

Type of turbine	Usual range of n_s (min^{-1})
Pelton	4 – 32
Bánki	70 – 150
Francis slow-running	50 – 150
Francis normal	150 – 250
Francis fast-running	250 – 450

Kaplan and propeller	300 – 1 000

Table 4.3 Specific Speeds of Turbines

For operational reasons, as a protection against the cavitation of turbines, it is not recommended to choose for individual turbines characterized with a certain n_s a higher head than those given in table 4.4.

n_s (min^{-1})	70	110	150	200	300	400	500	600	700	800
H_{max} (m)	260	181	111	75	41	26	17	13	10	8

Table 4.4 Head limits for turbines with given n_s

When restoring old hydropower sources with Francis turbines, the interested party sometimes faces a very difficult task, which is to determine (or at least) estimate the appropriate operating speed of the turbine, if the only turbine available is without any data, but with which it is possible to measure the diameter of the runner *D*, the maximum angle of pitch α and the input angle of the runner blades β. For these cases, Cink and Machek recommend using the relation:

$$n = 53{,}5 \cdot \frac{\sqrt{H}}{D} \cdot \sqrt{\frac{\sin(\beta - \alpha)}{\cos\alpha \cdot \sin\beta}} \tag{4.56}$$

where D is the diameter of the runner, measured to the center of the input edges of the runner blades (m), H denotes the net head (m), β indicates the input angle of the runner blades (°) and α the angle of the vanes of the wicket gate (°).

We should also mention so-called overspeed, which occurs when we disconnect the generator from the grid and the torque of the electricity grid ceases to act. All of the incoming water energy is consumed in spinning the turbine and overcoming hydraulic resistance and losses. This turbine overspeed n_{max} is in comparison with the operational speed n all the higher, the faster running the turbine is, i.e., the higher is the value of the specific speed that characterizes it. A comparison of overspeed with operating speed depending on the running speed is shown in Table 4.5.

n_s (min^{-1})	50	300	400	800	1,000
n_{max} (min^{-1})	1,6	1,8	1,9	2,4	2,6 - 3

Table 4.5 Overspeed in multiples of operating speed

Turbines according to running speed

Characteristics of turbines

For the investigation of the characteristics of turbines we utilize models of these turbines. We convert the values of the quantities we have measured on the model type based on the relations for the speed and flow rate of the unit (4.53). Based on these quantities, we will construct the universal characteristics of this turbine.

The characteristics shown in Figure 4.16 express the properties of a turbine runner. From these characteristics it is possible to find out how a given opening of the wicket gate changes efficiency depending on the change in the head, since according to relation 4.53 the unit speed n_1 at operating speed n = constant is dependent on the head. We can examine the impact of these changes on efficiency from the characteristics in advance. The curve $\eta_1 = 0$ corresponds to overspeed, at which the turbine is completely unloaded ($M = 0$). The operating characteristics referred to in Figure 4.16 is a prescription for universal characteristics. It is constructed for a concrete turbine at a power plant for concrete values of Q and H.

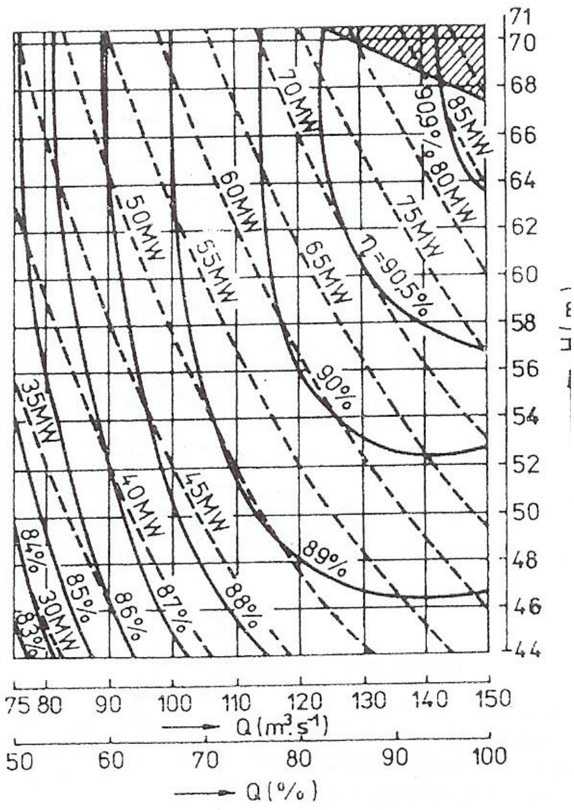


Fig. 4.16 Operating characteristics of a turbine

4.7 Flow-through hydroelectric power plants

The operational regime of a flow-through hydroelectric power plant is determined by the hydrological regime of the watercourse. The theoretical power of such a power plant between the input and the output profile of the power plant (see fig. 4.17) is calculated according to the following relationship:

$$P = (E_0 - E_2) \cdot \frac{1}{t} = \left[g \cdot (z_0 - z_2) + \frac{p_0 - p_2}{\rho} + \frac{\alpha_0 \cdot v_0^2 - \alpha_2 \cdot v_2^2}{2} \right] \cdot Q \cdot \rho = Y \cdot Q \cdot \rho \qquad (4.57)$$

Where $g \cdot (z_0 - z_2)$ is the change in the positional specific energy of the water between profiles 1 and 2 ($J \cdot kg^{-1}$),

$\frac{p_0 - p_2}{\rho}$ is the change in the pressure specific energy of the water between positions 1 and 2 ($J \cdot kg^{-1}$),

$\frac{\alpha_0 \cdot v_0^2 - \alpha_2 \cdot v_2^2}{2}$ is the change in the velocity specific energy of the water between profiles 1 and 2 ($J \cdot kg^{-1}$),

g is the gravity acceleration ($m \cdot s^{-2}$), Q represents the volumetric flow through the profile ($m^3 \cdot s^{-1}$), ρ is the water density ($kg \cdot m^{-3}$), t represents time (s), E_0 a E_2 represent the energy of the water flow in positions 0 and 2 (J) and α is the Coriolis number (a factor indicating the unevenness of distribution of velocity in the profile of the flow).

Calculation of the Utilizable Head of a Flow-through Hydroelectric Power Plant

We can write Equation 4.57 in the form:

$$P = g \cdot \left[(z_0 - z_2) + \frac{p_0 - p_2}{\rho \cdot g} + \frac{\alpha_0 \cdot v_0^2 - \alpha_2 \cdot v_2^2}{2 \cdot g} \right] \cdot Q \cdot \rho = g \cdot H \cdot Q \cdot \rho \qquad (4.58)$$

Where H represents the utilizable head of the power plant (m).

Fundamentally, we distinguish two types of head, the gross (overall, aggregate) head H_b and the utilizable (net) head H_v. The aim of the design engineer is to attain the highest value of gross and net head. This can be done through a damming construction (weir, dam) or by diverting the flow of the river (through derivation).

The gross head of the turbine (hydropower works) H_b is defined simply as the difference between the upper water level and the lower water level immediately beneath the waterworks. Its determination is easy and all that is needed for it is plain geodetic leveling. For the expression of the gross head H_b we will first express the pressure height h of the water column in meters:

$$h = \frac{p}{\rho \cdot g} \quad \Rightarrow \quad h_0 = \frac{p_0}{\rho \cdot g} \text{ and } h_2 = \frac{p_2}{\rho \cdot g} \; [\text{m}; \quad \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}, \quad \text{kg} \cdot \text{m}^{-3}, \quad \text{m} \cdot \text{s}^{-2}]$$

(4.59)

The gross head (also called the static head) H_b is calculated as follows:

$$H_b = H_0 - H_2 = (z_0 + h_0) - (z_2 + h_2) \quad [\text{m; m, m}] \tag{4.60}$$

The total utilizable head H_v of a hydroelectric power plant is given by the sum of the static (gross) and kinetic head:

$$H_v = H_b + \frac{\alpha_1 \cdot v_1^2 - \alpha_2 \cdot v_2^2}{2 \cdot g} \quad [\text{m}] \tag{4.61}$$

The usable (useful) head of a hydroelectric power plant *H* is calculated as the difference of utilizable head of the hydroelectric power plant H_v and the sum of all hydraulic head losses h_{zi} that arise in the water course through the pressure feeders at input $h_{z0,1}$ and the suction intake and the outflow channel at the output.

$$H = H_v - \Sigma h_z = H_b + \frac{\alpha_1 \cdot v_1^2 - \alpha_2 \cdot v_2^2}{2 \cdot g} - \Sigma h_{zi} \quad [\text{m}] \tag{4.62}$$

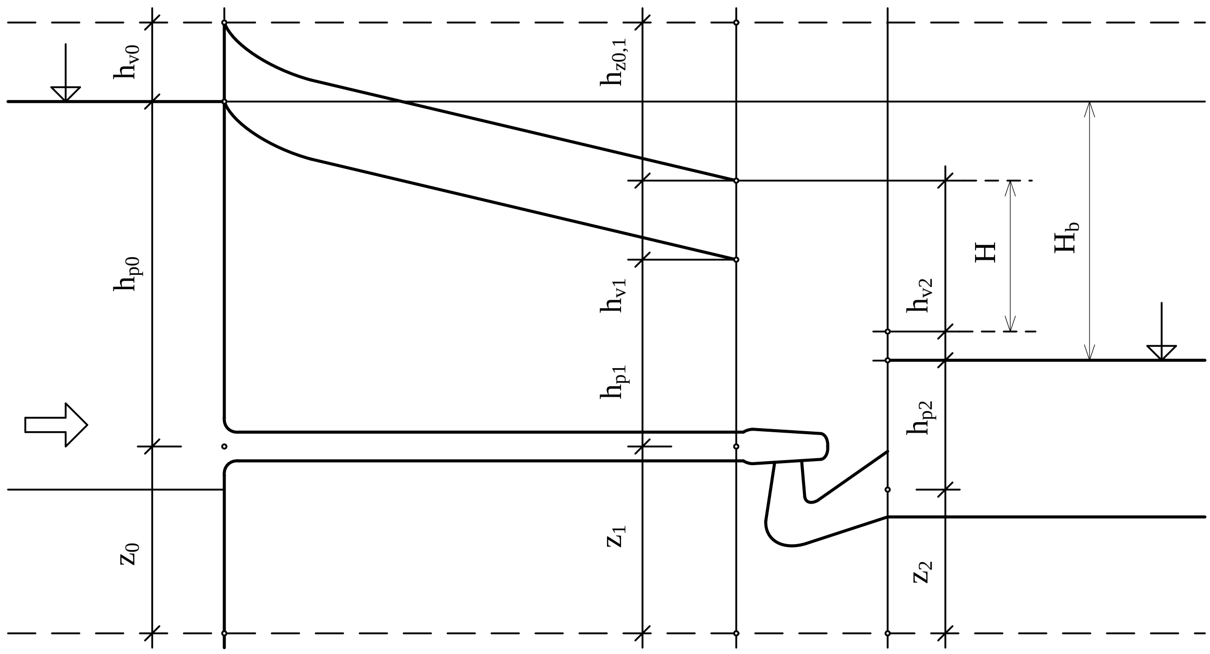


Fig. Figure 4.17 Determination of the values of the gross head H_b and the usable head H (h_{vi} are individual kinetic energies, $h_{z0,1}$ represent hydraulic losses in the feeder, h_{pi} are individual pressure energies, z_i are the relevant positions of individual locations of the water course)

Figure 4.17 could give the impression that the values of the gross and usable head are constant throughout the year. However, one must realize that on the contrary these values are variable, depending on the natural flow of the waterway. Determination the design net head of the turbine must be approached after a comprehensive analysis, taking into account flow changes as well as the specific characteristics of the turbines.

During the course of the year, hydroelectric power plants (especially SHPP) undergo three characteristic periods:

- Periods of insufficient heads and excess flows
- Periods of sufficient flows as well as heads
- Period of large heads and insufficient flows

This can be best expressed by the lines of exceeded flows and heads of Figure 4.18. We obtain the line of exceeded flows by sorting the daily flow rates according to size in the course of a typical year, and the line of exceeded heads as the line that corresponds to the relevant values of the flows, with the utilization of equation 4.63.

In the first period (I), in flow diversion during flooding, hydroelectric power plants (especially SMPP) must be shut down due to the fact that the net head drops below the limit value H_{min}, at which the machine set can no longer work effectively. The length of this negative period of rest is dependent primarily on the ability of the turbines to operate with varying head. For the reasons mentioned, turbines with double regulation are very favorably applied (Kaplan turbine and Bánki turbine), which shorten the rest period and lead to increased production. Shortening this unproductive period can also be achieved using an ejection water stream that idly overflows the weir area, thus slightly increasing the net head of the turbine.

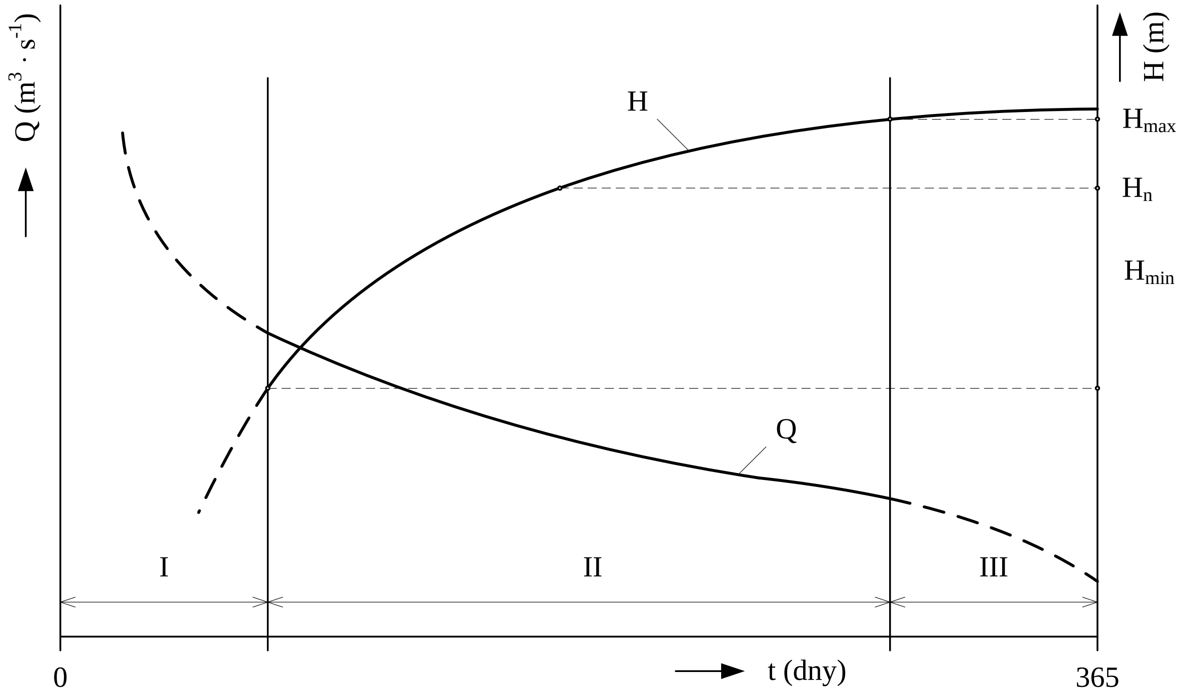


Fig. 4.18 Curves of exceeded flows and heads:

I – Periods of insufficient heads and excess flows

II – Periods of sufficient heads and flows

III – Periods of large heads and insufficient flows

The length of the second, and the longest time period, i.e. the period of production, is dependent on the ability of the turbines to operate with a changing net head, and the ability to handle a changing flow. This range can be extended to a certain extent by choosing a larger number of smaller machines, thus at least partly compensating the worse regulation of the turbines.

The length of the last block of time, i.e. the period of the large heads and insufficient flows, which can often cause the shutdown of the power plant, is dependent primarily on the number of turbines, or, where applicable, the size of the smallest machine. In order to shorten this period as much as possible or eliminate it altogether, one may in older power plants encounter various sizes of machine sets.

Determination of the Flow Rate through the Turbine and the Hydroelectric Power Plant

Because the turbine flow rate Q_t ($m^3 \cdot s^{-1}$), depending on the chosen number of turbines, is derived from the proposed flow through hydroelectric power plant Q_{nVE}, it seems paramount to carry out the design of the overall flow through the hydroelectric power plant. The determination of this flow is not a simple task, because the natural flow of some of our rivers is in the course of the seasons, but also the individual years, considerably variable. Individual rivers are characterized by lines of daily and (monthly) flow rates. From these chronological lines of flow duration we construct flow duration curves for wet, dry, and average years, see Figure 4.19.

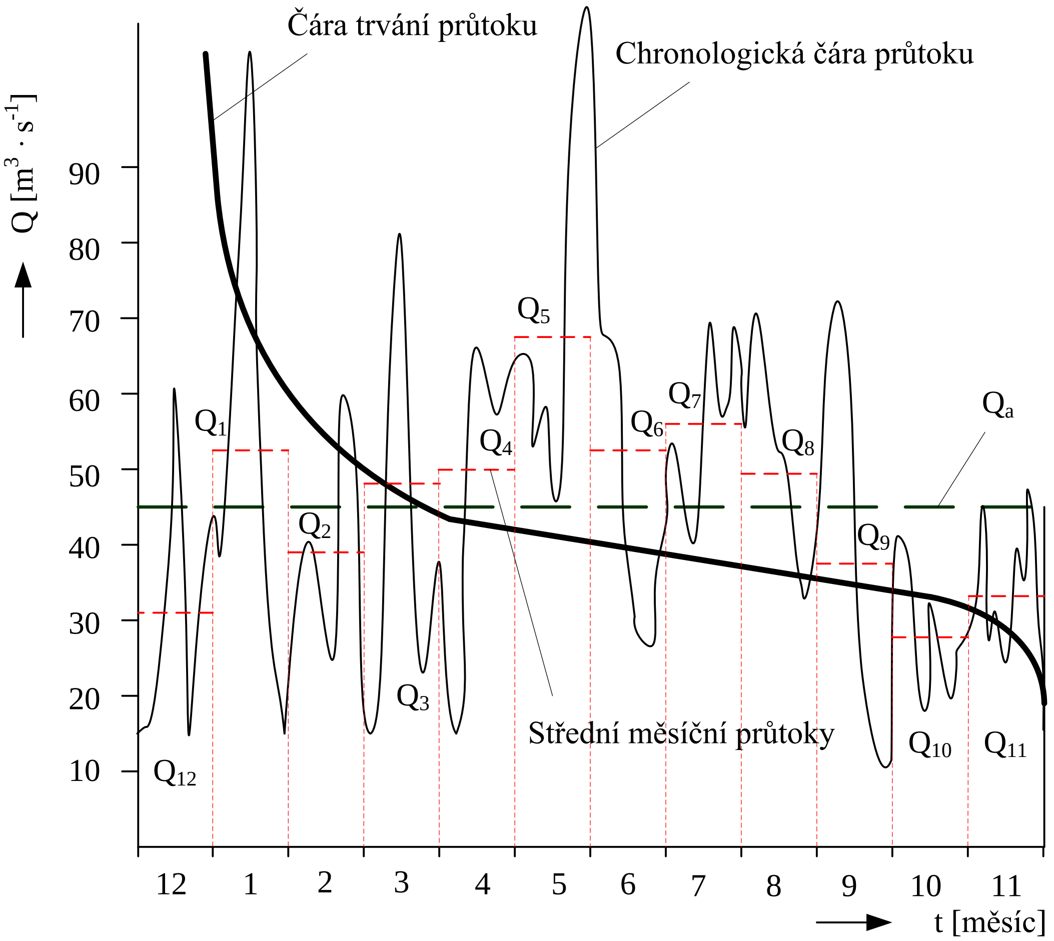


Fig. 4.19 The chronological flow rate line and the duration of flow line

In low-pressure hydroelectric power plants, it is common to elect a design flow rate in the range from the ninety-day flow Q_{90d} to the one-hundred-twenty-day flow Q_{120d}, see figure 4.20. With power plants at a weir (without derivative channels and pipes) the design flow rate Q_{nVE} approaches the flow rate Q_{90d}, and with derivative power plants to the flow rate of Q_{120d}. We strive to extract the entire efficient value of the hydropower potential of the watercourse, i.e. nearly the maximum of the given possibilities.

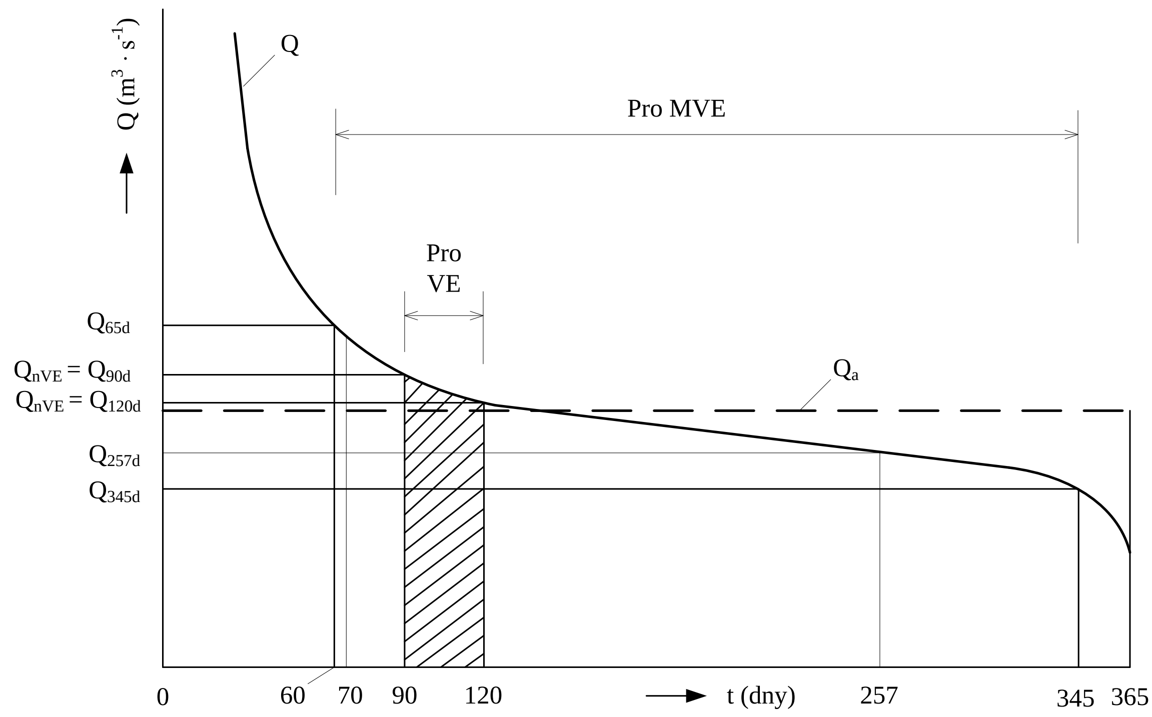


Fig. 4.20 Design flow rate of low pressure hydroelectric power plants:

Q_a ($m^3 \cdot s^{-1}$) – long term average flow rate, Q_{nVE} ($m^3 \cdot s^{-1}$) – design flow rate

In the case of small hydroelectric power plants, a number of other criteria are applied for the determination of the design flow Q_{nVE}, all more or more or less individual in character (the aim of the highest possible annual energy production with minimum investment and operating costs, the swallowing capacity of the offered turbines, ...), which markedly extends the interval in which the resulting design ranges. In such cases the Q_{nVE} ranges from Q_{65d} (SHPP Landshut) up to Q_{345d}. However, if there are no special reasons for the choice of special values of the flow, it is usual to elect a design flow for low-pressure SHPP also in the area from ninety-day flow Q_{90d} to one-hundred-twenty-day flow Q_{120d}.

When determining the lines of flow exceedence, it is necessary that they are based on flows provided by a professional institution – the Czech Hydrometeorological Institute, which are compiled in a hydrometeorological atlas.

If the mentioned hydrometeorological supporting documents are not available, if their acquisition takes too long, or if it is necessary to refine the value of the utilizable head for the turbine, we can proceed to the direct measurement of the flow rates in the expected profile of the hydropower works being prepared (this applies mainly for SHPP). Measurement of the natural flow is not easy, despite the existence of a number of methods of flow measurement in natural channels. The basic methods used primarily for determining flow rates for the design of SHPP are:

- Measurement of flow spillway on the weir
- Measurement of flow with measuring spillways
- Volume measurement
- Measurement of flow with a float

The energy produced during the period of one year is calculated from the relation:

$$E = \sum_{i=1}^{365} \rho \cdot g \cdot H_i \cdot Q_i \cdot \Delta t_i \cdot \eta_i \cdot 10^{-3}, \qquad \text{[kWh]} \tag{4.63}$$

Where Δt is a time interval with a constant flow rate and head (h), η is the resultant efficiency to the terminals of the alternator $\eta = \eta_t \cdot \eta_g$ in the time interval Δt, with the other variables described in Chapter 4.3.

In view of the fact that it is not economical to size a flow-through hydroelectric power plant for maximum achievable power, the maximum power of a hydroelectric power plant will move around in the left rising part of characteristic II in Figure 4.3.

The choice of the machine set for the water works being designed and its commissioned or calculated maximum power is not an unambiguous task. It needs to be addressed while taking into account a number of aspects. The best and the most common in our conditions is the choice of 2 to 5 machine units. Besides the technical aspect, we have to consider the task from the economic point of view. In addition, we must take account of the natural and ecological conditions, the requirements of the power grid, etc.

4.8 Regulatory hydroelectric power plants

Regulatory hydroelectric power plants usually work at the peak or half-peak part of the daily load diagram. According to the natural conditions, they may with natural accumulation (lakes in the river catchment area; weirs built at the outflow of the river from the lake) or an artificial accumulation (a river bed dammed by dam (valley dams); flooded basins in the vicinity of a river and the linking of the basin with a derivative channel).

According to the position of the water reservoir in relation to the power plant, we distinguish:

- Upper reservoirs – remote from the power plant and located on the river or its tributaries; the water is channeled into the power plant via the channel of the watercourse
- Own reservoirs – created by a dam at the power plant
- Lower reservoirs – placed under the regulatory hydroelectric power plant; they ensure an even river flow rate.

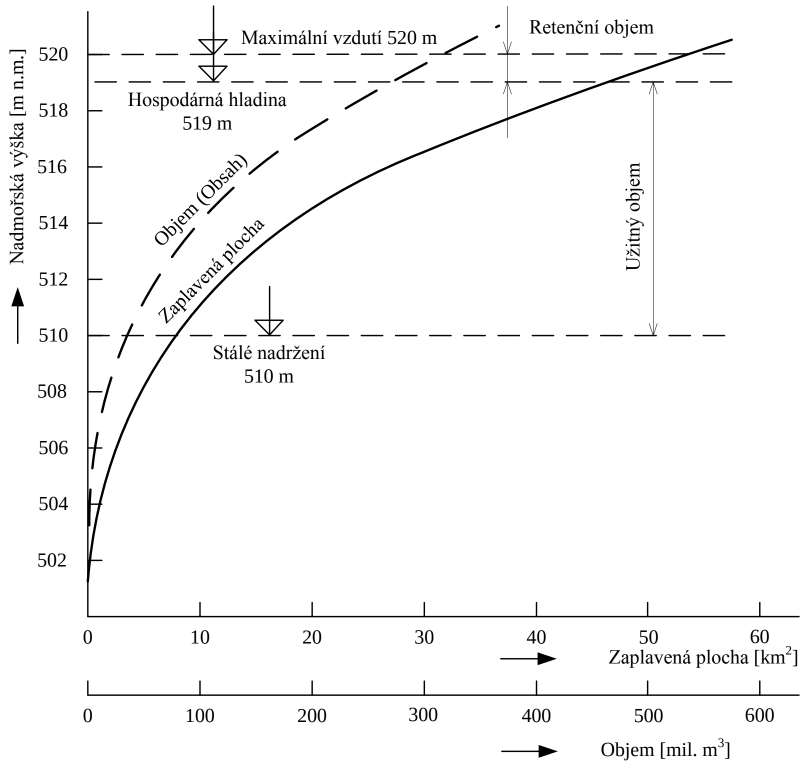


Fig. 4.21 Line of volume and flooded areas of an accumulation reservoir

According to the volume of their own accumulation reservoir, we sort hydroelectric power plants into those with a daily, weekly, yearly or even multi-year accumulation.

The volume of the own accumulation reservoir is divided into:

1) The permanent reservoir level (constant supply of water) is determined by the lowest level below which the water is no longer drawn from the accumulation reservoir.
2) The utilizable volume of is given by the difference between the highest and the lowest operational level.
3) The protective (retention) volume is used for capturing flood waves.

Each component of the volume of the own accumulation reservoir is shown in Figure 4.21.

Energy equivalent of the volume of the accumulation reservoir

In addition to the volume of the accumulation reservoir, it is sometimes also need to know the potential energy of the utilizable volume of the water reservoir. The size of this energy is calculated according to the relation:

$$E = \rho \cdot g \cdot V_0 \cdot H_{str} \cdot \eta , \quad [\mathrm{J;\ kg \cdot m^{-3},\ m \cdot s^{-2},\ m^3,\ m,\ -}] \tag{4.64}$$

When expressing potential energy in the unit kWh and assuming the specific density of water ρ = 1,000 kg · m^{-3} and with the gravity acceleration g = 9.81 m · s^{-2} we obtain the relation:

$$E = \frac{g \cdot V_0 \cdot H_{str}}{3\,600} \cdot \eta = \frac{V_0 \cdot Y_{str}}{3\,600} \cdot \eta = \frac{V_0 \cdot H_{str}}{3\,67{,}2} \cdot \eta , \qquad [\mathrm{kWh}] \tag{4.65}$$

$$Y_{str} = g \cdot H_{str} , \quad [\mathrm{J \cdot kg^{-1}}] \tag{4.66}$$

where V_0 is the utilizable volume of the reservoir, H_{str} is the mean value of the net head (the difference between the lower water level of the reservoir and the center of the utilizable volume of the reservoir after deducting losses in the penstock and the draft tube), η is the mean efficiency of the production unit (includes losses at the inlet, in the penstock, in the turbine, in the draft tube, in the alternator and the block transformer).

For the rough determination of the energy equivalent of the accumulation reservoir, we can, assuming the level of resultant efficiency η = 0.734, use the relation:

$$E = 2 \cdot V_0 \cdot H_{str} , \qquad [\mathrm{kWh}] \tag{4.67}$$

Utilizable volume of the accumulation reservoir of a hydroelectric power plant

Hydropower works with daily regulation of the outflow from the reservoir are built primarily on watercourses with constant or nearly constant flow. In these works, the daily production of electrical energy depends on the daily flow of the river. Uneven water consumption during the day is given by the need to regulate the supply of electrical power to the electricity grid on the basis of a request by the dispatcher of the operator of the transmission grid. An example of the daily load diagram and its corresponding quantity of water utilized is shown in Figure 4.22. Assuming a constant value of the head during the operation of the power plant, the utilized flow rate is directly proportional to the electrical power. The dependencies corresponding to this, $P = f(t)$ and $Q = f(t)$, are shown in Figure 4.22 a). The mean daily electric power P_s or the mean upper value of the flow Q_s are obtained from the relation:

$$P_s = \frac{1}{T} \cdot \int_0^T P(t)\, dt \qquad [\mathrm{W; s, W, s}]$$

$$Q_s = \frac{1}{T} \cdot \int_0^T Q(t)\, dt \qquad [\mathrm{m^3 \cdot s^{-1}; s, m^3 \cdot s^{-1}, s}] \qquad (4.68)$$

Because it is an accumulation hydroelectric power plant with a water accumulation reservoir, the volumetric flow rate of the water Q_p supplying the accumulation reservoir (we proceed from the instantaneous values of the flow) must be equal to the mean of the daily flow Q_s. The sum of all hatched areas (+, 2, 3 and 4) in Figure 4.22 will give us the needed the utilizable volume of the accumulation reservoir. With the exact calculation of this volume, we need to take account of the change in head and efficiency in the calculation of the flow rate $Q = f(t)$. This change in the head H = f (t) is indicated with a dashed line in Figure 4.22 a). The intervals 1 and 4 represent the period when the water is being accumulated in the reservoir. During this period the flow into the reservoir is larger that the flow through the turbines. On the contrary, the intervals 2 and 3 correspond to the period when the reservoir is being emptied and the inflow of water into the reservoir is larger than Q_s. The minimum and maximum flow rate through the turbines, which must be known for the proposal of the swallowing capacity and the number of turbines, will be determined from relations 4.1 and 4.4.

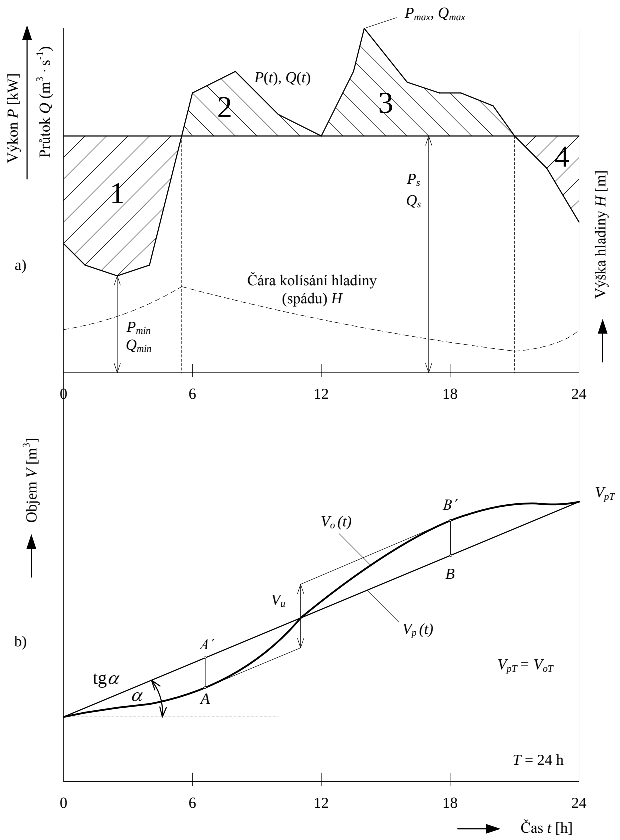


Fig. 4.22 The sum lines of inflow and extraction from the reservoir with the daily accumulation

Graphical method for determining the volume of an accumulation reservoir

The utilizable volume of an accumulation reservoir for daily accumulation can be specified by the graphical method, i.e., using lines of inflow and extraction, which are illustrated in Figure 4.6 b). Line V_p = f(t) corresponds to a constant inflow Q_s. It is determined by a straight line, whose slope tgα will be established as follows:

$$tg\alpha = \frac{V_p}{T}; \quad V_p = \int_0^T Q_p\left(t\right)dt, \qquad [\mathrm{m^3 \cdot s^{-1}; m^3, s; m^3 ; m^3 \cdot s^{-1}, s}] \qquad (4.69)$$

V_p is the volume of water (m^3) corresponding to the inflow of water Q_p (t) (m^3 · s^{-1}) into the reservoir during a one day period (T = 24 hours). At the end of this time interval, i.e., in 24 hours, the volume of water V_p that flowed into the reservoir must be equal to the volume V_o that flowed out of the reservoir.

$$V_{oT} = \int_0^T Q_o\left(t\right) dt, \qquad [\mathrm{m}^3 ; \mathrm{m}^3 \cdot \mathrm{s}^{-1}, \mathrm{s}] \tag{4.70}$$

Line V_o = f(t) corresponds to the uneven extraction of water $Q_o(t)$ from the reservoir. We use the lines $V_p(t)$ and $V_o(t)$ to determine the utilizable volume of the accumulation reservoir in such a way that through the extremes marked on figure 4.22 b) as A and B we lead tangents parallel with the line V_p (t). The vertical distance V_u corresponds to the required utilizable volume of the accumulation reservoir with the daily accumulation. The vertical distance A´-A corresponds to the largest increase of water in the reservoir and the distance B´ - B, on the contrary, to its largest decrease.

The uneven outflow of water from the regulatory hydroelectric power plant is evened out by a leveling reservoir with a small flow-through power station associated with the regulatory hydroelectric power plant. This power plant operates with a constant power output throughout the period T and thus maintains a uniform river flow rate.

An important role in covering the daily diagram is played by ***peak hydroelectric power plants***. They work with intermittent operation. The general course of extraction peaks, whose area is substituted by an equivalent area of a rectangle, is shown in the example of extraction $Q_1 \cdot T_1$ in Figure 4.23. This picture shows the examination of the utilizable volume of a peak hydroelectric power plant with daily accumulation. $V_p(t)$ represents the cumulative inflow line (m^3). It is the volume of water that had flowed into the reservoir during the period t:

$$V_p\left(t\right) = \int Q\left(t\right) dt \tag{4.71}$$

At constant inflow Q_s, it is a straight line. Its slope is $\mathrm{tg}\alpha = Q_s = V_{pT} / T$. $\mathrm{V_o(t)}$ is the cumulative outflows line (m^3). It represents the volume of water that flowed out of the reservoir in the period t. Its course corresponds to the extractions Q_1, Q_2 and Q_3 ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$) into the turbines. At the end of period T, V_{pT} equals V_{oT}. We determine the utilizable volume of the accumulation reservoir in the same way as in the previous case. From the maximum value marked at point B and the minimum value marked at point A, we draw parallel lines to the line $V_p(t)$. The distance marked V_u in Figure 4.23 indicates the utilizable volume of the reservoir.

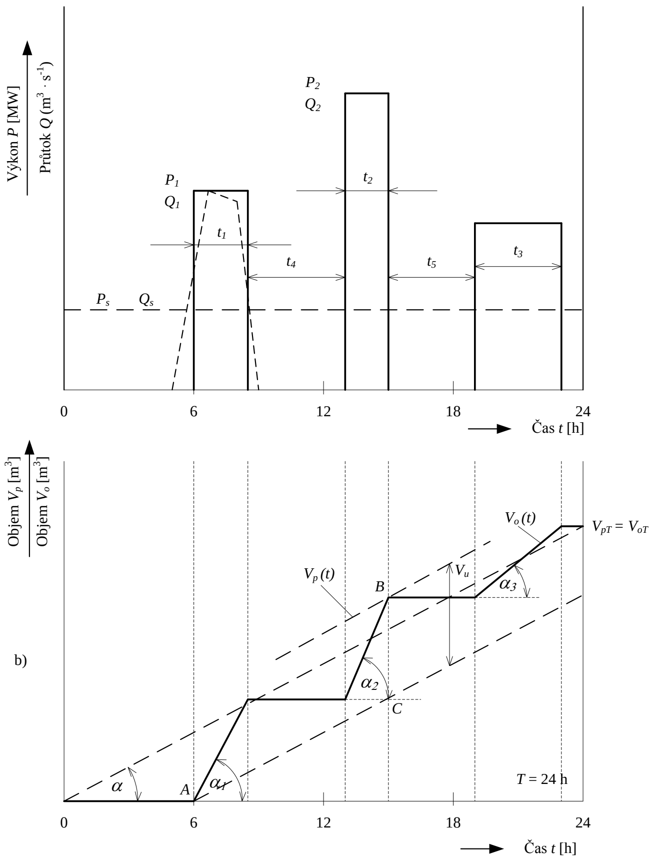


Fig. 4.23 Graphic examination of the utilizable volume of the reservoir with intermittent peak power output

Calculation of the utilizable volume of the accumulation reservoir during peak load

For the example given in Figure 4.23, it applies that:

$$V_{pT} = Q_{sT} \cdot T = V_{oT} = Q_1 \cdot t_1 + Q_2 \cdot t_2 + Q_3 \cdot t_3 \qquad [\mathrm{m}^3]$$

(4.72)

The vertical section between points B and C corresponds to the utilizable volume of the accumulation reservoir V_u. We will calculate it from the relation:

$$V_u = Q_s \cdot T - \left(Q_s \cdot t_1 + Q_s \cdot t_2 + Q_s \cdot t_3 + Q_s \cdot t_4 + Q_s \cdot t_5\right)$$

$$V_u = Q_s \cdot \left[T - \left(t_1 + t_2 + t_3 + t_4 + t_5\right)\right] \qquad [\mathrm{m}^3 ;\ \mathrm{m}^3 \cdot \mathrm{s}^{-1},\ \mathrm{s}] \qquad (4.73)$$

For the calculation of the volume of a peak power plant with continuous operation and with the extraction of turbines Q_1 for the period t_1 during constant inflow, which is of the same size as the mean value of the extraction $Q_s = V_{oT} / T$,we proceed from the assumption that at the end of the monitored period T, $V_{pT} = V_{oT}$. Then the following applies:

$$Q_I \cdot t_I = Q_s \cdot T, \qquad [\mathrm{m^3 \cdot s^{-1}, s, m^3 \cdot s^{-1}, s}] \qquad (4.74)$$

$$V_u = Q_I \cdot t_I - Q_s \cdot t_1 = Q_s \cdot T - Q_s \cdot t_1 = Q_s \cdot (T - t_I) = (Q_I - Q_s) \cdot t_I \qquad [\mathrm{m^3}] \qquad (4.75)$$

Sometimes we need to examine, for a known constant inflow Q_p and for its corresponding utilizable volume of the accumulation reservoir V_u, the possible period of peak load t_I for various large extractions Q_I. The period of peak load t_I is determined according to the relation:

$$V_u = Q_s \cdot (T - t_I) = (Q_I - Q_s) \cdot t_I ; \qquad t_I = T \cdot \frac{Q_s}{Q_I} \qquad (4.76)$$

Because we assume that inflow Q_p equals the mean value of the extraction by turbines Q_s and $Q_I > Q_p$, then $t_I < T$, because $t_I = T \cdot Q_p / Q_I$.

In practice it may happen that a hydroelectric power plant with a daily accumulation will have a certain period where the inflow Q_p is greater than the value for which the utilizable volume of the reservoir was designed. When utilizing the maximum swallowing capacity of turbines and the given utilizable volume of the reservoir, the period t_I would come out greater than would correspond to the needs of the daily diagram. In this case it is advantageous to use the surpluses of water so that the daily peak extraction is split into two periods. This also better meets the needs of the daily load diagram of the electricity grid (the morning and afternoon peaks). From the above it follows that with an intermittent peak load, the required utilizable volume is smaller than with a continuous load.

4.9 Pumped storage hydroelectric power plants (PHPP)

Pumped storage hydroelectric power plants play an irreplaceable role among the sources in the electricity grid. Despite markedly high investment demands, even though return on investment is around 7 years (e.g., the return on investment of the Dlouhé Stráně PHPP took approximately 6 years), they have a number of advantages over other types of power plants. Pumped storage hydroelectric plants fulfill primarily the following tasks:

a) ***Static function*** – in the time interval that the electricity grid is less loaded, water is pumped from the lower to the upper reservoir while electric power from electricity grid is simultaneously consumed. Conversely, at a time when consumption in the electricity grid rises, the water energy accumulated in the upper water reservoir is used to cover the peak load in the electricity grid. We call this circuit the small pumping cycle of the PHPP. It takes advantage of the difference in the price of electrical energy, which in the peak period is about four times more expensive than in the period of low consumption.

b) ***Dynamic function*** - they participate in covering the dynamic changes in the load on the electricity grid. In the form of support services, they participate in system services ensured by the operator of the transmission grid, by which they contribute to the stabilization of the electricity grid during emergency states. Because of this, considerable demands are placed on the automation of the PHPP (reliability, quality).

The combination of PHPP with multi-purpose reservoirs is very important in terms of environmental improvement, as pumped storage improves water quality, increases the oxygen content in the water and prevents slow eutrophication of the reservoir.

Pumped storage hydroelectric power plants can be divided on the basis of the water regime into two main groups:

1. Pumped-storage hydroelectric power plants with secondary artificial accumulation, having a closed water cycle between the bottom and top accumulation reservoirs and are also called pure or classic. They are usually used for larger heads. Typical examples are the Dlouhé Stráně PHPP and the Štěchovice II PHPP.
2. Pumped-storage hydroelectric plants with a mixed primary and secondary accumulation, in which the top reservoir is a dam reservoir on the watercourse with the primary natural accumulation, and the bottom reservoir is usually a leveling reservoir with a flow-through hydroelectric power plant, such as in the Czech Republic the Dalešice PHPP (formerly the Pastviny PHPP), or abroad the power system Kaprun – Limberg in Austria.

In terms of water management, there are pumped storage hydro power plants with a reservoir that controls a small river basin (in the order of tens of km^2, usually an artificial reservoir), and those with a reservoir controlling a larger catchment area (in the order of hundreds of km^2, a multi-purpose reservoir).

We can also divide PHPP by the location of the engine room (surface and underground), according to the pressure pipelines (pipes on the surface or buried, tunnels, shafts) according to the type of accumulation reservoir (artificial, natural), according to the size of the utilizable head, or we can divide the PHPP by the machinery arrangement of the pumping apparatus:

a) *The Four-machine configuration*, which consists of the machine sets turbine-alternator and electric motor with pump. This solution is historically the oldest.

b) *The Three-machine configuration*, most often in a vertical arrangement, it is made up of the motor-generator, turbine and accumulation pump, see Figure 4.X. The turbine is connected to the motor-generator by a fixed coupling and to the accumulation pump by a geared coupling.

c) *The Two-machine configuration* is made up of the motor-generator with a reverse turbine. In terms of the electricity grid, the machine set can work either as a source, an appliance or a synchronous compensator for the delivery or extraction of reactive energy. The advantages of the two-machine arrangement are mainly the lower investment needed for the construction of the PHPP compared to arrangements with more machines. To further increase the economic efficiency of investments, we need to achieve the greatest possible utilizable volume of the upper accumulation reservoir, obtain the maximum head with the minimum length of the feeder, and place the plant in the vicinity of the supply source or in the center of consumption of electric power.

All three pumped-storage hydroelectric plants located on the territory of the Czech Republic (Dlouhé Stráně PHPP, Dalešice PHPP and Štěchovice II PHPP, with a total installed power of 1,145 MW) are executed in this configuration.

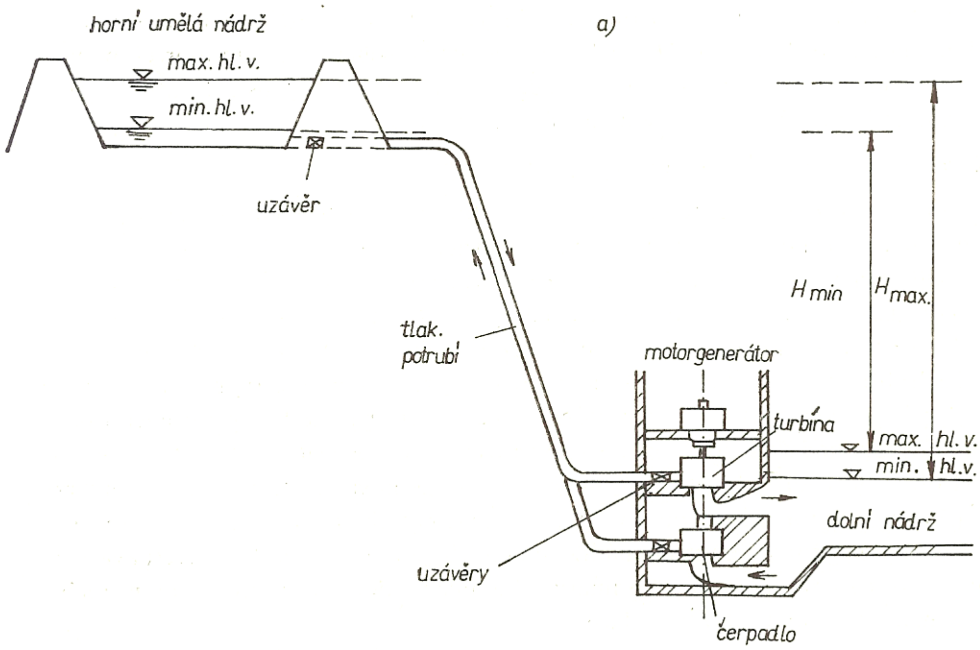


Fig. 4.24 Example of a PHPP with a three-machine configuration

In the case of a three-machine configuration of the PHPP, the power consumption during the operation of the pumps can be regulated by using a so-called hydraulic short circuit, which contributes to the improvement of the overall hydraulic efficiency of the pumped storage. This mode of operation is used if the excess energy that can drawn from the grid falls under the rated power input of the pump, as otherwise the power consumption would somehow have to be reduced. Because losses in the pump rise faster than in partially throttled turbines, a turbine is put into operation while the pump is fully loaded. The water flow rate obtained by the pump is not supplied entirely to the upper reservoir, however, but is partially fed back into the turbine, which then offsets the difference between the input of the pump and the extraction of energy from the grid.

In the assessment of the hydraulic efficiency of the PHPP, it is necessary to distinguish whether at issue is the efficiency of the great cycle or the small cycle of the transformation of electrical energy.

By the energy balance of the ***large cycle*** of pumped storage, we understand the overall efficiency of pumped storage, with respect to the power outlets on the VHV side from the base condensing power plant and on the inlet power supply on the VHV side at the place of consumption of peak power, including losses caused by the transmission and transformation of electric power. If we label the produced power at the terminals of the condensing power plant that provides power for night pumping as P_1(kW) and the operating duration of the pumping $t_č$ (h), then the supplied power is equal to $E_1 = P_1 \cdot t_č$ (kWh). If we label as P_2 (kW) the power on the side of the VHV at the place of consumption of peak power after previous transformation in the condensing power plant and the HPP, after losses in the pump operation and in the turbine operation during the period t_t (h) and in the transformation and after losses in the VHV power lines, then the power obtained is $E_2 = P_2 \cdot t_t$ (kWh). The efficiency of the large cycle of pumped storage is then:

$$\eta_v = \frac{E_2}{E_1} \quad [\text{-, kWh, kWh}] \qquad (4.77)$$

By the energy balance of the small cycle of pumped storage we understand the overall efficiency of pumped storage with respect to the inlets and outlets at the threshold of the HPP on the VHV side. If we label the supplied power at the threshold of the HPP on the side of the VHV as P_d [kW] and the period of pumping $t_č$ [h], then the supplied power is $E_d = P_d \cdot t_č$ [kWh]. If we label the obtained power at the threshold of the HPP on the side of the VHV as

P_z [kW] and the period of turbine operation t_t [h], then the obtained power is $E_z = P_z \cdot t_z$ [kWh]. The efficiency of the small cycle of pumped storage is then:

$$\eta_v = \frac{E_z}{E_d} \quad \text{[-, kWh, kWh]} \tag{4.78}$$

In practice, the overall efficiency of pumped storage usually concerns the small cycle, which we will also further consider here. Each component of the efficiency of the pumped storage process are illustrated in Figure 4.25.

The efficiency of the small pumped storage cycle in modern machine sets is usually 70 to 75%.

The machine set used today for both of the presented regimes (pumping, turbine) is a motor-generator with a reverse turbine, which equipped with an asynchronous starting motor for the pumping regime.

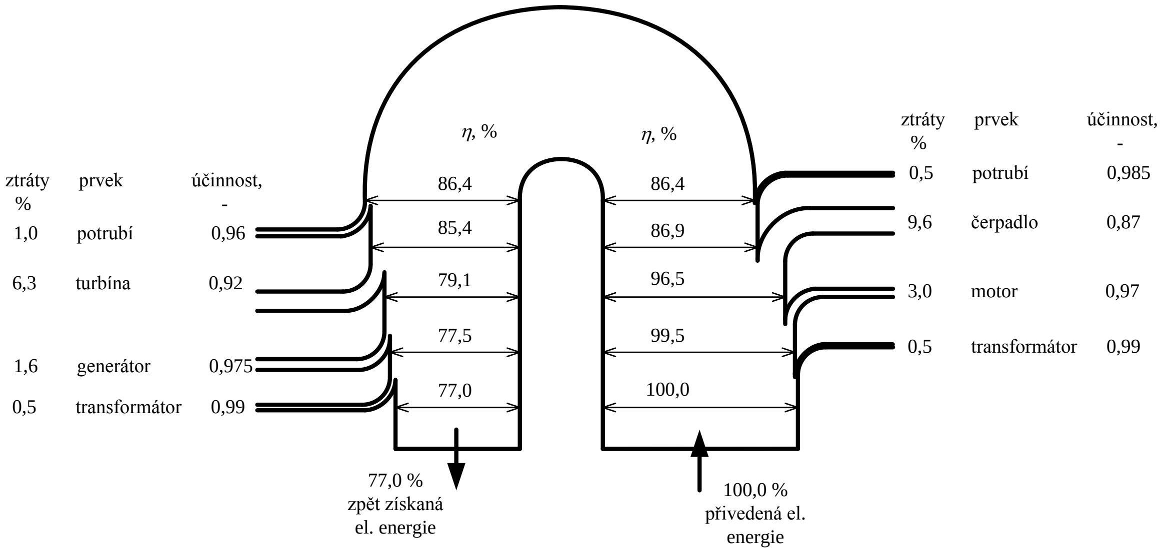


Fig. 4.25 The partial losses and the overall efficiency of a pumped storage hydroelectric power plant (the energy balance of the small pumped storage cycle).

Pumped storage hydroelectric plants have the following main facilities: a top and bottom accumulation reservoir, a pressure feeder with an inflow facility and closures, the engineering building of the power plant with the turbine and pumping machine sets and with other devices.

The placement of the pumped storage hydroelectric power plant

A pumped storage hydroelectric power plant is placed primarily with regard to suitable topographical and geological conditions of the terrain and should by as close as possible to the focal point of electric power consumption. The optimal overall efficiency of the hydraulic accumulation of energy is achieved if it is possible to fulfill the following main prerequisites:

1. Large reserve volume of the top accumulation reservoir
2. The largest possible head with the smallest possible length of the pressure feeder,
3. The most suitable ratio of the main parameters of the machines installed, especially in terms of water flow, power output, and input power.

Operational experience has shown that from the economic point of view, the ratio of the head H_b and the length of the feeder L should be an order of magnitude larger than $H_b/L \geq 0.1$.

The optimal ratio of the main parameters of the machines installed can be achieved only with four-machine configuration of the PHPP, whereas in a three-machine installation the parameters of the pumping and turbine operation are mutually dependent on each other. If the pumped storage machine set is to have greatest possible efficiency of the small cycle of hydraulic accumulation, the power and the swallowing capacity of the turbine (P_t, Q_t) and the pump ($P_{č}$, $Q_{č}$) must be in optimal proportion:

$$\frac{P_t}{P_{č}} = 1{,}0 \; až \; 1{,}5 \qquad \text{and} \qquad \frac{Q_t}{Q_{č}} = 1{,}2 \; až \; 1{,}8$$

To ensure a large range of regulation, the ratio must be $P_t/P_{č} \cong 1$.

The top and bottom accumulation reservoir

Classic PHPP with secondary accumulation of energy – operating volume is determined by the installed power and the period of turbine operation. Reserve volume is needed to replace the losses incurred through evaporation and seepage at both reservoirs. Retention volume is proposed only in a lower reservoir with a larger water catchment areas, if it is economically justified.

PHPP with mixed accumulation of energy – the maximum level of the reservoir is determined by the terrain and the buildings at the end of the backwater. The constant volume of the top reservoir is given by the minimum head on the turbines, while the constant volume of the bottom reservoir is the result of economic comparison between the height of the weir, or possibly the dredging of the riverbed, the pump inlet height, etc. Operating volume is determined by the installed power and the period of turbine operation.

Determination of the size of the volume of an artificial top reservoir without a natural inflow is based on the formula for energy equivalent:

$$V_u = \frac{3\,600 \cdot E}{g \cdot H_{str} \cdot \eta} \qquad [\mathrm{m^3; J, m \cdot s^{-2}, m, -}] \qquad (4.79)$$

where V_u is the utilizable volume of the reservoir, H_{str} is the mean value of the net head (the difference between the lower water level of the reservoir and the center of the utilizable volume of the reservoir after deducting losses in the penstock and the draft tube), η is the mean efficiency of the production unit (includes losses at the inlet, in the penstock, in the turbine, in the draft tube, in the alternator and the block transformer).

The utilizable volume of the accumulation reservoir of a pumped storage hydroelectric power plant can calculated using the same method that was used in the previous chapter. Due to the rapid transitions between the individual regimes of the pumped storage hydroelectric power plant, the steepness of the loading of hydroalternators can range around 5 to 10% P_n per second. It follows from this that the inflow of water Q_p into the reservoir during pumping operation or the extraction of water during turbine operation have a mostly rectangular progress which is dependent on time, as shown in Figure 4.8. The flows and extractions in the upper part of the image correspond to the cumulative line of inflow $V_p(t)$ and withdrawal $V_o(t)$ of water shown in the lower part of the image. During the considered period T the water volume V_{pT} pumped into the reservoir must equal the water volume V_{oT} withdrawn from the reservoir. The utilizable volume of the accumulation reservoir V_u is specified in the case shown in Figure 4.8 by an area proportionate to the longest period of pumping operation $V_u = Q_{č} \cdot t_{č}$.

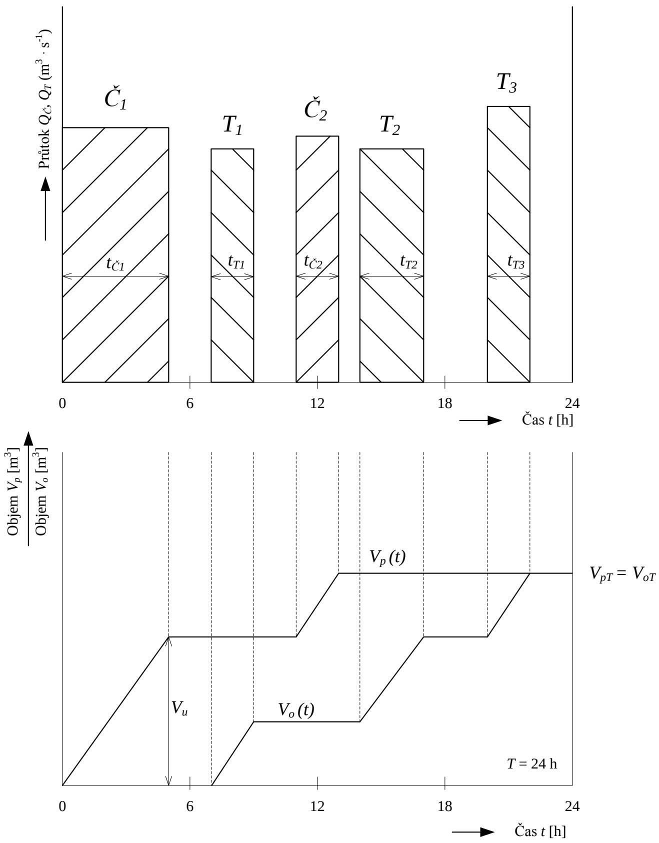


Fig. 4.26 PHPP operation – determination of the utilizable volume of the PHPP

The total utilizable volume of the artificial top reservoir V_{uc} therefore must equal the utilizable volume V_u increased by evaporation and seepage losses q [$m^3 \cdot s^{-1}$] in the course of the longest pumping.

The swallowing capacity of the turbine (maximum water flow through turbine) is calculated from the following equation:

$$Q_t = \frac{P_t}{g \cdot \eta_t \cdot \left(H_1 - \sum Z\right)} = \frac{P_t}{g \cdot \eta_t \cdot H_1{}'} \qquad [m^3 \cdot s^{-1}; kW, m \cdot s^{-2}, -, m] \qquad (4.80)$$

Where P_t is the power of the turbine, η_t is the turbine efficiency, H_1 is the gross mean geodetic head, ΣZ is the sum of height losses in the penstock during turbine operation and $H_1{}'$ is the net mean geodetic head.

At the present, both in the Czech Republic and in the world, near nuclear power plants (NPP) which operate in the base part of the daily load diagram, pumped storage hydroelectric power plants are also being built. An example of such a tandem construction domestically is the Dukovany NPP and the Dalešice PHPP.

Turbine flow rate -the total amount flowing through a turbine in 1 second. It is expressed in (m^3/s). The term swallowing capacity of the turbine is often used.

Swallowing capacity of the turbine - is (always for a specific head) the maximum flow rate through the turbine at this head.

Nominal swallowing capacity - the maximum flow rate (nominal flow rate) through the turbine with the nominal head (i.e. the head with the highest efficiency).

Swallowing capacity at maximum head - The largest guaranteed flow rate at the maximum head.

4.10 Automation and control of HPP operation

The main reasons for automation of HPP are:

a) To ensure the safe and reliable operation of the HPP (limitation of accidents caused by wrong handling and the extent of the damage to machines and equipment)
b) To limit unwanted outages of machines by early signaling of dangerous conditions (turning on of reserve sources and drives)
c) To increase the efficiency of operation (the shortest start time or transition from one regime to another; autostart takes 1 to 2 minutes, while manual start is considerably longer)
d) Reduction in the number of operational staff (reduction in operating costs)
e) Improving water management

Equipment for the automatic control of the HPP machine set monitors the state of the machine set and its accessories and processes the data and information obtained. On the basis of instructions by dispatching they control the operation of the machine set – relay technology was replaced by microprocessors and digital technology.

Automation instruments can be sorted into:

I) Input elements – monitor the state of technological equipment and the values of various physical quantities. The result is the sending of a two-valued analog or digital signal. This includes sensors (sensors of pressure, temperature, water and oil flow, water levels, number or revolutions of the machine set, position and the like) and converters.

II) Functional elements – receive and process signals from the input elements. They are circuits that perform logical operations and perform the functions of delay and memory (formerly – electromagnetic relays, switches and relays; currently – logical functional elements).

III) Output elements – amplify the impulses of functional elements, register the state of technological equipment and the values of certain quantities. These include action elements (electromagnets, hydraulic seals, motor drives and servomechanisms, contactors, switches), the display and registration instruments and the monitors and printers that belong to modern digital technology control.

Control systems used in hydroelectric power plants can be divided into three levels:

a) The first level of control – control of component technical equipment (component automation, control of action elements, primary blocking circuits). In the classic relay systems implementation or as more complex electronic circuits.
b) The second level of control – control of operational technological units, for example, the individual machine sets. These control systems are in the form sequential electronic automation.
c) The third level of control – control of the entire hydroelectric power plant. It incorporates the group machine set regulator, the connecting voltage regulator, the change of VHV/HV transformer taps, the information and diagnostic system of the power plant and the link to the parent dispatching office.

Despite full automation, emergency manual control from the engine room of the power plant must be preserved in case of testing and malfunctions of the parent automation. The reason is to protect the technological equipment from an error by the parent machine from incorrect handling during emergency manual control.

Technical and software equipment must allow for the long-term archiving of operating data and its automated selection including a lucid display (charts) for the purposes of technical diagnostics.

Group control of HPP operation – this is the automatic operation of a hydroelectric power plant with several machine sets, in which one common element controls the active power of the entire power plant (group control of active power) and another controlling element the entire required reactive power of the HPP (group control of reactive power). The number of machines that are to be in operation is stipulated by automatic equipment called the auto-operator. Active and reactive power is automatically distributed to machines working in parallel. Group control of the operation of HPP machine sets is supposed to improve the management of the HPP operation and simultaneously simplify the control of several machine sets as a whole, which is significant primarily in the remote control of the operation of the HPP from the dispatching office. The distribution of power to individual machine sets takes approximately 1 to 2 minutes, with a distribution precision of 2 to 3%. The specified value of the active power can be set either manually (locally or remotely) or is set by a regulator program.

A group regulator of machine sets consists of three main parts:

a) For the regulation of the active load of the machine sets
b) For the regulation of reactive load sets (voltage regulation in the VHV switching station in which the production blocks work)
c) Optimization and logical control, ensuring operation of the optimal number of machine sets for the required value of active power and voltage in the VHV switching station

A more detailed description of the group control of HPP operation is given in [1].

Automation of HPP machine set work processes

Designing the control system involves solving primarily these main technical problems:

- Automation of the individual machine sets
- Control of the HPP as a one production unit in relation to the ČED (group control of machine set operation)
- HPP protection system (primarily electrical protection of the reverse alternator and the whole block in the case of a two-machine reverse configuration)
- HPP control center and the automatic system for the collection and processing of information

The control of the operation of individual machine sets in our hydroelectric power plants is secured by sequential automatic devices.

Machine set startup - The startup and run-up of the machine sets into turbine or compensator operation is carried out in accordance with the following points:

a) Before startup, all actions and operations required for the startup of the machine set are automatically executed.
b) Turbine startup; simultaneously with the machine set run-up, the hydro-generator is excited.
c) Achieving synchronous speed, and after excitation of the alternator up to the grid voltage, automatic synchronization of the alternator to the grid occurs.

Technically more problematic is the handling of the startup of the machine set into pumping operation. In the asynchronous startup of an HPP machine set with a power in the order of magnitude of 100 MW, a number of problems must be dealt with, such as: ensuring a sufficiently large short-circuit power of the source, i.e., the electricity grid at the place of connection of the motor alternator, limitation of the size of inrush currents during run-up, warming up its rotor, the dynamic stress on the winding faces and pulsating moments. Just as challenging is the solution of the automatic startup of the whole machine set during pumping operation.

During compensatory operation, the hydro-alternator is connected to the electricity grid. It works as a motor in idling. To cover losses, it must draw active power from the electricity grid. In order for the losses to be as small as possible, it is necessary to aerate the space of the runner of the reverse turbine. If the hydroalternalor is to compensate for the reactive consumption of appliances, it must supply reactive power to the electricity grid.

Shutdown – Automatic shutdown of the machine set is one of the important and frequent automatic processes in the operation of hydroelectric power plants in various operating regimes. Before disconnecting the machines from the electricity grid, we need to lighten them power-wise to zero. After disconnection of the machine set, it begins to run-down. The rotating machine set has great kinetic energy, which is dissipated by friction losses in the bearings and ventilation losses. Because of the wear and tear of bearings at low speeds, the run-down of the machine set should be short with the highest intensity at the end of the deceleration. The most advantageous method is to brake at constant braking torque. Braking can be handled in various ways:

a) Free run-down – the machine set is braked only through ventilation losses and losses in the bearings. Brake power decreases at a rate of the first up to the third power of the speed and the run-down takes 10 to 30 minutes. This is the simplest method of braking and advantageous in terms of automation.

b) Mechanical braking – it uses the brake blocks placed in with a special brake lining that are pressed against the perimeter of the hydro-alternator magnet wheel. The disadvantage of this system is the need for replacement of the brake linings and the fouling of the alternator windings with dust from the brakes. Brake power decreases with speed.

c) Electric braking – connecting the outlet of the alternator to an external resistive load, or the direct short-circuiting of the stator winding of the alternator. In this case, the kinetic energy of the machine set is thwarted by the electrical resistance of the stator winding of the alternator.

The dependence of the short-circuit current on the speed of the hydro-alternator is given by the relation:

$$i_k = i_f \cdot \frac{\sqrt{\left(\frac{r_s}{\omega}\right)^2 + x_q^2}}{\left(\frac{r_s}{\omega}\right)^2 + x_q \cdot x_d} \tag{4.81}$$

Where i_k is the short-circuit current in relative units (related to I_N), i_f is the excitation current in relative units, x_d is the longitudinal and x_q is the transverse synchronous reactance in relative units, r_s is the resistance of the stator winding phase in relative units and ω is the actual angular frequency.

It follows from equation 4.81 that the short-circuit current i_k is directly proportional to the excitation current i_f. Depending on the speed (for the entire run-down period) it is almost constant. From this it follows that the ratio r_s / ω is considerably smaller than x_q and x_d. Brake power is then expressed as follows:

$$p_b = r_s \cdot i_k^2 \qquad \text{[p.j.]} \tag{4.82}$$

And the braking torque:

$$m_b = \frac{p_b}{\omega} = \frac{r_s}{\omega} \cdot i_k^2 = \frac{r_s}{\omega} \cdot i_f \cdot \frac{\left(\frac{r_s}{\omega}\right)^2 + x_q^2}{\left[\left(\frac{r_s}{\omega}\right)^2 + x_q \cdot x_d\right]^2} \qquad \text{[p.j.]} \tag{4.83}$$

Brake power is relative to the rated power of the alternator, and the braking torque to the rated torque of the machine set:

$$P_b = p_b \cdot S_n \qquad \text{and} \qquad M_b = m_b \cdot M_n$$

(4.26)

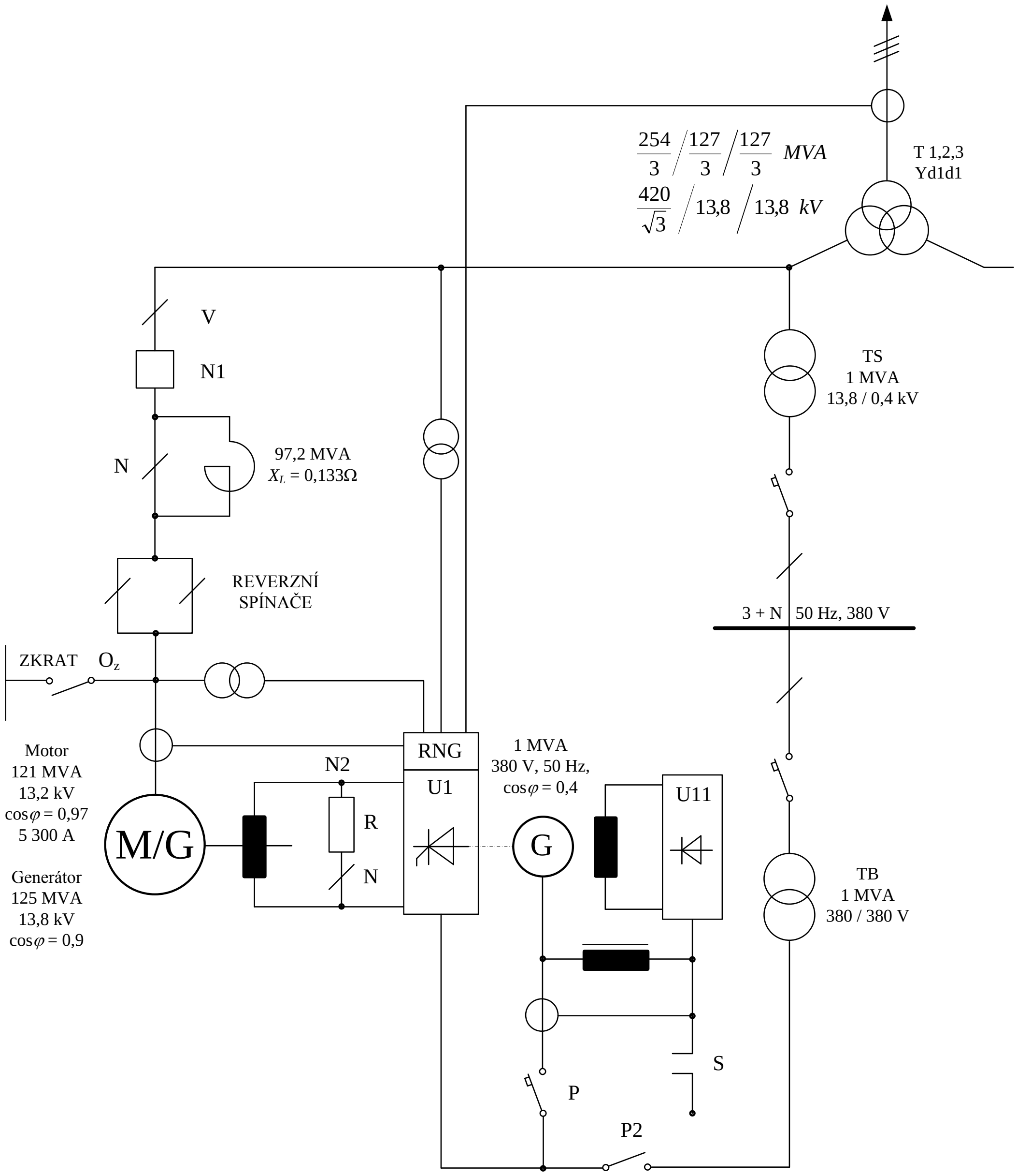


Fig. 4.27 Overview unipolar circuit diagram of the Dalešice HPP

(for one motor alternator)

As the number of revolutions decreases, the braking torque increases. This is why electric braking is better suited than other ways of braking. Brake power remains constant throughout the period of braking, and only at low speeds drops to zero. With electric braking, we need to continue exciting the alternator until the complete stopping of the machine. In machines with external excitation, the excitation current is supplied by an exciter powered by an asynchronous motor (older HPP). In most modern hydro-alternators, the exciter is located on a common shaft.

In the case of the Dalešice HPP, the alternator is excited during normal operation from the auxiliary alternator G through the rectifier U_1. During a failure or electric braking, the rectifier U=1 is powered by from transformer TB. After disconnection of the alternator from the electricity grid with switch N_1, the alternator is de-excited by shunting N_2, followed by switching on the short-circuit isolator O_z and disconnecting of the AC exciter G, activating the power off switch P_2 and turning on transformer TB. After the stopping of the machine, the excitation circuit and the short-circuit isolator are turned off and the excitation is switched to own AC source. If the machine set is electrically braked, the mechanical brakes are blocked. Electrical braking operation is fully automated.

References:

[1] DOČEKAL A., BOUČEK S.: *POWER PLANTS II – Lectures* (*ELEKTRÁRNY II – Přednášky),* Czech Technical University, Prague, 1998.

[2] ŠTOLL Č., KRATOCHVÍL S. and HOLATA M.: *Utilization of water power* (*Využití vodní energie*), SNTL, Prague, 1977.

[3] HOLATA M.: *Small hydroelectric power plants – design and operation* (*Malé vodní elektrárny – projektování a provoz*) , Academia, Prague, 2002.

[4] CENKA m. and coll.: *Renewable energy sources (Obnovitelné zdroje energie)* , FCC PUBLIC s.r.o., Prague, 2001.

[5] KOPŘIVA M. and coll.: *Pumped storage hydroelectric power plant Dlouhé stráně* (*Přečerpávací vodní elektrárna Dlouhé stráně*), Trifox, Šumperk, 1997.

[a] The website of the Povodí Vltavy, a.s. Company: www.pvl.cz

[b] The website of the ČEZ, a.s. Company: www.cez.cz

C The website of the energy server: www.energ.cz

Review Questions

1) **Define the terms utilizable head, the overall turbine efficiency, the swallowing capacity of the turbine and the energy equivalent!** (2 points)
2) **Name the basic types of hydroelectric power plants.** (1 point)
3) **Define the concept of the specific speed of a geometrically similar turbine!** (2 point)
4) **How does overall turbine efficiency change depending on the utilizable power?** (1 point)
5) **What is the small cycle of a PHPP and what is its efficiency?** (2 points)
6) **What are the two basic functions of the PHPP?** (2 points)

Summary

New findings and concepts:

- Knowledge of the principle of the function of hydroelectric power plants
- Ability to design a flow-through hydroelectric plant
- Orientation in the issues of hydroelectric power plants

Key to questions

1) **Define the terms utilizable head, the overall turbine efficiency, the swallowing capacity of the turbine and the energy equivalent!** (2 points)

The utilizable (useful) head of a hydroelectric power plant H is calculated as the difference of utilizable head of the hydroelectric power plant H_v and the sum of all hydraulic head losses h_{zi} that arise in the water course through the pressure feeders at input $h_{z0,1}$ and the draft tube and the outflow channel at the output.

$$H = H_v - \Sigma h_z = H_b + \frac{\alpha_1 \cdot v_1^2 - \alpha_2 \cdot v_2^2}{2 \cdot g} - \Sigma h_{zi} \qquad [\mathrm{m}] \qquad (4.62)$$

The overall turbine efficiency η_t can be defined as the ratio of the actual utilizable power of the turbine P (measured on the shaft of the turbine) to the theoretical lossless power P_0 corresponding to the water volume flow Q and the relevant head H while deducting losses in other elements of the water path.

$$\eta_t = \frac{P}{P_0} \qquad [\text{-; W, W}] \qquad (4.6)$$

The swallowing capacity of the turbine (maximum water flow through turbine) is calculated from the following equation:

$$Q_t = \frac{P_t}{g \cdot \eta_t \cdot \left(H_1 - \sum Z\right)} = \frac{P_t}{g \cdot \eta_t \cdot H_1'} \qquad [\mathrm{m^3 \cdot s^{-1}; kW, m \cdot s^{-2}, -, m}] \qquad (4.80)$$

Where P_t is the power of the turbine, η_t is the turbine efficiency, H_1 is the gross mean geodetic head, ΣZ is the sum of height losses in the penstock during turbine operation and $H_1'$is the net mean geodetic head.

In addition to the volume of the accumulation reservoir, it is sometimes also need to know the potential energy of the utilizable volume of the water reservoir. The size of this energy is calculated according to the relation:

$$E = \rho \cdot g \cdot V_0 \cdot H_{str} \cdot \eta\,, \qquad [\mathrm{J; kg \cdot m^{-3}, m \cdot s^{-2}, m^3, m, -}] \qquad (4.64)$$

When expressing potential energy in the unit kWh and assuming the specific density of water ρ = 1,000 kg · m^{-3} and with the gravity acceleration g = 9.81 m · s^{-2} we obtain the relation:

$$E = \frac{g \cdot V_0 \cdot H_{str}}{3\,600} \cdot \eta = \frac{V_0 \cdot Y_{str}}{3\,600} \cdot \eta = \frac{V_0 \cdot H_{str}}{3\,67{,}2} \cdot \eta\,, \qquad \text{[kWh]} \tag{4.65}$$

$$Y_{str} = g \cdot H_{str}\,, \qquad [\text{J} \cdot \text{kg}^{-1}] \tag{4.66}$$

where V_0 is the utilizable volume of the reservoir, H_{str} is the mean value of the net head (the difference between the lower water level of the reservoir and the center of the utilizable volume of the reservoir after deducting losses in the penstock and the draft tube), η is the mean efficiency of the production unit (includes losses at the inlet, in the penstock, in the turbine, in the draft tube, in the alternator and the block transformer).

For the rough ***determination of the energy equivalent of the accumulation reservoir***, we can, assuming the level of resultant efficiency η = 0.734, use the relation:

$$E = 2 \cdot V_0 \cdot H_{str}\,, \qquad \text{[kWh]} \tag{4.67}$$

2) **Name the basic types of hydroelectric power plants.** (1 point)

Flow-through hydroelectric power plants

Regulatory hydroelectric power plants

Pumped Storage Hydroelectric Power Plants

3) **Define the concept of the specific speed of a geometrically similar turbine!** (2 points)

For the preliminary determination of the rated speed of the turbine, experience has shown the following relation can be applied:

$$n = \frac{n_s \cdot H \cdot \sqrt[4]{H}}{\sqrt{P_t}} \cdot 1{,}166 \tag{4.55}$$

Where n is the rated operating speed of the turbine (min^{-1}), n_s indicates the ***specific speed of a geometrically similar turbine*** (min^{-1}), defined as the operating speed of a turbine with such a runner diameter, that with a head H = 1 m it provides the power of 0.7336 kW (i.e. precisely the power of one horsepower); the specific speed represents a characteristic mark that represents the properties of a turbine regardless on its type – turbines can be compared and evaluated on the basis of this characteristic; H is the net head (m), P_t indicates the turbine output shaft power (kW).

To be able to present the appropriate operating speed of the proposed turbine according to equation 4.55, it is necessary to know the specific speed of turbines which are under consideration. Table 4.3 lists the specific speed of some turbines.

Type of turbine	Usual range of n_s (min^{-1})
Pelton	4 – 32
Bánki	70 – 150
Francis slow-running	50 – 150
Francis normal	150 – 250
Francis fast-running	250 – 450
Kaplan and propeller	300 – 1 000

Table 4.3 Specific Speeds of Turbines

4) How does overall turbine efficiency change depending on the utilizable power? (1 point)

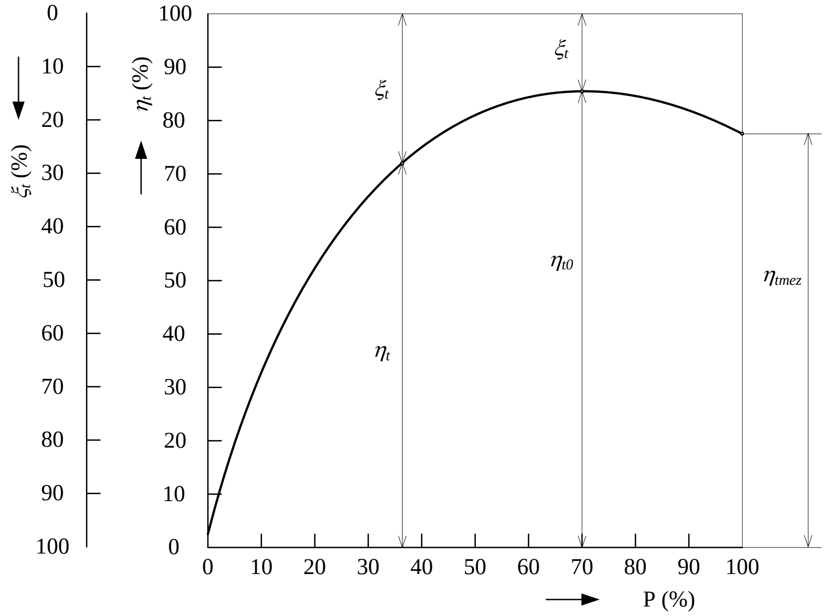


Fig. 4.1 The dependence of overall efficiency η_t and the loss coefficient ξ_t of the turbine on utilizable power P

5) What is the small cycle of a PHPP and what is its efficiency? (2 points)

If we label the produced power at the terminals of the condensing power plant that provides power for night pumping as P_1(kW) and the operating duration of the pumping $t_č$ (h), then the supplied power is equal to $E_1 = P_1 \cdot t_č$ (kWh). If we label as P_2 (kW) the power on the side of the VHV at the place of consumption of peak power after previous transformation in the condensing power plant and the HPP, after losses in the pump operation and in the turbine operation during the period t_t (h) and in the transformation and after losses in the VHV power lines, then the power obtained is $E_2 = P_2 \cdot t_t$ (kWh). The efficiency of the large cycle of pumped storage is then:

$$\eta_v = \frac{E_2}{E_1} \quad [\text{-, kWh, kWh}] \tag{4.77}$$

By the energy balance of the small cycle of pumped storage we understand the overall efficiency of pumped storage with respect to the inlets and outlets at the threshold of the HPP on the VHV side. If we label the supplied power at the threshold of the HPP on the side of the VHV as P_d [kW] and the period of pumping $t_č$ [h], then the supplied power is $E_d = P_d \cdot t_č$ [kWh]. If we label the obtained power at the threshold of the HPP on the side of the VHV as P_z [kW] and the period of turbine operation t_t [h], then the obtained power is $E_z = P_z \cdot t_z$ [kWh]. The efficiency of the small cycle of pumped storage is then:

$$\eta_v = \frac{E_z}{E_d} \quad [\text{-, kWh, kWh}] \tag{4.78}$$

In practice, the overall efficiency of pumped storage usually concerns the small cycle, which we will also further consider here. Each component of the efficiency of the pumped storage process are illustrated in Figure 4.25.

The efficiency of the small pumped storage cycle in modern machine sets is usually 70 to 75%.

The machine set used today for both of the presented regimes (pumping, turbine) is a motor-generator with a reverse turbine, which equipped with an asynchronous starting motor for the pumping regime.

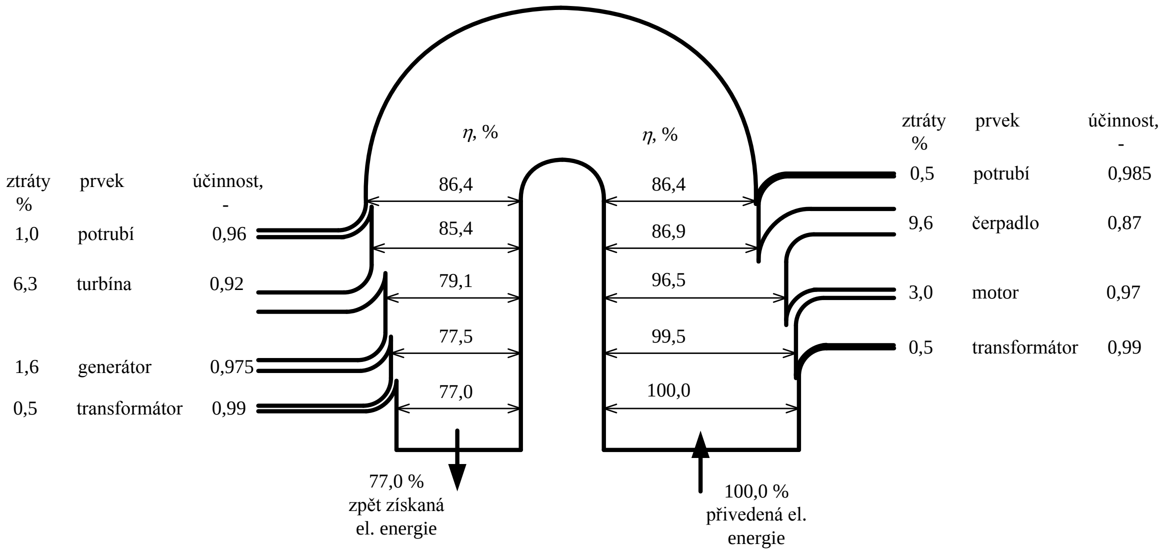


Fig. 4.25 The partial losses and the overall efficiency of a pumped storage hydroelectric power plant (the energy balance of the small pumped storage cycle).

6) What are the two basic functions of the PHPP? (2 points)

Pumped storage hydroelectric plants fulfill primarily the following tasks:

a) ***Static function*** – in the time interval that the electricity grid is less loaded, water is pumped from the lower to the upper reservoir while electric power from electricity grid is simultaneously consumed. Conversely, at a time when consumption in the electricity grid rises, the water energy accumulated in the upper water reservoir is used to cover the peak load in the electricity grid. We call this circuit the small pumping cycle of the PHPP. It takes advantage of the difference in the price of electrical energy, which in the peak period is about four times more expensive than in the period of low consumption.

b) ***Dynamic function*** - they participate in covering the dynamic changes in the load on the electricity grid. In the form of support services, they participate in system services ensured by the operator of the transmission grid, by which they contribute to the stabilization of the electricity grid during emergency states. Because of this, considerable demands are placed on the automation of the PHPP (reliability, quality).

This study material was created within the framework of the project

Central European Energy Institute - CZ.1.07/2.2.00/28.0256