Electrical Lighting and Heating Technology

Part Heating

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1. ELECTROTHERMAL TECHNOLOGY

1.1. The basics of heat transfer

TIME TO STUDY:

3 hours

TARGET:

After studying this paragraph, you will be able to

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

EXPLANATION

Concepts, symbols, quantities, units

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

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

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

$$P = \frac{Q}{t} \qquad (1.1)$$

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

$$q = \frac{\mathrm{d}P}{\mathrm{d}S} \qquad (1.2)$$

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

❑ Calorimetric calculations

Calorimetric calculations belong to the basic tasks of thermal engineering. The type of material determines how much heat must be supplied to 1 kg of a substance to heat it by 1 temperature degree. The ability of a substance to store heat is determined by the specific heat capacity *c*. This is usually a constant over a certain temperature interval. Tab. 1.1 gives the values of this quantity for the most common substances and materials.

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

Tab. 1.1 Specific heat capacity of substances and materials

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

$$Q = m \cdot c \cdot \Delta T \qquad (1.3)$$

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

$$Q_e = P \cdot t \qquad (1.4)$$

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

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

$$m \cdot c \cdot \Delta T = P \cdot \eta \cdot t \qquad (1.5)$$

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

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

Tab. 1.2 Relationships between units

Energy transfer and heat transfer

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

$$w = \frac{\mathrm{d}W}{\mathrm{d}V} \qquad (1.6)$$

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

$$P = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{1.7}$$

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

$$\boldsymbol{q} = \frac{\mathrm{d}P}{\mathrm{d}\boldsymbol{S}} = \frac{\mathrm{d}^2Q}{\mathrm{d}\boldsymbol{S}\cdot\mathrm{d}t} \tag{1.8}$$

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

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

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

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

Heat transfer by conduction

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

$$\vartheta = \vartheta(x, y, z, t) \tag{1.9}$$

If follow equation is valid,

$$\frac{\partial \vartheta}{\partial t} = 0 \tag{1.10}$$

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

Connections of points with the same level of thermal energy (same temperature) are called isotherms (Fig. 1.1), or isothermal surfaces. If the properties of the material in terms of heat conduction are the same in all directions, it is an isotropic environment.

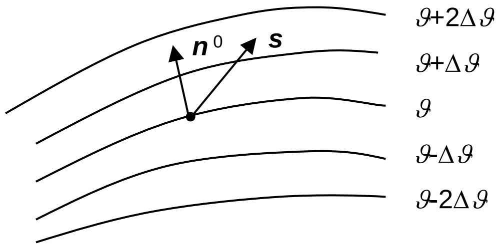


Fig. 1.1 Isotherms

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

$$\text{grad }\vartheta = \lim_{n\to 0}\frac{\Delta\vartheta}{\Delta n}\boldsymbol{n}^0 \qquad (1.11)$$

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

❑ Heat conduction through a plane wall

Heat flux Φ (W) through a homogeneous plane wall with thickness l, area S, thermal conductivity coefficient of the material λ and the surface temperature difference ϑ_1-ϑ_2 (Fig. 1.2a) is

$$\Phi = \frac{\lambda}{l}\cdot S\cdot(\vartheta_1-\vartheta_2) \qquad (1.12)$$

The temperature ϑ decreases linearly with distance x from the value ϑ_1 at the left interface to the temperature ϑ_2 at the right interface (equation 2.17). The dashed line on Fig. 1.2 and above the linear waveform show the actual waveform for ceramic materials, and below the linear waveform for pure metals. In Fig. 1.2b the isothermal surfaces are shown in dashed lines.

$$\vartheta = \frac{\vartheta_1-\vartheta_2}{l}\cdot x+\vartheta_1 \qquad (1.13)$$

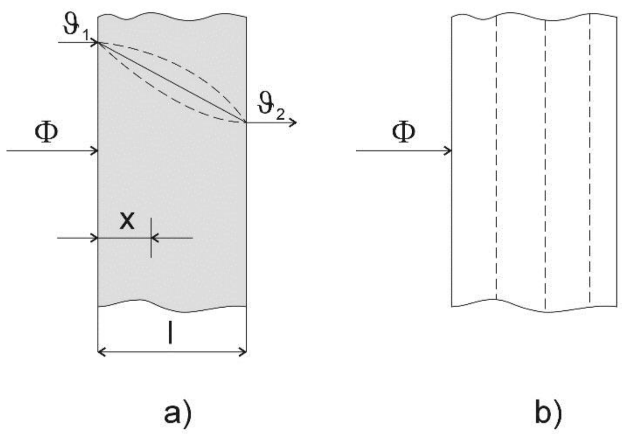


Fig. 1.2 Heat conduction through a single plane wall

If the wall is composed of several different layers of materials with different thermal conductivity (Fig. 1.3), then the heat flux through the structure is

$$\Phi = \frac{S \cdot (\vartheta_1 - \vartheta_2)}{\frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + ... + \frac{l_n}{\lambda_n}} \qquad (1.14)$$

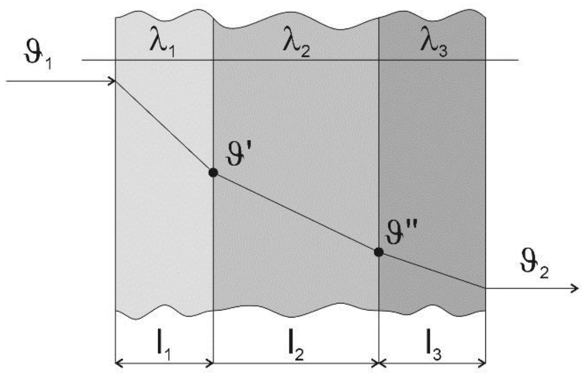


Fig. 1.3 Heat flux through a composed plane wall

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

$$\vartheta' = \vartheta_1 - \frac{\Phi \cdot l_1}{\lambda_1 \cdot S} \qquad (1.15)$$

$$\vartheta'' = \vartheta_2 + \frac{\Phi \cdot l_2}{\lambda_2 \cdot S} \qquad (1.16)$$

Heat conduction through the cylindrical wall

When heat is conducted from the inner surface of a thick-walled cylindrical tube to the outer surface (Fig. 1.4), as the diameter increases, the area through which the heat passes also increases. The temperature versus radius curve therefore takes the form of a logarithmic curve. For the heat flux, the relation

$$\Phi = \frac{2 \cdot \pi}{\frac{1}{\lambda} \cdot \ln \frac{r_2}{r_1}} \cdot l \cdot (\vartheta_1 - \vartheta_2) \tag{1.17}$$

For a composed cylindrical wall (Fig. 1.4), the relation

$$\Phi = \frac{2 \cdot \pi \cdot l \cdot (\vartheta_1 - \vartheta_2)}{\frac{1}{\lambda_1} \cdot \ln \frac{r_2}{r_1} + \frac{1}{\lambda_2} \cdot \ln \frac{r_3}{r_2} + \ldots + \frac{1}{\lambda_n} \cdot \ln \frac{r_{n+1}}{r_n}} \tag{1.18}$$

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

$$\begin{aligned} \vartheta' &= \vartheta_1 - \frac{\Phi}{\pi \cdot l} \cdot \frac{1}{2 \cdot \lambda_1} \cdot \ln \frac{d'}{d_1} \\ \vartheta'' &= \vartheta_2 - \frac{\Phi}{\pi \cdot l} \cdot \frac{1}{2 \cdot \lambda_3} \cdot \ln \frac{d_2}{d''} \end{aligned} \tag{1.19}$$

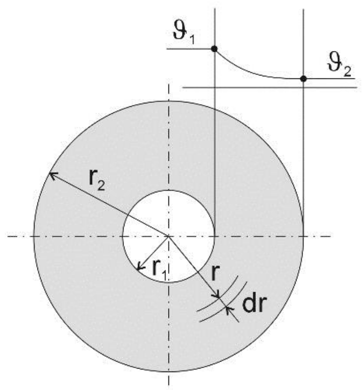


Fig. 1.4 Heat conduction through the cylindrical wall

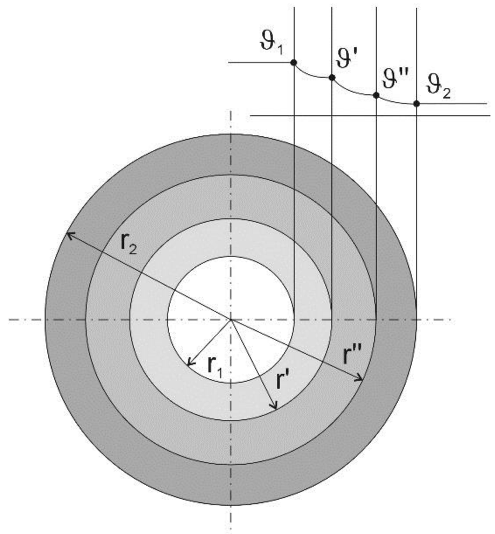


Fig. 1.5 Heat conduction through the composed cylindrical wall

The following table gives the thermal conductivities of selected materials.

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

Tab. 1.3 Thermal conductivities of selected materials

heat transfer by convection

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

- natural convection,
- forced convection.

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

$$\mathbf{q}_k = \alpha \cdot (T_p - T_i) = \alpha \cdot \Delta T \qquad (1.20)$$

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

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

Tab. 1.4 Heat transfer coefficient values [2]

Heat transfer by convection is one of the most difficult computational problems in thermal engineering. It is dealt with in many scientific literatures. In important cases, it is best to determine the heat transfer coefficient α ourselves by measuring it on a model as close as possible to our case using the given relations in which α occurs. For the heat transfer through the flow (Fig. 1.6), Newton's law applies:

$$\Phi = \alpha_1 \cdot (\vartheta_{p1} - \vartheta_1) \cdot S \tag{1.21}$$

$$\Phi = \alpha_2 \cdot (\vartheta_2 - \vartheta_{p2}) \cdot S \tag{1.22}$$

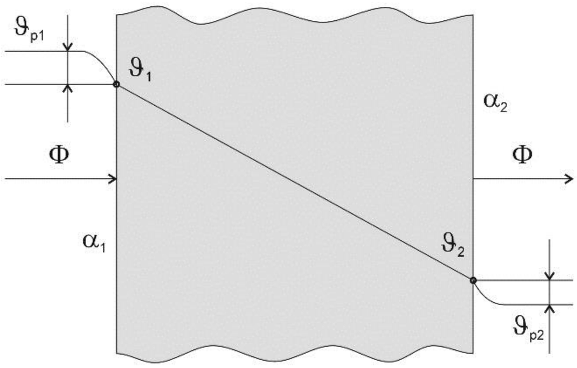


Fig. 1.6 Heat transfer by flow

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

❑ Heat transfer by radiation

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

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

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

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

They following have to apply:

$$A + B + C = 1 \tag{1.23}$$

The following extremes can be defined:

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

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

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

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

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

$$A_\lambda + B_\lambda + C_\lambda = 1 \qquad (1.24)$$

❑ The laws of radiation

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

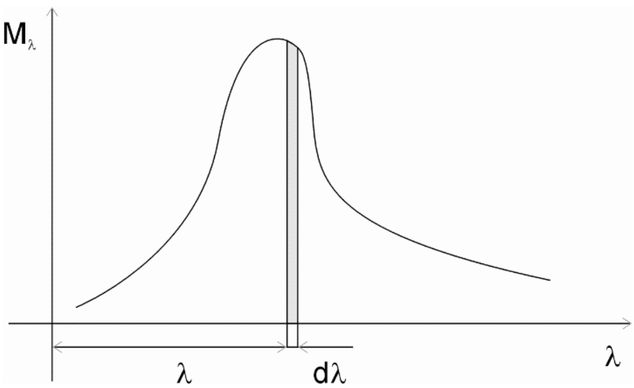


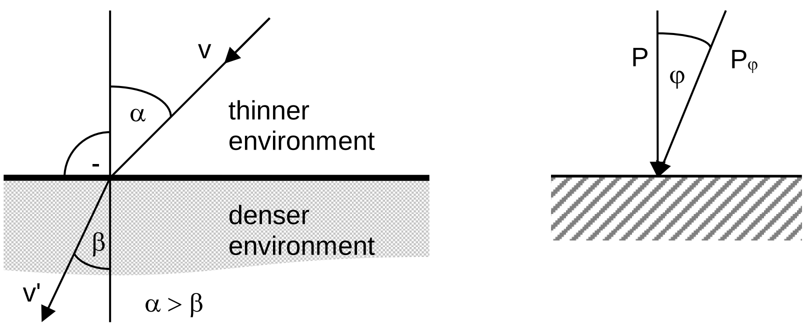
Fig. 1.7 Spectral radiance versus wavelength

❑ Snell's Law

Snell's law expresses the nature of the propagation of radiation as it passes from one medium to another (Fig. 1.8). For the direction of spread, the relationship applies:

$$\frac{\sin\alpha}{\sin\beta} = \frac{v}{v'} = n \qquad (1.25)$$

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



Snell's Law

Lambert's Law

Fig. 1.8 Radiation spreading at the transition of two environments [4]

Lambert's Law

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

$$P = P_{\varphi} \cdot \cos\varphi \qquad (1.26)$$

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

Stefan-Boltzmann law

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

$$M = \sigma \cdot T^4 \qquad (1.27)$$

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

Planck's law

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

$$M_{\lambda} = f(T, \lambda) = \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda \cdot T}} - 1 \right)} \qquad (1.28)$$

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

Equations (1.28) gives the radiated power from a 1 m^2 area for only 1 wavelength . The total radiated power will be the sum for all wavelengths, i.e., for $\lambda = 0$ to $\lambda = \infty$.

$$M(T) = \int_0^{\infty} M(T, \lambda) \cdot d\lambda = \int_0^{\infty} \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda \cdot T}} - 1 \right)} \cdot d\lambda \qquad (1.29)$$

By integrating and inserting constants we get the relation

$$M(T) = \sigma \cdot T^4 \qquad (1.30)$$

which is the relationship expressing the Stefan-Boltzmann law - see equation (1.27).

Wien's law

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

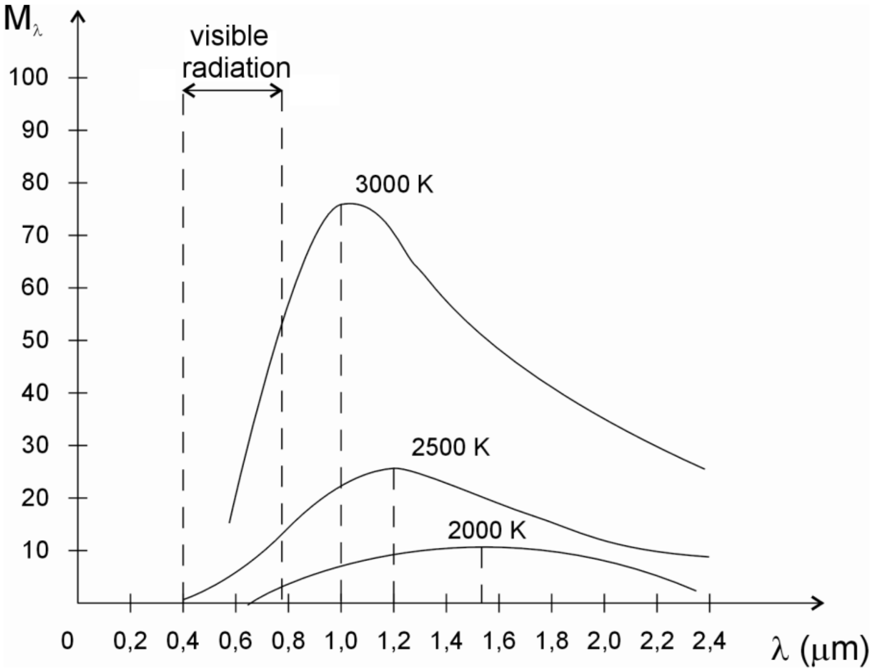


Fig. 1.9 Wien's displacement law

$$\lambda_{\mathrm{m}} = \frac{2892}{T} \tag{1.31}$$

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

$$T = \frac{2892}{0{,}5} = 5784\,\mathrm{K} \tag{1.32}$$

Kirchhoff's Law

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

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

$$\frac{M_{\mathrm{G}}}{A_{\mathrm{G}}} = f(T) = \frac{M_{\mathrm{B}}}{A_{\mathrm{B}}} = M_{\mathrm{B}} \tag{1.33}$$

$$\frac{M_{\lambda\mathrm{G}}}{A_{\lambda\mathrm{G}}} = f(T,\lambda) = M_{\lambda\mathrm{B}} \tag{1.34}$$

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

From the curves on Fig. 1.9 we see that the absolute black body emits a continuous spectrum of radiance, uninterrupted by gaps. For most real, i.e. physically grey surfaces, the spectral radiance curve is also unbroken and is similar to that of a black body (Fig. 1.10). We can therefore write:

$$\frac{M_{\lambda G}}{M_{\lambda G}} = \text{konst.} = \varepsilon \qquad (1.35)$$

Or else:

$$A_G = \frac{M_G}{M_B} = \frac{\varepsilon \cdot \sigma_B \cdot T^4}{\sigma_B \cdot T^4} = \varepsilon \qquad (1.36)$$

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

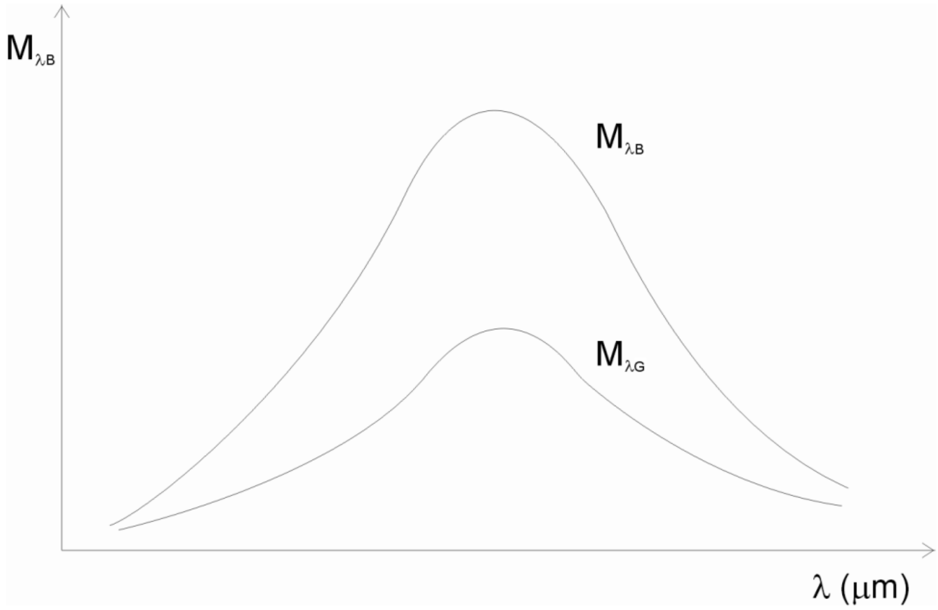


Fig. 1.10 Spectral radiance for black and grey surfaces

Informative emissivity values are given in the following table.

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

Tab. 1.5 Emissivity values [2]

Mutual irradiation of body surfaces

A body of area S emits a radiant flux

$$\Phi = M \cdot S = \sigma \cdot T^4 \cdot S \tag{1.37}$$

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

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

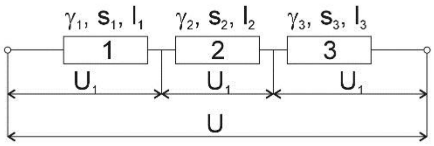
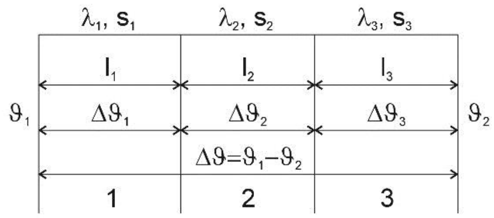
$$\Phi = \frac{S \cdot \sigma_B \cdot \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{1.38}$$

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

$$\Phi = \frac{S_1 \cdot \sigma_B \cdot \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{S_1}{S_2} \cdot \left(\frac{1}{\varepsilon_2} - 1\right)} \tag{1.39}$$

Analogy between temperature and electric field

The analogy greatly simplifies heat transfer calculations in simpler systems and in steady state. The stationary current field and the stationary temperature field are non-vortex, non-swirling, therefore Laplace's theorem applies. Tab. 1.6 gives examples of the analogy between electric and temperature fields.

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

Tab. 1.6 Examples of electrothermal analogies [3]

Summary of terms 1.1.

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

Questions 1.1.

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

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

1.2. Resistance electrothermal devices

TIME TO STUDY:

3 hours

TARGET:

After reading this paragraph, you will

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

EXPLANATION

Direct resistance heating

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

$$Q = R \cdot I^2 \cdot t = P \cdot t \qquad (1.40)$$

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

$$R = \frac{\rho \cdot l}{s} \qquad (1.41)$$

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

$$R_\vartheta = R \cdot (1 + \alpha \cdot \Delta T) \qquad (1.42)$$

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

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

$$Q = Q_u + Q_z \tag{1.43}$$

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

$$P \approx \frac{dQ}{dt} \tag{1.44}$$

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

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

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

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

The principle of resistance heating is shown schematically in Fig. 1.11. The length of the heated rod must be at least 10 times longer than its diameter to ensure that the heating is sufficiently uniform along its entire length. A large current is introduced into the rod 1 of constant cross-section from the control transformer 2 by the contacts 3. The heating is very fast and efficient.

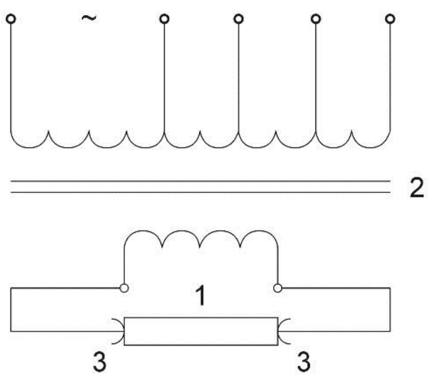


Fig. 1.11 Heating of long metal rods, wires and belts

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

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

The power, temperature and loss histories for direct resistance heating of a steel bar without voltage switching are shown in Fig. 1.12. The power input decreases as the resistance of the rod increases with temperature, and the heat loss increases. If the power input equals the losses, the temperature has reached its limiting value. The heating temperature must be less than the limit.

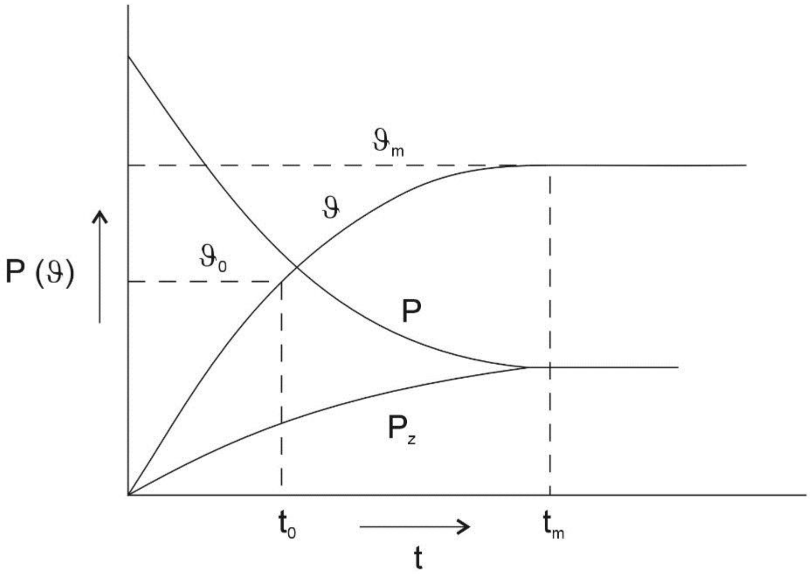


Fig. 1.12 Power, temperature and loss waveforms [5]

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

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

$$a = \sqrt{\frac{2 \cdot \rho}{\omega \cdot \mu_0 \cdot \mu_r}} \qquad (1.45)$$

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

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

The device for continuous heating of the wire or strip is shown schematically on Fig. 1.13. The wire or strip 1 is connected to the current circuit of the output side of the transformer 2 by pulleys 3 (or graphite blocks).

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

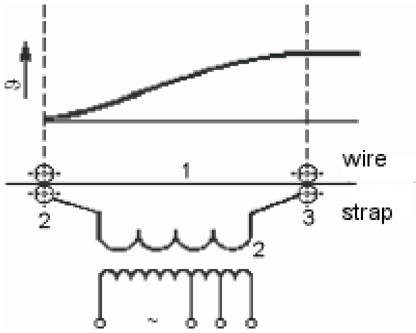


Fig. 1.13 Continuous heating equipment

❑ Graphite and silicon carbide furnaces

Graphite and silicon carbide (carborundum) are produced in Acheson furnaces (Fig. 1.14). Graphite is produced from carbon by so-called graphitization, a chemical process occurring at a temperature of about 2500 °C, in which amorphous carbon is structurally transformed into graphite with excellent physical, chemical, and mechanical properties.

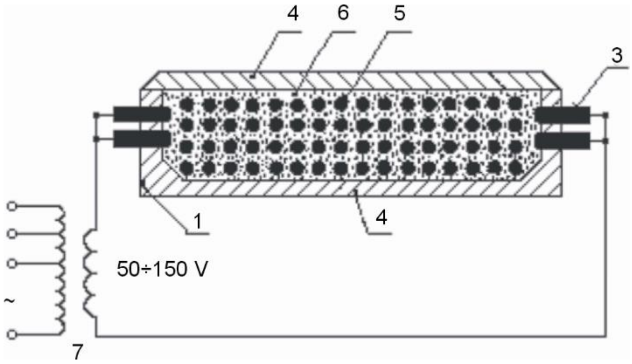


Fig. 1.14 Acheson's graphite furnace

In Fig. 1.14 1 is the furnace bottom, 2 is the front wall, 3 is the graphite blocks, 4 is the furnace lid, 5 is the liner, 6 is the backfill mixture, and 7 is the power transformer.

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

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

❑ Thermal electrolysis

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

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

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

❑ Electrode salt baths

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

- The current passes not only through the electrolyte but also through the charge immersed in the electrolyte, the power consumption depends on the charge. At Fig. 1.15 are 1 the electrodes, 2 the ceramic crucible and 3 its thermal insulation.
- The insert is placed in the salt in a place where there is no electric field and no current passes through the insert, the power does not depend on the insert.

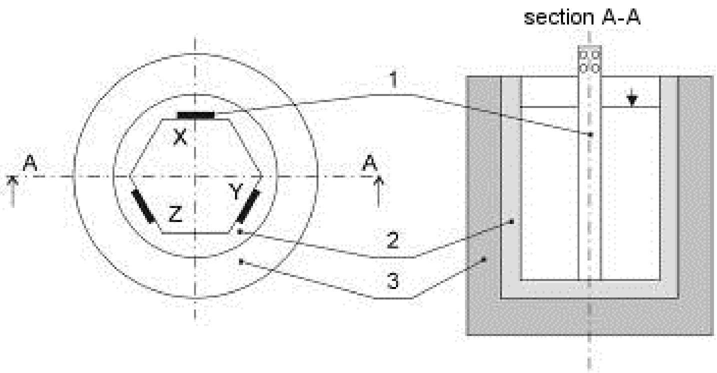


Fig. 1.15 Salt bath type 1

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

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

Tab. 1.7 Chemical composition of some of the salts used and range of applications

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

Electrode water heating

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

Many different designs of electrode boilers are used. They are constructed not only for 231 V and 400 V, but also for voltages as high as 30 kV. Instantaneous water heating boilers are built from a few kilowatts to several megawatts. Often water is heated by night current as a storage medium for heating and technology in the paper, textile, food industry, etc. For example, electrode steam boilers are usually used for cooking (Fig. 1.16), which is distributed to the cooking boilers and returned as condensate. For industrial hot water and steam production, boilers are built with a capacity of up to 60 MW at an operating voltage of 30 kV and an overpressure of up to 4 MPa.

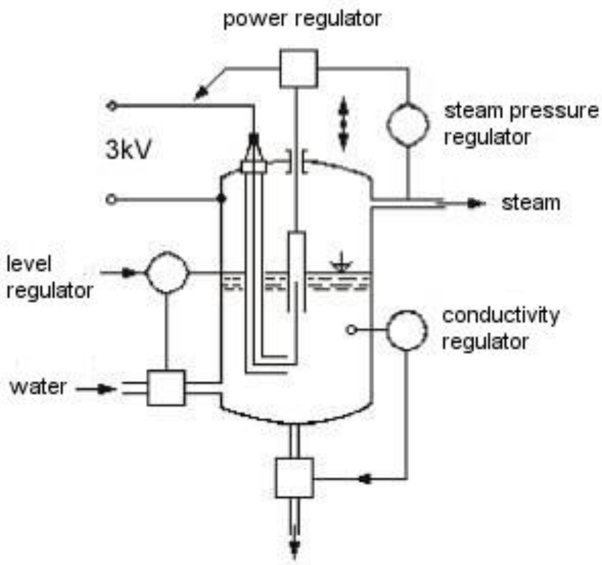


Fig. 1.16 Single-phase electrode boiler

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

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

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

Indirect resistance heating

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

According to the temperature of the furnace:

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

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

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

According to the use in furnace operation:

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

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

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

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

Resistance furnaces with stable charge

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

Chamber furnaces

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

Shaft furnaces

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

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

Hood furnaces

Hood furnace (Fig. 1.17) has a well-insulated heating hatch 1 (bell) of circular or square cross-section and has a heating winding 6 on its inner surface. The insert is covered by a heat-resistant muffle 2 (hatch) against direct radiation from the heating elements and thus against local overheating. The furnace has several working platforms and muffles. Hood furnaces are built to outputs of several hundred kilowatts.

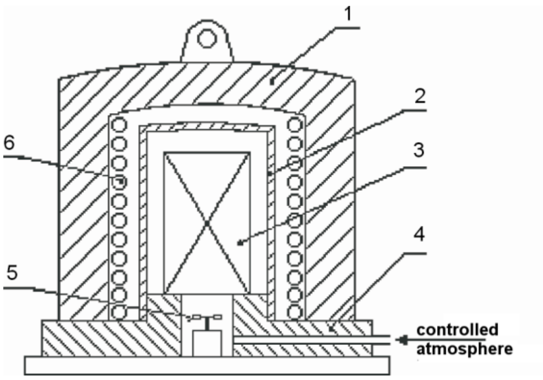


Fig. 1.17 Hood furnace

Elevator furnaces

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

Crucible melting furnaces and melting tanks

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

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

❑ Continuous resistance furnaces

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

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

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

Conveyor belt furnaces

Charge to the conveyor belt furnace (Fig. 1.18) is loaded manually or by means of a special automatic machine via the feeding table 5 onto the conveyor belt 3 passing through the furnace. The belt is made of metal mesh for light components and of stamped plates for heavy components, which are connected to each other by pins and couplings. It is tensioned by means of a device 7, 4 is the belt drive. At the end of the furnace, the material is removed from the working area 6. The 2 NiCr heating elements are mostly located on the ceiling and bottom, below the upper level of the belt. A refractory lining 1 surrounds the furnace working area. The belt furnaces are designed for heat treatment of smaller parts up to a temperature of 900 °C.

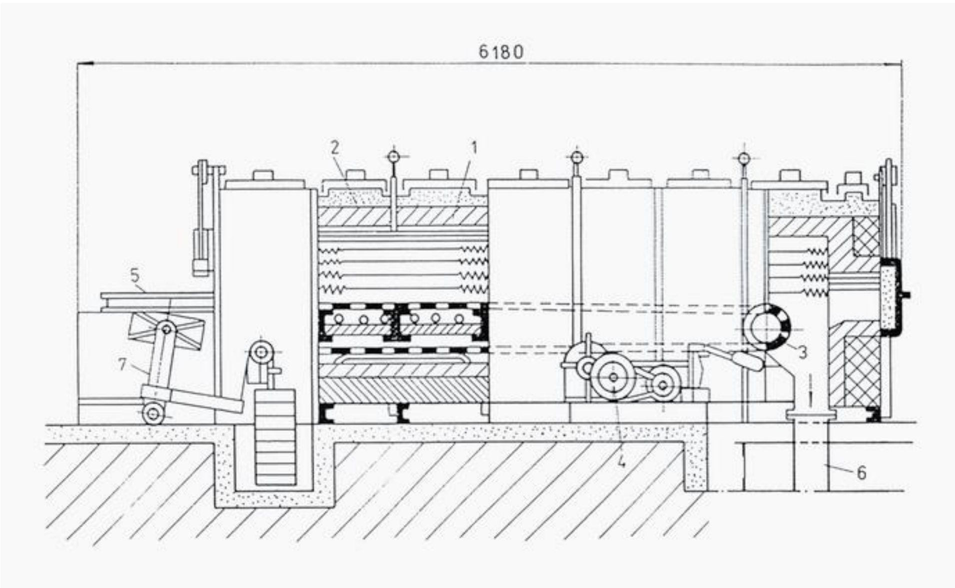


Fig. 1.18 Belt furnace

Roller furnaces

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

Pusher furnaces

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

Jolt ramming furnaces

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

Step furnaces

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

Drawing furnaces

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

Drum furnaces

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

Carousel (rotary) furnaces

Carousel furnaces are designed for the highest temperatures because the furnace mechanisms are completely outside the working temperature area. The furnace cross-section is in Fig. 1.19. The actual furnace body 1 is rotary, with heating elements 2. The floor of the furnace 3 is rotatable and the charge 4 is placed on it. The rotation is provided by an electric motor 5. The charge is inserted into the furnace through a door opening 6 and after one rotation it is removed from the exit opening with the door next to the entrance. The door is closed by a device 7. The heating time of the charge varies according to the change in the rotation speed of the floor.

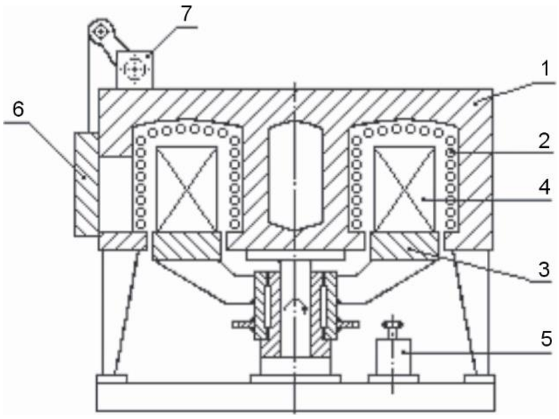


Fig. 1.19 Carousel furnace

❑ Materials and components of electric resistance furnaces with indirect heating

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

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

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

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

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

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

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

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

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

Materials for heating elements are divided into two basic groups:

- metal materials,
- non-metallic materials.

❑ Materials for metal heating elements

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

Austenitic alloys

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

Ferritic alloys

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

Pure metals

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

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

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

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

Steel and special resistance alloys

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

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

❑ Non-metallic materials for heating elements

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

Silicon carbide (SiC)

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

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

Cermet elements

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

The operating temperatures of the elements are 1600 °C to 1700 °C. The refractoriness is due to the protective SiO_2 layer formed on the element surface during operation. Cermet elements are fragile and do not tolerate shocks. They are resistant to oxidizing, nitrogen, argon and CO atmospheres. They are damaged by sulphur and chlorine. The resistivity varies considerably with temperature (at 20 °C, ρ = *0*.25 μΩ·m, at 1600 °C, ρ = 3.5 μΩ·m), so they are connected via control transformers.

Carbon and graphite heating elements

The basic raw materials and graphite production were described in Fig. 1.14. Heating elements are produced in the form of rods, tubes, etc. Operating temperatures are up to 2000 °C in a vacuum or controlled atmosphere to prevent oxidation. Under normal atmospheres, oxidation occurs from about 400 °C for carbon elements and from about 600 °C for graphite elements. The resistance of the carbon decreases with increasing temperature, e.g. at 1400 °C to about 67 % of the full value at 0 °C. For graphite, from 100 % at 0 °C, the resistivity first decreases with increasing temperature, to about 77 % at about 400 °C and then increases again. At 1400 °C the resistivity is about 96 % of the original value.

❑ Basic use of resistance furnaces in industry and engineering

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

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

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

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

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

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

❑ Connecting and controlling of electric resistance furnaces

The most common electrical wiring of a resistance furnace is shown in Fig. 1.20.

Electric resistance furnace, connected according to Fig. 1.20, is connected to the three-phase network with a neutral conductor via contactor 2. The heating elements of the furnace are represented by resistors of the same value R_1, R_2, R_3. The furnace is switched on by switch 5. By switching off this switch, we close the auxiliary switching circuit consisting of the following elements: contactor coil 3, mercury switch of the automatic temperature controller 4, fuse heating wire in the furnace 6, door contact 7. At the same time, the motor of the automatic temperature controller 10 starts. When the switching coil 3 is energized, the contactor 2 switches on and connects the heating elements to the mains. The thermocouple 9 supplies voltage to the instrument indicating the temperature in the furnace. When the desired temperature is reached, the mercury switch of the automatic temperature controller 4 is flipped, the current in the control circuit is interrupted and contactor 2 disconnects the heating elements from the mains. In the diagram Fig. 1.20. it is only possible to control the temperature in the furnace by switching off and on the total power supply.

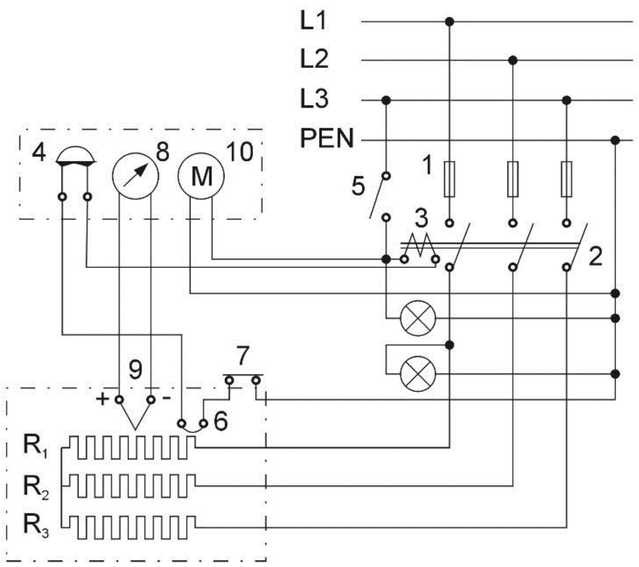


Fig. 1.20 Resistance furnace wiring

❑ Automatic temperature control in resistance furnaces

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

Step control is most easily achieved by switching off and on the entire power input of the furnace. We can also use the switching of star-delta resistive sections or switching of groups of resistive cells. The temperature and power waveform for a resistance furnace with single-pole and double-pole step control is shown in Fig. 1.21.

In the first part Fig. 1.21 shows the single-pole on-off control. The second part of the figure shows dipole temperature and power control using star-delta resistive section switching.

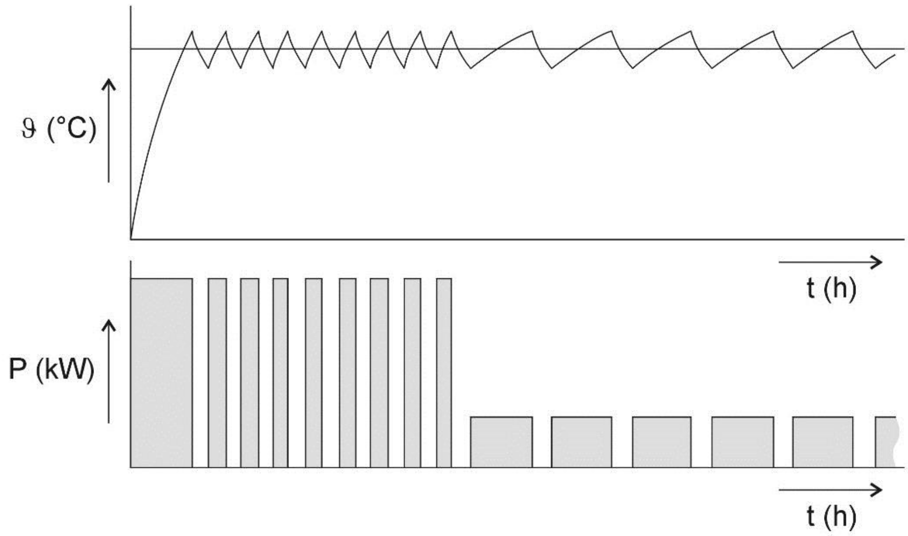


Fig. 1.21 Temperature and power waveform of a resistance furnace with single and dipole step control

By using this infinitely variable control the resistance furnace results in a significant flattening of the temperature profile, as shown in Fig. 1.22.

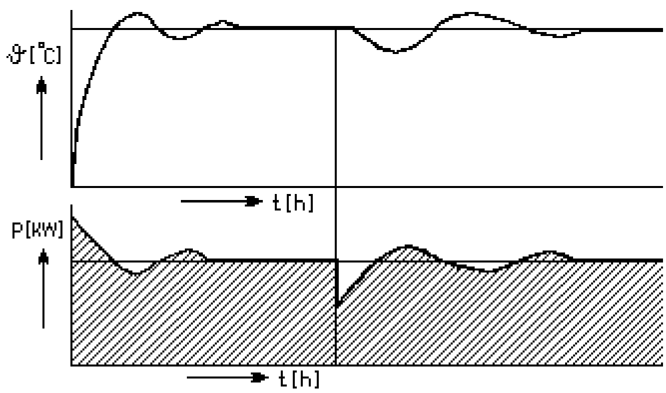


Fig. 1.22 Continuous control of resistance furnace

Calculations of resistance electrothermal devices for indirect resistance heating

Basics of design and calculation of resistance furnaces

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

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

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

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

Calculation of the total power input of the furnace

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

The power losses is determined by the losses:

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

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

The following applied

$$P_z = P_{z0} + P_{zv} \qquad (1.46)$$

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

Useful performance

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

$$W_u = \int_{\vartheta_0}^{\vartheta_k} c \cdot m \cdot d\vartheta \qquad (1.47)$$

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

$$W_u = c_{av} \cdot m \cdot (\vartheta_k - \vartheta_0) \qquad (1.48)$$

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

$$P_u = \frac{W_u}{t_h} \qquad (1.49)$$

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

$$P_p = P_z + P_u \qquad (1.50)$$

Since we have to take into account a certain inaccuracy of the calculation, a margin for voltage drop in the network, aging of heating elements, increase of furnace losses, etc., we choose a certain safety factor k_s = 1.2 to 1.7. Then the input power of the furnace is given by the equation (1.51). In practice, however, we usually do not know the heating time of the charge t_h, and have to calculate it.

$$P_p = k_s \cdot (P_z + P_u) \qquad (1.51)$$

Summary of terms 1.2.

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

Questions 1.2.

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

1.3. Electric arc heating equipment

TIME TO STUDY:

3 hours

TARGET:

After reading this paragraph, you will

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

EXPLANATION

DC arc formation in an electric field

The origin of the electric arc will be explained using the simple example of an electrical circuit powered by a DC voltage source *E*, containing a control resistor R and a variable arc resistance R_o (Fig. 1.23).

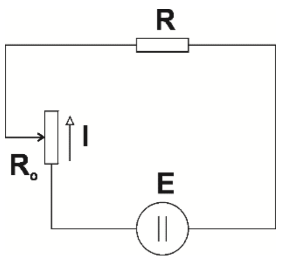


Fig. 1.23 Example of an electrical circuit powered by a DC source

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

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

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

Arc discharge consists of an ionised column through which a current flows and surrounding gases (aureole) at high temperature. The length of the arc then bounds the electrodes, cathode and anode (Fig. 1.24).

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

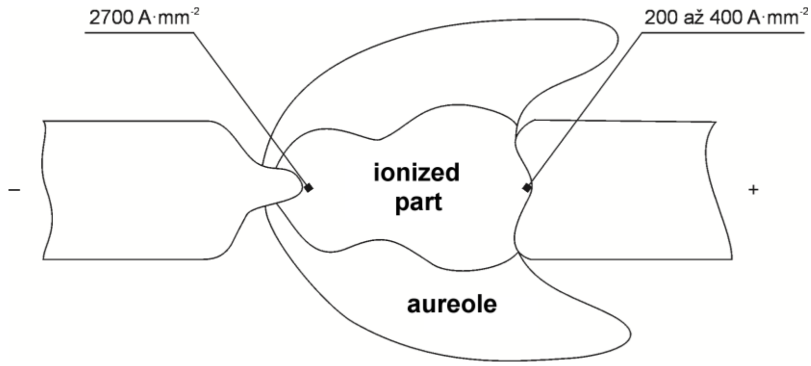


Fig. 1.24 Electric arc

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

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

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

❑ DC arc characteristics

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

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

$$V = a + b + l + \frac{c}{I} + \frac{d \cdot l}{I} \tag{1.52}$$

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

According to Ayrton's relation, they are constructed (Fig. 1.25) two volt-ampere characteristics of the DC arc. It can be seen that as the current increases, they asymptotically approach the steady-state voltage value. Curve 1 is for an arc length of 2 cm, curve 2 for an arc length of 6 cm.

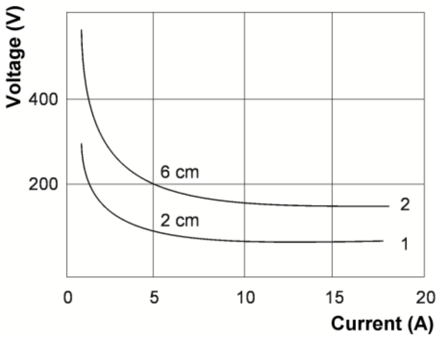


Fig. 1.25 Volt-ampere characteristics of the DC arc

Characteristics of the AC arc

To derive the characteristics of the AC arc, we use the alternate circuit diagram with arc according to Fig. 1.26.

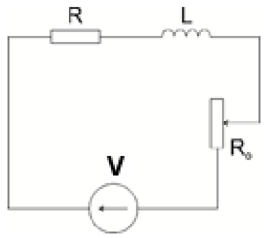


Fig. 1.26 Alternate circuit diagram with AC arc

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

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

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

At Fig. 1.27 shows the voltage and current waveform in a circuit containing only ohmic resistance without inductance.

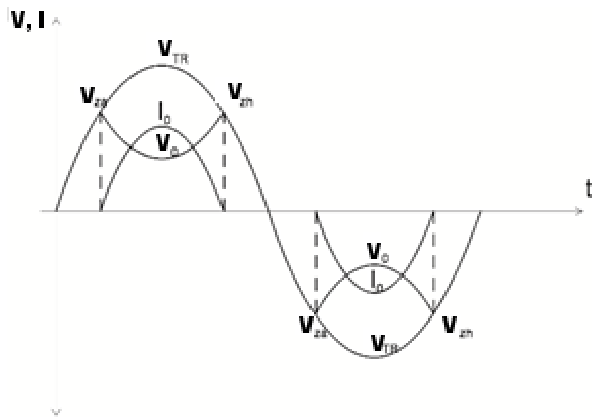


Fig. 1.27 Voltage and current waveform in the circuit

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

Stabilization of an AC arc by phase shifting

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

It can be shown by calculation that a minimum phase shift of PF = 0.85 is required for sustained arc burning. Fig. 1.28 shows the idealised voltage and current waveform at PF = 0.85. The voltage on the arc is rectangular. This is characteristic of arcs for very high currents, where there is virtually no more change in voltage as a function of current.

Stabilization of AC arc by increasing the voltage on the transformer

The stabilization of the AC arc by increasing the voltage on the transformer is shown in Fig. 1.28 in dashed lines.

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

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

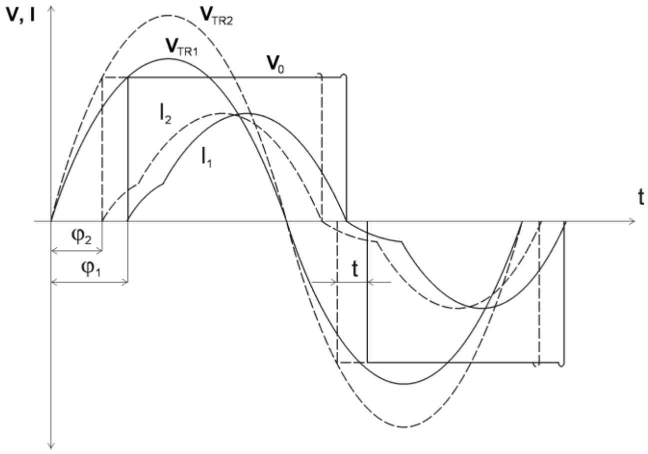


Fig. 1.28 Stabilization of the AC arc

❑ Theoretical basics of electric arc furnaces

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

Furthermore, the arc resistance is represented in the current circuit, which can be replaced by a variable ohmic resistance (Fig. 1.29).

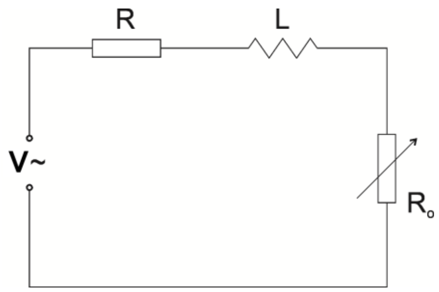


Fig. 1.29 Example of an electrical circuit

The fictitious arc resistance R_O is a variable value. This value is obtained by dividing the arc voltage by the furnace circuit current. It can vary from zero when the electrodes are in short circuit to infinity when the circuit is broken and the arc is not burning. The ratios in the furnace can be well represented by the vector diagram on Fig. 1.30.

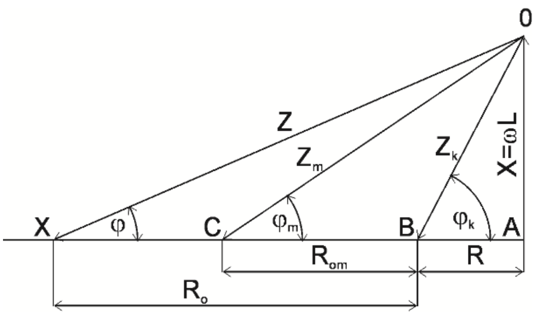


Fig. 1.30 Vector diagram

From the diagram on Fig. 1.30 shows the **short-circuit impedance**. The short-circuit impedance determines the short-circuit furnace current. The operating point moves along the line BX depending on the magnitude of the arc resistance. The resistance of the furnace then also determines the instantaneous value of the furnace impedance, where Z_m is the impedance for the maximum output of the furnace.

$$Z = \sqrt{(R + R_o)^2 + (\omega \cdot L)^2} \quad (1.53)$$

In the relationship (1.53), R_o is the variable value of the arc resistance. From the vector diagram, the furnace power factor PF can also be determined.

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

$$PF = \frac{R}{\sqrt{R^2 + (\omega \cdot L)^2}} \quad (1.54)$$

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

$$PF = \frac{R + R_o}{\sqrt{(R + R_o)^2 + (\omega \cdot L)^2}} \quad (1.55)$$

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

$$I = \frac{U}{Z} = \frac{U}{\sqrt{(R + R_o)^2 + (\omega \cdot L)^2}} \quad (1.56)$$

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

In Fig. 1.31 is a circle with the points A´, B´, C´, X´, *O´* marked. These individual points are equivalent to the inverted value of the impedance *Z*, which varies depending on the value of the arc resistance.

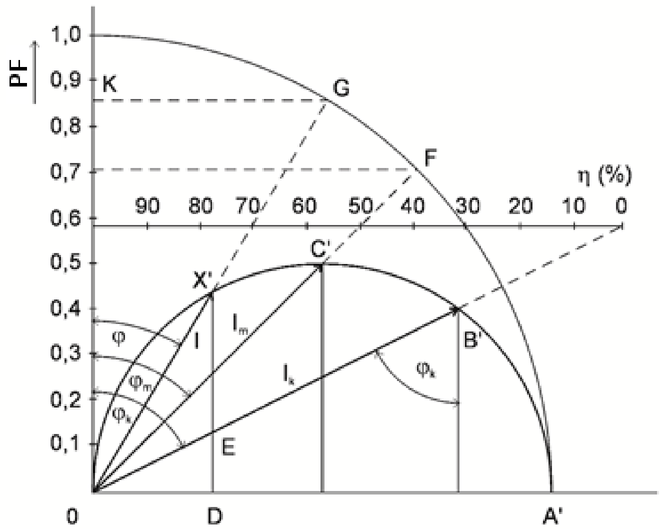


Fig. 1.31 Circular diagram

Point A in Fig. 1.30 corresponds to point A′ on the circle (Fig. 1.31). The line 0B = Z_K (Fig. 1.30) corresponds to the line 0B′, expressing the short-circuit current. The line segment C0 (Fig. 1.30) corresponds to the line C0′ (Fig. 1.31) is the point for maximum furnace output. The line 0X (Fig. 1.30) i.e. the arbitrary arc current, corresponds to the line segment 0X′ in the circular diagram.

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

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

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

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

$$\frac{I}{I_{SC}} = \frac{\text{working current}}{\text{short circuit current}} \tag{1.57}$$

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

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

On the circle diagram we distinguish three basic areas:

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

Three-phase arc furnace equipment

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

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

The most important group is the power circuit. It represents the bulk of the value of the furnace electrical equipment and has a significant effect on the operation of the furnace. The second essential part is the automatic electrode movement control circuit. The function of the power circuit is to conduct electrical energy into the furnace working area and convert it into heat. The power circuit of a three-phase arc furnace is shown schematically in Fig. 1.32.

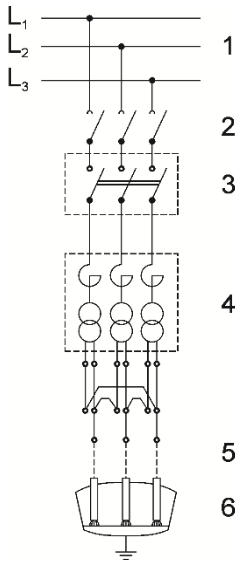


Fig. 1.32 Power circuit of a three-phase arc furnace

Description of the power circuit of a three-phase electric arc furnace (Fig. 1.32):

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

❑ High voltage power supply network

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

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

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

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

Disconnector

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

High Voltage Power Switch

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

Furnace transformer

The output of the furnace transformer limits the heat input to the furnace and thus the output of the furnace. This is particularly evident in the melting stage of the charge, where the duration of this process depends mainly on the amount of heat supplied. The selection of the furnace transformer output is made according to the size of the furnace charge and the selected operating mode (Fig. 1.33).

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

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

The selected ultra-high productivity melting (UHP) mode is characterised by a short arc. The ratio of the furnace transformer outputs for UHP mode and normal mode is 2.1 to 2.4 (Fig. 1.33.)

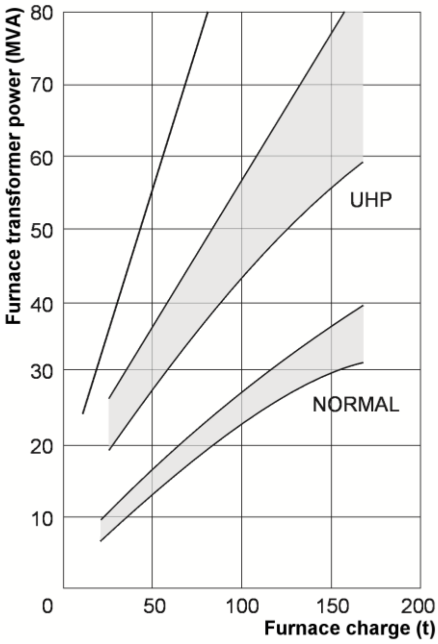


Fig. 1.33 Ratio of furnace transformer powers for UHP and normal mode

Chokes

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

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

A short network

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

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

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

The reactance of individual phases is influenced not only by the length of their conductors, but also by their relative position and the position of the surrounding steel structures of halls and cranes. Uneven power distribution in the individual phases has an adverse effect on the furnace operation and the life of the lining. The most advantageous measure to reduce the asymmetry is to implement a short network bifurcated line (Fig. 1.34).

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

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

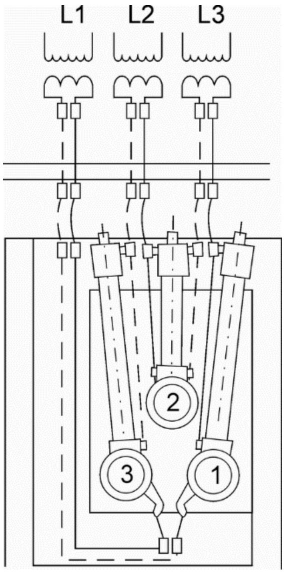


Fig. 1.34 Bifilar design of the short path

❑ Electrodes

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

The main requirements for electrodes are:

- Good electrical conductivity
- High mechanical strength
- High oxidation temperature
- Low ash and sulphur content

Three types of electrodes are practically used for arc heating:

- Carbon electrodes
- Graphite electrodes
- Hopper electrodes (Söderberg)

Primary and secondary metallurgy

At present, the electric power plants use a technological system with the following aggregates (in the given order):

- EAF (electric arc furnace)
- LF furnace (ladle furnace)
- Vacuuming

The system of a modern steel mill is characterized by a massive volume of material flow, where the input material (scrap and additives in lump or bulk) is transformed into continuous ingots. In addition to these ingots, waste is generated, namely slag and unwanted impurities. The transformation takes place in a sequential material transfer EAF - LF - Vacuum. In practice, of course, not all aggregates have to be used, but it always starts in the EAF.

EAF - Electric Arc Furnace - Fig. 1.35 (low wall furnace)

- represents the so-called primary metallurgy
- the furnace unit is used to produce liquid "crude" steel
- energy for production is supplied mainly by electric arc, but we can help with oxygen burners or by burning carbon

LF furnace - ladle furnace

- belongs to the so-called secondary metallurgy equipment
- this device maintains or increases the temperature of the liquid steel in the casting pan
- it is also used for final alloying, breaking away from the pan (adding legur)

Vacuuming

- another of the so-called secondary metallurgy facilities
- the equipment is used to improve the quality of the steel produced
- definitively gets rid of residual unwanted gases

A classic electric arc furnace is shown on Fig. 1.35

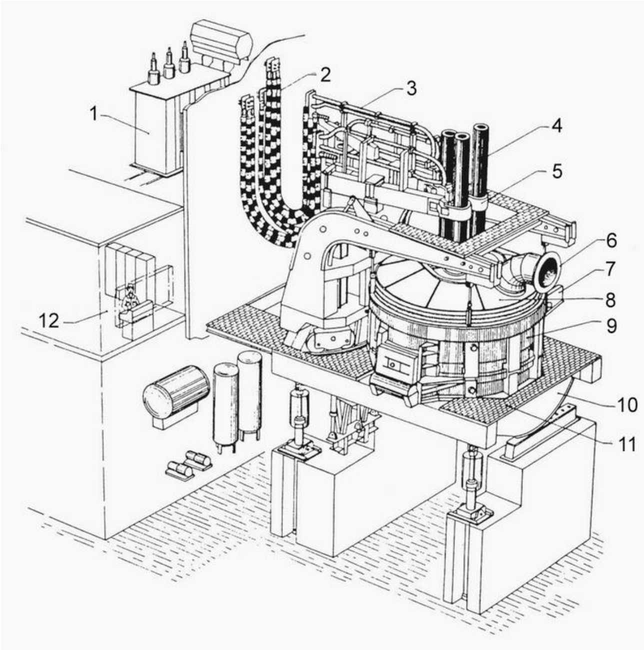


Fig. 1.35 Three-phase electric arc furnace [6]

Description of three-phase electric arc furnace Fig. 1.35:

1 - Furnace transformer; 2 - Flexible water-cooled cables; 3 - Horizontal water-cooled tubular conductors; 4 - Electrodes; 5 - Electrode holders; 6 - Furnace compartment gas outlet; 7 - Steel outlet during tipping; 8 - Water-cooled furnace lid; 9 - Furnace compartment; 10 - Furnace tilting mechanism; 11 - Assembly platform; 12 - Control workstation.

❑ Types of EAF according to the arc used

Electric arc furnaces are most often connect directly on three-phase AC current. They usually have three electrodes and the arc burns between the electrodes and the charge. The charge usually does not have a reverse zero wire, so it develops a medium potential against which the individual arcs burn.

Furnaces with a direct arc

In these furnaces, the arc between the electrode and the charge burns. Sometimes these furnaces are called dependent arc furnaces. These furnaces are mainly used to produce steel and cast iron. Since the current circuit is closed across the melt by the burning of the arc between the electrode and the charge, the heat transfer to the charge is direct, which contributes to a higher heating rate of the melt. Reducing the melt time and thus reducing the wall heating time reduces losses and increases efficiency. Vertical electrode placement reduces the possibility of electrode breakage and failure rates.

Furnaces with indirect (independent) arc

The arc burns between the two electrodes and the heat enters the charge exclusively by radiation, which is why these furnaces are called radiant arc furnaces. An arc burning independently of the charge is called an independent arc. The furnaces are used to produce cast iron, bronze, copper, iron-alloys, carbides and some alloy steels. However, these furnaces have several disadvantages compared to the previous furnaces, mainly in the greater consumption of electricity per unit of charge, and in the horizontal arrangement of the electrodes, which often break and thus carburize the charge, which is not good from a metallurgical point of view. Due to the independent burning arc, there is more wear on the walls. The advantages of these furnaces are lower investment costs and ease of operation.

Furnaces with covered arc

The arc again burns between the electrodes and the charge, but the electrodes are immersed in molten slag and covered with a load of ores and impurities, so the arc is completely covered. Some current passes between the electrodes through the slag and the charge, which are well conductive when hot. This actually results in simultaneous resistive heating of the slag and the charge by the direct passage of an electric current, which is why the furnaces are also called arc-resistance furnaces. This mechanism is mainly used in ore thermal furnaces.

❑ Operating characteristics steel melting arc furnaces

Steel arch furnaces have a bath lined with an alkaline lining. The content of the charge is up to 100 tonnes of steel. The electrical input power reaches tens of MW. The optimum operating mode of electric steel arc furnaces depends on a number of technological factors, furnace design, electrode quality, lining composition, etc.

The main influencing factor, however, is the correctly selected electrical mode of the furnace. This mode can be controlled either by changing the voltage applied to the furnace electrodes or by changing the arc length - i.e. the current.

The first method is commonly used in the individual stages of melting in an electric arc furnace and is directly related to the metallurgical process. The second method is defined by the operation of automatic electrode motion control, which maintains a constant, optimum power input to the melt at a given voltage level.

For a proper understanding of the optimum operation of an electric arc furnace, we will become familiar with the dependence of the main electrical quantities of furnace circuits, i.e. power, power factor, efficiency, on the independently varying current.

The electrical characteristics of an electric arc furnace can be determined either by calculation or graphically using an electric arc furnace ring diagram, or by measurements on specific electric arc furnace equipment.

Let's express the power circuit of an electric arc furnace by a simple substitute diagram according to Fig. 1.36. The single-phase elements of the electric arc furnace electrical equipment are connected in series. By successive simplifications we obtain a transformed replacement scheme for the resistors R_N, X_N, R_o, thus starting, of course, from certain simplifications that cannot be ignored in practice.

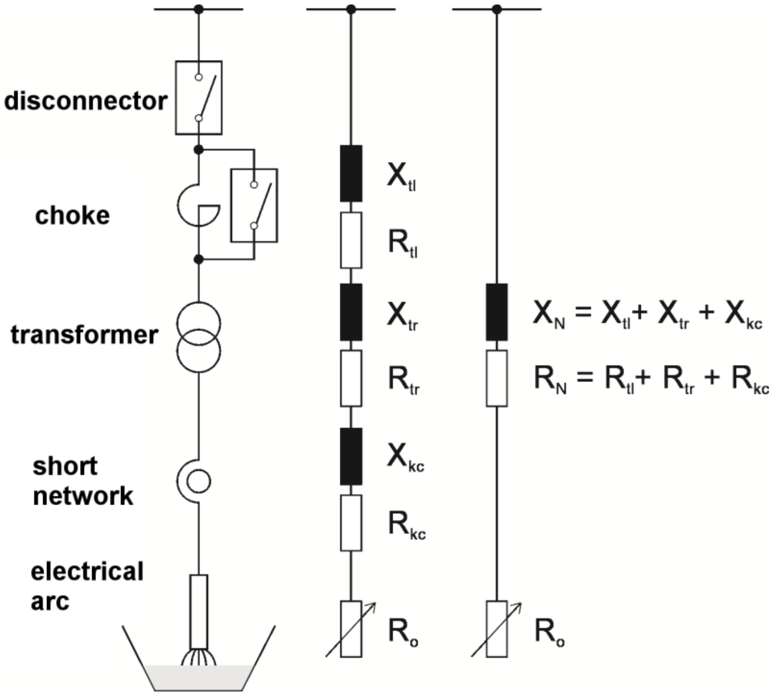


Fig. 1.36 Diagram of the arc furnace electrical system

The mains voltage is symmetrical and independent of the load. The impedances of the individual phases (excluding arc resistance) are equal and independent of current. The arc resistance is linear. The transformer no-load current is zero. The values of the surrogate resistances X_N and R_N are usually found during short-circuit measurements.

The actual electrical characteristics can then be constructed using circular diagrams. An example of the theoretical characteristics are shown in Fig. 1.37.

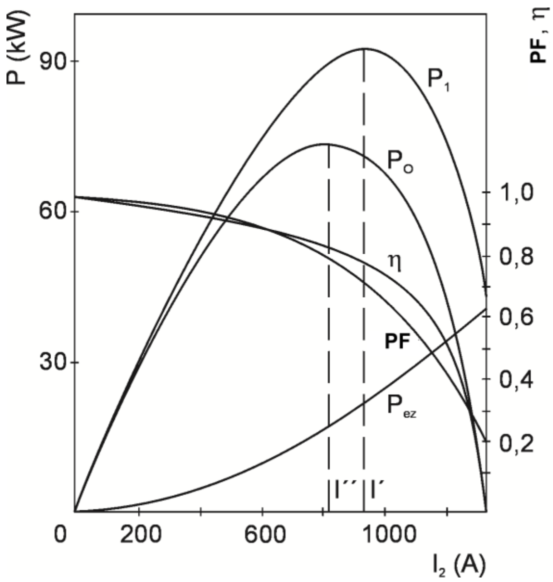


Fig. 1.37 Theoretical operating characteristics

The characteristics can be marked with the current corresponding to the maximum primary power *I´* and the maximum arc current *I´´*. This current is sometimes mistakenly considered as the optimum current corresponding to the highest melting rate. However, determining the optimum current value only from the theoretical characteristics is a much reduced approach.

Above all, these simplifying assumptions cannot be accepted in practice. Furthermore, it is necessary to consider the heat losses (especially at the end of melting), which are greater than the electrical losses and thus affect the melting rate and the specific power consumption. These heat losses can be considered constant and essentially independent of the electrical quantities. The power to compensate for these heat losses is subtracted from the electric arc power. The useful power is therefore equal to

$$P_{up} = P_1 - P_{el} - P_{tl} \tag{1.58}$$

where P_{tl} is the power to compensate for thermal losses; P_{el} is the power to compensate for electrical losses.

The energy efficiency of melting can be expressed by

$$\eta_{en} = \frac{P_{up}}{P_1} \cdot 100 \tag{1.59}$$

The specific power consumption *w* will be equal to

$$w = \frac{W_u}{\eta_{en}} \tag{1.60}$$

where W_u is the energy consumed to melt one tonne without considering losses.

The relationship for the melt rate is given by the ratio of the total useful power consumed to melt the charge alone to the useful energy input.

$$G = \frac{P_{up}}{W_u} \tag{1.61}$$

According to the variables in the relations (1.58) - (1.61) we can assess the cost-effectiveness of the EAF operation.

Thus, we see that considering the effect of heat loss allows us to express energy efficiency, specific energy consumption and melting rate as a function of current. In Fig. 1.38 are the operating characteristics of a 10-tonne electric arc furnace for a voltage level of 220 V.

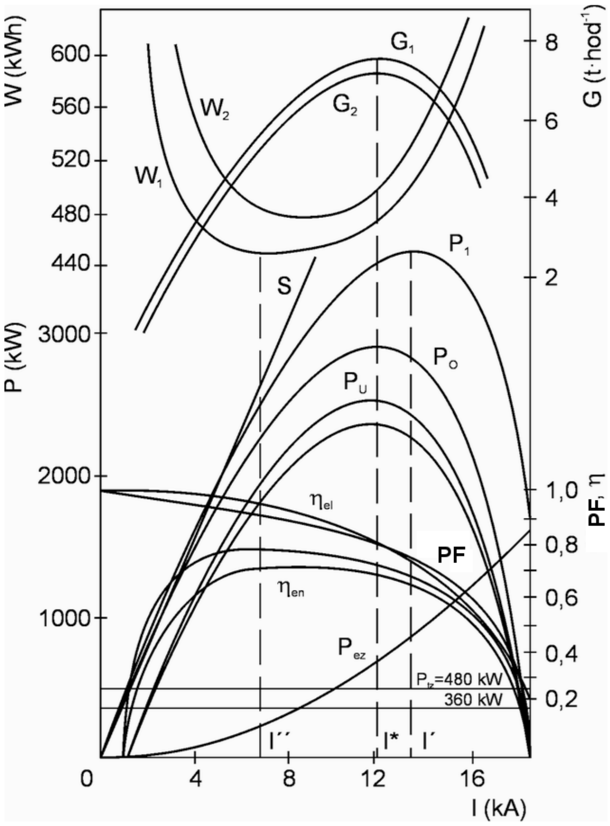


Fig. 1.38 Operating characteristics of a 10 tonne electric arc furnace for 220 V voltage level

From the graph we can find the value of the current *I´´* corresponding to the maximum energy efficiency η_{en} and the minimum specific energy consumption w_1, w_2. It is true that *I´´* < *I**. This means that the minimum power consumption regime is achieved at a lower power input than the maximum melting rate regime.

Therefore, it can be said that the characteristic values of currents *I´´* and *I** for a given voltage level and for a given value of heat losses define the operating mode range.

It is irrational to work outside this area according to theoretical work characteristics. It is also possible to consider the effect of higher heat losses on the individual dependent variables.

The graphical dependencies show that higher heat losses result in a decrease in the melting rate, an increase in specific power consumption and a shift of its minimum to higher current intensities. However, the position of the maximum melt rate is not affected by the amount of heat loss.

❑ DC electric arc furnaces

A new technology in the field of arc heat recovery is the DC power supply for arc furnaces (Fig. 1.39).

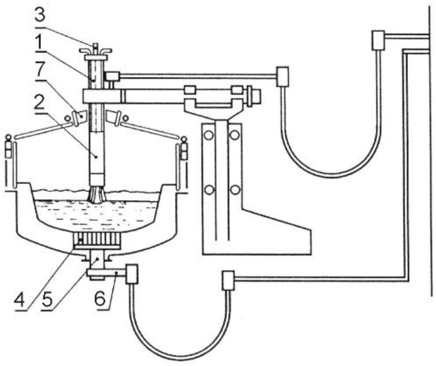


Fig. 1.39 Diagram of a DC arc furnace

Description of DC arc furnace by Fig. 1.39:

1 - electrode cooling; 2 - graphite part of the electrode; 3 - Ar or N_2 supply; 4 - conductive bottom (anode); 5 - bottom electrode; 6 - DC power supply circuit; 7 - ceramic electrode cap.

A rectifier is placed between the transformer and the arc furnace. The electrical path and the furnace itself are different from the traditional AC power supply method. The power supply is composed of a control transformer and the actual transformer with fixed conversion to low voltage. In addition, a fully controlled six-pulse rectifier in a bridge circuit is included to ensure good transformer power utilization and to meet the dynamic requirements of the arc furnace.

In the DC part of the furnace power supply circuit, there is a DC reactor. This inductor limits the stress on the thyristors by operating short circuits and helps to stabilize the arc.

Power factor compensation and higher harmonic filtering devices are not necessary for DC furnaces. It is only used when the local power system has insufficient short-circuit power at the point of connection of the DC arc furnace (Fig. 1.40).

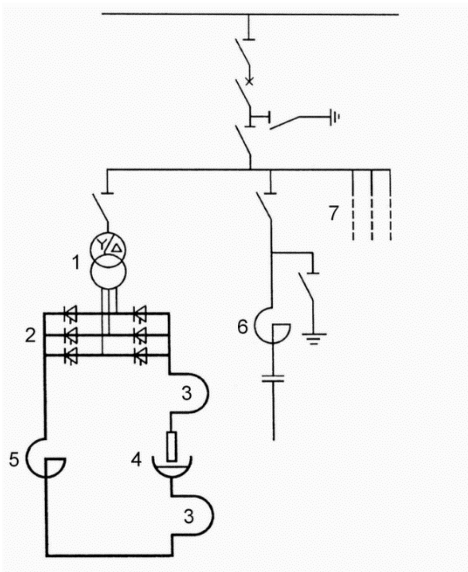


Fig. 1.40 Electrical wiring diagram of a DC arc furnace [7]

Description of DC arc furnace by Fig. 1.40:

1 - control transformer; 2 - six-pulse bridge rectifier; 3 - short network; 4 - arc furnace; 5 - choke; 6 and 7 - filter-compensation devices.

The DC arc furnace bath itself must have a conductive bottom and a special design to conduct the circuit current through the bottom electrode system. The greatest advantage of DC arc furnaces is the substantial reduction in graphite electrode consumption, which in some cases reaches up to 50 %. Furnaces with one electrode are designed up to 30 tons of charge. These then show less wear on the furnace linings due to the uniform distance of the electrode from the furnace walls. Another advantage is the elimination of disturbing influences on the supply network, especially dynamic voltage variations. The operating noise is reduced from 110 dB to 90 dB compared to AC power. The DC arc furnace is operated with a long arc and therefore the highest possible voltage level in the power transformer. The long arc requires the use of foam slag. The electrically conductive bottom of the DC furnace needs to be operated with liquid charge immediately at the start of melting. Therefore, a portion of the liquid steel is left in the furnace after casting to allow the electrical network circuit to be connected. The advantage is that existing AC arc furnaces can be converted to DC with the original power transformer retained.

Summary of terms 1.3.

Electric arc, electric arc furnace (EAF), vector diagram, circular diagram, working characteristics, primary and secondary metallurgy.

Questions 1.3.

1. Explain the formation of DC and AC arc, draw diagrams.
2. Draw the shape of the anode and cathode in a prolonged burning DC arc.
3. Draw the time waveform of voltage and current in an alternating arc.
4. Explain and draw the stabilization of an alternating arc by inductance.
5. Explain what primary and secondary metallurgy is.
6. How do we sort the EAF according to the arc used? Describe the different furnaces.
7. Draw the volt-ampere characteristics of a DC arc.
8. What are the parts of power EAF circuit?
9. What are the parts of the short EAF network?
10. What are the operating characteristics of EAF? Draw.
11. Which parameters characterize the operation of the EAF?

1.4. Induction electric heat

TIME TO STUDY:

2 hours

TARGET:

After reading this paragraph, you will

- to know the principle of heat generation in a plant during induction heating
- be able to explain the principle of heating in crucible and channel induction furnaces
- know how to connect induction furnaces to the power supply network

EXPLANATION

The principle of heat generation in induction devices

Induction heating is only possible with electrically conductive material. Eddy currents are induced in a conductive material which is placed in a magnetic field and heats it up. It is often simplistically compared to a transformer, where the secondary winding is the load and is short-circuited. The heat transfer to the load is therefore not by thermal gradient as in, for example, resistive devices with indirect heating. The heat is transferred by a magnetic field and is generated directly in the load. The die is the hottest object in the whole system, while everything else may be cold. The generation of heat directly in the charge, which is not mechanically coupled to anything, is one of the greatest advantages of induction heating.

Induction heating allows unusually high specific power inputs to the charge. By selecting the frequency of the current that powers the heating winding (inductor) and in whose magnetic field the die is placed, the distribution of heat developed in the die can be suitably influenced.

Every induction device always consists of a coil through which alternating current passes, a source and a charge that receives the electromagnetic waves radiated by the coil. By passing of current through a plane emitter produces plane electromagnetic waves in its surroundings. By passing of current through a cylindrical emitter produces cylindrical electromagnetic waves in the surroundings of the emitter. The cylindrical coil through which an alternating current passes radiates cylindrical electromagnetic waves into its cavity.

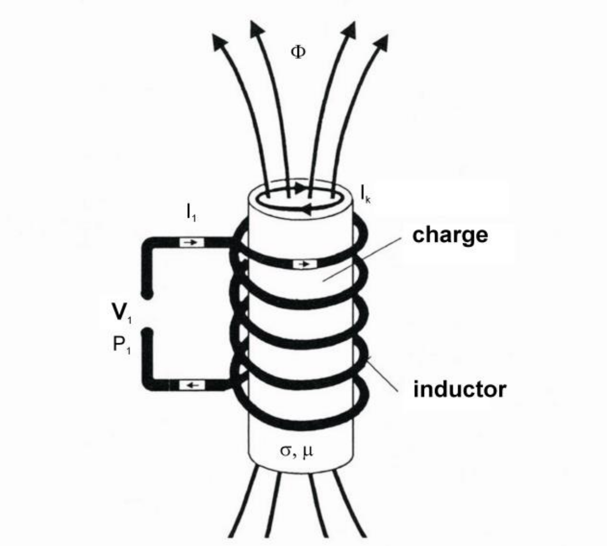


Fig. 1.41 Induction device principle

If we pit a cylindrical electrically conductive charge in the coil, then the incident electromagnetic waves enter the charge through the surface and cause induced currents, which heat up the charge. The penetrating electromagnetic waves are damped and their energy is converted into thermal energy. The depth of penetration of the radiation depends on the frequency.

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \sigma}} = \sqrt{\frac{2}{2\pi \cdot f \cdot \mu \cdot \sigma}}_{r} \qquad (1.62)$$

where δ is the penetration depth (m), f is the frequency (Hz), μ is the permeability ($H \cdot m^{-1}$), σ is the conductance ($S \cdot m^{-1}$).

Dependence of penetration depth of electromagnetic waves on frequency is in Tab. 1.8 and is shown in Fig. 1.42.

Frequency (Hz)	**Penetration depth (mm)**					
	Cu		**Al**		**Steel**	
	20 °C	1100 °C	20 °C	660 °C	20 °C	800 °C
50	9,5	31,8	12,2	31,5	8	71,2
1000	2,1	7,1	2,7	7	1,8	15,9
10000	0,67	2,25	0,86	2,2	0,56	5
1000000	0,067	0,22	0,086	0,22	0,056	0,5

Tab. 1.8 Dependence of penetration depth on frequency

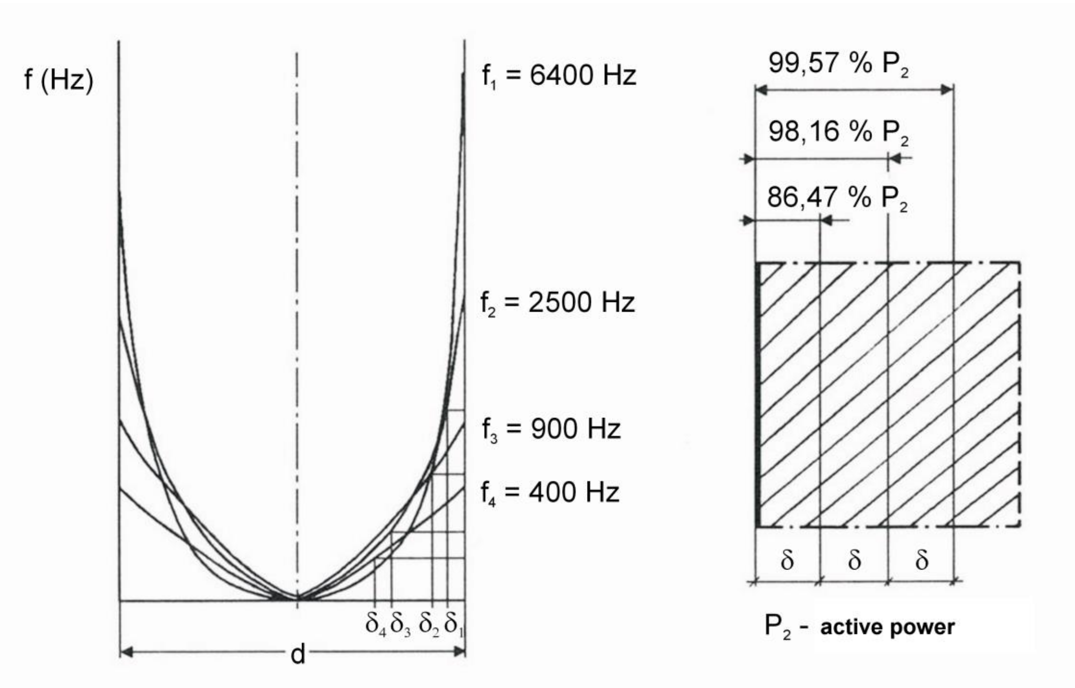


Fig. 1.42 Dependence of electromagnetic wave penetration depth on frequency

The electrical efficiency of induction heating depends on the ratio *d/δ* - Fig. 1.43. The material of the heated object and its temperature also affect the resulting induction heating efficiency.

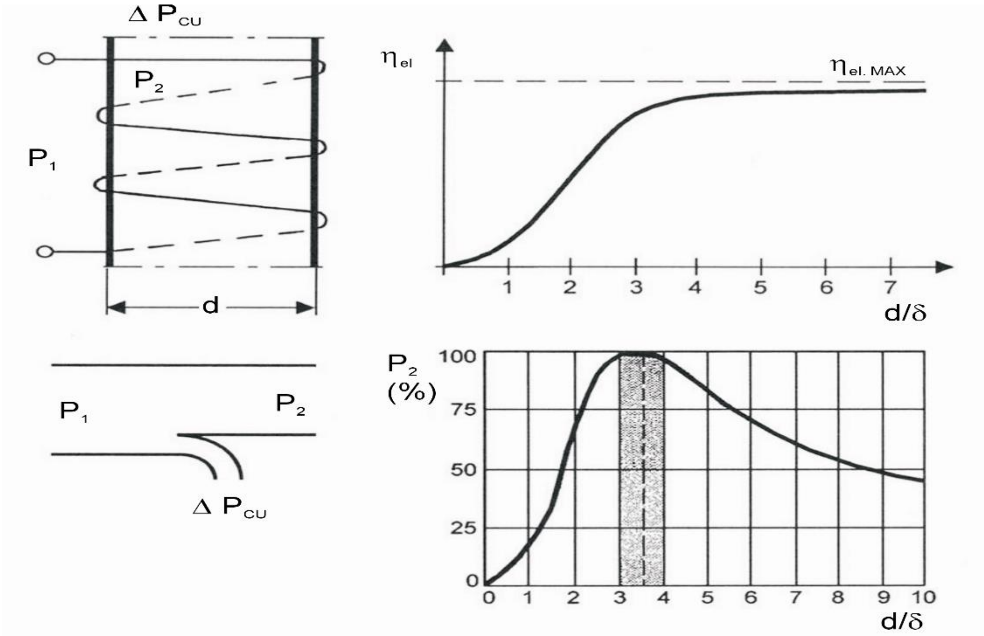


Fig. 1.43 Electrical efficiency of induction heating

Induction crucible furnaces with non-conductive crucible

The coil contains a crucible which is filled with ceramic material. The furnace has either a copper shielding jacket or a steel jacket that carries bundles of transformer plates on the inside (Fig. 1.44). A schematic of this type of furnace is shown in Fig. 1.45.

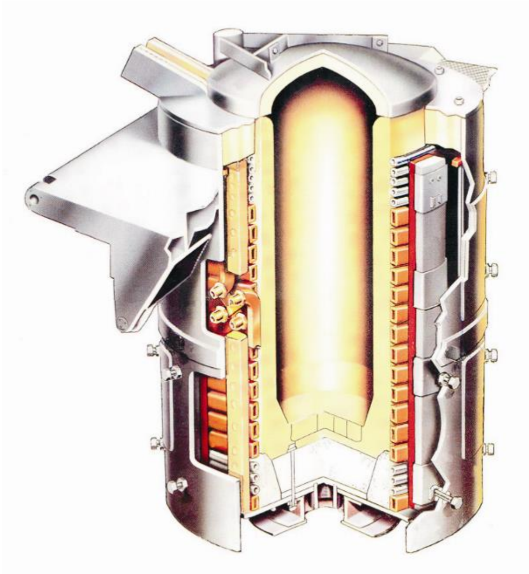


Fig. 1.44 Induction crucible furnace

Induction crucible furnace with conductive shielding

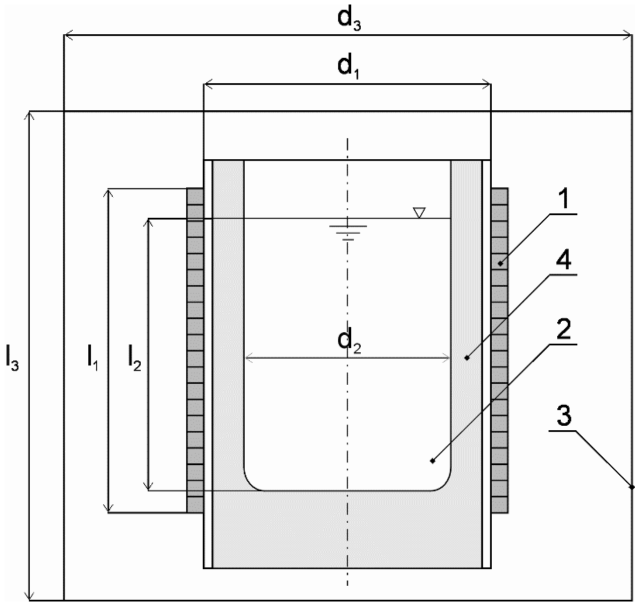


Fig. 1.45 Induction crucible furnace with conductive shielding

A ceramic crucible 4 of cylindrical shape, electrically non-conductive, containing a charge 2, is wrapped by a coil 1. The coil is usually wound from a copper tube of rectangular cross-section. The coil carries a current of increased frequency (500 to 1000 Hz) or a current of mains frequency 50 Hz. The inner surface of the coil emits electromagnetic waves into its cavity, which fall perpendicularly on the surface of the coil, are absorbed by it, and the electromagnetic energy is converted into thermal energy. A magnetic flux passes through the cavity of the coil and is enclosed outside the coil. Appropriate measures must be taken to keep the intensity of the magnetic field outside the furnace as low as possible to prevent heating of the furnace support structures. This can be achieved either by providing the furnace with a shielding jacket of a well conducting material of suitable diameter or by placing a core of iron plates outside the coil to enclose the magnetic flux. Induction crucible furnaces always have shielding, either as a conductive shielding jacket or as a core of transformer plates outside the coil. However, when calculating smaller furnaces, we can neglect the effect of the shielding and calculate the furnace as if it had no shielding. In the calculation we consider only the coil and the load, i.e. only two interacting electrical circuits. This simplifies and shortens the calculation.

Induction crucible furnace with iron core outside the coil

If the induction crucible furnace is equipped with a conductive shielding jacket, the magnetic field strength outside the jacket is reduced very significantly. A similar effect can also be achieved by placing an iron core made of a large number of transformer sheet bundles outside the coil instead of the shielding conductive sheath, according to Fig. 1.46. The bulk of the magnetic flux excited by the coil will be confined outside the coil by a magnetically well-conducting path, i.e., bundles of transformer plates fixed on the inside of the furnace shell of boiler plate. The inclusion of the magnetically conductive bundles will reduce the magnetic resistance for the magnetic flux excited by the coil, so that the flux will increase somewhat. The intrinsic inductance of the furnace coil, i.e. the magnetic flux for a unit current, is increased. The self-inductance and mutual inductance of M_{12} will also increase. A shielded furnace requires a coil with a somewhat higher number of turns and a larger capacitor bank than a core furnace. The useful power is lower and the losses in the coil are higher in a shrouded furnace than in a core furnace. The electrical efficiency is significantly lower for a shell furnace than for a core furnace. The most important result of the comparison made is the finding that the efficiency of the furnace with an iron core is almost 5 % higher than that of the furnace with a shielded jacket. This results in considerable savings in electricity in operation, especially for large furnaces with continuous operation. The design of the induction crucible furnace with an iron core is therefore a technically superior solution. However, this furnace is more expensive to manufacture and, if the crucible melts during operation, the damage to the furnace is usually worse or the furnace is completely destroyed.

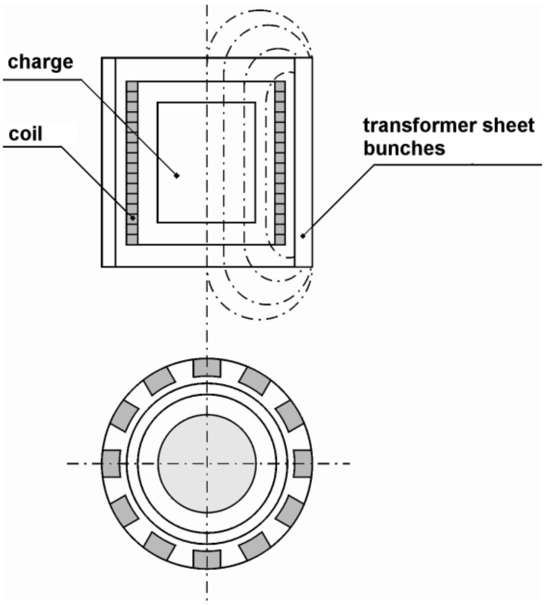


Fig. 1.46 Induction crucible furnace with transformer sheet bunches

❑ Induction crucible furnace with conductive crucible

An induction furnace with a non-conducting crucible has a low electrical efficiency when melting well conducting materials such as copper and its alloys, aluminium and its alloys, etc. The electrical efficiency increases considerably if the furnace is fitted with a conducting crucible schematic by Fig. 1.47 (for melting Al and Cu). For lower temperatures, such as those involved in the melting of aluminium and its alloys, the crucible is made of steel. For higher temperatures, so-called graphite crucibles are used. They are made of a mixture of fireclay and graphite. The more graphite, the more conductive the crucible. However, high conductivity is not desirable. There is a ceramic insulating layer between the crucible and the coil, which reduces the heat loss from the hot crucible to the water-cooled coil. If a current is introduced into the coil, the electromagnetic waves radiated by the inner surface of the coil impinge on the outer surface of the conducting crucible, enter its wall, induce a current in the wall, and through its passage the crucible is heated. It then transfers the heat to the insert in its cavity. The proportions are usually such that a larger part of the incident electromagnetic energy is converted into heat in the wall of the crucible, but a smaller part passes through the wall and heats the insert directly. The ratio between the wall thickness $š_3$ and the penetration depth d_3 is crucial. If the penetration depth is small compared to the wall thickness, all the electromagnetic energy in the crucible wall is absorbed. The calculation is the same as for two coaxial cylinders in a furnace with a non-conducting crucible. In the calculation, we consider the crucible as an insertion. However, if there is no $d_3 << sh_3$, a significant amount of electromagnetic energy will pass through the crucible wall into the charge.

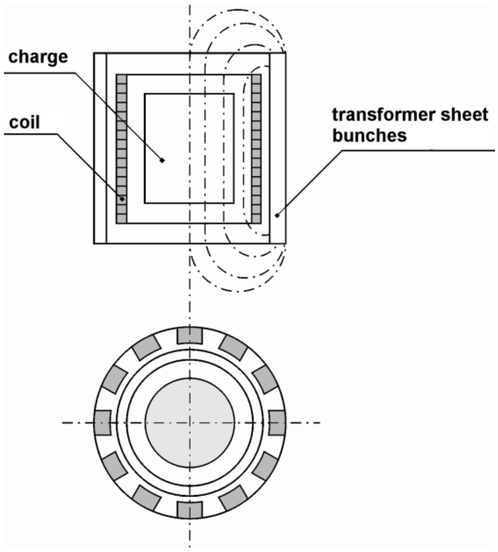


Fig. 1.47 Induction crucible furnace with conductive crucible

Induction heat-soaking device

In plants where components are made by forging or hot pressing, uniform heating of the material is an important issue. Metal forgings of cylindrical or square shape, usually steel, must be heated to forging temperature (steel C° 1150 to C° 1250). In older forges, fuel-fired furnaces heated by gas, pulverized coal or oil are used to heat the forgings. However, it takes too long to heat evenly throughout the cross-section and during this time the material oxidises on the surface. Several per cent of the material is destroyed and, in addition, the resulting scaling damages the dies and shortens their service life during the next operation. In contrast, heating in an induction furnace takes a very short time, so that there is virtually no oxidation on the surface. The economic advantages are the reason for the rapid introduction of induction heating in newly built forges. The induction furnace (induction heater) for forging is usually cylindrical in shape, schematically according to Fig. 1.48.

The main part of the induction heater is the induction coil 1, usually about 1 m long. Its diameter is chosen according to the diameter of the coils to be inductively heated. The inductor usually has a larger number (4 to 7) of coils of the same length.

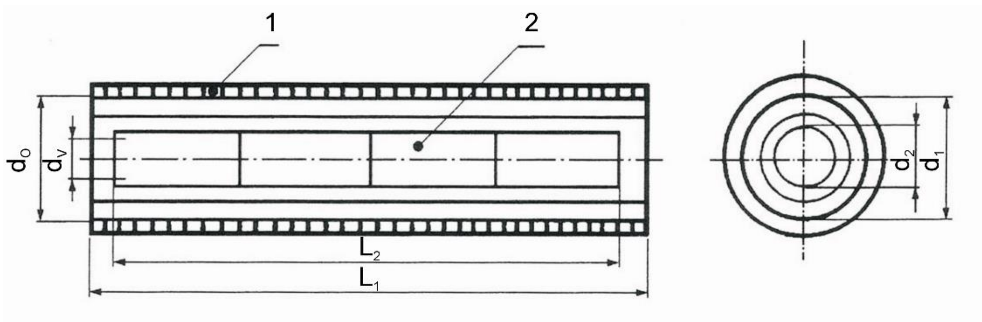


Fig. 1.48 Induction heat-soaking scheme

Frequency and heat-soaking time selection

Uniform heating occurs by spreading the heat from the surface layer where it originates by conduction into the interior of the cylinder. From this point of view it is preferable that the layer in which the heat develops is not too weak, which in other words means that the frequency must not be too high. It is therefore necessary to choose a suitable frequency and thus the layer in which the heat is developed so that the energy is absorbed with good efficiency but the surface does not overheat. The optimum frequency is one at which approximately $r_2 = (2.5$ *to* $3.0) - \delta_2$. We take the penetration depth for a material already heated, i.e. magnetic if it is steel. In practice, the frequency for induction heating of steel is chosen depending on the diameter of the forgings according to Tab. 1.9. From the table we see that each frequency can be used for diameters varying over a considerable range.

f (Hz)	50	500	1000	2000	4000	8000
d (mm)	160÷500	80÷280	50÷180	35÷120	22÷70	15÷50

Tab. 1.9 Frequency selection for induction heating of steel

From the chart shown on Fig. 1.49 shows that the specific consumption in kWh to heat 1 kg of steel to 1200 °C increases as we approach the lower end of the range of averages. The material becomes electromagnetically transparent. For a diameter d_2 = 10.0 cm of steel, the specific power consumption of the grid is about 0.40 $kWh \cdot kg^{-1}$ at a frequency of 1000 Hz. The time t required to heat the steel uniformly is usually not calculated and is taken from the relevant diagram according to Fig. 1.50.

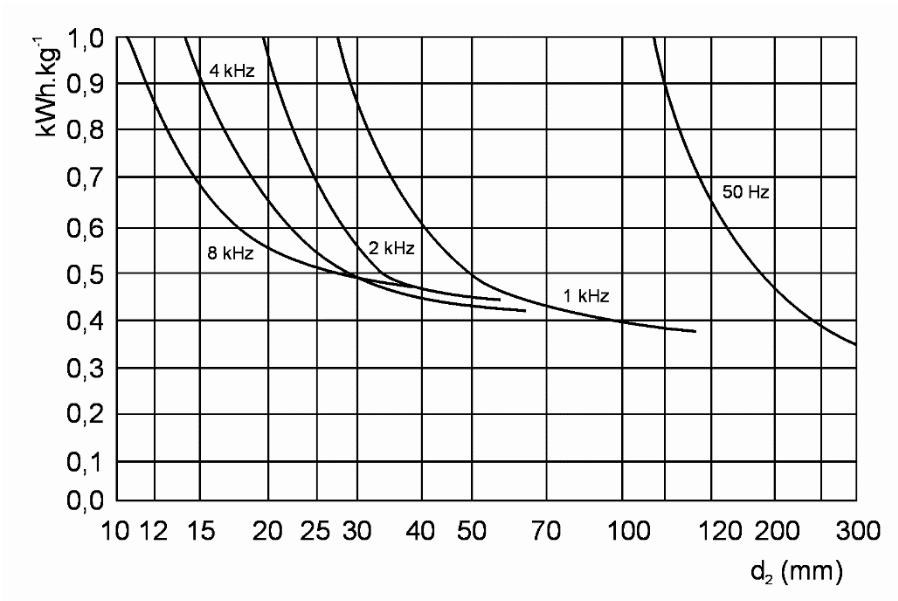


Fig. 1.49 Graph of specific consumption

The uniformity of the heating of the barrel is sufficient if, at the end of the heating process, the temperature difference between the surface and the axis is not greater than 100 °C. The unevenness is further reduced during the additional, usually several tens of seconds that elapse between the end of the heating and the forging operation in the press. From Fig. 1.50 we can deduce that the appropriate time to heat a steel forging with a diameter of d_2 = 100 mm is about 7 min, at the considered frequency of 1000 Hz. The heating time can be reduced by about one third in the case of so-called rapid heating. In fast heating, the part of the coil at the beginning of the inductor through which the cold coils enter is made with thickened coils. In this part, there are more N_{11} threads per 1 cm of coil length. This will increase the magnetic field strength $H_1 = N_{11}\ I_1$ ($A \cdot cm^{-1}$) at the inlet of the inductor, and since the heat developed depends on the square of H_1^2 , the pieces inserted in this part of the inductor will heat up faster to a higher temperature and the overall heating time will be reduced. The larger temperature difference at the surface and in the axis of the roll is then compensated for in the subsequent slower heating process. [8].

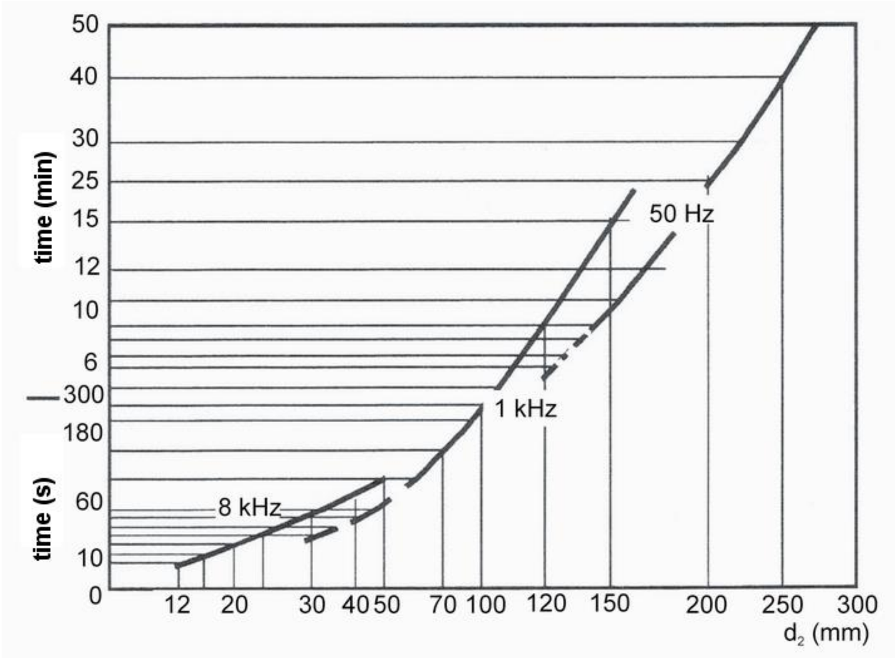


Fig. 1.50 Diagram of the time to heat-soaking a steel rolled product

Induction equipment for surface heating

For surface heating of objects up to a depth of 10 mm we use high frequencies, in the order of 10^4 to 10^6 Hz. In industry, induction heating devices, inductors, are used for these technological purposes:

- Hardening
- Soldering
- Welding
- Refining remelting

The depth of the heated layer depends on the frequency as follows Tab. 1.10.

Frequency *f* (kHz)	Penetration depth δ (mm) (steel 1000 °C)	Depth of heated layer $g = (2 \text{ to } 3)\,\delta$ (mm)
10	5,00	10 - 15
100	1,60	3,2 - 5
1 000	0,50	1 - 1,5
10 000	0,16	0,3 - 0,5
30 000	0,09	0,2 - 0,3
100 000	0,05	0,1 - 0,15

Tab. 1.10 Depth of heated layer as a function of frequency

Hardening

For hardening we use specific power in the range of 1 to 20 $kW \cdot cm^{-2}$. The optimum frequency is calculated from the relation

$$\frac{0{,}015}{d^2} < f < \frac{0{,}25}{d^2} \qquad (1.63)$$

where d is the hardening depth (mm), f is the frequency (kHz).

In Fig. 1.51 and in Tab. 1.10 it is possible to observe the depth of cloudiness d depending on the frequency and hardness of the steel used. Curve 1 is for f = 400 kHz, 2 is for f = 10 kHz and 3 is for f = 4 kHz.

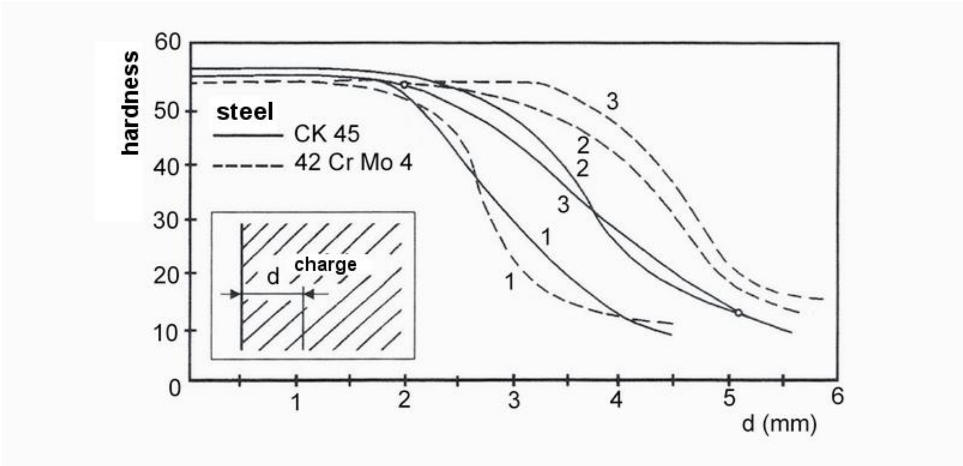


Fig. 1.51 Depth of hardening zone

Soldering

When soldering, we use a frequency in the range of 2 kHz to 2.5 MHz. The principle of soldering via a special inductor is shown in Fig. 1.52 a Fig. 1.53 Special inductor for soldering three different shapes simultaneously. The brazing uses a power output of 0.5 to 5 kW for temperatures from 150 to 450 °C. Brazing uses 3 to 30 kW for temperatures from 450 to 1 050 °C. At Fig. 1.53 1 is the inductor, 2 is the soldering iron.

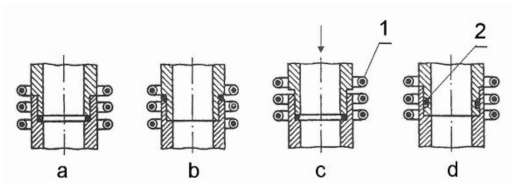


Fig. 1.52 Principle of induction soldering

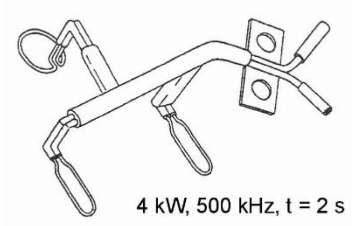


Fig. 1.53 Special inductor for soldering three different shapes simultaneously

Welding of pipes

The principle of pipe welding using a sliding inductor is shown in Fig. 1.54. Power sources with a frequency of 8 to 500 kHz and outputs of 50 to 700 kW are used, depending on the different depth of heating.

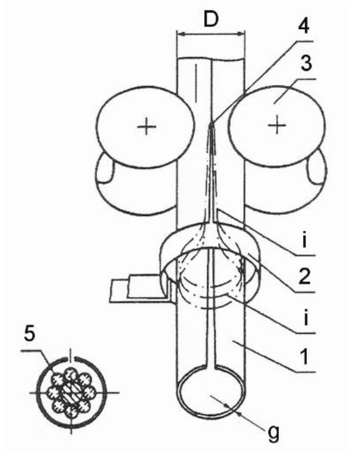


Fig. 1.54 Principle of induction welding of tubes

1 - tube, 2 - inductor, 3 - pulleys, 4 - weld, 5 - magnetic core, i - induced current, v = 15 - 100 $m \cdot min^{-1}$, f = 8 - 500 kHz, P = 50 - 700 kW, g = 0.4 - 12 mm, D = 8 - 500 mm.

Refining remelting

The principle of refining is illustrated in Fig. 1.55where 1 is the inductor and 2 is the charge (Si). Sources with a frequency of 400 kHz to 5 MHz at powers of 10 to 50 kW are used.

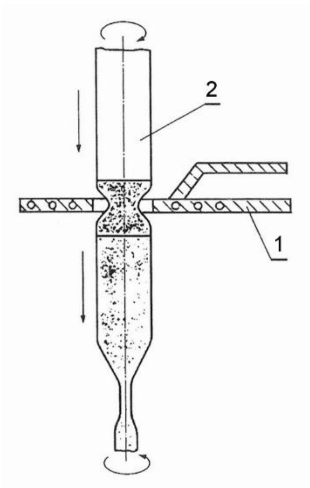


Fig. 1.55Principle of refining remelting

❑ Channel induction furnaces

Channel induction furnace design

An induction channel furnace is essentially a transformer with a closed iron core, with a primary coil connected to the mains. The channel filled with molten metal is the secondary side of the transformer. It's actually a short-circuited coil Fig. 1.56.

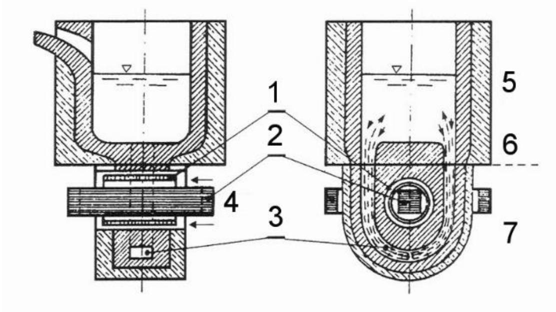


Fig. 1.56 Channel induction furnace

1- air cooled heating coil (marked by arrows), 2-core of transformer plates of shell type, on the middle column of which is the heating coil 1, 3-channel, which surrounds the heating coil as a short coil, 4-cooling air, 5-bath furnace, 6-separating gap, 7-inductor.

Electric induction channel furnaces are used for melting non-ferrous metals, especially copper and its alloys, aluminium and its alloys, or for heating cast iron melted beforehand, for example in the cupola. When increasing the power input to the furnace with an exposed channel, it was found that an undesirable effect, the so-called 'squeaking effect', occurs when a certain critical value of the current in the charge is exceeded. Due to the electrodynamic forces acting in radial planes in all directions perpendicular to the surface of the liquid conductor, the continuous ring of molten metal is broken. At this moment, however, the electrodynamic action ceases, the ring rejoins and the phenomenon repeats. Surges are generated which prevent the furnace from operating properly. This phenomenon has been partly counteracted by a suitable design of the furnace coil. However, a solution with a covered channel embedded in the bottom of the furnace proved to be even more suitable. The hydrostatic pressure of the molten metal largely prevents the creep phenomenon. During casting, about one-third of the charge is left in the furnace, filling the channel and the bottom of the furnace, so that heat can be generated in the closed thread after the transformer is switched on. The furnace is then filled with the charge, which is melted by immersion in a superheated bath at the bottom of the furnace. In these furnaces, heat is generated only in the charge found in the channel. By the action of electrodynamic pressure, the metal is continuously forced out of the channel into the crucible and the cooler metal from the crucible flows into the channel. This transfers the heat from the channel to the entire charge in the substrate. If the channel has a vertical surface, the temperature difference helps the hot metal to penetrate intensively from the channel, because the hotter metal is lighter.

❑ Connecting channel furnaces to the network

Single-phase furnaces

Single-phase furnaces usually have one channel. They are connected to a 3 x 400 V, 50 Hz mains phase or line voltage. Single-phase furnaces are manufactured up to an apparent power input of 150 kVA. There are usually a larger number of similar furnaces in the smelter and by connecting them to different phases in a staggered manner, the load is roughly balanced on all three phases. The connection of a single-phase induction furnace with one channel is shown schematically on Fig. 1.57.

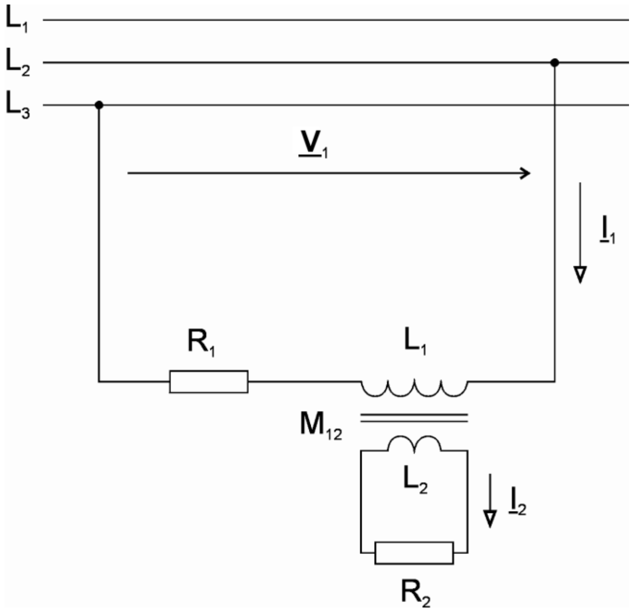


Fig. 1.57 Connection of single-phase induction furnace

Symmetrical loading of a three-phase network by a tuned single-phase furnace can be achieved by using a so-called symmetrizing device. It is an artificial load consisting of three branches. In one branch there is a resistance R_Z, replacing the tuned induction furnace, in the second branch there is an inductance *L* of suitable size and in the third branch there is a suitably sized capacitance *C*. These three branches of the symmetrizing device can be connected in a triangle or a star. In either case, if the phases are properly sequenced, exactly symmetrical loading of all three phases can be achieved by PF = 1.0.

In Fig. 1.58 shows the symmetrizing device in a delta connection.

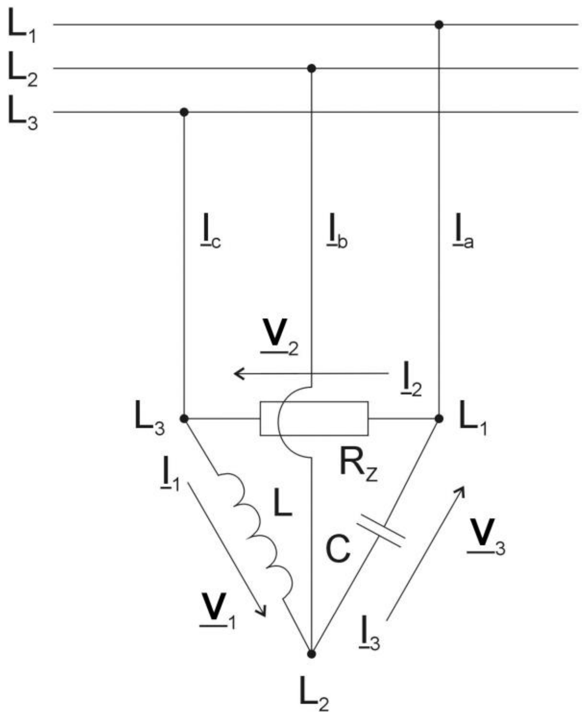


Fig. 1.58 Delta connected symmetrizing device

For the value of the required inductance *L* and capacitance *C*:

$$L = \frac{\sqrt{3} \cdot R_Z}{\omega}\ ;\ C = \frac{1}{\omega \cdot \sqrt{3} \cdot R_Z}\ ;\ \omega L = \frac{1}{\omega C} = \sqrt{3} \cdot R_Z \qquad (1.64)$$

When installing a furnace with a symmetrizing device, ammeters shall be inserted in all three inlets. With the correct phase sequence, all ammeters show the same deflection. If the phase sequence is incorrect, the ammeters in phases *a* and *c* show a higher current than in phase *b*. If any two leads are swapped, the correct phase sequence is obtained.

The connection of the symmetrization device to the star is in Fig. 1.59.

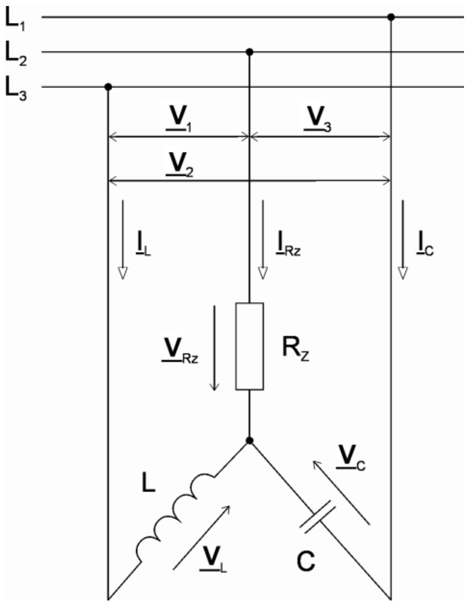


Fig. 1.59 Symmetrization device connected to a star

The furnace will experience an increased voltage U_R equal to three times the phase voltage, which is advantageous for larger furnaces. For the magnitude of the required inductance *L* and capacitance *C* the following applies:

$$L = \frac{R_Z}{\sqrt{3} \cdot \omega}\ ;\ C = \frac{\sqrt{3}}{\omega \cdot R_Z}\ ;\ \omega L = \frac{1}{\omega C} = \sqrt{3} \cdot R_Z \qquad (1.65)$$

If we compare the equation (1.65) with the equation (1.64), we see that in the symmetrical star connection, the required inductance is 3 times smaller and the required capacitance 3 times larger than in the triangular connection - in both cases based on the load resistance R_Z. Since in the star connection, for a furnace of the same input power, the load resistance R_Z is 3 times larger (the voltage across the furnace is $3^{1/2}$ times larger), the actual values of *L* and *C* are exactly the same in both cases.

Two-phase furnaces

These are induction furnaces with two or even four channels, two of which are always connected in parallel and have a common furnace transformer for both channels. A symmetrical distribution to all three phases of the network is achieved either by using two furnace transformers in a Scott circuit or a special symmetrization circuit can also be used. See Fig. 1.60 is a furnace with two identical channels in a Scott circuit.

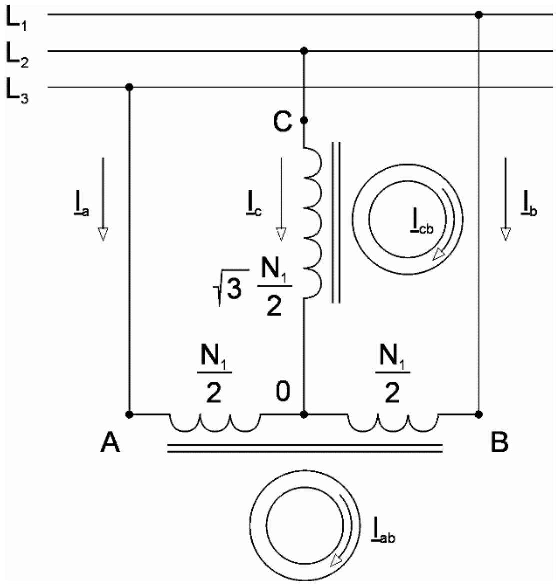


Fig. 1.60 Scott's circuit of a two-phase induction furnace

Each of the two channels has its own furnace transformer, connected to the three-phase network. Between points A and B on Fig. 1.60 is connected to the so-called "main" transformer, which has the primary winding divided into two equal parts. We have denoted the number of turns in each part by N_1 /2. Between the third phase (point C) and the centre of the winding of the main transformer (point 0) is connected an "auxiliary" transformer with a number of turns of $3^{1/2}$ /2. N_1. Both channels are exactly the same. In this arrangement, the currents drawn from each phase are equal. The currents induced in both channels are also the same, and therefore the amount of heat developed in them is also the same.

Three-phase furnaces

Three-phase furnaces with three or six channels, two of which are always connected in parallel to a common core. These furnaces have a three-phase furnace transformer in either a core or shell design. Each of the three cores carries a furnace coil, around which is either one or two identical channels in parallel. All three coils are connected to the mains in either a triangular (coils are on line voltage) or star (coils are on phase voltage) connection. The load of all three phases is symmetrical, to improve the PF a three phase capacitor bank must be connected. In Fig. 1.61 is a three-phase furnace with three channels and a three-phase transformer, designed for melting non-ferrous metals. This furnace symmetrically loads a three-phase network [9].

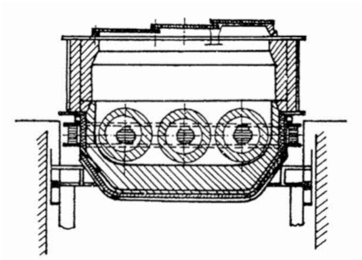


Fig. 1.61 Three-phase furnace with three channels

Summary of terms 1.4.

Induction heating, inductor, eddy currents, depth of penetration, crucible furnace, channel furnace, symmetrization device.

Questions 1.4.

1. Explain the principle of induction heat.
2. Write the relationship for the depth of penetration in induction heating.
3. List the basic types of induction furnaces.
4. What is the difference between an induction furnace with a conductive and a non-conductive crucible?
5. How is the frequency selected for induction heat-soking devices?
6. For what technological purposes is induction surface heating used?
7. How do we classify induction channel furnaces in regard to connection to the power supply network?
8. Explain the nature of symmetrization in connecting a single phase induction channel furnace to a three phase power supply network.

1.5. Electric heating

TIME TO STUDY:

3 hours

TARGET:

After reading this paragraph

- you will understand the issues of thermal comfort and environmental thermal status
- you will be able to calculate the heat loss of rooms
- you will be able to choose the appropriate type of electric heating
- understand the meaning and basic principles of heating control

EXPLANATION

Thermal comfort issues of a human in a room

The main task of heating is to ensure favourable thermal conditions in closed rooms during the cold winter period, when the outside temperature is lower than the desired room temperature and when other weather influences (e.g. wind) cause the rooms to cool down. It is about ensuring so-called thermal comfort.

This means that thermal conditions must be achieved in such a way that one feels comfortable. A person's thermal comfort is influenced by his or her health, age, and the type of activity he or she performs. The feeling of good thermal comfort is essentially determined by the balance of a person's thermal regime with the environment in which he or she is.

An important component of the human thermal regime is the sharing of heat from the body surface to the environment, which is governed by physical laws and can therefore be expressed mathematically. During the metabolic transformations taking place in the human body, a certain amount of heat is released, which depends mainly on the intensity of physical exertion and the weight of the person. This heat must be dissipated into the environment. Thermal equilibrium, i.e. a state in which the environment removes as much heat from the human body as the person is currently producing, is therefore the first and essential prerequisite for thermal comfort.

The human body is cooled by conduction, convection, radiation and, in addition, by evaporation of sweat and respiration. With little physical exertion, most of the heat is removed from the surface of the body by convection and radiation - dry cooling. Achieving thermal equilibrium in dry cooling, without excessive sweating, is the second prerequisite for human thermal comfort.

If the ambient temperature rises above a certain threshold or heat production increases during physical exertion, dry cooling is not sufficient and the excess heat is dissipated by evaporation to ensure thermal balance - wet cooling.

Thermal equilibrium condition can be generally expressed by the relation

$$\Phi_{\mathrm{M}} = \Phi_{\mathrm{V}} + \Phi_{\mathrm{D}} + \Phi_{\mathrm{K}} + \Phi_{\mathrm{S}} \qquad (1.66)$$

where Φ_{M} is the heat flux produced by the human body (W), Φ_{V} is the heat flux removed by evaporation, Φ_{D} is the heat flux removed by respiration, Φ_{K} is the heat flux removed by convection (flow), Φ_{S} is the heat flux removed by radiation.

Heat flow by convection and radiation first passes through the layer of clothing, is conducted through it, and only on the outer surface is the heat transferred to the surroundings. The thermal equilibrium equation then changes as follows:

$$\Phi_{\mathrm{M}} - \Phi_{\mathrm{V}} - \Phi_{\mathrm{D}} = \alpha \cdot A \cdot (T_B - T_C) = \Phi_{\mathrm{K}} + \Phi_{\mathrm{S}} \qquad (1.67)$$

where α is the permeability of the garment ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$), A is the total body surface area ($\mathrm{m^2}$), T_{B} is the body surface temperature (K), T_{C} is the clothing surface temperature (K).

Thermal state of the environment

Thus, several factors determine the thermal sensation of a person in enclosed rooms: the degree of physical exertion (internal heat production Φ_M), the thermal insulation capacity of clothing (thermal transmittance α), the ambient air temperature ϑ_{V} , the effective temperature of surrounding surfaces ϑ_{p} , the humidity of the surrounding air (relative humidity), and the airflow velocity.

The factors ϑ_{V} , ϑ_{p}, humidity and air velocity characterize the thermal state of the environment, which is reflected in the resulting thermal effect of the environment on humans. However, we usually try to express the thermal state of the environment in a single, easily measurable quantity.

Air temperature in the room

The air temperature ϑ_v measured in the area where the human is staying will be used to assess the thermal state. Air temperature can be considered a satisfactory measure of the thermal state of an environment where it is an environment of near-calm air and where the temperature of the surrounding surfaces differs only slightly from the air temperature. In these circumstances, the air temperature also coincides with the resulting temperature ϑ_r.

The air temperature ϑ_v is usually not the same throughout the room, and therefore it is necessary to assess its local variation, unevenness. The vertical non-uniformity of the air temperature in heated rooms, which is caused by uneven heat input and uneven cooling of the individual walls, floors and ceilings of the rooms, is very important. The vertical distribution of room temperatures for different heating methods is shown in Fig. 1.62.

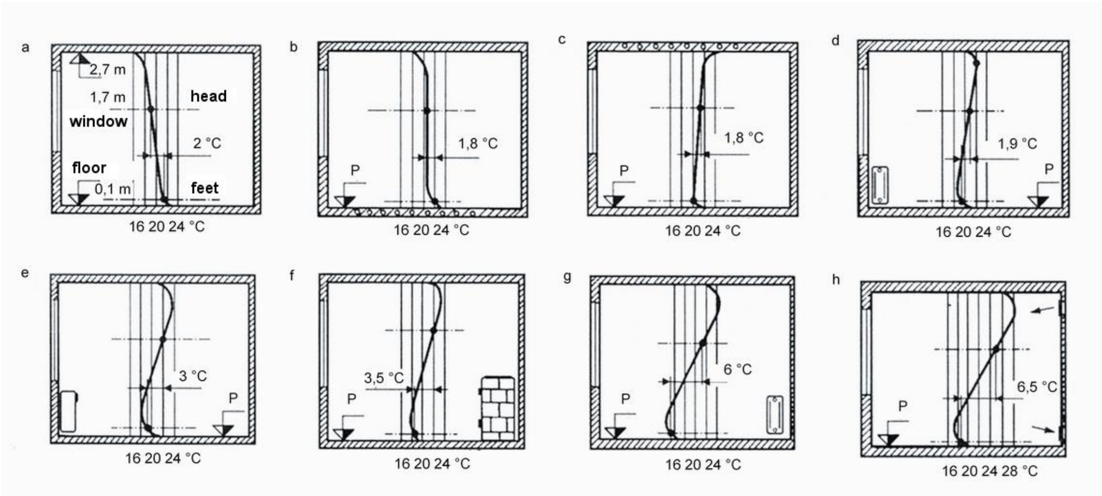


Fig. 1.62 Vertical temperature distribution in the room for various heating systems

a-ideal heating, b-floor heating, c-ceiling heating, d - hot-water heating, e-convector heating, f-local heating with a tiled stove, g - hot-water heating (radiator on the inside wall), h - hot-air heating.

The temperature of the lower air layer at the feet (0.1 m above the floor) is decisive for a comfortable feeling. Next, we are interested in the air temperature at head level (1.7 m above the floor) and then the difference between these two temperatures, which has a great influence on the thermal comfort in the room.

The ideal heating is such that the temperature at foot level is approximately 21 °C and at head level for a standing person approximately 19 °C. In terms of thermal comfort, the temperature difference between head and foot level should therefore be no more than 2.0 °C for a standing person and 1.5 °C for a sitting person. For each heating method, the relevant temperature difference is always indicated in the figure. It is clear from the figure that underfloor heating is the most advantageous in terms of vertical temperature distribution.

Effective ambient temperature

In order to be able to assess the resulting radiative effect of the surrounding surfaces with a single quantity, the so-called effective temperature of the surrounding surfaces is introduced ϑ_p. This temperature is defined as the common temperature of all surrounding surfaces at which the total radiant heat flux between the body surface and the surrounding surfaces would be the same as in reality. For the effective temperature of the surrounding surfaces, if the temperatures of the individual surrounding surfaces do not vary much, the follows relation is valid:

$$\vartheta_p = \sum_{i=1}^{n} \varphi_i \cdot \vartheta_i \qquad (1.68)$$

where φ_j are the ratios of the irradiance of each surrounding surface by the area of the human body (-) , ϑ_i are the temperatures of the surrounding surfaces (°C).

The effective temperature therefore depends on the temperatures of all surrounding surfaces and on the irradiance ratios relative to the area of the human body. In practice, however, this requirement is waived and the values are related to an elementary sphere, a point usually located in the centre of the object.

Resulting room ambient temperature

Starting from the relation for thermal equilibrium expressed in terms of heat fluxes to the body surface *A* and using a simplification for the convection and radiation heat transfer coefficients $\alpha_k = \alpha_s$ (for air flow velocities less than -0.3 m·s^{-1}), we obtain the equation for the resulting temperature of the environment required for providing of thermal comfort.

$$\vartheta_i = 0{,}5 \cdot \vartheta_v + 0{,}5 \cdot \vartheta_p \qquad (1.69)$$

It follows that the thermal comfort of a person depends only on the air temperature and the effective temperature of the surrounding surfaces for a given internal heat production and a given thermal transmittance of the garment. However, the ratio of the two temperatures ϑ_v and ϑ_p cannot be completely arbitrary. If the air temperature ϑ_v is assumed to be between 15 °C and 25 °C in rooms where the resulting temperature ϑ_i = 18.5 °C and 21.5 °C is required, the effective temperature of the surrounding surfaces ϑ_p may vary between 12 °C and 28 °C. This 'thermal comfort zone' is shown by the scraping in Fig. 1.63 [10].

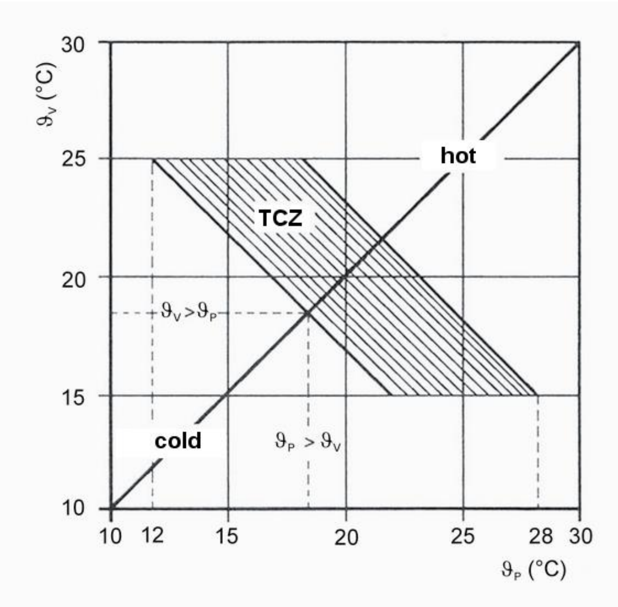


Fig. 1.63 Thermal comfort zone (TCZ)

❑ Practical calculation of heating devices

From the point of view of sizing the heating system, it is necessary to know the maximum value of the heat losses of the building, i.e. the amount of heat that pass from the indoor environment of the rooms with temperature ϑ_i to the cooler outdoor environment with temperature ϑ_e. The heating system must be sized for this maximum value in the year. The calculation of heat losses is based on ČSN 06 0210, Heat Losses Calculation.

The suitability of a building for electric heating is assessed on the basis of the calculated heat loss and heat consumption per^2 1 m of living area. The following documents are required for the calculation of the heat loss of buildings with central heating:

- site plan showing the location of the building in relation to cardinal points, the height and distance of surrounding buildings, the elevation of the site and the prevailing wind direction and intensity,
- floor plans of each floor of the building with all main dimensions, including window and door dimensions, at a scale of at least 1:100,
- sections through the building with all main heights (rooms, height of window sills, etc.),
- data on the materials and construction of walls, floors, ceilings and roofs to determine or calculate the heat transfer coefficient,
- data on the material and construction of windows and doors needed to calculate heat loss through penetration and infiltration,
- data on the use of individual rooms to determine the indoor temperature ϑi,
- description of the intended method of heating each room.

❑ General procedure for calculating heat losses

The total heat loss of a room Φ_c according to CSN 06 0210 is equal to the sum of the heat loss through walls Φ_p and the heat loss through ventilation Φ_v minus the permanent heat gains Φ_z [11]

$$\Phi_c = \Phi_p + \Phi_v - \Phi_z \qquad (1.70)$$

The heat loss through walls is determined from the (basic) heat loss by adding allowances according to

$$\Phi_p = \Phi_o \cdot (1 + p_1 + p_2 + p_3) \qquad (1.71)$$

where Φ_o is the basic heat loss through heat transfer (W), p_1 is the surcharge to compensate for the effect of cold structures (-), p_2 is the surcharge to accelerate the heating (-), and p_3 is the surcharge to the cardinal direction (-).

The basic heat loss Φ_o is equal to the sum of the heat fluxes through the individual walls enclosing the heated room to the outside environment or adjacent rooms.

$$\begin{aligned}\Phi_o &= \alpha_1 \cdot S_1 \cdot (\vartheta_i - \vartheta_{e1}) + \alpha_2 \cdot S_2 \cdot (\vartheta_i - \vartheta_{e2}) + \ldots \\ &+ \alpha_n \cdot S_n \cdot (\vartheta_i - \vartheta_{en}) = \sum_{j=1}^{n} \alpha_j \cdot S_j \cdot (\vartheta_i - \vartheta_{ej})\end{aligned} \qquad (1.72)$$

where S_j is the area of the wall to be cooled (m^2), α_j is the heat transfer coefficient (W·m^{-2}·K^{-1}), ϑ_i is the calculated internal temperature (°C), ϑ_{ej} is the temperature on the outside of the j-th wall (°C).

If the temperature on the outside of one of the walls is higher than the temperature in the heated room, the heat flux through this wall is negative. In this case, the heat gain Φ_z, which reduces the basic heat loss Φ_o.

Tab. 1.11 shows the values of the calculated indoor temperature ϑ_i for different room types.

Type of heated room	Internal temperature ϑ_i (°C)
living room, like a living room	
bedrooms, study rooms, children's rooms	20
kitchens	20
bathrooms	24
toilets	20
hallways, corridors	15

Tab. 1.11 Calculated indoor temperature values ϑ_i for different room types

The cold wall allowance p_1 allows the indoor air temperature to be raised so that the desired indoor temperature ϑ_i, for which the basic heat loss is calculated, is achieved in the heated room at the lower surface temperature of the cooled walls ϑ_p. This allowance depends on the average heat transfer coefficient α_c of all the walls of the room, which can be expressed by

$$\alpha_c = \frac{\Phi_o}{\sum S \cdot (\vartheta_i - \vartheta_e)} \qquad (1.73)$$

where $\sum S$ is the total area of all structures that enclose the heated room (m^2), ϑ_e is the calculated outdoor temperature for a specific area given by the standard (°C).

The premium to compensate for the effect of cold structures p_1 can then be determined from the relation $p_1 \sim 0.15\text{-}\alpha_c$ or approximately determined from Tab. 1.12.

α_c (W·m^{-2} ·K)$^{-1}$	up to 0.1	0,1 - 0,9	0,9 - 1,5	1,5 - 2,0
p_1	0	0,03 - 0,12	0,15 - 0,21	0,25 - 0,30

Tab. 1.12 Allowance to compensate for the effect of cold structures p_1

The surcharge for accelerating the flooding p_2 is only taken into account in residential construction, hospitals, etc. in cases where uninterrupted heating operation cannot be ensured even at the lowest outside temperatures. Under normal circumstances, the p_2 surcharge is not taken into account. For intermittent operation, it is selected according to the heating time as follows p_2 = 0.1 for daily heating times longer than 16 hours, p_2 = 0.2 for daily heating times shorter than 16 hours.

The position of the most cooled building structure of the room determines the amount of the surcharge to the world side p_3, in case of more cooled structures the position of their common corner. The values of the surcharge p_3 are given by Tab. 1.13.

Cardinal direction	S	SW	W	NW	N	NE	E	SE
p_3	-0,05	0	0	0,05	0,1	0,05	0,05	0

Tab. 1.13 Markup amount p_3 by cardinal direction

The ventilation heat loss Φ_V expresses the heat loss due to natural ventilation by infiltration or forced ventilation by negative pressure and is calculated according to the relation

$$\Phi_V = c_V \cdot V_V \cdot (\vartheta_i - \vartheta_e) \qquad (1.74)$$

where c_V is the volumetric heat capacity of air at 0 °C, $c_V = 1300\ J \cdot m^{-3} \cdot K^{-1}$, V_V is the volume flow of ventilation air ($m^3 \cdot s^{-1}$).

As can be seen, the calculation of heat losses of buildings according to ČSN 06 0210 is quite complex. For a preliminary estimation of heat losses, when deciding on the heating method, it is sufficient to use the approximate determination of heat losses according to Tab. 1.14. The table gives the heat loss per 1 m^3 of heated space. The total heat loss of the building is then equal to the sum of the heat losses of the individual rooms [10].

Method of cooling rooms	Heat loss (W)
Middle room (both sides of the heated room):	
a) above an unheated cellar and protected from above by a heated room	34 - 47
b) above the heated room and above the heated room	30 - 40
c) above the heated room and cooled from above by the soil	37 - 53
Corner room with windows in both walls:	
a) above an unheated cellar and protected from above by a heated room	40 - 58
b) above the heated room and protected from above by the heated room	35 - 49
c) above the heated room and cooled from above by the soil	44 - 65
d) above an unheated cellar and cooled from above by the soil	47 - 73
Bathroom	40 - 80
Lobby	15 - 30
Staircase	18 - 35
Average heat loss in 1 m^3 of heated space of a family house	35 - 60

Tab. 1.14: Approximate determination of heat losses

Calculation of heat losses - Standard EN 12831

Standard [12] sets out the procedure for calculating the heat supply required for heating and achieving the required internal temperature. A new element is the inclusion of thermal bridges, whereas the standard does not consider any heat gains. This can be a problem in the calculation for low-energy to passive houses.

$$\Phi_i = \Phi_{T,i} + \Phi_{V,i} \qquad (1.75)$$

where Φ_i is the heat loss through penetration and ventilation (W), $\Phi_{T,i}$ is the proposed heat loss through construction (W), $\Phi_{V,i}$ is the proposed heat loss through ventilation (W).

Heat loss through penetration and thermal bridges

The design heat loss through the penetration is determined by the relationship

$$\Phi_{T,i} = (H_{T,ie} + H_{T,iue} + H_{T,ig} + H_{T,ij}) \cdot (\vartheta_{int,i} - \vartheta_e) \qquad (1.76)$$

where $H_{T,ie}$ is the heat loss through penetration directly to the outdoor environment (W-K^{-1}), $H_{T,iue}$ is the heat loss through the unheated space (W-K^{-1}), $H_{T,ig}$ is the heat loss through penetration to the soil (W-K^{-1}), $H_{T,ij}$ is the heat loss through a space heated to a significantly different temperature (W-K^{-1}), $\vartheta_{int,i}$ is the design indoor temperature (°C), ϑ_e is the design outdoor temperature (°C).

The term thermal bridge is the main new feature of the new standard and characterises the heat loss through the wall at the point of contact between two different structures. The thermal bridge is characterised by the linear heat transfer coefficient (W·m^{-2}·K^{-1}) and also by its length (m).

$$H_{\mathrm{T,ie}} = \sum_k S_k \cdot U_k \cdot e_k + \sum_l \Psi_l \cdot l_l \cdot e_l \qquad (1.77)$$

where S_k is the area of the building part in m^2, e_k, e_l are the weathering correction factors (-), U_k is the heat transfer coefficient of the building part in W·m^{-2}·K^{-1}, l_l is the length of the thermal bridge in m, ψ_l is the heat transfer coefficient of the thermal bridge in W·m^{-1}·K^{-1}.

Heat loss by ventilation

To determine the heat loss through ventilation, we should base our considerations on the following equation:

$$\Phi_{\mathrm{V,i}} = H_{\mathrm{V,i}} \cdot (\vartheta_{\mathrm{int,i}} - \vartheta_{\mathrm{e}}) \qquad (1.78)$$

where V_i is the air exchange in the heated space (m^3 ·h^{-1}).

For the determination of V_i it is particularly important whether the ventilation is natural or forced. In natural ventilation, sufficient air exchange is determined by infiltration through the building envelope and the hygienic amount of air that must be exchanged.

$$V_{\mathrm{min,i}} = n_{\mathrm{min}} \cdot V_{\mathrm{i}} \qquad (1.79)$$

where n_{min} is the minimum outdoor air exchange rate per hour (h^{-1}), V_i is the volume of the heated room (m^3).

The minimum air exchange rate is 0.5 for the basic living room and 1.5 h^{-1} for the bathroom.

Proposed thermal power

$$\Phi_{\mathrm{HL,i}} = \Phi_{\mathrm{T,i}} + \Phi_{\mathrm{V,i}} + \Phi_{\mathrm{RH,i}} \qquad (1.80)$$

where $\Phi_{HL,i}$ is the design heat output (W), $\Phi_{T,i}$ is the heat loss through the structure (W), $\Phi_{V,i}$ is the heat loss through ventilation (W), $\Phi_{RH,i}$ is the flood power required during intermittent heating (W).

Evaluation of the comparison of standards CSN 06 0210 and CSN EN 12831

The biggest difference in both standards is the heat loss through the structure, which is mainly distinguished by the presence or absence of thermal bridges. Another element that differentiates the standards is the absence of heat gains in the calculation in EN 12831, either permanent (presence of humans) or variable (solar radiation).

It is therefore necessary to approach the calculation in great detail to ensure the correct design of the heat source to maintain the optimal ratio of investment to operating costs, because under dimensioning will result in investment savings at the expense of higher operating costs and vice versa.

Calculation of heating input

For the calculation of the heat source input power, the chosen method of electric heating, the heating mode at nominal or damped temperature, and the method of forced ventilation are decisive. The actual installed electrical input of the heaters may be higher than the calculated total input maximum:

- 20 % for power input up to 50 kW,
- 10 % for power inputs higher than 50 kW.

If the calculated input power of the electric heater is within the first third of the difference in input power of the heater type series, the type with the lower input power shall be selected. The calculation of the heating input has its specifics for each type of electric heating. In the following we will discuss the calculation of heating input separately for direct, storage and mixed (hybrid) electric heating systems.

Direct electric heating

The input power of a convection or radiant heater P_k is determined from the relationship

$$P_\mathrm{k} = \Phi_\mathrm{c} \cdot \mathrm{K} \qquad (1.81)$$

where P_k is the input power of the convection or radiant heater (W), Φ_c is the total heat loss of the building (W), K is the heating process coefficient, a value of 1.0 is selected for continuous operation, 1.1 for heating breaks up to 4 hours, 1.2 for breaks longer than 4 hours, 1.4 for intermittent use.

Storage electric heating

This heating method uses electricity consumption during selected, usually low tariff hours (charging from 10 pm to 6 am) and in justified cases during selected daytime hours (charging after 2 hours or more). The input of the storage heat source can be determined from the total daily heat demand Φ_d , which depends on the total heat loss per hour Φ_c , the required heating time to full temperature t_v and the damped heating time t_t . The heating time t_v includes the ramp-up time to the required temperature. The electrical input power is the same for continuous and staggered charging time t_n = 8 hours.

The heating operating modes for the calculation of the heat source input are determined from the full heating time t_v at ϑ_i = 20 °C. The accumulate heating is designed for the operating mode given by the time t_v (h) kitchen 10 h, kitchen with dining room 12 h, living rooms 14 h, children's rooms 14 h, other rooms 12 h. The sizing of accumulate heaters is carried out according to the relation

$$P_\mathrm{a} = \Phi_\mathrm{d} \cdot \mathrm{k_v} \qquad (1.82)$$

where P_a is the power input of the accumulate heater (stove) (W), k_v is the coefficient of operation (h^{-1}) see. Tab. 1.15

Heating break t_s (h)	Traffic coefficient k_v (h^{-1})		
	Dynamic with fan III.	Static with control damper II.	Static without control damper I.
0	0,14	0,18	0,20
2	0,15	0,23	---
4	0,17	0,31	---
6	0,19	(0,50)	---
8	0,22	(1,25)	---

Tab. 1.15 Operating coefficient value

The daily heat demand is then

$$\Phi_d = \Phi_c \cdot t_v \tag{1.83}$$

Electric central accumulate heating is proposed for full heating for 12 hours. The remaining daytime operation is either dimmed or intermittent. The total daily heat demand Φ_d for hot water systems shall be determined according to the following formula

$$\Phi_d = \Phi_{dd} + \Phi_{dn} \tag{1.84}$$

$$\Phi_{dd} = \frac{\Phi_c}{\eta} \cdot (t_{vd} + t_{td} \cdot f) \tag{1.85}$$

$$\Phi_{dn} = \frac{\Phi_c}{\eta} \cdot (t_{vn} + t_{tn} \cdot f) \tag{1.86}$$

where Φ_{dd} is the daytime heat demand (Wh), Φ_{dn} is the low tariff heat demand (Wh), t_{vd} is the required heating time to full temperature in daytime (h), t_{vn} is the required heating time to full temperature in low tariff (h), t_{td} is the required damped heating time in daytime (h), t_{tn} is the required damped heating time in night time (h), f is the building structure influence coefficient, considered equal to 0.3 for heavy, 0.4 for medium and 0.5 for light structure, η is the heating system efficiency of 0.95.

The required input power is then determined by the formula

$$P_a = \frac{\Phi_d}{t_n} \tag{1.87}$$

Mixed (hybrid) electric heating

Mixed heating consists of a storage part and a direct heating part. The accumulate heating system draws electricity for a maximum of 8 hours per day during night time hours set by the electricity supplier. Direct heating operates at lower outdoor temperatures during off-peak times of the day (e.g. 11am to 5pm).

Mixed heating makes it possible to connect more electric heating equipment to the existing grid, as the consumption rate is lower than for pure accumulate heating. It is also important to reduce the size of the equipment and thus the purchase costs.

The design of the electric hybrid heater is carried out separately for the storage part and for the direct heating part.

$$P_{\mathrm{h}} = 0{,}6 \cdot P_{\mathrm{a}} \tag{1.88}$$

where P_h is the power input of the hybrid heater (W), P_a is the power input of the accumulate heater calculated according to the relation for accumulate heaters and for the charging time T_n = 8 hours (W).

The direct heating part of the hybrid heater shall be determined according to

$$P_{\mathrm{ph}} = 0{,}4 \cdot P_{\mathrm{a}} \tag{1.89}$$

However, the input of the direct heating part must cover at least 90 % of the heat loss of the room. The central accumulate heat source for mixed heating shall be sized at 60 % of the input of a pure accumulate central heating system with an eight-hour charging time. The input power of the direct heating part of the hybrid system shall be at least 10 % higher than the heat loss of the room and shall be about half the input power of a pure accumulate source with an eight-hour charging period.

Electric heating systems

The irregularity of daily consumption, resulting from the normal rhythm of human life, has led to an attempt to use the available power plant capacity during off-peak periods. This made possible the introduction of accumulate appliances for heating or hot water, which were switched on only at night. However, further developments have shown that with only storage heat, the possibilities of the electricity system would soon be exhausted, which is why today the electricity industry also offers direct heating and hybrid systems.

Storage electric heating

This heating method uses electricity consumption during selected, usually low tariff hours (charging from 10 pm to 6 am) and in justified cases during selected daytime hours (charging after 2 hours or more).

The electrical energy is converted into heat in resistance heating cells or cables that are stored in the accumulate material. This takes the form of a heater, boiler or is a concrete part of a building structure, usually a floor. Heating requires a reliable knowledge of the heating time t_v to the calculated internal temperature ϑ_i , which includes the so called ramp-up time to full temperature and the damped heating time t_t .

There are several possible ways of electric accumulate heating.

Storage heaters

Magnesite and fireclay are generally used as the accumulation material. Three types of accumulate heaters are distinguished according to their design and the way the heat is shared during room heating (discharge of the heater), as shown in Fig. 1.64.

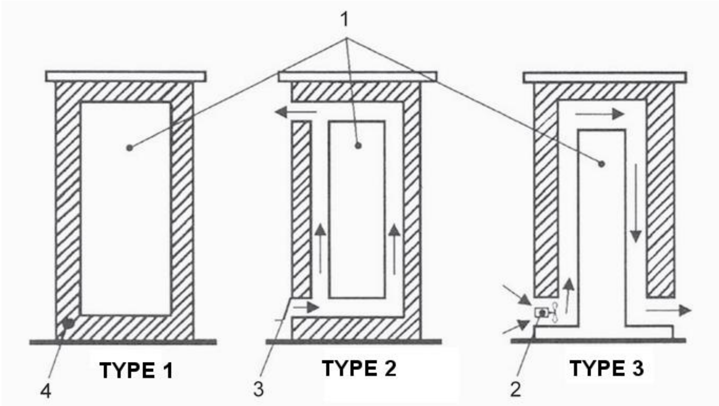


Fig. 1.64 Three types of accumulate heaters

1 - accumulation substance, 2 - fan, 3 - control damper, 4 - thermal insulation

Electric accumulate central heating consists of a traditional hot water heating system - an electric, usually resistive heat source and a water accumulator. The heat is transported from the accumulator to the heated room. This suppresses the basic principle of electric heating, which is to bring the energy up to the heated room with maximum controllability of its conversion.

Another possible type of accumulate heating is the so-called large-area underfloor accumulate heating. The heat source is heating cables laid in the concrete screed of the floor construction. The surface temperature of the floor shall not exceed 25 °C. Long service life and a guarantee are prerequisites for the application of the heating system.

A purely accumulate system of electric underfloor heating, charged exclusively by the night current for 8 hours, is particularly suitable for new and renovated buildings used only in the morning, at most in the early afternoon. It is not suitable for rooms heated all day. It is characterised by good thermal insulation underneath (combination of polystyrene foam and mineral fibre insulation) and, in particular, by the large thickness of the accumulation plate (90 to 150 mm). The heating plane with heating cables is placed in the lower half of the accumulation plate Fig. 1.65.

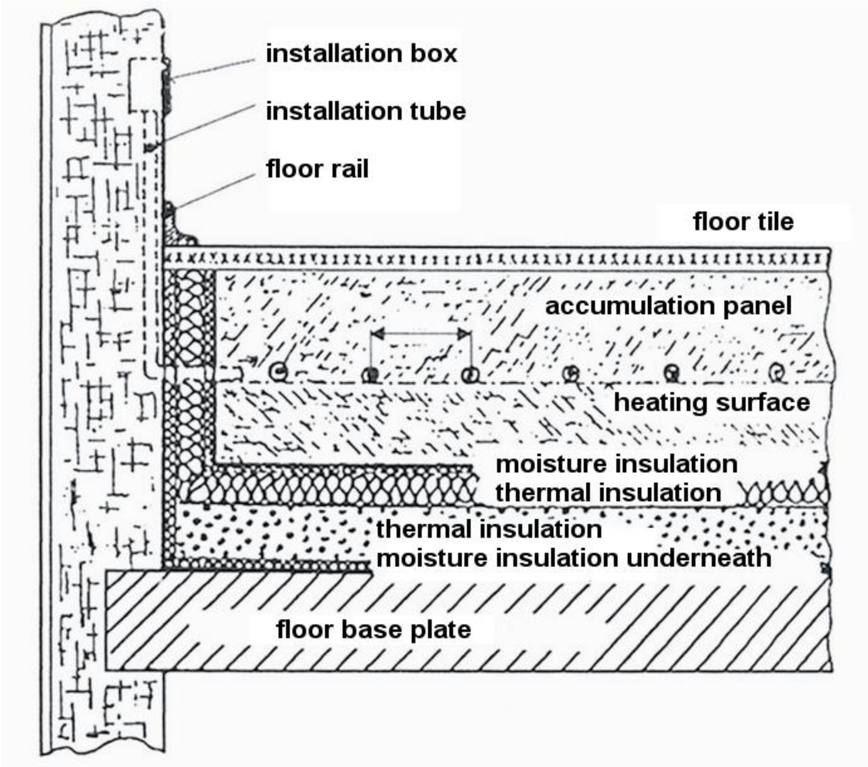


Fig. 1.65 Storage electric underfloor heating

❑ Direct electric heating

It consists of a distribution system, direct-fired heaters with heating elements or electrodes and a control circuit to ensure the optimum heating cycle. Depending on the location of the heat source and the method of heat sharing, electric direct heating systems can be classified as follows:

Local

- convectors and hot air heaters,
- electric underfloor heating cables,
- radiant heating systems.

Central

- hot water electric boilers.

Convection electric heating

Convector heaters are electric heaters that convert all the electricity supplied into heat. Cold air enters the convector from the bottom and heated air leaves from the top, which then heats the whole room by natural circulation Fig. 1.66.

Natural convection heaters are mobile, portable or designed for fixed installation on the wall. They are either radiators with a heated cartridge, usually oil, or convector heaters with heating resistance. These are usually tubular stainless steel heating elements with pressed aluminium fins, adapted for quiet operation. The ambient air is heated by natural convection around the heating element. Modern convector heaters are equipped with a high quality control system with the possibility of central control of their operation. Forced convection heaters are portable or wall-mounted direct-heating appliances in which the air is blown past the heating resistors by means of a fan.

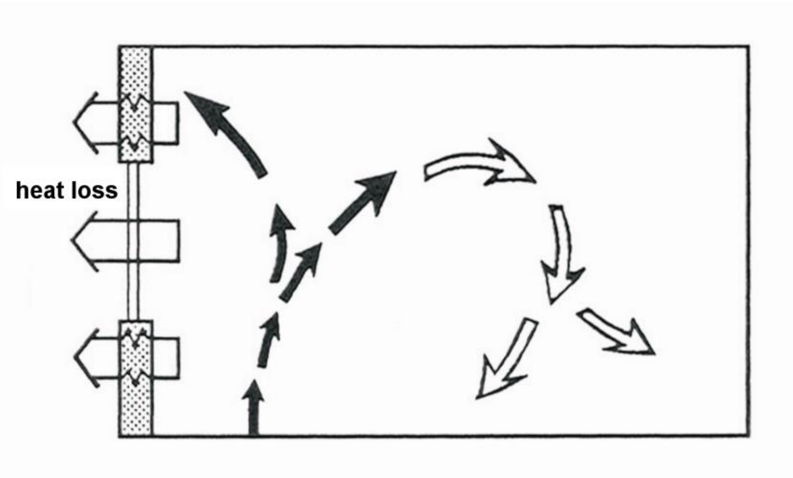


Fig. 1.66 Air circulation in the room

Underfloor heating with heating cables

Large-scale floor systems, made by pouring special electric heating cables into the concrete floor, are Fig. 1.67, are popular mainly because of their high efficiency, even heat distribution over the whole area, excellent use of the heated space, relatively easy implementation and the creation of thermal comfort at a lower air temperature than e.g. convectors.

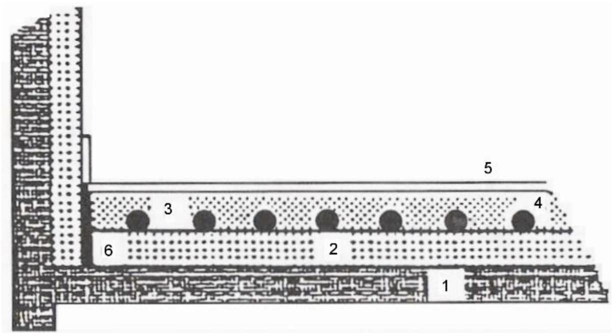


Fig. 1.67 Underfloor heating with heating cables

1-base concrete, 2-polystyrene (about 40 mm), 3-concrete layer (30-50 mm), 4-heating cables, 5-paving, 6-insulation connection

Radiant electric heating

While in convection heating the body is heated mainly by air, which transfers heat by flowing over the surface of the heated object, in radiant heating the heat is transferred mainly by radiation Fig. 1.67. Each body radiates electromagnetic energy into its surroundings. Of the wide range of wavelengths, we are interested only in those that can be absorbed by objects and converted into thermal energy.

Radiant heaters may be infrared radiant heaters where the heating element has a surface temperature greater than 250 °C and the radiation is directed by a reflector in a specified direction.

Low-temperature radiant heating is provided by radiating the surface of surfaces heated to 25 to 40 °C. Special foils or panels are usually fixed to the ceiling and walls. In a room heated in this way, the air temperature and relative humidity are lower than with convection heating. The energy consumption is also lower, mainly due to heating to a lower desired room temperature. The energy savings compared to convection heating are roughly between 18 and 24 %.

The use of radiant panels is very wide. They are intended for creating thermal comfort of workshops with clearance heights up to 3.2 m, for breeding of blooded animals, tempering of greenhouses, etc. Panels with lower power ratings are intended for heating residential premises.

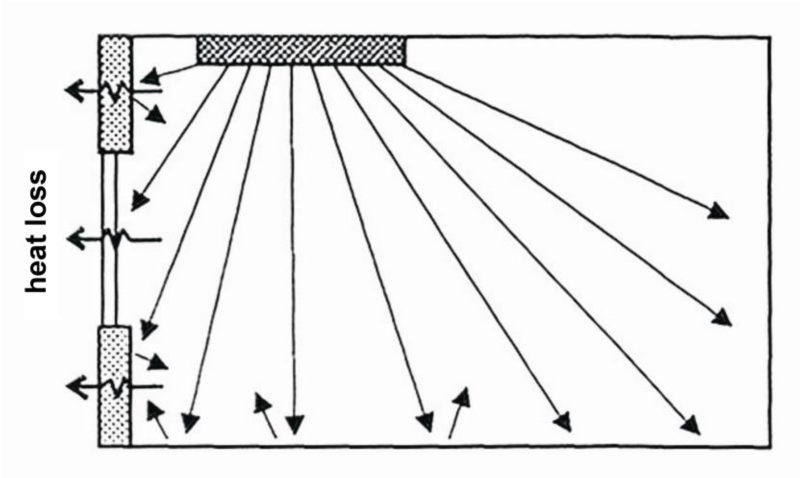


Fig. 1.68 Radiant electric heating

Heating with hot water electric boilers

Electric boilers can be used for heating new buildings, but they are also very suitable as a replacement for solid fuel boilers in central heating systems of family houses and terraced houses.

Hot-water electric boilers - the heating medium is water, which is heated in a closed vessel, the boiler, from which it is then piped to radiators or similar equipment in individual rooms. The heating of the water in the boiler is provided either by heating elements based on the resistive principle, i.e. a classical resistance boiler, or by electrodes, i.e. an electrode boiler, in which heat is generated by the passage of an electric current through the water (electrolyte) between the electrodes.

❑ Mixed (hybrid) electric heating

Mixed heating consists of a storage part and a direct heating part. The storage heating system draws electricity for a maximum of 8 hours per day during night time hours set by the electricity supplier. The direct part of the heating system operates at lower outdoor temperatures during off-peak hours of the day. It can be assumed that in future years this type of electric heating will find many more users than it has done so far.

Mixed heating systems can be designed as follows:

- electric hybrid heater,
- combination of central storage heating with direct heaters,
- combination of large area underfloor storage heating with direct heaters.

Mixed heating allows more electric heating equipment to be connected to the existing grid, as the consumption rate is lower than for pure storage heating. It is also important to reduce the size of the equipment and thus the purchase costs.

The central storage heat source for mixed heating shall be sized at 60% of the input power of pure storage central heating with an eight-hour charging time. The input power of the direct heating part shall be at least 10 % higher than the heat loss of the room and shall be about half of the input power of a pure storage source with eight hours charging.

Issues of automatic heating control

The purpose of automatic control is to maintain a physical variable that is subject to change at a desired value without human intervention. In room heating, this variable is usually the internal temperature of the room. Maintaining the quantity at the desired value can be achieved by:

- by measuring the actual value of the controlled variable (in this case temperature),
- by comparing the measured actual value with the desired (set) value,
- by acting on the regulated variable (temperature or water flow) to reduce the detected difference.

For the design of the control device it is necessary to know:

- user requirements,
- basic characteristics of the building structure and heating system,
- applicable regulations.

The requirements of the flat user are generally expressed in terms of the indoor temperature required in the whole or part of the house or flat or in individual rooms whose use is known. The basic characteristics of a building include knowledge of the magnitudes of heat loss expressed by the thermal performance of the building and knowledge of the storage properties of the structure.

The type of heating system is selected according to the heat loss of the building. The storage properties will influence the design of the heating system with regard to the selection of the control device so that the temperature control is stable and accurate. The characteristics of the heating system make it possible to specify:

- the required heat output of the heating surface to cover the heat losses,
- the response time of the heating system when the internal temperature changes, allowing the selection of the control device.

Selected response times of the heating system:

- cast iron heating 20 min to 1 hour,
- steel heating 10 min to 20 min,
- convector 5 min to 10 min,
- large floor heating area 2 to 5 hours.

In all heating systems, with the exception of large-area heating, it is possible to use control according to the indoor air temperature. In some cases, the output of the heating system is controlled according to the outside temperature. The control is based on a predetermined dependence of the output on the outdoor temperature and is not controlled by the indoor temperature. Therefore, outdoor temperature control should be supplemented by indoor temperature control.

Control circuits

The control device consists of the following parts:

- a sensor that measures the actual value of the regulated variable, usually temperature, and converts it into a physical quantity (electric current or voltage) that can be easily and conveniently processed in the controller,
- a controller, in which the actual value of the regulated variable (temperature) is compared with the desired setpoint, can be built into the control part or sensor,
- the control part that carries out the control (e.g. electrically operated mixing valve or contactor that disconnects the electric heating appliance from the mains).

Closed control circuit

In a control circuit, there are three basic variables: the controlled, control and fault variables. The controlled variable is the internal temperature. The disturbance variables affect the controlled variable (heat loss, heat gain, wind).

The controller evaluates the actual value of the regulated variable (setpoint) and the value of the control variable. The resulting control deviation is processed in the controller, which sends a signal to the controlling authority. The change in the output of the body is reflected by a change in the internal air temperature and the sensor registers the changed temperature value. The circuit is closed.

Closed feedback control circuit

The added feedback makes it possible to predict the response and thus accelerate the action of the regulation. For example, the heating water supply temperature (auxiliary value) is sensed and fed into the controller. This feedback control circuit is used for individual indoor air temperature control. Simple and inexpensive ways of controlling the indoor temperature with a room thermostat with feedback are used for flats.

Open control circuit

It is mainly used in central heating, if we know sufficiently the response of the regulated circuit to changes in outdoor temperature, which is the main fault variable. The auxiliary variable is the heating water temperature. It is therefore a circuit that is used in controlling according to the outdoor temperature. This simplification of the control process is conditional on the knowledge of the dependence of the outdoor temperature and the heating water temperature for a given indoor temperature in the rooms of the building. The circuit is used in central control of several rooms in one building. The change of each disturbance variable (temperature, wind, and glare) is sensed by a sensor and the information obtained is transmitted to the controller. The controller controls the control part according to the set dependencies of the disturbance variables on the controlled variable.

The whole control process is carried out according to the determined dependencies set in the controller and the accuracy and stability of the control depends on how accurately the dependencies have been determined and set. This control is also called equithermic control. For a given room, a set of so-called equithermic curves can be determined (also called "heating curves"), which describe the interdependence of the heating water temperature, the room temperature and the outside temperature. Based on the desired room temperature, a specific curve can be selected and the heating water temperature can be regulated according to the outside temperature.

Note

Throughout the chapter 1 uses verbatim quotations, figures and tables from the literature [13]. Additional information on the issues addressed in this chapter can be found in this book.

Summary of terms 1.5.

Heating, thermal comfort, thermal state of the environment, effective ambient temperature, heat loss, direct heating, storage heating, hybrid heating, heating control, equithermic control.

Questions 1.5.

1. Explain the concept of thermal comfort.
2. Write a relationship for the thermal equilibrium of a person.
3. What is the thermal state of the environment?
4. Draw the ideal vertical temperature distribution in the room.
5. What is the effective ambient temperature? Give the relationship for the calculation.
6. Write a relationship for the resulting ambient room temperature.
7. Draw what the thermal comfort zone looks like.
8. State the relationship for the total heat loss of a room Q_c .
9. List the basic types of electric heating.
10. List the possibilities of direct electric heating.
11. Describe the options for controlling electric heating.
12. What are equithermic curves?

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