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Faculty of Metallurgy and Materials Engineering



INDUSTRIAL FURNACES

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1. BASIC RELATIONS IN HEAT TRANSFER

Fundamentals of heat transfer are essential for understanding the heating of materials and technological systems of industrial furnaces. The following overview provides basic information necessary for a proper understanding of the problem of heat transfer. Therefore, this section is included as an introduction chapter, we can say as a refresher.

Motto:

1. The total energy in the universe is constant.
2. Energy can never be destroyed.
3. Energy can convert in different ways. Basic energy conversions are shown in Figure 1.1. Under the second law of thermodynamics, energy is transferred from a body with a higher temperature to bodies with lower temperature through the following types of heat transfer: conduction, convection, and radiation.

Chemical energy (food) → motion (jogging)
Chemical energy (fules) → car/vehicles motion
Radiant energy (sun) → chemical energy (photosynthesis)
Electical energy → thermal energy (electrical heating)

Fig. 1.1 Basic energy conversions



Study time: 20 hours



Objective

After reading this section, you should be able to

- Define basic concepts in heat transfer.
- Describe various mathematical equations related to heat conduction (1st and 2nd Fourier's law) and heat convection (determination of the convective heat transfer coefficient on the basis of a general criterion equation), as well as equations related to heat transfer through radiation (especially the Stefan-Boltzmann law).
- Understand the basic concepts of hydrodynamics and important equations that are used in fluid flow.

- Define the concepts of thermodynamics (1st and 2nd laws of thermodynamics, equation of state, reversible changes).



Presentation

Heat conduction in substances

Heat conduction takes place primarily in solids and also in liquid materials, which are not in motion.

The basis of heat conduction is the formation of a temperature field. The temperature field is generated when the temperature difference is present in material. The resulting temperature field spreads in all directions – i.e. in respective axes - x , y , z . Temperature field may or may not be time dependent. But there may be variations. Generally, the temperature field is described through following mathematical expression

$$t = f(x, y, z, \tau) \quad (^\circ\text{C})$$

The temperature field in the material with different temperatures creates a **heat field**. Areas with identical temperatures are created in the thermal field, which we call the **isothermal surfaces**. The temperature in the material can be varied in all directions. Increase (decrease) in temperature is given by the **temperature gradient**, which is a vector perpendicular to the isotherm and pointing to the side of the increase (decrease) in temperature,

$$\text{grad } t = \frac{\partial t}{\partial x} + \frac{\partial t}{\partial y} + \frac{\partial t}{\partial z} = \nabla t \quad (\text{K}\cdot\text{m}^{-1}), \text{ where } \nabla \text{ is Hamilton operator } (\text{m}^{-1}).$$

The amount of heat transferred through the isothermal surface over time is the **heat flux** P . The heat flux per unit area of the isothermal surface (per 1 m^2) is called the **heat flux density** q ($\text{W}\cdot\text{m}^{-2}$). The correlation is

$$P = q \cdot S \quad (\text{W})$$

The quantity of **heat** Q passing through the isothermal surface is given by a simple product of the heat flux P and time τ , i.e.

$$Q = P \cdot \tau = q \cdot S \cdot \tau \quad (\text{J})$$

Basic laws of heat transfer by conduction

The first Fourier's law – heat flux density is proportional to the negative of the temperature gradient

$$q = -\lambda \cdot \text{grad } t = -\lambda \cdot \left(\frac{\partial t}{\partial x} + \frac{\partial t}{\partial y} + \frac{\partial t}{\partial z} \right) \quad (\text{W} \cdot \text{m}^{-2})$$

The minus sign relates to the fact that heat is transferred from hotter areas to colder areas. The constant of proportionality is λ – **thermal conductivity coefficient** ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). Coefficient of thermal conductivity is a thermophysical property of the material and is a function of temperature.

Thermal conductivity coefficient can be expressed as the amount of heat that passes in a unit of time (1 sec) through a unit of isothermal surface (1 m^2) in a body with a unit temperature gradient ($\text{K } 1$), namely

$$\lambda = -\frac{Q}{\text{grad } t \cdot S \cdot \tau} \quad (\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1})$$

Thermal conductivity coefficient takes different values. For gaseous, liquid substances it is in the range of tenths and hundredths of $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. For solids, the situation is different. The coefficient depends on whether the material is conductive (metals), non-conductive (insulating materials), or a semiconductor, or whether it is a porous material (bricks, etc.). All the necessary values can be found in the material properties tables.

The second Fourier's law. Derivation of the equation for the second Fourier's law is not as easy as with the first law. However, again it is based on the knowledge of the temperature field. Determination of the final shape of the equation is based on a balance of the heat added and taken away from the material, provided that the material is homogeneous and isotropic, the physical properties of the material are constant, the internal volumetric sources are uniformly distributed in the material, and assuming that the action takes place at a constant pressure.

So the final shape of the second Fourier's law after complicated derivation is as follows

$$\frac{\partial t}{\partial \tau} = a \cdot \nabla^2 t + \frac{q_V}{c_p \cdot \rho} \quad (\text{K} \cdot \text{s}^{-1})$$

where ∇^2 is Laplace operator. The new variable is here a – **thermal diffusivity coefficient** $a = \frac{\lambda}{c_p \cdot \rho}$, the unit is $\text{m}^2 \cdot \text{s}^{-1}$. The thermal diffusivity coefficient is a thermophysical

property of a substance and characterizes the rate of change of the temperature field. The higher the value of a , the faster the change in the temperature on the surface is reflected within the body. Metallic substances have a greater thermal diffusivity coefficient than non-metals.

We can also write the second Fourier's law in the following (simplified) forms:

$$\frac{\partial t}{\partial \tau} = a \cdot \nabla^2 t + \frac{q_V}{c_p \cdot \rho} \quad (\text{K} \cdot \text{s}^{-1})$$

basic equation,

$$\frac{\partial t}{\partial \tau} = a \cdot \nabla^2 t \quad (\text{K} \cdot \text{s}^{-1})$$

the heat transfer by conduction is without internal volumetric sources

$$a \cdot \nabla^2 t + \frac{q_v}{\lambda} = 0 \quad (\text{K} \cdot \text{m}^{-2})$$

Poisson's equation for steady-state heat conduction with inner volumetric sources,

$$\nabla^2 t = 0 \quad (\text{K} \cdot \text{m}^{-2})$$

Laplace's equation for stationary heat conduction without internal volumetric sources

To solve the second Fourier's law or second order partial differential equation, defined simplifications, the so called **boundary conditions**, are used. We divide the boundary conditions to:

- geometric,
- physical,
- initial, and
- surface.

Geometric conditions – define the basic shape of the body - its dimensions. We always try to adapt the geometry of the body to be as simple as possible for calculation.

Physical conditions - are determined by the physical characteristics of the body - such as density, specific heat capacity, thermal conductivity coefficient, thermal diffusivity coefficient, viscosity, etc. These conditions must be known also as depending on the temperature, or pressure (chart).

The initial condition - characterizes the temperature distribution in the body at the beginning of a process at the time τ_0 . The initial condition for stationary processes (time-invariant) is not specified. It is specified if the temperature varies with time.

Surface conditions – are those which relate to the body surface. It is about what happens on the surface of the body or around the surface of the body. We distinguish five surface conditions.

The first (Dirichlet) surface condition – the temperature on the surface of the body is known. The temperature distribution over the surface t_{pov} is a function of coordinates and time.

$$t_{\text{pov}} = f(x, y, z, \tau)$$

The second (Neumann) surface condition – the heat flux density on the surface of the body is known. The distribution of heat flow density q over the surface of the body is a function of coordinates and time.

$$q = f(x, y, z, \tau)$$

The third (Fouriér) surface condition – the body with a temperature t_{pov} is in the environment with an ambient temperature t_{ok} . We know how the surrounding area behaves – the heat transfer coefficient α_c is known.

$$q = \alpha_c \cdot (t_{\text{pov}} - t_{\text{ok}})$$

The fourth surface condition – the contact of two bodies. Two different bodies are in perfect contact and their contact surfaces have the same temperature.

$$-\lambda_1 \cdot \left(\frac{\partial t_1}{\partial x} \right) = -\lambda_2 \cdot \left(\frac{\partial t_2}{\partial x} \right) \dots t_1 = t_2$$

The fifth surface contact – the phase transformation. It applies when the phase of material changes (e.g. solidification - conversion from a liquid to a solid).

$$-\lambda_1 \cdot \left(\frac{\partial t_1}{\partial x} \right) = -\lambda_2 \cdot \left(\frac{\partial t_2}{\partial x} \right) + \rho \cdot l \cdot \frac{\partial \xi}{\partial \tau},$$

where l is a specific latent heat ($\text{J} \cdot \text{kg}^{-1}$) and ξ is a thickness of the liquid phase (m).

Heat transfer during convection

Convective heat transfer takes place during *movement* of fluid with a simultaneous *exchange (sharing) of heat*, such as between the liquid and the solid – the flowing liquid adds or removes heat from the surface of the surrounding objects.

We divide convection into natural (free) and forced. **Natural convection** is most often caused by effect of the gravitational field on an unevenly warmed fluid. **Forced convection** is induced by an external intervention in the fluid.

Convection between the liquid and the solid – is the heat transfer from the wall to the fluid. In mathematics, this can be expressed as a specific heat flux q in the direction of the normal line n to the surface or as the equality of the first Fourier's law and Newton's law

$$q_{\text{konvekce}} = -\lambda \left(\frac{\partial t}{\partial n} \right) = \alpha_{\text{kon}} \cdot (t_{\text{povrch}} - t_{\text{tekutina}}),$$

where the convective heat transfer coefficient α_{kon} can be expressed from this equation as

$$\alpha_{\text{kon}} = -\frac{\lambda}{t_{\text{povrch}} - t_{\text{tekutina}}} \cdot \left(\frac{\partial t}{\partial n} \right) \quad (\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}).$$

The convective heat transfer coefficient is the amount of heat transferred in a unit of time between the liquid and the unit area of the wall surface, if the difference of temperatures between the surface and the fluid is 1K. The values of convective heat transfer coefficient vary between different limits according to the character of a process.

The calculation of the heat transfer coefficient is based on physical modelling and is determined using criteria, or a general criterion equation

$$Nu = f(Re, Gr, Pr, Fo, Po, \xi_x, \xi_y, \xi_z) \quad (1),$$

where ξ_x, ξ_y, ξ_z are dimensionless coordinates.

The meaning of various criteria is shown in the following table.

Criterion	Symbol	Formula	Text
Nusselt's	Nu	$Nu = \frac{\alpha_{kon} \cdot l}{\lambda}$	Convective heat transfer
Reynolds's	Re	$Re = \frac{v \cdot l}{\nu}$	The ratio of inertial forces to viscous forces
Grashoff's	Gr	$Gr = \frac{g \cdot \gamma \cdot \Delta T \cdot l^3}{\nu^2}$	Natural convection of real (viscous) fluid
Prandtl's	Pr	$Pr = \frac{\nu}{a}$	Heat transfer in liquids
Fouriér's	Fo	$Fo = \frac{a \cdot \tau}{l^2}$	The speed of heat propagation in a body Dimensionless time
Pomerancev's	Po	$Po = \frac{q_v \cdot l^2}{\lambda \cdot \Delta T}$	Temperature field with an internal volumetric source

Criterion equations are then applied to the individual processes for natural or forced convection. Such processes can be the natural convection both in open and in restricted spaces, forced convection during the flow in pipes and channels, along a flat plate, transverse bypassing of pipes, etc.

Heat transfer through radiation

Heat transfer through radiation is the third type of heat transfer. Unlike those two earlier described types of heat transfer, the radiation heat transfer is not bound to a physical environment, which means that radiation can take place even in a vacuum.

Radiation heat transfer is carried out by electromagnetic waves that travel at the speed of light. We distinguish between two theories of the behaviour of light - wave theory and corpuscular (particle) theory, i.e. the light is actually both a wave and a particle, hence the *wave-particle* duality of light. Under certain circumstances, the light can be described using a classical **electromagnetic theory** (wave/Maxwell), i.e. the propagation of light, refraction, reflection, diffraction, etc., in other cases it is necessary to use a **quantum** (corpuscular) **theory** (the interaction of light and matter, laser, etc.). **Light** is an electromagnetic radiation with a wavelength between 390 nm and 760 nm.

The amount of radiated energy depends on the temperature of the body. Body, which emits (absorbs) at each wavelength the maximum possible amount of radiant energy for a particular temperature is called a **black body**. Because black body does not in fact exist, the concept of a **grey body** was introduced. At the same temperature and wavelength, the greybody radiation is smaller than the blackbody radiation.

The **basic laws** of radiation heat transfer include:

Planck's law: "The intensity of radiation from a black body is dependent upon the wavelength. For each temperature, there is a maximum emitted energy at a certain wavelength". The intensity of black body radiation

$$E_{0,\lambda} = \frac{c_1}{\lambda^5 \cdot \left(e^{\frac{c_2}{\lambda \cdot T}} - 1 \right)} \quad (\text{W} \cdot \text{m}^{-3}), \quad c_1 = 3,7412 \cdot 10^{-16} \text{ W} \cdot \text{m}^{-2}, \quad c_2 = 1,4388 \cdot 10^{-2} \text{ m} \cdot \text{K},$$

Wien's displacement law: "With higher temperatures, the peak of radiated energy shifts to shorter wavelengths". The intensity of black body radiation

$$E_{0,\lambda,\max} = 1,286 \cdot 10^{-5} \cdot T^5 \quad (\text{W} \cdot \text{m}^{-3}).$$

Stefan-Boltzmann law: "The intensity of black body radiation is proportional to the fourth power of its thermodynamic temperature". The intensity of black body radiation

$$E_0 = \sigma \cdot T^4 \quad (\text{W} \cdot \text{m}^{-2}) \quad \sigma = \frac{c_1 \cdot \pi^4}{c_2^4 \cdot 15} = \frac{3,7415 \cdot 10^{-16} \cdot \pi^4}{(1,4388 \cdot 10^{-2})^4 \cdot 15} = 5,67 \cdot 10^{-8} \text{ (W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}),$$

For grey bodies, it applies that

$$E = \varepsilon \cdot E_0 = \varepsilon \cdot C_0 \cdot \left(\frac{T}{100} \right)^4 \quad (\text{W} \cdot \text{m}^{-2}).$$

where ε is the emissivity of a material (1)

Lambert's law describes the radiation of energy into each half-space direction.

Kirchhoff's law describes the interdependence between emissivity ε and absorptivity A of a body.

$$A = \varepsilon = \frac{E}{E_0} = \frac{E}{\sigma \cdot T^4} \quad (1)$$

Radiant flux between the two bodies having different surface temperatures, different surface areas and different emissivities

$$P_{12} = \frac{C_0}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \cdot \varphi_{12} \cdot S_1 \quad (\text{W}).$$

The formula for composite emissivity has the following shape

$$\varepsilon_n = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

Basic equations of hydrodynamics

Hydrostatics deals with the balance of forces acting on the fluid at rest. This balance occurs when the particles do not move towards each other, i.e. the shape of the fluid volume does not change. The forces that can act on the fluid are the *weight* and *pressure*.

Hydrodynamics describes the fluids in motion and forces in addition to weight and pressure are the *friction forces* F_t and *inertial forces* F_s .

The table shows equations used in fluid mechanics.

Equation name	Equilibrium of forces	Resulting equation
<i>Euler's equation of hydrostatics</i>	$F_m + F_p = 0$	$\bar{a} - \frac{1}{\rho} \text{grad } p = 0$
<i>Euler's equation of hydrodynamics</i>	$F_m + F_p = F_s$	$\bar{a} - \frac{1}{\rho} \cdot \text{grad } p = \frac{d\bar{v}}{d\tau}$
<i>Continuity equation</i>	----	Steady flow $\rho \cdot S \cdot v = \text{konst.} = Q_m$ $S \cdot v = \text{konst.} = Q_v$
<i>Navier – Stokes's equation</i>	$dF_p + dF_m + dF_t = dF_s$	$\bar{a} - \frac{1}{\rho} \cdot \text{grad } p + \nu \cdot \nabla^2 v = \left(\frac{d\bar{v}}{d\tau} \right)$
<i>Bernoulli's equation</i>	$dF_p + dF_m = dF_s$	$h \cdot g \cdot \rho + p + \frac{v^2 \cdot \rho}{2} = \text{konst.},$ $h + \frac{p}{g \cdot \rho} + \frac{v^2}{2 \cdot g} = \text{konst.},$

Basic relations in thermomechanics

The first law of thermodynamics (it is generally valid for both the ideal and real gas). The principle of conservation of energy: The amount of energy in a closed system is constant. The principle of equivalence: Heat can be converted into mechanical work, and vice versa, according to a particular mathematical relationship.

1st mathematical formulation:

$$dq = du + da = c_v \cdot dT + p \cdot dI$$

Heat transferred = internal energy + volume work

2nd mathematical formulation:

$$dq = di + da_i = c_p \cdot dT + v \cdot dT$$

Heat transferred = enthalpy + technical work

The internal energy is given by the kinetic and potential energies of molecules. At heat transfer of dq for 1 kg of gas, its temperature changes by dT and its volume by dV . The temperature change is related to changes in the internal kinetic energy. With the change of volume, the internal potential energy is modified.

Enthalpy is the sum of internal (thermal) energy and external (mechanical) energy given by the pressure and volume of the working substance.

The equation of state for an ideal gas

For conversion to a different state: $\frac{p_1 \cdot V_1}{T_1} = \frac{p_2 \cdot V_2}{T_2} = \frac{p_n \cdot V_n}{T_n}$

For 1 kg of gas: $p \cdot v = r \cdot T$ where: $r = \frac{R}{M}$

For gas of mass m : $p \cdot V = m \cdot r \cdot T$

For one kmol of gas: $p \cdot V_m = R \cdot T$ where: $R = 8314 \text{ J.kmol}^{-1} \cdot \text{K}^{-1}$

For amount of substance n : $p \cdot V = n \cdot R \cdot T$

the molar gas volume in the normal state - $V_{m,n} = 22.4 \text{ m}_n^3 \cdot \text{kmol}^{-1}$

when converted to normal conditions: pressure $p_n = 101325 \text{ Pa}$, $T_n = 0^\circ\text{C}$

Equations of state are generally all the equations that each weighs the state quantities in steady state. These quantities are - temperature, pressure, and volume.

The relations for the specific heat capacities of an ideal gas

$$c_p - c_v = r \quad k = \frac{c_p}{c_v}$$

$$c_v = \frac{r}{k-1} \quad c_p = \frac{r}{k-1} \cdot k \quad [\text{J.kg}^{-1} \cdot \text{K}^{-1}]$$

$k = 1.66$ for monoatomic gases

$k = 1.4$ for biatomic gases

$k = 1.33$ to 1.3 for triatomic and multiatomic gases

Thermodynamic changes - Overview of reversible changes of state of an ideal gas

Isochoric change - change at a constant volume

1. $v = \text{const.}$ $v_1 = v_2$
2. Charles's law: $\frac{p_2}{p_1} = \frac{T_2}{T_1}$
3. $a = 0$
 $a_t = v \cdot (p_1 - p_2)$

$$4. q = u_2 - u_1 = c_v \cdot (T_2 - T_1)$$

Isobaric change - change at a constant pressure

1. $p = \text{const. } p_1 = p_2$
2. Gay-Lussac's law: $\frac{v_2}{v_1} = \frac{T_2}{T_1}$
3. $a = p \cdot (v_2 - v_1)$
 $a_t = 0$
4. $q = c_p \cdot (T_2 - T_1)$

Isothermal change - change at a constant temperature

1. $T = \text{const. } T_1 = T_2$
2. Boyle's law: $v_1 \cdot p_1 = v_2 \cdot p_2 = v \cdot p = \text{const}$
3. $a = p_1 \cdot v_1 \cdot \ln \frac{v_2}{v_1}$
 $a_t = r \cdot T_1 \cdot \ln \frac{p_1}{p_2}$
4. $q = a = a_t$

Adiabatic change - change, in which no heat is exchanged with the environment

1. $dq = 0$
2. $p_1 \cdot v_1^k = p_2 \cdot v_2^k = \text{const}$
 $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$
3. $a = -c_v \cdot (T_2 - T_1)$
 $a = \frac{p_2 v_2}{k-1} \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \right]$
 $a_t = -c_v \cdot (T_2 - T_1); a_t = k \cdot a$
 $a_t = \frac{k \cdot r T_1}{k-1} \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \right]$
4. $q = 0$

Polytropic change - general reversible change that can replace all the previous equations

1. General reversible change, where usually $1 < n < k$
2. $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{n-1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$
3. $a = \frac{p_1 v_1}{n-1} \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \right]$
 $a_t = n \cdot a$
4. $q = c_n \cdot (T_2 - T_1)$, where $c_n = c_v \cdot \frac{n-k}{n-1}$

Reversible changes are represented using p-V and T-s diagrams. In the p-V diagram, the area under the curve represents the work of this change done by the working substance. In the

T-s diagram, the area under the curve represents the amount of heat transferred. This diagram allows for assessing the effectiveness of thermal circulations. Thermal circulation is a sequence of thermodynamic changes going one after another so that the working substance returns to its original state. The most famous working circulation is the Carnot's cycle

The second law of thermodynamics

“It is impossible to construct a periodically operating machine which constantly takes heat from the heat storage and does work equivalent to such heat.“

or

“Heat cannot spontaneously flow from a cold to a hot body”.

The second law of thermodynamics restricts the validity of the first law of thermodynamics by saying that all the applied heat cannot be converted into mechanical work.



Questions to Chapter 1

1. Define the temperature field in a substance.
2. Explain the difference between the heat flux density, heat flux and heat.
3. Explain the difference between the first and second Fourier's law.
4. Explain the difference between the thermal conductivity coefficient and thermal diffusivity coefficient.
5. What are the conditions of uniqueness used for? Please list them.
6. What types of convection exist?
7. How we express the convective heat transfer coefficient?
8. Describe the general criterion equation for the heat transfer through convection.
9. Explain how the radiation heat transfer proceeds.
10. Explain why the concept of a black body was introduced.
11. What is the difference between the black and grey body?
12. Describe the five basic laws of heat transfer.
13. Define the difference between hydrostatics and hydrodynamics.
14. Explain the importance of Navier- Stokes's equation in hydrodynamics.
15. Define the first and second law of thermodynamics.
16. List the basic state quantities and write the basic mathematical relationships between them.
17. Describe the individual reversible changes of an ideal gas.

2. THERMOPHYSICAL PROPERTIES OF MATERIALS



Study time: 5 hours



Objective

After reading this section, you should be able to

- Define the basic thermophysical properties of materials.
- Describe the basic numerical relationships and units.



Presentation

Basic properties

Heat of combustion (gross calorific value) (Q_s) – amount of heat released by complete combustion of unit mass of fuel (kg, m^3), with water vapour condensing out in flue gases. For gaseous fuels, the heat of combustion is calculated from the heats of combustion and volume fractions of the individual components, which can be generally written down as:

$$Q_s = \varphi_i \cdot Q_{s,i} \text{ (kJ}\cdot\text{m}^{-3}\text{)}$$

φ_i - volume fractions of individual fuel components.

Heating value (net calorific value) (Q_i) – amount of heat released by complete combustion of unit mass of fuel (kg, m^3), no water vapour condensing out in flue gases. The unit of heating value for solid fuels is $\text{kJ}\cdot\text{kg}^{-1}$ and for gaseous fuels $\text{kJ}\cdot\text{m}^{-3}$. The gross and net calorific values can be determined even experimentally in a calorimeter.

Calculation of net calorific value for solid and liquid fuels is carried out according to the equations that can be found in the tables, such as the lattice equation, Dulong's equation, Mendeleev's equation, etc.

For gaseous fuels, whose composition is given by volume fractions, it is calculated from the heats of combustion or heating values of the individual gases, which can be generally expressed by the equation:

$$Q_i = \varphi_i \cdot Q_{i,i} \text{ (kJ}\cdot\text{m}^{-3}\text{)}$$

The following table shows the gross and net calorific values for different gases.

Gas	Chemical formula	Gross calorific value (heat of combustion) Q_s (MJ·m ⁻³)	Net calorific value (heating value) Q_i (MJ·m ⁻³)
Carbon monoxide	CO	12.64	12.64
Hydrogen	H ₂	12.77	10.76
Methane	CH ₄	39.85	35.8
Ethane	C ₂ H ₆	70.42	64.35
Propane	C ₃ H ₈	101.82	93.57
Butane	C ₄ H ₁₀	134.02	123.55
Pentane	C ₅ H ₁₂	150.72	140.93
Ethylene	C ₂ H ₄	64.02	59.02
Propylene	C ₃ H ₆	94.37	88.22
Butylene	C ₄ H ₈	114.51	107.01
Acetylene	C ₂ H ₂	58.99	56.94
Benzol	C ₆ H ₆	146.29	140.38
Hydrogen sulphide	H ₂ S	25.71	23.7

Enthalpy – a thermodynamic quantity depending on the internal energy and the product of pressure and volume. For thermal engineering calculations, the enthalpy is used in a functional dependence of the specific heat capacity c_p and temperature t .

$$i = c_p \cdot t \quad (\text{J kg}^{-1}; \text{J m}^{-3})$$

Specific heat capacity - the amount of heat required to heat 1 kg of a substance by one temperature degree (1 K or 1°C). The value of the specific heat capacity is dependent upon temperature. For larger temperature intervals, the mean specific heat capacity \bar{c} is introduced.

For gases, we distinguish a specific heat capacity at constant pressure marked c_p and a specific heat capacity at constant volume marked c_v . The relationship between these specific heat capacities is determined by the Poisson's constant (κ) and Mayer's relation.

Density - the mass per unit volume of a liquid. Density changes with changing temperature and pressure. The equation for calculation:

$$\rho = \frac{m}{v} \quad (\text{kg m}^{-3})$$

Fluid density is the reciprocal of the specific volume, which is expressed as:

$$v = \frac{V}{m} \quad (\text{m}^3 \cdot \text{kg}^{-1})$$

Thermal diffusivity coefficient is a thermophysical parameter of a substance which characterizes the rate of change of the temperature field, i.e. how quickly the temperature changes on the surface of a body. The higher the value of thermal diffusivity coefficient, the faster the change in the temperature on the surface is reflected within the body. It is also a constant of proportionality - the rate of change of temperature of a body is directly proportional to the factor of temperature diffusivity. This factor is calculated as follows:

$$\alpha = \frac{\lambda}{c_p \cdot \rho} \quad (\text{m}^2 \cdot \text{s}^{-1})$$

Thermal conductivity coefficient is a physical parameter of a substance, which generally depends on temperature, pressure and composition of that substance. It is determined by measuring the density of heat flux, temperature gradient and then from the equation:

$$\lambda = - \frac{dQ}{\text{grad } t \cdot dS \cdot d\tau} \quad (\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1})$$

So the thermal conductivity coefficient is the amount of heat that passes in a unit of time through a unit area of isothermal surface. With increasing temperature the value of λ grows for gases and mostly falls for liquids. Thermal conductivities of some metals and liquids are shown in Figure 2.

Viscosity is the internal resistance of a fluid to shear deformation that occurs in real fluids. Shear stress τ arises due to the friction between adjacent layers of real fluids. It is the greater, the more the velocity changes from layer to layer. The change in velocity can be

characterized by velocity gradient $\frac{dv}{dy}$. Newton formulated the equation for calculating shear stress:

$$\tau = \eta \cdot \frac{dv}{dy} \quad (\text{Pa})$$

η is the dynamic viscosity, which characterizes the proportion between the velocity gradient and shear stress. The dynamic viscosity relationship applies:

$$\eta = \frac{\tau}{\frac{dv}{dy}} \quad (\text{Pa} \cdot \text{s})$$

The expression $\frac{\eta}{\rho}$ often occurs in hydromechanics, which is referred to as the kinematic viscosity. It examines the motion in terms of its trajectory, velocity and acceleration. Kinematic viscosity of gases is shown in Figure 2.2. It is calculated as follows:

$$\nu = \frac{\eta}{\rho} \quad (\text{m}^2 \cdot \text{s}^{-1})$$

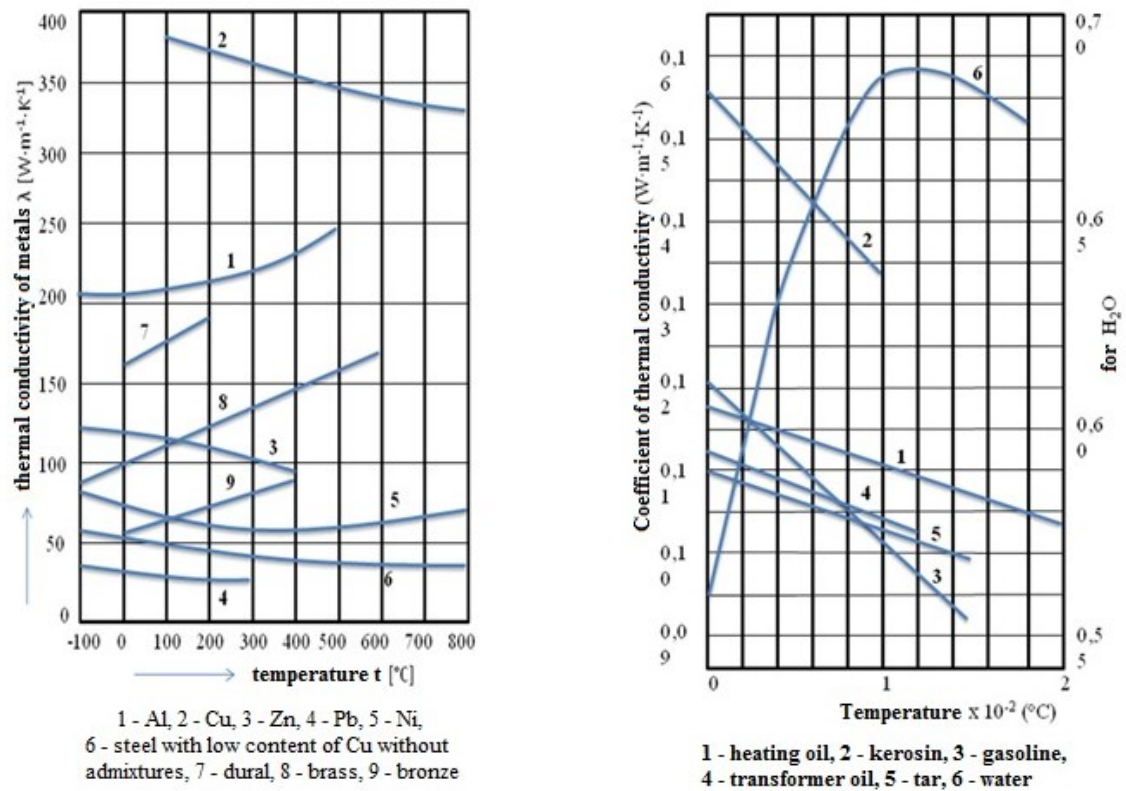


Fig. 2.1 Coefficients of thermal conductivity of some metals and liquids

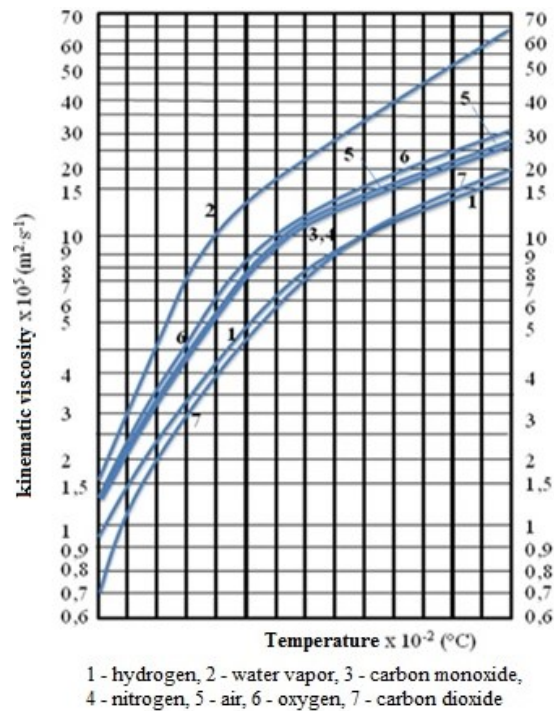


Fig 2.2 Kinematic viscosity of gases

Emissivity is the radiation characteristic of a body, which is determined as the ratio of the intensity of radiation E of a body to the intensity of black body radiation E_0 , at the same temperature. Since the black body emits the maximum amount of energy, its emissivity is assumed to be 1. However, only grey bodies exist, which may only approach 1. Grey bodies absorb part of the radiation and part of it is reflected. Emissivity is dependent on the material surface and is a function of temperature. The equation for calculating emissivity:

$$\varepsilon = \frac{E}{E_0} \quad (1)$$



Summary of terms from Chapter 2

Viscosity of fluids is associated with the internal resistance of fluids to shear deformation. We distinguish between kinematic and dynamic viscosity. Dynamic viscosity is based on Newton's law. Viscosity is dependent upon temperature.

The radiation characteristic of a body that determines the ratio of the intensity of radiation to the intensity of black body radiation is called **emissivity**. For black body it applies that $\varepsilon = 1$, while grey bodies only approach this value. It is dependent on the material surface and is a function of temperature.

Coefficient of thermal conductivity implies the amount of heat that passes in a unit of time through a unit area of isothermal surface. It depends on temperature, pressure and surface of material.

The rate of change of the temperature field is characterized by the **thermal diffusivity coefficient**. The higher its value, the faster the change in the temperature on the surface is reflected within the body.

Specific heat capacity is the amount of heat required to heat 1 kg of a substance by one temperature degree. For gases, we distinguish a specific heat capacity at constant pressure (c_p) and a specific heat capacity at constant volume (c_v). It is dependent upon temperature. For

larger temperature intervals, the mean specific heat capacity is given.

Density is the mass per unit volume of a liquid. Density changes with changing temperature and pressure.

Enthalpy depends on the internal energy and the product of pressure and volume. But in thermal engineering calculations it is used in a functional dependence of the specific heat capacity and temperature.



Questions to Chapter 2

18. What is viscosity and what types we known?
19. How do we calculate the thermal diffusivity coefficient?
20. Explain the concept of the emissivity.
21. When emissivity takes the value 1?
22. What is the difference between the gross and net calorific values?
23. How do we determine the net calorific value for solid and liquid fuels and for gases?
24. Equation for calculation of dynamic viscosity.
25. What is the specific heat capacity and what is its unit?
26. What specific heat capacities we distinguish with gases?
27. What is the enthalpy and how do we calculate it?

3. HEAT TRANSFER IN THE WORKING SPACE OF THE FURNACE

Heat work of a furnace is the sum of all the processes of heat exchange taking place in the working space (chamber) of the furnace. It is divided into useful work meaning that the heat is transferred to the processed material and useless work, which includes other types of heat consumed in the furnace. The exchange of heat that takes place within the zone of the technological process is called the internal heat transfer. By the term external heat transfer we then call the exchange of heat between the surface of the technological process zone and the zone of heat generation, or between the lining and ambient air.



Study time: 6 hours



Objective After reading this section, you should be able to

- Define the internal and external heat transfer.
- Determine the total amount of heat absorbed by the surface of the material.
- Divide the bodies into thin and thick using the Biot's and Stark's criterion.



Presentation

External heat transfer

External heat transfer takes place mainly by radiation and convection. Radiation is decisive type of heat transfer in furnaces with a temperature above 800°C , where it constitutes 85-95% of the total heat transferred to the charge surface. The rest of the heat is transferred by convection. With increasing temperature, the importance of radiation increases as well. In furnaces for heat treatment, which operate at lower flue gas temperatures, convection is more significant.

The working space of the furnace is a closed system, generally consisting of four elements that participate in the exchange of heat through radiation and convection. Two elements (charge and walls of the working space) are grey, the third is formed by flue gas, and the fourth element is a flame or electric arc.

The entire process of heat exchange is described by a system of integral and differential equations, the analytical solution of which is not generally possible.

The derivation is based on the following simplifying assumptions:

- the process being explored is stationary

- the effect of flame is neglected
- the flue gas temperature is the same at all points of the considered volume, the same is true for the surface points of the heated material and the furnace masonry
- the relative absorption of flue gas is the same in all directions

The highest temperature in the furnace is shown by flue gases that transfer the heat by radiation to the surface of the charge and the inner surface of the furnace lining. Furnace masonry performs two tasks. The first task is the insulation of the working space towards the environment in order to achieve the smallest possible losses. The second task is the intensification of heat transfer between the flue gas and heated material, which leads to shorter heating times. Exchange of heat in the furnace space is shown in Figure 3.1.

The following applies to the resulting amount of heat absorbed by the surface of the material:

$$Q_{r,m} = Q_{z,m} + Q_{sp,m} + Q_{m,m} + Q_{k,m} - Q_{m,ef} \quad (W)$$

where:

$Q_{r,m}$ – heat absorbed by the surface of the material (W)

$Q_{z,m}$, $Q_{sp,m}$, $Q_{m,m}$ – heat transferred to the material through radiation from the masonry, flue gas and surrounding charge (W)

$Q_{k,m}$ – heat transferred to the material through convection (W)

$Q_{m,ef}$ – effective (self) radiation of the surface of the material (W)

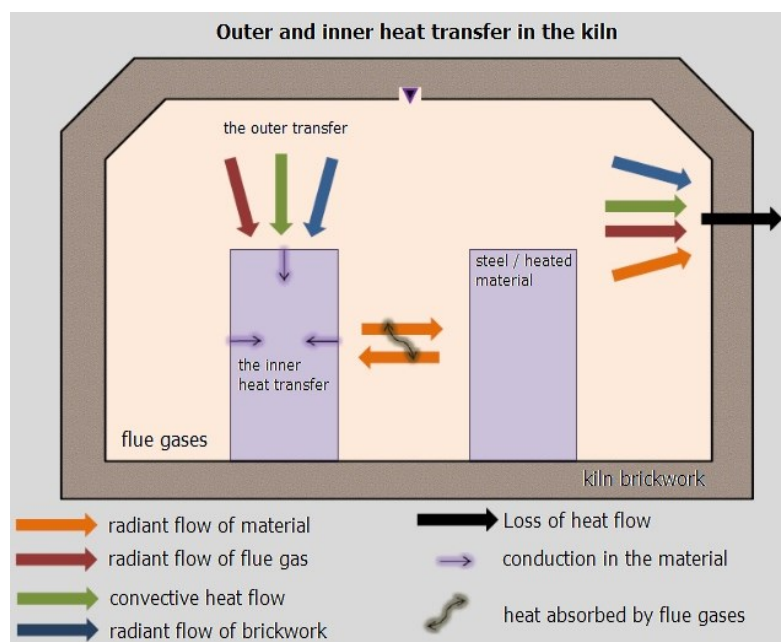


Fig. 3.1 External heat exchange in the working space of the furnace

The resulting external heat flux to the material is determined from the flue gas temperature. The flue gas temperature cannot be measured accurately because the sensor is hit by radiant energy from the furnace masonry and charge. Therefore, the concept of the furnace temperature is introduced. We don't distinguish individual items of the heat exchange, but we imagine that the charge takes the heat from the furnace.

Furnace temperature – t_{pec} – is determined using a *radiation pyrometer* located in the plane of the charge surface and directed into the furnace space. It follows from Stefan-Boltzmann law that the furnace temperature is very close to the temperature of the masonry.

In practice, the furnace temperature can be regarded as the temperature measured by a thermocouple, the heat junction of which is pushed slightly out of the lining into the furnace space.

We can imagine the furnace as the equivalent black body and the amount of heat absorbed by the charge surface.

$$Q_{r,m} = C_{pec} \cdot \left[\left(\frac{T_{pec}}{100} \right)^4 - \left(\frac{T_m}{100} \right)^4 \right] \cdot S_m \quad (W)$$

The equation does not include the amount of heat transferred to the charge through convection. The calculation takes the convection into account via *correction factor*, by which we divide the right side of the equation.

More precise results are obtained using the **zonal method**, which consists in decomposing the volume of flue gas, flame and heat transfer surfaces involved into a series of smaller isothermal sections (zones).

Internal heat transfer

In addressing the heating or cooling issues, it is necessary to determine the temperature field of the body over time. During heating, a temperature difference occurs between the surface and centre of the body, the size of which depends on the ratio of internal and external thermal resistance. This ratio is called Biot's criterion.

$$Bi = \frac{\frac{b}{\lambda}}{\frac{1}{\alpha}} = \frac{\alpha \cdot b}{\lambda} \quad (1)$$

where:

α – heat transfer coefficient on the surface of a body ($W \cdot m^{-2} \cdot K^{-1}$)

b – thickness of a body (m)

λ – thermal conductivity coefficient of a body ($W \cdot m^{-1} \cdot K^{-1}$)

If the temperature difference during heating can be neglected (the surface temperature t_p during heating is equal to the temperature of the centre t_c), it is a **thin body**. If the temperature difference during heating cannot be neglected, it is a **thick body**.

When calculating:

Bi < 0.25 → thin body

Bi > 0.5 → thick body

There is a transition area between these values where the body can be considered either thin (approximate calculations) or thick (the exact calculations). The same body may behave depending on the external heat transfer intensity once as “thin” and next time as “thick”.

To divide bodies into thin and thick, **Stark’s criterion** (ratio of internal and external thermal resistance in heat transfer through radiation) is used as well.

$$Sk = \frac{c_{p\text{sec}}}{10^8} \cdot \frac{b}{\lambda} \cdot T_{p\text{sec}}^3 \quad (1)$$

The body is thin if **Sk < 0.25**



Question to Chapter 3

28. What type of heat transfer prevails in furnaces with a temperature above 800°C?
29. Describe the difference between internal and external heat transfer.
30. Which criteria we use for dividing the bodies into thin and thick? Describe their calculation.
31. What body is it, if it is not possible to neglect the temperature difference between the surface and centre of the material?
32. What is the zonal method and what is it used for?
33. With increasing temperature, does the importance of radiation increase or decrease?
34. Give the values of Biot’s and Stark’s criterion for a thin body.
35. Explain why you cannot accurately measure the temperature of the furnace.

4. METHODS OF HEATING MATERIALS



Study time: 8 hours



Objective After reading this section, you should be able to

- Describe the various methods of heating thin and thick bodies.
- Describe the modes of heating the material.
- Calculate the heating time.



Presentation

Heating of thin bodies

This section will describe the methods of heating, which have the greatest practical importance - heating at a constant furnace temperature, constant heat flux and at a furnace temperature which is a linear function of time.

Constant furnace temperature

The derivation is based on a differential equation expressing the equilibrium between the heat flux to the surface of a body and its enthalpy increment.

$$\alpha \cdot (t_{psec} - t) \cdot S_m \cdot d\tau = V_m \cdot c \cdot \rho \cdot dt \quad (J)$$

where:

V_m – volume of a body [m^3]

dt – increment of body temperature during a time interval $d\tau$ [K]

Assuming that the size of α , c , and ρ is constant, the previous equation can be solved by separation of variables and subsequent integration. For **heating time** of a thin body τ_k from an initial temperature t_0 to a final temperature t_k then applies

$$\tau_k = \frac{V_m \cdot \rho \cdot c}{S_m \cdot \alpha} \cdot \ln \frac{t_{psec} - t_0}{t_{psec} - t_k} \quad (s)$$

For all three bodies (plate, cylinder, and sphere) we can write

$$\frac{V_m}{S_m} = \frac{b}{k_1} \quad (m)$$

where:

k_1 – shape coefficient, for plate $k_1 = 1$, for cylinder $k_1 = 2$, and for sphere $k_1 = 3$

Dimension b is the computational body thickness. For cylinders and spheres, it is the radius, for a symmetrically heated plate it is the half-thickness and for a plate heated on one side only the entire thickness is introduced as b . Using the previous equation, we can express the heating time as

$$\tau_k = \frac{b \cdot \rho \cdot c}{k_1 \cdot \alpha} \cdot \ln \frac{t_{pec} - t_0}{t_{pec} - t_k} \quad (\text{s})$$

With the known heating time, the final temperature of a thin body is determined from the equation,

$$t_k = t_{pec} - (t_{pec} - t_0) \cdot \exp \left[-\frac{\tau_k \cdot k_1 \cdot \alpha}{b \cdot \rho \cdot c} \right] \quad (^\circ\text{C})$$

But in fact, the values α , ρ and c are not constant, their size changes during heating, and therefore they must be introduced into formulas for an average temperature of the material \bar{t} .

The average temperature of the material \bar{t} , for which it applies that:

$$\bar{t} = \frac{1}{\tau_k} \cdot \int_0^{\tau_k} t \cdot d\tau \quad (^\circ\text{C})$$

after integration and adjustment we obtain the following relationship

$$\bar{t} = t_{pec} - \frac{t_k - t_0}{\ln \frac{t_{pec} - t_0}{t_{pec} - t_k}} \quad (^\circ\text{C})$$

More accurate calculation results we achieve by dividing the heating time into several time intervals for which we always determine t and the corresponding mean values of c and ρ . If the size of the heat transfer coefficient is not directly specified, it is calculated from the convection formula:

$$\alpha = \frac{q}{t_{pec} - \bar{t}} \quad (\text{W m}^{-2} \text{K}^{-1})$$

If **constant heat flux q** acts on a thin body surface during heating, for which it applies that

$$q = \alpha \cdot (t_{pec} - t) \quad (\text{W m}^{-2})$$

the heating time is calculated from the equation

$$\tau_k = \frac{b \cdot \rho \cdot c}{k_1 \cdot q} \cdot (t_k - t_0) \quad (\text{s})$$

The furnace temperature is a linear function of time

When this surface condition applies, the temperature of the furnace is described by the equation

$$t_{pec} = t_{pec}^0 + Z \cdot \tau \quad (^\circ\text{C})$$

where:

t_{pec}^0 – furnace temperature over time $\tau = 0$ ($^\circ\text{C}$)

Z – increment of temperature in a unit of time (K s^{-1})

Since a certain moment of heating, the difference between the furnace temperature and the temperature of a body remains virtually unchanged and its size is equal to

$$t_{p\text{ec}} - t = Z \cdot \frac{b \cdot \rho \cdot c}{k_1 \cdot \alpha} \quad (\text{K})$$

The average temperature of the material during the entire heating

$$\bar{t} = t_{p\text{ec}}^0 + \frac{Z \cdot \tau_k}{2} + \frac{t_k - t_0}{A \cdot \tau_k} \quad (^\circ\text{C})$$

The above described formulas for linear time-varying temperature of the furnace can be used even for more complex courses of the furnace temperature. The total heating time must be divided into smaller sections, in which the temperature curve will be replaced with line segments. The calculation must be carried out in stages.

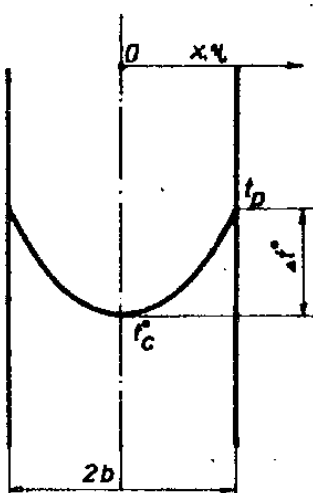
Heating of thick bodies

The calculation of thick bodies heating is much more complex than that of thin bodies because their temperature depends not only on time, but is also a function of the coordinates. The theoretical basis of all methods for calculating the heating of thick bodies is solving the **Fourier's partial differential equation of heat conduction**. The definite solution of the Fourier's equation requires knowing the conditions for uniqueness.

We usually solve the Fourier's equation analytically only for one-dimensional cases in bodies having basic geometric shapes (plate, cylinder, and sphere) with simple initial and surface conditions.

Constant surface temperature

In an infinitely large plate of thickness $2b$, the compensation of temperatures takes place over the cross section at a constant temperature of surface t_p . The initial temperature distribution in the cross section is described by a parabola equation.



$$\text{Initial condition: } t^0 = t_c^0 + \Delta t^0 \cdot \eta^2$$

$$\text{Surface condition: } t_p = \textit{konst.}$$

Where:

t_0 – temperature in time $\tau = 0$ ($^\circ\text{C}$)

t_0^c – temperature of the centre of a plate in time $\tau = 0$ ($^\circ\text{C}$)

η – dimensionless coordinate (1)

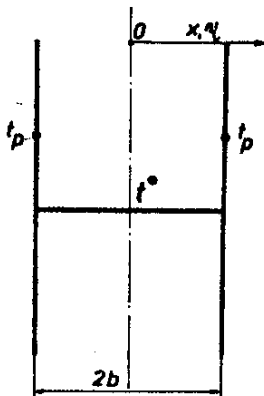
In practice, we can encounter this surface condition in the buffer zone of heating furnaces.

Temperature of the furnace:

$$t_{psec} = 100 \cdot \sqrt[4]{\frac{q}{c_{psec}} + \left(\frac{T_p}{100}\right)^4} - 273 \text{ (}^\circ\text{C)}$$

The surface temperature is a linear function of time

We are exploring an infinite plate of thickness $2b$, which initially has a constant cross section temperature t^0 and the surface temperature during heating varies linearly with time.



Initial condition: $t^0 = konst.$

Surface condition: $t_p = t^0 + Z \cdot \tau$

Where:

Z – surface temperature increment in a unit of time ($\text{K} \cdot \text{s}^{-1}$)

When heating thick bodies, it is always important to know the difference of temperatures over the cross section, i.e. the temperature gradient between the surface and centre of the body.

The maximum temperature difference between the surface and centre of the body is directly proportional to the rate of heating and square of thickness and inversely proportional to the factor of temperature diffusivity.

More often than a constant temperature over the cross section at the beginning of the heating, we encounter an uneven distribution of temperature.

The physical principle of non-steady heat conduction processes is such that if the constant surface condition applies (e.g. surface temperature, rate of heating, heat flux), a certain regularity manifests itself in the temperature distribution over the cross section of the body at a certain moment from the beginning of the heating. The same applies also to the change of temperature of any body in dependence on time. At the same time the temperature field no longer depends on the initial condition and we talk about **regular** phase of heating. The initial phase of heating is called **irregular**.

The temperature of the furnace in the criterion shape for the plate

$$\frac{t_{psec} - t_p}{2 \cdot \Delta t_m} \cdot Bi = 1 - G_2^d \quad (1)$$

and for the cylinder

$$\frac{t_{psec} - t_p}{2 \cdot \Delta t_m} \cdot Bi = 1 - 2 \cdot G_2^v \quad (1)$$

With a dominant radiant heat transfer, the temperature of the furnace is calculated from the following equation

$$t_{psec} = 100 \cdot \sqrt[4]{\frac{q}{c_{psec}} + \left(\frac{T_p}{100}\right)^4} - 273 \text{ (}^\circ\text{C)}$$

into which the value of the heat flux is introduced, e.g. from the equation

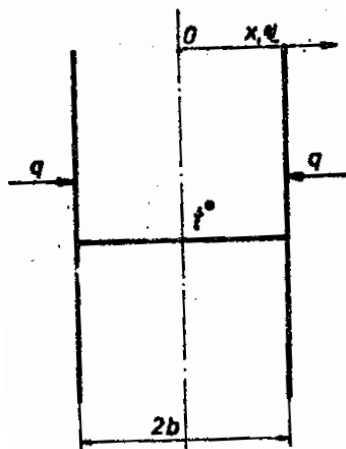
$$q = Z \cdot b \cdot \rho \cdot c \cdot [1 - G_2^d(Fo)] \text{ (W}\cdot\text{m}^{-2}\text{)}$$

Conclusions:

- The furnace temperature increases with increasing temperature of the surface.
- Both the furnace temperature and heat flux increases with increasing rate of heating Z , coefficient of thermal conductivity λ and difference of temperatures Δt_m .
- At the same rate of heating, the furnace temperature and heat flux are higher for bodies of greater thickness.
- When heating the plate and cylinder, the furnace temperature and heat flux for the cylinder are less, under otherwise identical conditions.

Constant heat flux on the surface

This surface condition is of practical importance for the calculation of heating in different types of furnaces. The method of solution is an infinite plate of thickness $2b$, heated symmetrically by heat flux q , with initial temperature t_0 .



Initial condition: $t^0 = konst.$

Surface condition: $q = konst.$

The temperature of the furnace can be calculated from the equation

$$\alpha = \frac{q}{t_{psec} - \bar{t}} \text{ (W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}\text{)}$$

into which the surface temperature is introduced as determined from the equation

$$(t - t_0) \cdot \frac{2\lambda}{q \cdot b} = F_3^d(Fo, \eta)$$

The temperature of the furnace in the criterion shape for the plate

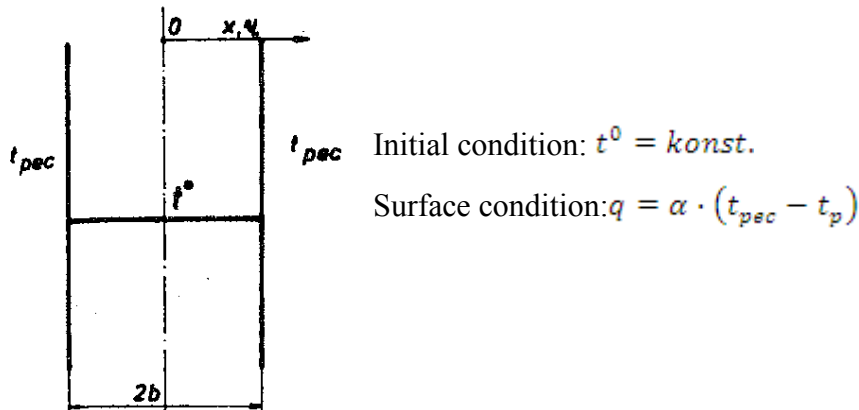
$$\frac{t_{psec} - t^0}{2 \cdot \Delta t_m} = \frac{Bi \cdot (3 \cdot Fo + 1) + 3}{3 \cdot Bi} - G_3^d(Fo)$$

and for the cylinder

$$\frac{t_{pec} - t^0}{2 \cdot \Delta t_m} = \frac{Bi \cdot (8 \cdot Fo + 1) + 4}{4 \cdot Bi} - G_3^v(Fo)$$

Constant furnace temperature

This case is the most complex because the body temperature depends also on the size of the Biot's criterion. Consider an infinite plate of thickness $2b$ with an initial temperature t_0 , symmetrically heated in a furnace with a constant temperature t_{pec} .



We determine the difference between the temperature of the surface and centre of the plate from the formula

$$t = t_p - t_c = (t^0 - t_{pec}) \cdot \sum_{n=1}^{\infty} \frac{2 \cdot \sin \mu_n}{\mu_n + \sin \mu_n \cdot \cos \mu_n} \cdot \cos(\mu_n \cdot \eta) \cdot \exp(-\mu_n^2 \cdot Fo) \quad (K)$$

Mode of metal heating

Heating mode depends on the furnace design, the type, shape and dimensions of steel ingots or billets, and on technological requirements of operation. When selecting the mode, find out the final temperature of metal heating and permissible heating non-uniformity, then calculate temperatures of the surface and centre of the body, temperature gradient over the cross section, furnace temperature, heat fluxes, thermal performance and fuel consumption.

Furnace heating mode is determined depending on the type of steel, dimensions and shape of the body to be heated, temperature of the charge and furnace design. We distinguish between:

- **Single-phase heating** – for heating thin bodies (sheet metals, thin-walled tubes) if lying freely. It is not necessary to pay attention to thermal stress and temperature compensation over the cross section
- **Two-phase heating** - typically consists of preheating and heating phase. It is used for heating carbon and alloy steel billets, large number of small objects or bundles of sheets and pipes. Thermal stress is usually not dangerous.
- **Three-phase heating** – preheating, heating and buffer zone. It is used for heating carbon and alloy steels of different dimensions charged into a furnace when cold.

- **Poly-phase heating** - during the heat treatment, when it is necessary to change the rate of heating or charge compensatory phases during heating.

Empirical relationships to determine the heating time:

For carbon steels:

$$\tau = 10\chi d\sqrt{d} \text{ (h)}$$

For high alloy steels:

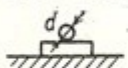
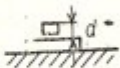
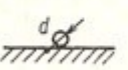

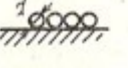
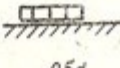
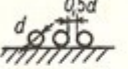
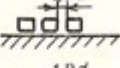
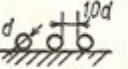
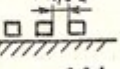
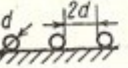
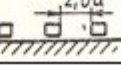
$$\tau = 20\chi d\sqrt{d} \text{ (h)}$$

where:

d – thickness or diameter of the heated material (m),

χ – coefficient showing the influence of material distribution within the furnace, it is determined from the table

Coefficient χ illustrating the influence of material distribution within the furnace in the following table

placement of the material in the kiln	χ	placement of the material in the kiln	χ
	1,0		1,0
	1,0		1,25
	2,0		4,0
	1,4		2,2
	1,2		1,4
	1,1		1,3



Questions to Chapter 4

36. What modes of heating metals do you know?
37. What determines the selection of mode of heating metals?
38. What is the irregular phase of heating?
39. Explain the concept of regular heating phase.
40. Describe the different cases of heating thin bodies.
41. Describe the different cases of heating thick bodies.
42. Enter the formula for calculating the heating time for carbon steel.

5. TECHNOLOGICAL PRINCIPLES OF HEATING THE MATERIAL

Heating is frequently occurring and very important process, which precedes the hot mechanical working of metals or forms part of the heat treatment. The quality of heating determines the quality of the end product and efficiency of operation. The most important factors in metal heating technology include the permissible rate of heating, final temperature of the metal, the method of placing material inside the furnace and the temperature and thermal modes of heating the material.



Study time: 6 hours



Objective After reading this section, you should be able to

- Explain the concept of final heating temperature.
- Characterize thermal stresses during heating or cooling.
- List the principles of placing material inside the furnace.
- Explain the concepts of scale and burn-off.
- Divide the controlled atmospheres and briefly describe.
- Explain the principle of rapid heating.



Presentation

Final temperature of metal heating

For steel to be hot worked, the selection of heating temperature depends on several factors, mainly on the properties of steel and type of processing. Normally, these temperatures are in the range from 1050°C to 1300°C for steel.

Increased temperature of the heated steel has positive implications in its processing, because the deformation resistance decreases, as well as the energy consumed during its processing. It is also possible to reduce the metal removal rates, reduce the risk of fracture and increase the service life of cylinders and other parts of the rolling mill. The temperature increase, however, is limited by grain growth, intensified oxidation, etc. These factors indicate the upper limit of heating. The maximum heating temperature of the metal should be from 100°C to 150°C below the solidus curve. The lower limit of heating for any metal is determined for metal from the permissible temperature at the end of processing.

Thermal stresses during heating (cooling) steel

During heating or cooling, uneven temperature fields are formed in the material, in which thermal stresses occur. When heating a cold charge, the outer metal layers have higher temperature than the internal layers and therefore tend to be more stretched. The inner layers have a lower temperature than the average temperature of the metal.

Thermal stresses occur in the metal if there are differences in temperature and at the same time the metal is in the elastic region (flexible state). If thermal stresses do not exceed the elastic limit, they disappear after the temperature difference is levelled. This is the case of a flexible (elastic) stress.

If at any place there is a plastic deformation (elastic limit is exceeded), then in places that were not plastically deformed, a redistribution of thermal stresses will take place. After levelling the temperature differences, a residual stress remains in the metal. The size, distribution, formation and removal of thermal stresses depends on the conditions of heating and cooling, the physical and mechanical properties of the material and its size and shape.

Thermal stresses occur in the first phase of heating, in the range of temperatures from 0°C to 500°C. Above this temperature the steel is plastic, stresses are reduced and relieved.

Permissible rate of heating

The rate of heating for a thin body is limited by conditions of the external heat transfer, while for a thick body also the heat conduction within the heated body applies.

Placing of material within the furnace chamber

Placing of material within the furnace differs according to the type and design of the furnace, the shape and dimensions of the body, movement of material within the furnace, the method of charging, etc. In all cases, the guiding principle is that the placing of the material within the furnace should be such that:

- the proportion of the heated surface to the body weight was as large as possible,
- the heating is symmetrical.

Influence of time and heating temperature on the formation of scale and burn-off

Oxidation of the steel during heating causes the loss of metal due to its burn-off, but also wasters when scale is rolled or forged in. Scale erodes the refractory materials and causes the growth of the hearth bottom.

Rusting is the oxidation of the steel at room temperature. If the temperature increases to 200-300°C and above, the surface of the steel will be covered with reaction colours. The higher the temperature, the faster the oxidation proceeds and it is most intensive at temperatures above 1000°C. It is the reaction between the oxidizing gases (O₂, CO₂, and H₂O) and iron with its impurities, upon which the scale is formed. Scale is therefore a mixture of iron oxides in various stages of oxidation of iron and its impurities. During oxidation, three iron oxides are formed:

- wüstite – ferrous oxide FeO,
- magnetite – ferrous-ferric oxide Fe₃O₄,

- hematite – ferric oxide Fe_2O_3 .

The oxidation of metal is a two-way diffusion. It is the diffusion of oxygen and the core of gas flow to the surface of the heated material, subsequent absorption on this surface, diffusion of reactants through the scale layer and crystallochemical transformation associated with the change in composition. At the same time, diffusion takes place also in the opposite direction as a diffusion of metal atoms through the scale layer on the metal surface.

As a whole, the scale by its composition comes close to Fe_3O_4 and therefore the average Fe content in the scale is between 73% and 76%. Also the scale adhesion to the surface of the metal has a significant impact on the process of oxidation of iron. The scale formation takes place during heating in the furnace (furnace scaling), as well as during rolling and cooling (mill scale). Burn-off is expressed as a percentage by weight (burn-off by weight), which is the weight of scale to the weight of a billet or ingot, or as the weight of scale which forms on 1 m^2 area of the ingot (surface burn-off).

Metal burn-off depends, inter alia, on factors that affect the diffusion (time and temperature of heating, the composition of the furnace atmosphere, the chemical composition of steel).

- Effect of temperature and heating time - scale formation begins at temperatures above 600°C to 650°C . At temperatures up to 900°C , the process is slow, while above this temperature the scale layer grows faster. At temperatures from 1275°C to 1300°C , a sudden increase of oxidation occurs in the context of scale melting, which causes constant exposing of an unoxidized metal.
- Influence of furnace atmosphere - the furnace atmosphere is determined by the chemical composition and type of fuel, excess air coefficient and burner design. The gases in the furnace atmosphere can act on the material depending on the temperature and their mutual proportions either in oxidizing, reducing or neutral manner. In addition, they may have carburizing or decarburizing effect. The table below shows which furnace gases act on iron, iron compounds with carbon and iron oxides in oxidizing, reducing and neutral manner and which of them are carburizing and which are decarburizing.

Effect of gases on iron, iron compounds with carbon and iron oxides is shown in the following table

	O_2	CO_2	CO	H_2	CH_4	H_2O	N_2
Pure iron	O	O	A	N	A	O	N
Carburized iron (Fe_3C)	O, E	O, E	N	E	N	O, E	N
Iron oxide (FeO , Fe_3O_4)	N	N	R	R	R	N	N

O – Oxidizing, R – Reducing, N – Neutral, A – Carburizing, E - Decarburizing

- The influence of the chemical composition of the metal and other factors - in low carbon steels porous scale layers form, which only lightly adhere to the steel surface and thereby enable further penetration of oxygen to the non-oxidized steel. In steels with a higher carbon content less burn-off occurs due to the fact that during oxidation of carbon to form CO, there is a partial protection of the metal surface from further oxygenation. For alloy steels containing Cr, Al, Si, and Ni, the alloying element forms a well adherent protective oxide on the surface that prevents diffusion of oxidizing gases and thus also further oxidation of the material.

Controlled atmospheres

We divide controlled atmospheres used during heat treatment according to their effect on the material surface to:

- Protective – prevent adverse reactions from happening (oxidation, decarburization, carburization),
- Active – produce the desired chemical reaction in the material (carburization, decarburization, nitridation).

They are formed outside the working chamber of the furnace (usually in a generator) and can be classified into several groups by the production technology used.

Exothermic atmospheres

They are obtained by burning natural gas, propane, butane, gasoline, heating oil and coke oven gas. With small quantities of air a rich atmosphere is created, while large quantities of air result in poor atmosphere. Poor atmosphere has a small content of combustibles (H₂, CO) and a high proportion of CO₂, N₂, with a rich atmosphere it is the opposite.

The primary atmosphere from a generator is further transformed in drying, cleaning and decarburizing facilities. Water vapour is removed in various ways, e.g. by drying under pressure, in a freezer, using absorbents, etc.

Exothermic atmospheres are not suitable for annealing steels with carbon content above 0.4%, as they decarburized them. Therefore, they are modified to become mono-atmospheres containing predominantly N₂, H₂ and CO. According to the value of dew point, exothermic atmospheres are broken down to:

- EXO I with dew point between 20°C and 25°C
- EXO II with dew point between -8°C and 0°C
- EXO III with dew point between -50°C and -18°C.

Endothermic reaction of fuel with air in the presence of a catalyst produces an **endothermic atmosphere**. They are made from propane, butane and natural gas. They are explosive, toxic and tend to separate out the soot.

The atmosphere formed by cleavage of ammonia contains 75% H₂ and 25% N₂. It is produced by cleavage of anhydrous ammonia in a dissociation device on a nickel catalyst at temperatures between 850°C and 950°C. The atmosphere is very explosive. Its explosiveness

is reduced by burning hydrogen to between 20% and 1% content. The volume of gas is increased and the resulting atmosphere is cheaper.

The nitrogen atmosphere is obtained in metallurgical oxygen plants as a waste product of the fractional distillation of air. It is cheaper than gas obtained from ammonia or mono-gas from the exothermic combustion.

The hydrogen atmosphere is very effective, but expensive. A combination of hydrogen with air is inflammable and explosive. There are several options how to make it, for example, by diffusion purification of cleaved ammonia or technical hydrogen using palladium membranes or by electrolysis, with subsequent purification to remove oxygen and water vapour.

Rapid heating

The principle of rapid heating consists in that the charge is heated at those stages when it is permissible, at a maximum permissible rate of heating. To intensify the rate of heating, it is possible to use radiant heat transfer, which increases the temperature gradient between burnt gases, or between the furnace masonry and surface of the heated material, or convective heat transfer can be used by increasing the velocity of burnt gases flow around the charge, or both described methods can be used. These ways result in longer heating times of alloyed steels or steels with higher carbon content under otherwise identical conditions in comparison with conventional steels. The quality of heating of alloyed and high carbon steels depends on the temperature and uniformity of heating.

The rapid heating mode in arbitrarily shaped billets of various kinds of steels can be divided into:

- Two-phase mode - suitable for thin bodies of any steel and thick bodies made of soft steels. The first phase proceeds at $t_{pec} = \text{constant}$, where t_{pec} is the maximum permissible temperature of the furnace (given by the furnace design). The second phase proceeds at $t_p = \text{constant}$, when the temperature of the surface of the heated billet is constant.
- Three-phase and four-phase mode - appropriate for thick bodies of medium and high carbon steels and alloy steels. Three-phase mode differs from the two-phase mode by additional preheating phase with a limited rate of heating. This phase takes place at a constant heat flux. Four-phase mode is selected, where the furnace conditions allow, and this mode adds a preheating phase with condition of $t_{pec} = \text{constant}$, where the maximum furnace temperature is set.



Questions to Chapter 5

43. What are endothermic atmospheres produced from?

44. Explain the principle of rapid heating.
45. When does the heat stress occur?
46. How we divide the controlled atmosphere? Describe their function.
47. What is rusting?
48. Enter the guiding principle for placing the material within the furnace.
49. Describe the two-phase rapid heating mode.
50. How the nitrogen atmosphere is produced?
51. What factors does the metal burn-off depend on?
52. What is scale?
53. What oxides of iron are formed in the metal oxidation process?

6. HEATING SYSTEMS IN FURNACES

This chapter briefly outlines the heating systems in furnaces. Individual furnaces are described in more detail in Chapter 10 - Part 1 and Chapter 11 - Part 2.



Study time: 10 hours



Objective After reading this section, you should be able to

- Characterize individual heating systems in furnaces.
- Explain the direct and indirect resistance heating.
- Break down the electrical discharges that we distinguish in arc heat.
- Describe the practical use of individual heating systems.



Presentation

Resistance heat

The electrical conductivity of metals is determined by the number of free electrons, their mobility and the mean free path, which is the average distance the electron travels between collisions. Electrical conductivity arises as a result of the movement of free electrons in the crystal lattice of consisting of positive ions. When travelling in the metals, electrons constantly collide with the metal lattice of ions, thus their movement is hindered and the electrical resistance arise.

Electrical resistance is dependent on temperature, impurity content, deformation, lattice imperfections, etc. The specific electrical resistivity of pure metals is small, because they have a regular crystal lattice. Due to impurities and alloying elements or impurities, however, specific thermal resistance increases. It is the result of a breach of the regularity of the lattice.

Resistive materials

Resistive materials are characterized by technical and economic requirements:

- large specific thermal resistance,
- low temperature coefficient of resistance,
- low coefficient of thermal expansion,
- sufficient mechanical strength at operating temperatures,
- economic availability,
- chemical resistance.

Figure 6.1 illustrates the dependence of the specific thermal resistance on temperature for alloys and some pure metals. Resistive materials are classified into several groups:

Depending on the application:

- resistive materials for measuring instruments – up to 20°C,
- resistive materials for resistors – up to 200°C, and
- resistive materials for electro-thermal systems – up to 1376°C.

Depending on the type of material or alloy used:

- resistance alloys (Cr-Fe-Ni, Fe-Cr-Al),
- high-melting pure metals (W, Mo, Ta, Pt),
- metal-ceramic couples based on powder metallurgy ($\text{MoSi}_2 + \text{SiO}_2$), and
- non-metallic materials (C, SiC).

Depending on specific resistance:

- group with low specific resistance with operating temperatures up to 500°C (Cu alloys + FeCr),
- group with high specific resistance with operating temperatures up to 1200°C (Cr-Fe-Ni),
- group with extra high specific resistance with operating temperatures between 1000°C and 1375°C (Fe-C-Al).

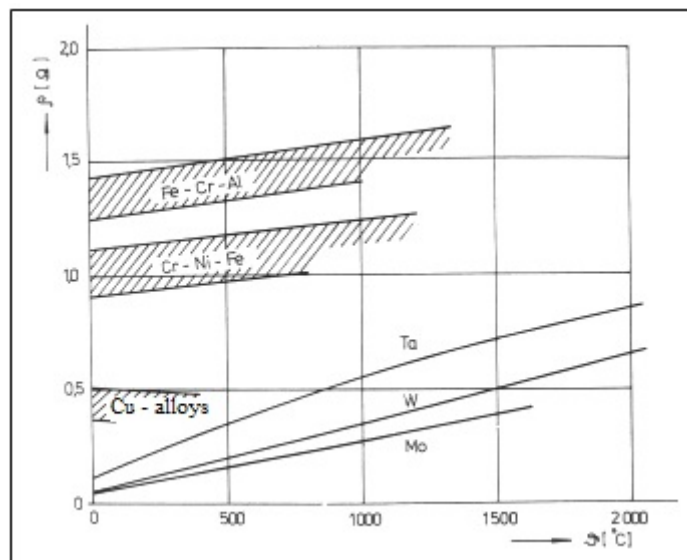


Fig.6.1 Course of specific electrical resistance versus temperature for resistance alloys and some pure metals

Direct resistance heating

It is used in practice for following technical applications: heating of wires, sheets, rivets, and bars and in furnaces with direct resistance heating for the production of graphite and

silicon carbide, which may be stationary or nonstationary. The heated material is of ordinary structural steel, austenitic steel or pure iron.

Direct resistance heating has a high efficiency between 70% and 85%. Direct resistance heating can also be used for heating of liquids – electrolytes. This group includes the production of hot service water (electrode boilers - Figure 6.2), glass melting, salt bath and electroslag remelting of steel.

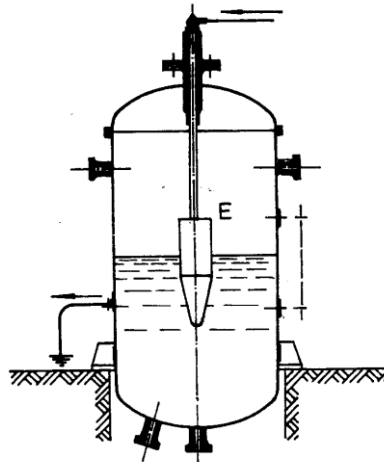


Fig. 6.2 Low voltage electrode boiler

Indirect resistance heating

The criteria for classification of resistance furnaces

According to the movement of heated material:

- resistance devices with heated material at rest (stationary heating) – chamber furnaces, shaft furnaces;
- resistance devices with heated material in motion (non-stationary heating) – round furnaces, drum furnace, etc.

According to their purpose:

- resistance devices with low temperatures (up to 600°C) – used for drying the windings of electric machines and instruments prior to impregnation, various coatings and materials, including food,
- resistance devices with medium temperatures (up to 1050°C) – used for heat treatment of metals (annealing, hardening, tempering),
- resistance devices with high temperatures (up to 1350°C) – used for hardening special steels, melting of metals with a lower melting point, in the glass industry, etc.

According to the type of atmosphere in the furnace:

- with the normal atmosphere,
- with artificial atmosphere (nitridation, reduced oxidation, etc.),
- without atmosphere – vacuum furnaces.

According to the placing of material:

- on solid supports (rails, trays, stands, racks),
- in baskets (containers, frames, muffles).

Arc heat

By its nature, the electric arc belongs in the area of electric discharges in gases. The condition for the flow of current through gas is a gas ionization, which can be performed by means of:

- electric field,
- radioactive radiation,
- high temperature and thermo-electronic emission,
- electromagnetic radiation.

We distinguish between three types of electrical discharges depending on the intensity of the current passing through:

- glow discharge - occurs between the electrodes in a gaseous environment at low pressures;
- spark discharge – occurs if a large number of electric charges is transferred in a strongly ionized gas environment; and
- arc discharge - occurs through thermoelectric emission of electrodes and thermal ionization of gases environment between the electrodes.

The electric arc contains an arc with temperature between 4000 and 6 000 K and a coating formed by substantially ionized gases. Appearance of the arc depends on the electrode material, the type and gas pressure and external factors, such as magnetic field, gas flow, etc.

Induction heat

If a metal object is placed coaxially and is connected to an AC power source, the generated electromagnetic waves enter the metal object, in which currents are induced. Electromagnetic waves are attenuated and the energy is converted to heat energy.

If the coil is energized in a different frequency than the mains, the division of induction heating will be as follows:

- with low frequency (50 – 150 Hz),
- with medium frequency (500 - 105 Hz),
- with high frequency (105 – 106 Hz).

Induction heating with low frequency is used for hot metal working and other thermal processing, tempering welds and other special induction heating (induction boilers, soldering, etc.).

The second group consists of induction heating for melting materials. It is carried out in furnaces powered by electricity of low or medium frequency. These furnaces are divided into induction furnaces with an iron core and without it.

Dielectric and microwave heat

Dielectric devices are designed to heat the electrically non-conductive materials. Dielectric heating is one of the modern methods of heating materials, mainly insulators. The heating of the material depends on its dielectric properties, and neither depends on the depth of the material nor its thermal conductivity.

Inside the dielectric, polarization occurs according to the type of charge carriers. The resulting polarization is the sum of partial or fractional polarizations and it then determines the final value of the dielectric constant.

In individual cases the polarization occurs

- due to the charge displacement or deformation:
 - electron polarization – displacement of an electron shell relative to the core due to the action of a larger electric field (crystals of quartz, rock salt, mica, etc.),
 - atomic polarization – displacement of individual atoms or radicals forming a molecule due to the action of the electric field,
- due to orientation – by rotating permanent natural dipoles,
- on the boundary – displacement of charges on the boundary of an inhomogeneous dielectric. It occurs in materials containing water.

Practical applications of dielectric heating:

- wood drying,
- welding of thermoplastic materials,
- preheating, hardening of rubber materials.

Microwave heating

The microwave spectrum is in the range between 0.3 GHz and 300 GHz. This range is also occupied by radio bands, so it is necessary to ensure a safe distance to avoid the interference to radio and television from technical application of the microwave heat.

Microwave heat allows the solution of such heating issues that even dielectric heating could not bring to effect.

Current thermal processes place increasing demands on the precise dosage of energy. The biggest advantage of microwave heating is the ability to perform various thermal processes with a well-defined amount of heat.

The use of microwave heating:

- food industry,

- wood and paper industry,
- electrotechnical industry,
- agriculture, medicine.

Plasma heating

Plasma is considered as the fourth state of matter after solids, liquids, and gases. Unlike gas, it has other specific properties. It is electrically conductive and has a large thermal capacity and conductivity. It is subject to the effects of electric and magnetic fields. Plasma as a whole behaves as a neutral environment, because the total number of positive and negative particles is the same. There are two types of plasma - partially ionized and completely ionized.

At higher pressure, and when the plasma is in equilibrium, the typical temperature of a partially ionized plasma is between 5 000 K and 15 000 K. The temperature of a completely ionized plasma reaches 100 000 K.

Plasma moves very quickly during transportation. It is slowest at the outlet from the discharge nozzle. Plasma expands and converts its potential energy into kinetic energy. This case is used in plasma torches.

Plasma generators are divided into:

- Plasma generators with electrodes:
 - plasma is obtained by means of a self-sustained and non-self-sustained electric arc,
 - plasma is obtained using a high frequency electric field.
- Plasma generators without electrodes:
 - plasma is obtained using a high-frequency electromagnetic field.

Figure 6.3 shows the most commonly used plasma generator with electrodes with a stabilized arc.

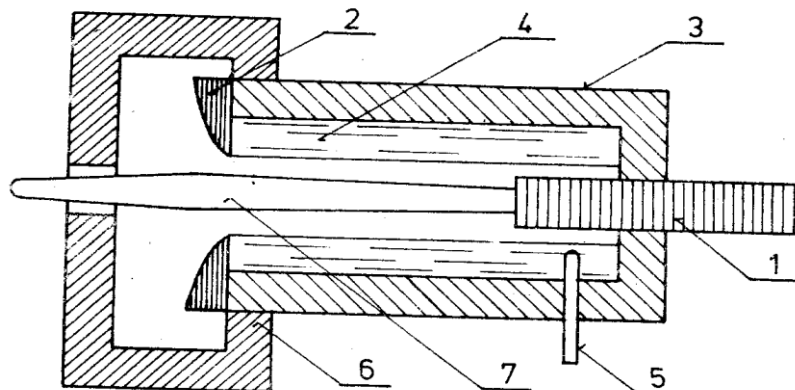


Fig. 6.3 Schema of the plasma generator

(1 – cathode, 2 - anode, 3 - insulating cylinder, 4 - cooling layer of water, 5 - tangential coolant inlet, 6 – coolant outlet, 7 - plasma)

Plasma torches are used in:

- material coating,
- welding,
- cutting,
- melting of materials, chemical reactions.

Electron heating

Heat generation principle:

The incandescent cathode surface emits electrons, which are accelerated by an electric field. Electrons produce beams with a considerable energy, which is given over upon impact on the anode or other material. The process takes place in a substantial vacuum.



Questions to Chapter 6

54. How does the electrical conductivity of metals arise?
55. What determines the electrical resistance?
56. What are the technical requirements that characterize the resistive materials?
57. Classify the resistive materials by type of application and type of material or alloy used.
58. What is the condition for the flow of current through gas and when it is met?
59. Name three electrical discharges and describe when they arise.
60. Where can we use the microwave heating?
61. In which activities we use a plasma torch?
62. Characterize the plasma.
63. What materials are used in dielectric devices?

7. REFRACTORY MATERIALS FOR FURNACE SYSTEMS

Refractory lining performs two tasks. The first of these is to define a space for running technological processes and separate it from the surrounding environment and the second task is to reduce heat losses of the furnace. Technological processes in furnaces take place at high temperatures. Furnace lining is normally done as a multilayer of different materials. The refractory material forming the working layer of the lining is subject to different technological influences, such as the effect of scale and slags, mechanical and chemical action of the processed material, gases, flue gases, alternating of reducing and oxidising environments, temperature changes, etc.



Study time: 10 hours



Objective

After reading this section, you should be able to

- Define the basic properties of refractory materials,
- Classify different materials, describe their properties and use,
- List the advantages and disadvantages of the basic refractory materials.



Presentation

Basic properties of refractory materials

Knowledge of the basic properties of refractory materials finds its use in their manufacture, quality evaluation, lining design, etc. In addition, it guides us through the extensive group of materials used for lining the furnaces and heating equipment and allows for correct identification of their use from technical, economic, as well as energetic aspects. Basic properties are specified in standards that define the test procedures.

Chemical composition specifies the weight percentage of individual components of which the material is composed.

Density is the ratio of the weight and volume of the dried sample material. For porous and granular materials, only the volume really filled in by material is counted (the volume does not include the pores and cavities).

Volume weight is the ratio of the weight of the dried sample material to its volume, including the volume of closed and open pores.

True porosity is the ratio of the volume of open and closed pores and cavities of the test sample to its volume, including pores and cavities.

Apparent porosity is expressed as the ratio of the volume of open pores and cavities of the test sample to its volume, including pores and cavities.

Absorption capacity is the percent by weight of water absorbed by the test sample to the weight of the test sample.

Apparent density is the ratio between the weight of a dried specimen and its volume, including closed pores.

Thermal expansion specifies the dependence of length changes of the material on temperature. It has an effect on the amount of stress generated in the lining during heating or cooling. Length changes are reversible. When cooled, the body takes its original dimensions. They must be distinguished from the irreversible changes that are caused by crystallographic transformations and chemical influences. In case of irreversible changes, permanent linear changes occur.

Permanent changes under heat stress represent irreversible dimensional changes of shaped refractory products caused at high temperatures. They are given as a percentage of linear shrinkage (negative value) or increase (positive value). These changes occurring in the heat must be taken into account in the design of the lining and they are characteristic of different kinds of refractory materials.

Compressive strength is an important property for the design of furnace linings. It determines also the resistance to point loads, shocks, abrasion, etc. In case of shaped refractories, the compressive strength attains 10-50 MPa, for silicon carbide up to 75 MPa and for special material it reaches up to 400 MPa. The value of compressive strength varies with temperature. Figure 7.2 illustrates the dependence of compressive strength on temperature.

Tensile strength is the ratio of the maximum force that test specimen can withstand during the tensile test and the initial cross section. Knowledge of this quantity is important for the design of linings subjected to tension or bending (suspended roofs, lining with unilateral or asymmetric heating, etc.). Dependence of tensile strength on temperature is shown in Figure 7.1.

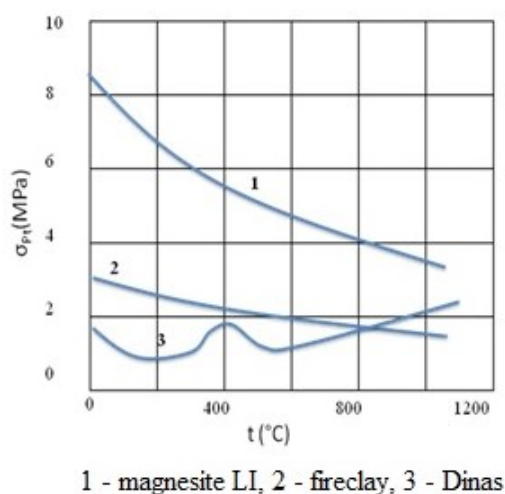


Fig. 7.1 Tensile strength values vs. temperature

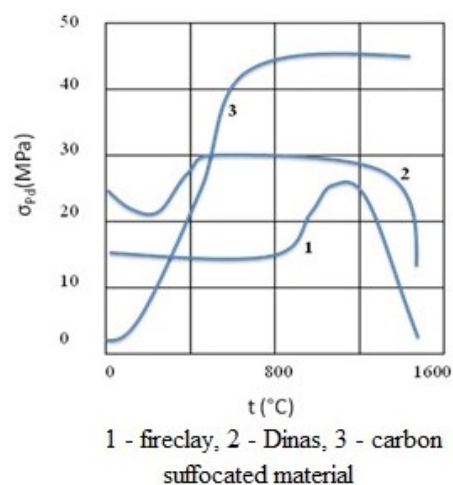


Fig. 7.2 Compressive strength values vs. temperature

Bending strength is determined by a static or impact test. Static bending strength is the stress at which the test specimen subjected to bending breaks. Impact bending strength (impact strength) is the work needed to break the test specimen.

Resistance against thermal shock (sudden temperature changes) is the ability of ceramic materials to withstand sudden temperature changes during sharp cooling down of the heated body. The measure of the resistance is the difference of the heated and cooled samples, at which the bending strength is reduced to 2/3 of the strength of samples, in which no temperature change took place.

Refractoriness (heat resistance) is the ability of the unloaded material to withstand high temperatures without melting. At high temperatures, the melt is formed within the material; its increasing amount and reduction in viscosity leads to distortion of cohesion of the material and its deformation.

Resistance to deformation under heat and load is the ability of a material to resist high temperatures. It is expressed as a temperature of deformation, at which defined deformation occurs and as a temperature of disruption, at which a sudden disruption of the test sample takes place.

True resistance to deformation and creep under heat and load is a feature characterized by a temperature at which the defined deformation of the test sample occurs at uniformly increasing temperature.

Specific thermal conductivity affects the heat removal through the furnace lining, temperature fields and stresses in the lining, as well as other properties of refractories. It is influenced by the chemical and mineralogical composition of the material, its porosity, etc. During operation, the value of thermal conductivity changes due to technological processes or crystallographic transformations (scale, absorption capacity, diffusion, gases, fly ashes, etc.). The values of specific thermal conductivity versus temperature are shown in Figure 7.3.

Specific heat capacity is the amount of heat required to raise the temperature of 1 kg of a substance by 1 degree (1 K or 1°C). The value of the specific heat capacity is dependent upon temperature. For larger temperature intervals, the mean specific heat capacity \bar{c} is introduced.

Classification of refractory materials

Refractory materials can be classified depending on:

- chemical and mineralogical composition,
- porosity,
- the form, in which they are used: shaped, granular,
- the manner in which the shaped products are formed:
 - pressed or moulded,
 - from semi-dry or dry matters,
 - casted from suspensions,

- heat treatment: burnt, non-burnt, etc.

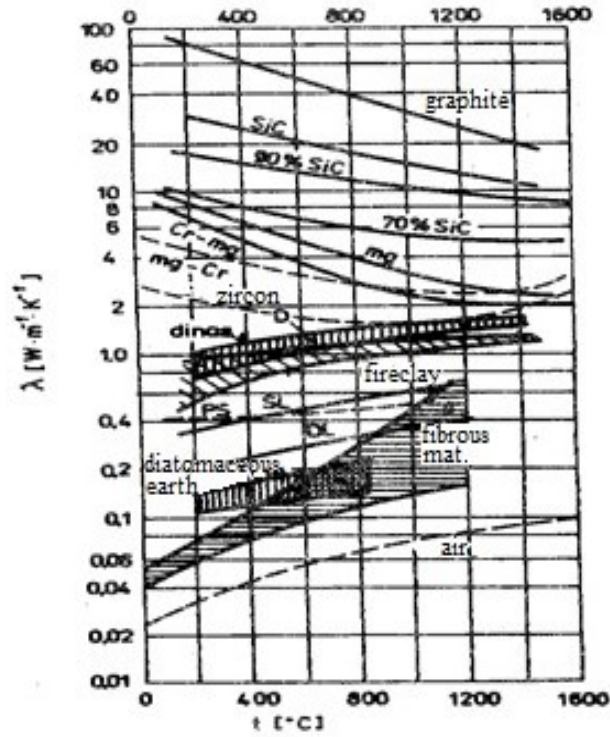


Fig. 7.3 Dependence of specific thermal conductivity of refractories and air on temperature

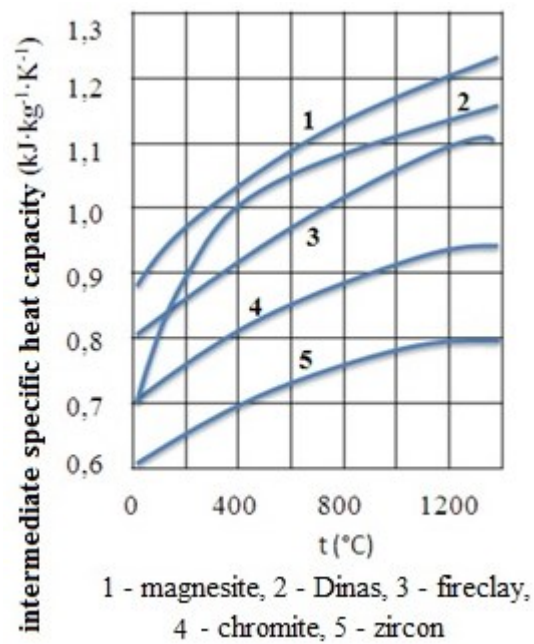


Fig. 7.4 Dependence of mean specific heat capacity on temperature

Shaped refractory materials

The most suitable classification of these materials is in terms of their chemical and mineralogical composition. From this perspective, the materials are classified to 10 different kinds, which are further subdivided according to the content of the main components.

Siliceous materials

Siliceous material with SiO_2 content above 93% is called **silica (dinas)**. Silica materials with additives have a lower SiO_2 content, but at least 80%. Silicon dioxide (SiO_2) is present in several modifications shown in Figure 7.5, along with temperatures of individual transformations:

The major modifications: quartz tridymite cristobalite silica glass

The secondary modifications: α, β α, β, γ α, β

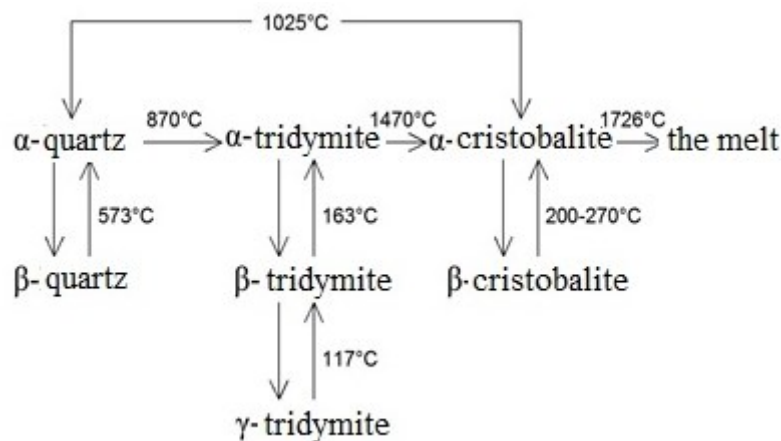


Fig. 7.5 Main transformations of SiO_2

The various modifications differ in the arrangement of atomic lattice. Transformations of major modifications are difficult, mostly taking place only in the presence of substances accelerating crystallographic transformations, which we call mineralizers. Transformations of secondary modifications take place relatively easily. When changing the modifications, changes occur in the volume, and thereby the density. It is made as compact and expanded.

Advantages of silica:

- low thermal expansion in temperatures over 600°C,
- compressive strength (higher than fireclay),
- high resistance to deformation under heat and load, and
- resistance to acidic slags.

Disadvantages:

- decrease in tensile and bending strength in the area of crystallographic transformations,
- low resistance to sudden changes in temperature (up to 600°C), and
- high coefficient of thermal expansion.

Silicas with additives

In order to improve certain properties, the process of silica making involves added ingredients, such as CuO, Cr₂O₃, ZrO₂, SiC.

- **Dinas chromite** – silica with the addition of chrome ore. It has a higher resistance to slags and fly ashes with iron oxide content.
- **Dinas zircon** – acidic refractory containing 50% of SiO₂ and 48% of ZrO₂. It has a higher specific thermal conductivity and low thermal expansion.
- **Dinas with silicon carbide** – higher compressive strength and abrasion resistance. It is used in the coking chambers for wall and floor linings.

The use of silica: coke oven batteries, hot blast stoves, electric arc furnaces, induction melting furnaces, and soaking furnaces.

Aluminosilicate materials

Oxides Al₂O₃ and SiO₂ are basic refractory components. Their proportion determines the chemical nature of refractory material, as well as characteristic properties of the different groups of aluminosilicate materials. They are the most commonly used class of refractory materials. They are used lightweight and compact, shaped and unshaped, or burnt and non-burnt. Burnt aluminosilicate products form a group called fireclay (chamotte).

- **Silicious fireclay materials**

They are referred to as acid fireclay (SK). They have a lower heat resistance, resistance to deformation and lower resistance to sudden temperature changes than ordinary fireclay. They are used in coke oven batteries for lining of canals and latticework for regenerator chambers.

- **Fireclay materials**

Fireclays are among the most widely used materials for the construction of furnaces. Their heat resistance and resistance to deformation under heat depend on their chemical composition. With increasing Al₂O₃ content they grow and with increasing content of SiO₂, TiO₂, Fe₂O₃ these properties decline. It is produced as common fireclay (S), semi-hard fireclay (SP) and hard fireclay (ST). According to Al₂O₃ content, various types of fireclay are divided into several grades. With the same Al₂O₃ content, fireclays S, SP and ST differ in the degree of compaction, which affects their porosity, volume weight, absorption capacity,

specific thermal conductivity, etc. The distinguishing feature of fireclays is the beginning of softening at lower temperatures.

Advantages of fireclay:

- Resistance to temperature changes throughout the application range,

Disadvantages:

- low resistance to slags, fly ashes, etc.,
- higher temperatures (above 1400°C) leads to greater wear of lining.

Materials with a lower volume weight, compressive strength and specific thermal conductivity are called expanded fireclay. They are identified by their standardized designations or trade names.

Application of fireclay: coke oven batteries, blast furnaces, hot blast stoves, heating furnaces, and electric arc furnaces.

- **Aluminosilicate materials with higher content of Al_2O_3**

These materials contain over 45% of Al_2O_3 . This group of materials include kaolinite, sillimanite, mullite and corundum. With increasing content of Al_2O_3 , also the density, heat resistance, specific thermal conductivity, etc. increases. They are used in different parts of blast furnaces, in the hot blast stoves, burners, pusher furnaces and steel making pans.

Magnesium and magnesia spinel materials

These alkaline materials are resistant to molten metals and slags. The most important representatives of this group are magnesite, magnesite chrome, chrome magnesite and chromite. They have a higher thermal conductivity than fireclays and silicas.

- **Magnesite** – the refractory component of magnesite is periclase (MgO). By increasing the MgO content, materials become more resistant to deformation.
- **Magnesite chrome** – depending on the amount of chrome ore, materials are termed either magnesite chrome or chrome magnesite. Magnesite chrome is resistant to high temperatures and chemical effects of furnace atmosphere, has a lower thermal expansion than chrome magnesite.
- **Chrome magnesite** – is characterized by a high resistance to thermal shock.
- **Chromite** – is made of chrome ore with the addition of magnesite. It is resistant to temperature changes. It is used for an intermediate layer between the alkaline and acid layers.

Magnesium calcium materials

The main components of these materials are oxides, MgO and CaO. Depending on their proportion, these materials are referred to as calcium dolomitic, magnesium dolomitic and dolomitic magnesium. They are resistant to thermal shock.

Magnesium silicate materials

Refractory components are oxides MgO and SiO₂, possibly Cr₂O₃. They have a high resistance to sudden temperature changes, but they are not resistant to alkaline slags.

Zirkonate materials

Basic components are ZrO₂ and SiO₂, or Al₂O₃. Zirconate materials are used to produce blocks for lining of pans, burner tiles and cups, caps and sinks for pouring ladles. The properties depend on the content of ZrO₂. Heat resistance is between 1750°C and 1820°C. They are stable in their volume and resistant to molten metals and slags.

Carbon materials

The refractory component is carbon in the form of graphite. They are highly resistant to heat, thermal shock and have a small linear thermal expansion.

Silicon carbide materials

Silicon carbide (SiC) is the basis of these materials. They are characterized by high specific thermal conductivity, resistance to deformation, compressive strength, abrasion resistance and resistance to thermal shock. They are disrupted by alkaline slags, molten steel, etc.

Silicon carbide matters with clay as a bonding material are resistant to heats above 1850°C. They are used in the manufacture of recuperator tubes and thermocouple protection tubes.

Special refractory materials

They are made of oxides, borides, silicides, carbides and sulphides of high purity. They are used in laboratory and technical facilities with high operating temperatures (nuclear reactors, melting of metals, and production of reactive engine nozzles).

Unshaped materials

Other materials include unshaped refractory products - ceramic compounds that are used to create linings and their parts, blocks, in brickwork, masonry surface finish, etc. This group of materials includes refractory concrete, products with a chemical binder, products with a ceramic binder, expanded materials and fibrous materials.

Products made of inorganic fibres – they have shape of a plate or mat, whose basic components are fibres made by defibering molten inorganic compounds, rocks or glass. In

thermal technology, inorganic fibres are applied even in the free, loose state, in the form of cotton or wool. They are made either fireproof or non-fireproof.

Expanded materials – they are used in furnace linings as insulating or structural-insulating materials. They are characterized by higher porosity and lower volume weight. The most commonly used are expanded aluminosilicate and silicate materials.

Refractory concretes are concretes intended for temperatures over 200°C, in which after a prolonged exposure to high temperatures the hydraulic bond transforms into ceramic bond. At higher temperatures, the sintering of refractory concrete takes place and the monolith gets the character of a fired ceramic product (the compressive strength increases). It consists of a hydraulic binder, aggregates and additives. Aggregates are the key component of refractory concrete and may be both natural and artificial cohesionless materials.



Summary of terms from Chapter 7

The chapter begins with brief description of basic properties of refractory materials. The best-known properties are **chemical composition, density, absorption capacity, apparent and true porosity, apparent density, specific thermal conductivity, specific heat capacity and volume weight**.

Other important features include **linear thermal expansion**, which expresses the dependence of linear material changes on temperature. It has an effect on the amount of stress generated in the linings during heating or cooling. Length changes are reversible.

Irreversible dimensional changes of refractory shaped products, which are caused by high temperatures, are called **permanent changes under heat stress**. They are given as a percentage of linear shrinkage and the resulting value can be positive or negative.

Strengths are no less important properties. We know **tensile strength**, which is the ratio of the maximum force that test specimen can withstand during the tensile test and the initial cross section. Knowledge of this quantity is important for the design of linings subjected to tension. Static or impact test determines the **bending strength**. It is the stress at which the test specimen subjected to bending breaks. Third type of strength is the **compressive strength**. The compressive strength values also determine the resistance to point loads, shocks, abrasion, etc.

Resistance against thermal shock is the ability of ceramic materials to withstand sudden temperature changes during sharp cooling down of the heated body.

The main feature of refractory materials is their **heat resistance**. It is the ability of a material to withstand high temperatures without melting.

Another property which characterizes the resistance of the material to high temperatures is the **resistance to deformation under heat and load**. It is expressed as a temperature of deformation and temperature of disruption.

True resistance to deformation and creep under heat and load is a feature characterized by a temperature at which the defined deformation of the test sample occurs at uniformly increasing temperature.



Questions to Chapter 7

64. List the basic properties of refractory materials.
65. By what criteria the refractory materials are classified?
66. What is a heat resistance?
67. How do we call siliceous materials with SiO_2 content above 93%?
68. What are the advantages and disadvantages of using silica?
69. List the major modification of SiO_2 .
70. What ingredients are added to the silica to improve its properties?
71. What are the special heat resistant materials produced from?
72. What are refractory concretes?
73. What are the features of expanded materials?
74. Describe the major modifications of SiO_2 .
75. List the main representatives of magnesium and magnesia spinel materials and briefly characterize them.
76. What are the special refractories used for?
77. What do you know about fireclay materials?
78. Explain the concepts of compressive, tensile, and bending strengths.
79. Explain the concept of linear thermal expansion.

8. HEAT EXCHANGERS

The greater the temperature of the flue gases leaving the working space of the furnace and the lower the thermal efficiency of the furnace, the greater the amount of heat taken away by the flue gases from the working space of the furnace. It is not only practical, but also economical to return part of this heat into the working space through preheating of combustion media. Devices, in which the heat of flue gases is transmitted to the combustion air or gas, are called the heat exchanger.



Study time: 10 hours



Objective After reading this section, you should be able to

- Define the concept of heat exchanger.
- Describe the different types of heat exchangers and their differences.
- Compare hydraulic and thermal calculation for recuperator.
- Calculate the heat transfer area of heat exchanger.



Presentation

Heat exchangers are divided into two basic groups:

- **recuperators** – heat is transmitted from the flue gas flow to the heated medium via a combined transfer of heat through the dividing wall,
- **regenerators** – use the heat accumulation in a refractory material.

By preheating the combustion components, it is possible to achieve fuel savings that increase with increasing temperature of preheating and temperature of waste flue gases, and decreasing fuel efficiency. Preheating also raises the temperature of combustion and the furnace capacity is enhanced.

Fuel economy

$$U = \frac{Q_{ch} - Q_{ch}}{Q_{ch}} \cdot 100 = \frac{i_p + L_{skut} \cdot i_{vz}}{Q_n + i_p + L_{sk} \cdot i_{vz} - V_{sp}^v \cdot i_{sp}} \cdot 100 \quad (\%)$$

where:

Q_{ch} – chemical heat of fuel (W),

Q'_{ch} – chemical heat of fuel transferred into the furnace without recuperation in a unit of time (W),

Q_n – fuel efficiency ($J \cdot kg^{-1}$; $J \cdot m^{-3}$),

i_p – enthalpy of preheated fuel ($J \cdot kg^{-1}$; $J \cdot m^{-3}$),

i_{vz} – enthalpy of preheated combustion air ($J \cdot m^{-3}$),

L_{skut} – actual amount of combustion air per unit of fuel ($m^3 \cdot kg^{-1}$; $m^3 \cdot m^{-3}$),

V_{sp}^v – amount of wet flue gases from a unit of fuel ($m^3 \cdot kg^{-1}$; $m^3 \cdot m^{-3}$).

The equation shows that fuel economy gets better with increasing preheating temperature and temperature of waste flue gases and decreasing fuel efficiency

Increasing the temperature of combustion

Theoretical temperature of combustion

$$t_t = \frac{Q_n + i_p + L_{skut} \cdot i_{vz}}{V_{sp}^v \cdot c_{sp}} \quad (^\circ C)$$

where:

c_{sp} – mean specific heat of flue gases in the temperature interval between $0^\circ C$ and t_t ($J \cdot m^{-3} \cdot K^{-1}$)

With the use of heat recovery, we can also burn fuels that are unusable in some cases due to their adiabatic temperature of combustion (to replace highly efficient fuels by less valuable ones). In facilities with closed metallurgical cycle, where there is an excess of blast furnace gas and shortage of coke oven gas, the preheating helps to offset the adverse balance of fuel.

Raising the furnace capacity

When the temperature in the furnace chamber increases, the time of melting or heating the charge gets shorter. E.g. when heating thermo-technically thin bodies in a chamber furnace to temperature of $1250^\circ C$, we get 2.3 times shorter heating time by increasing the furnace temperature from $1300^\circ C$ to $1500^\circ C$.

Recuperators

Recuperators can be broken down by various criteria as follows:

- according to the material of the wall dividing the heated and heating media to **metal** and **ceramic**,
- according to the method of heat transfer to **radiation**, **convection**, and **radiation-convection**, and
- according to the flow path of heat transfer media to **co-current**, **counter current**, **cross current**, and **multiple cross current**.

Quick review of heat exchangers according to the heat transfer method:

Convection recuperators

- Needle type recuperators (ribbed)

It must not be in a channel where there are too dusty flue gases, otherwise the ribs gets clogged.

- Recuperators with straight tubes

Better tightness; tubes can be placed both horizontally and vertically.

- Flue recuperators

For flue gases contaminated by solid particles of fly ashes (flue gases flow inside the tubes); their advantage is the possibility of cleaning.

- Loop recuperators

Tubes are connected to a U-shape, each loop can freely dilate.

Radiation recuperators

- Cylindrical recuperator

Combination of co-current and counter current; even very dirty flue gases can be used.

- Tube-type recuperator

There is a cage of tubes in the outer shell; better heat transfer; can be used even for larges pressures.

Radiation–convection recuperators

- Schack's recuperator

High coefficient of heat transfer; the possibility of achieving a high preheating temperature. Both the radiation and convection sections are positioned in a single shaft.

Calculation of the recuperator is divided into two parts - **thermal** part and **hydraulic** part.

Thermal calculation

Thermal calculation of recuperator consists in calculating the solution of the equation

$$Q = \int_0^S k \cdot \Delta t \cdot dA \quad (W)$$

where:

Q – amount of heat transferred in the recuperator from the flue gas to air in a unit of time (W),

S – total area of recuperator (m),

k – heat transfer coefficient ($W m^{-2} K^{-1}$),

Δt – difference between the temperature of flue gases and temperature of air, $\Delta t = t_{sp} - t_{vz}$ (K),

dA – differential of area (m²).

Integration of the equation cannot be done directly. For the determination of the temperature difference, it is necessary to know the temperature curves of flue gases and air along the length of the exchanger. The solution is based on the energy balance equation.

$$m \cdot \frac{di}{dA} = k \cdot (t_{sp} - t_{vz}) \quad (\text{W m}^{-2})$$

where:

m – mass flow (kg s⁻¹),

i – enthalpy (J kg⁻¹).

The previous relationship can determine the temperature of the flue gases or air

$$t_{sp} = t_{vz} + \frac{m_{vz}}{k} \cdot \frac{di_{vz}}{dA} \quad (^\circ\text{C})$$

$$t_{vz} = t_{sp} + \frac{m_{sp}}{k} \cdot \frac{di_{sp}}{dA} \quad (^\circ\text{C})$$

Character of temperature curves of flue gases and air along the length of the recuperator:

$$t_{sp} = t_{0,sp} - (t_{0,sp} - t_{0,vz}) \cdot \frac{K_{vz}}{K_{sp} + K_{vz}} \cdot (1 - e^{-MA}) \quad (^\circ\text{C})$$

$$t_{vz} = t_{0,vz} - (t_{0,sp} - t_{0,vz}) \cdot \frac{K_{sp}}{K_{sp} + K_{vz}} \cdot (1 - e^{-MA}) \quad (^\circ\text{C})$$

The system of equations shows that K_{sp} and K_{vz} uniquely characterize the course of flue gases and air for a particular recuperator. E.g. for a co-current,

K_{sp} < K_{vz}, flue gas temperature will fall faster than the air temperature will rise,

K_{sp} > K_{vz} and vice versa,

K_{vz} = K_{sp} the decrease in flue gas temperature will be exactly equal to the increase of air temperature.

Both the flue gas temperature and air temperature are a linear function of the heat exchanger area.

Temperature of the wall of the recuperator

The thermal calculation of the recuperator includes the determination of the temperature of the **heat transfer surface**. Its maximum value must not exceed the temperature specified for the type of material used. Risk of overheating (burning) threatens mainly metal recuperators.

The intensity of the heat flux through the dividing wall can be expressed by equations

$$q = k \cdot (t_{sp} - t_{vz}) = \alpha_{sp} \cdot (t_{sp} - t_{st}) = \alpha_{vz} \cdot (t_{st} - t_{vz}) \quad (\text{W m}^{-2})$$

where:

t_{st} – temperature of the wall surface on the flue gas side (°C),

t'_{st} – temperature of the wall surface on the air side (°C).

By solving the previous system, we obtain

$$t_{st} = t_{sp} - \frac{k \cdot (t_{sp} - t_{vz})}{\alpha_{sp}} \quad (^\circ\text{C})$$

$$t'_{st} = t_{vz} + \frac{k \cdot (t_{sp} - t_{vz})}{\alpha_{vz}} \quad (^\circ\text{C})$$

For metallic materials, the thermal resistance of the wall can be neglected, $t_{st} = t'_{st}$

$$\alpha_{sp} \cdot (t_{sp} - t_{st}) = \alpha_{vz} \cdot (t_{st} - t_{vz}) \quad (\text{W}\cdot\text{m}^{-2})$$

By a simple adjustment of equation we obtain the dependence for the temperature of the wall in the criterion form

$$\Theta = \frac{t_{st} - t_{vz}}{t_{sp} - t_{vz}} = \frac{1}{1 + \frac{\alpha_{vz}}{\alpha_{sp}}} \quad (1)$$

The equation shows that the wall temperature is always less than the flue gas temperature and higher than the air temperature at a given location. For recuperators, there are always efforts to achieve the lowest possible temperature of the wall (the measure to increase α_{vz}).

Hydraulic calculation

The aim is to determine the pressure loss on the side of both media. It belongs among the most important values characterizing the particular type of heat exchanger. The higher the velocity of the flowing medium, the greater the heat transfer coefficient. With speed, also the hydraulic losses grow, thus increasing the operating costs. The total pressure loss in the heat exchanger is determined from the relationship:

$$p_z = p_{z,t} + p_{z,m} + p_{z,n} + p_{z,g} \quad [\text{Pa}]$$

Friction pressure losses ($p_{z,t}$) and losses due to local resistances ($p_{z,m}$) are determined in the same way as in the subject of Heat Transfer and Convection.

Pressure loss due to non-isothermal flow ($p_{z,n}$) and pressure loss caused by the geometric buoyancy ($p_{z,g}$) can have a negative value. In such case their effect is positive and they reduce the total pressure loss.

Regenerators

Regenerators include *hot blast stoves*:

- they work alternately, intermittently, i.e. one transfers heat to the air, while the other is preheated,
- they are heated with blast furnace gas with the addition of natural gas or fuel oil,
- preheated air (700 - 1000°C) is conveyed by means of blowers through the lined piping to hot blast tuyeres,

- each blast furnace includes 3-5 hot blast stoves.

The use of wind in the blast furnace:

- oxygen delivery for the combustion of coke
- maintaining consistency of the charge (swirling)
- prevents caking at the bottom of the furnace



Questions to Chapter 8

80. What is the heat exchanger and how we classify them?
81. How to calculate the temperature of the wall of the recuperator?
82. What is the principle of hydraulic calculation of recuperator?
83. What criteria are used to classify recuperators?
84. Classify recuperators according to the method of heat transfer and give main representatives for each group.
85. Briefly describe the hot blast stoves.
86. What are the advantages of preheating combustion components?
87. Enter the formula for calculating fuel economy.

9. MEASUREMENT OF TEMPERATURE, PRESSURE, AND FLOW. GAS ANALYZERS.

Measurement and measuring technology in the metallurgical industry is used in many areas and in many variations. The measurement is especially important for technological purposes. The measurement is becoming increasingly important especially at a time when the main challenges of smelters include automation of production processes and reduction of costs of operation.



Study time: 8 hours



Objective After reading this section, you should be able to

- Describe the principle of operation of thermocouples.
- Describe the different types of thermocouples.
- Explain the principle of measuring using spectral pyrometers.
- Describe the ways of measuring pressure and flow, and list the main representatives in the various categories.
- Describe gas analysers.



Presentation

Measurement of temperature

For most metallurgical operations, temperature is a major technological variable, which affects the quality of production, economy of operation and performance of individual production units.

Temperature can be defined as a measure of the kinetic energy of moving molecules. On the basis of the second law of thermodynamics, Kelvin elaborated the thermodynamic temperature scale in 1848, which was adopted as the basis for measuring temperature. The basic unit was “degree Kelvin” (symbol °K) and the temperature of the triple point of water (in degrees Kelvin = 273, 16°K). Later, a new name was introduced - kelvin (K). But especially in Europe, different temperature scale applies – the Celsius scale. Its basic unit is the melting point of ice 0°C and the boiling point of water 100°C.

Thermocouples

Temperature measurement using thermocouples is based on the thermoelectric phenomenon (Seebeck, 1821). A thermocouple is formed by a pair of electrically conductive wires of different chemical composition. If the joined end of these wires (hot end of the thermocouple) is heated to a higher temperature than the temperature of the opposite ends of the wires (cold end), an electromotive force arises - thermocouple voltage. The principle of thermocouple is illustrated in Figure 9.1.

Thermocouple properties are characterized by sensitivity, thermal and chemical resistance and thermoelectric stability. The maximum temperature of measured point becomes the main criterion for choosing the appropriate type of thermocouple.

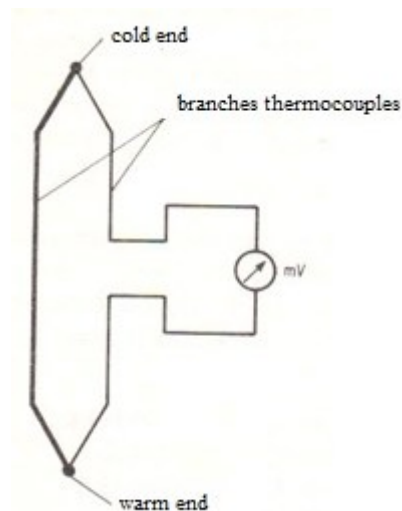


Fig. 9.1 Principle of thermocouple

Fe-Const thermocouple

The positive leg is composed of pure iron, the negative leg of a constantan. It is suitable for measuring low to medium temperatures, operates reliably up to 600°C. Moist environment is not ideal, as it speeds up the oxidation of Fe-leg. Oxidizing or reducing environment does not affect the measurement accuracy.

Cu-Const thermocouple

The positive leg is composed of pure copper, the negative leg of a constantan. It is resistant to rust, which is an advantage over the previous type. The upper limit is around 300°C. This type is suitable for measuring very low temperatures up to -200°C.

NiCr-Ni thermocouple

The positive leg is of NiCr, the negative leg of Ni. It can be used up to 1000°C. Since the temperature of 500°C, Ni branch is sensitive to gases containing sulphur. The thermocouple is detrimentally affected by a gas mixture, in which the oxygen content falls below 1%. Such low oxygen content does not make it possible to create a protective oxide

layer on the surface of the wires and the so called green plague is formed - the life of the thermocouple is reduced and also changes if the thermoelectric voltage takes place.

NiCr –Const thermocouple

This type of gives a higher thermocouple voltage than the previous type, it can be used up to a temperature of 700°C.

PtRh-Pt thermocouple

Thermocouples of precious and noble metals are used for measuring higher temperatures and in areas with adverse environmental effects. It works at temperatures of 1300°C, with appropriate connection even up to 1600°C. This type of thermocouple is produced with a varying content of rhodium. Rhodium may be present also in the second leg. Alloy wires have higher thermal resistance.

The key part of the thermocouple circuit is the measuring end (hot junction) of thermocouple. Measuring ends can be made in different ways. Most often, the two wires are soldered using a fill metal (solder), whose melting point is higher than the maximum measured temperature will be. Both legs must be electrically isolated. To protect the thermocouples, protective tubes of various materials and various designs are used.

Thermocouple design

Shell type thermocouples

Thermocouple wires are made of conventional thermocouple materials, but with a substantially smaller diameter. Wires are inserted in a powdered ceramic material (Al_2O_3) and the protective shell is made of stainless steel. They can be bent in operation. Due to the small diameter of wires, the response time is significantly shorter than with conventional thermocouples. Because of the small wire diameter, it is difficult to produce measuring junctions.

Tube type thermocouples

They were developed in order to achieve long life and short response. They are used for measuring temperatures of salt and other hardening and tempering baths, during the heat treatment of metals.

Flat type thermocouples

Both legs are in the shape of strips, which are mutually insulated. They allow measurement in narrow slits.

Contact type thermocouples

They measure the surface temperature of the material. They are used to control the temperature of the rolled material, furnace shells, to measure the temperature on the surface of the working rolls in rolling mills.

Penetration type thermocouples

The ends of the wires are treated and pointed to penetrate into the measured material. They are used in the production of non-ferrous metals.

String type thermocouples

For surface temperature measurements, in particular of cylindrical bodies. The device is usually used as a handheld portable device for control purposes.

Immersion thermocouples

These thermocouples were created in response to the problems of measuring the temperature of molten steel in steelmaking furnaces, i.e. temperatures exceed 1600°C and the thermocouple is subject to aggressive effects of certain elements contained in the steel and slag.

It is capable to measure the temperature of steel over short periods. Due to the limited life of the measuring end, various design options were developed allowing for the replacement of hot junction.

Resistance thermometers

Measuring temperature using a resistance thermometer is based on the temperature dependent change of the ohmic resistance of the wires. They are used in a temperature range between -250°C and 850°C . The materials, from which resistance thermometers are produced, must meet the following demands:

- physical and chemical stability over their entire rated temperature range,
- high sensitivity (high temperature coefficient of resistance),
- good formability in cold drawing,
- good reproducibility to allow for replacement of damaged sensors.

Platinum wires are the most commonly used for measuring. Platinum is resistant to high temperatures, is not susceptible to corrosion and chemical attacks. Another material used is nickel. It is suitable for lower temperatures.

Semiconductor resistance thermometers

Semiconductor thermally dependent resistors are known as thermistors. The temperature coefficient of thermistors is negative, i.e. with increasing temperature their ohmic resistance decreases. They can be used at temperatures between -100°C and 350°C . As the base material, metal oxides are used that are processed into the shape of beads, rods, discs or other special shapes. They are used for measuring the surface temperature, and they are inserted into the glass or metallic protective tubes.

Dilatation thermometers

They work on the basis of expansion of solid, liquid or gaseous substances.

Bimetallic thermometers

They are used in thermal protection of electric motors, transformers and other high voltage equipment. They consist of a two-layer metal strip, where one layer has a significantly different coefficient of expansion from the second layer. When heated, due to different expansions of these two layers a bending stress occurs in the strip, which forces the entire strip to bend. The resulted deformation then signals the attainment of temperature limit states.

Pressure thermometers

They are based on a pressure change with temperature at constant volume of filling. We distinguish between liquid, gas and steam pressure thermometers. A number of substances can be used as fillings. For example, mercury or methanol in liquid thermometers, acetone or methyl chloride in steam thermometers and nitrogen, hydrogen, helium and oxygen in gas thermometers.

Pyrometers

Pyrometers measure the temperature of an object or heat transfer medium by sensing the heat or light radiation. Each object that is heated to a temperature higher than the temperature of its surroundings emits an electromagnetic radiation of certain wavelengths. Solids heated to lower temperatures do not show any visible radiation, because they emit radiation of longer wavelengths, so-called infrared radiation. Solids heated to very high temperatures provide radiation of shorter wavelengths - ultraviolet radiation. Figure 9.2 shows the various types of electromagnetic radiation.

Proximity pyrometric methods are used in places where high temperature are measured in difficult conditions or when we need to measure the temperature of moving material.

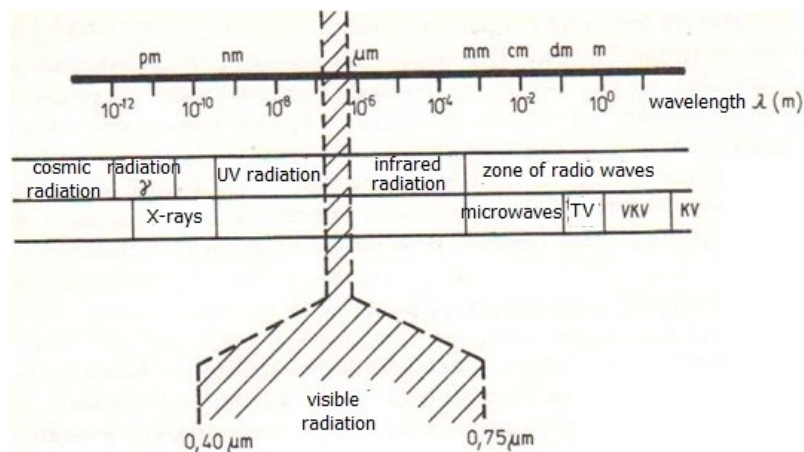


Fig. 9.2 Illustration of various kinds of electromagnetic waves showing visible radiation

Adverse environment for pyroelectric measurement is too moist air, steam, flue gases, glass, CO_2 , ice and air containing dust. Conversely, dry air, oxygen, nitrogen, and crystals of certain minerals have heat penetration of 100%, and these environments are suitable for transferring the heat radiation from the emitter to the detector of the pyrometer.

They are divided into groups, depending on which area of radiation they use for temperature measurement:

Radiation pyrometers

They react to almost the entire spectrum of the transmitted radiation, which means that they detect the total radiation energy.

Spectral pyrometers

They react only to one wavelength (to very narrow band of wavelengths).

Colour pyrometers

They measure energy at two (or three) wavelengths, and the proportion of these energies is decisive for determining the temperature.

Measurement of pressure

These are the most common operational measurements. When measuring pressure, we usually compare the measured pressure with the pressure of air on the earth's surface. If the measured pressure is higher than atmospheric pressure, we talk about overpressure, if less, it is underpressure.

Liquid pressure sensors

They are based on the balance of the measured pressure and force effect of the liquid column. They are suitable for measuring low pressures and differential pressures. As a liquid filling, a variety of substances is used - water, mercury, benzol, kerosene, ethyl alcohol. The choice of a substance is given by the range of measured pressures and temperature conditions.

U-shaped tubes

It's the most simple pressure device (Fig. 9.3). It is used for control measurements, during calibration, for setting up automatic control systems or adjusting the pressure modes of metallurgical plants. If one arm of the tube is closed and evacuated, it is possible in this way to measure absolute pressures.



Fig. 9.3 U-shaped tube

Inclined manometer

It performs accurate control measurements of small pressures or small pressure differences. A substantial increase in sensitivity and reduction of the measuring range is achieved by tilting one arm and by the diverging cross-section of arms. It is illustrated in Figure 9.4.

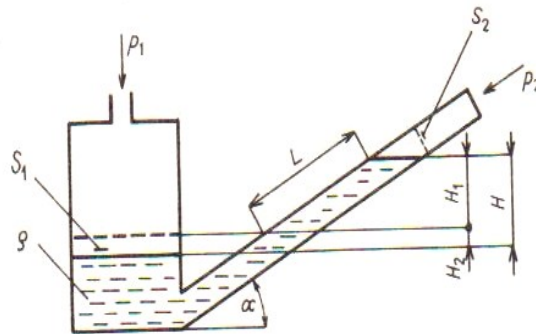


Fig. 9.4 Inclined manometer

Float-type manometer

It works on the principle of a U-tube. Level movement in the vessel is followed by a float, whose shaft is provided with a mechanical drive to transfer the movement of the float to an indicator.

Piston manometer

This is a very accurate pressure measurement device capable of measuring pressures up to 10 MPa with accuracy better than $\pm 0.5\%$. There is a protective layer of oil in the measuring chamber, which protects the piston from undesirable effects of the medium that is measured. It is used for control purposes in calibrating facilities and for accurate operational measurements.

Deformation pressure sensors

The basis of deformation manometers is an elastic element that is capable of elastic deformation under compressive load. Individual deformation manometers differ in their structure and location of the deformation member.

Bourdon manometer

The deformation element here is the so called Bourdon tube, coiled into a circular shape. The cross-section of the tube and the wall thickness depend on the size of the measured pressure. When the internal pressure is in place, the tube tries to take up a circular cross section. Therefore the original curvature transforms into a circle of larger radius and the free end of the tube performs a movement. This movement is mechanically converted into the motion of gauge hands.

Membrane manometer

The elastic member is formed by a circular membrane clamped between two flanges. It measures overpressures, underpressures, and differential pressures.

Box manometer

It has a flat disk as the elastic element, whose bottoms are made up of membranes. They are used for measuring low pressures.

Bellows type pressure gauge

It has a substantially greater deformation of the measuring element. It measures underpressures, overpressures, and differential pressures. For their high sensitivity, they are often used in pneumatic control units.

Measurement of flow rate

The amount of energies of various kinds, which are fed to metallurgical aggregates, should be continuously monitored in order to regulate them.

When measuring the flow rate, it is necessary to distinguish between the two basic ways of measuring. Measured is either the flowing amount (an amount which, at some moment, flows through the pipe) or the total quantity that flew through over a unit of time (consumption).

Flow rate measurement using differential pressures

For measurement, we can use the difference between static pressures in the pipeline bottleneck (shutter flow meters and Venturi meters), the difference between dynamic and static pressure (Prandtl tube) or changes in the distribution and difference between static pressures when the fluid flows through a curved pipeline (elbow flow meters).

Shutter flow meters and nozzles

The measurement is based on the change in the static pressure of the measured substance flowing through a constricted pipeline cross-section. During the flow, the flow cross-section near the shutter becomes reduced, and consequently the flow rate grows and the static pressure of the flowing substance is reduced. The accuracy of measurement might be significantly affected by unsuitably located shutters and nozzles within the pipeline. Location must be chosen so that the flow of the medium in front of the shutter and behind it was smooth and not affected by the pipeline curvature, etc. According to the location of the sampling points, we distinguish between single-point, multi-point and chamber methods.

Prandtl tube

It allows you to measure total and static pressures (Fig. 9.5). The front opening senses the total pressure, and side slits sense the static pressure. The main disadvantage of this measurement method is the manual handling required during measurement and alignment of the tube at each point. It is used in one-shot verification measurements.

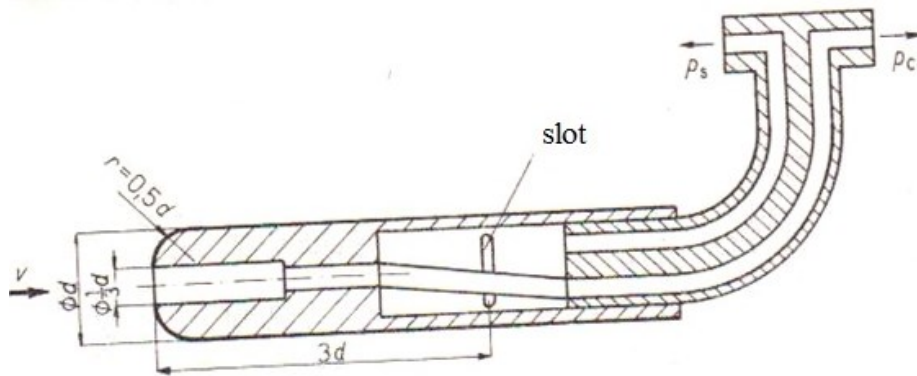


Fig. 9.5 Prandtl tube

Elbow flow meters

When medium flows through the elbow, the static pressure at the outer circumference of the elbow increases, while at the inner circumference it decreases. The advantage of elbow flow meters is the zero pressure loss as a result of the measurement, insensitivity to dirt and the possibility of using the existing pipeline elbows for measurement.

Positive displacement flow meters

They are based on the static force effect of the medium being measured. Positive displacement flow meters with discontinuous cycle allow very accurate measurement of the amount, but their main drawback is the intermittent flow of the medium. Positive displacement flow meters with continuous cycle work so that the measured medium gradually fills several chambers and the pressure effect occurs as the movement of the separating element. The gradual emptying of chambers ensures the smooth flow of media.

Oval gear flow meters

It works with a continuous cycle. It consists of two toothed rollers of an oval cross section that rotate in the flowmeter chamber so that they maintain the tightness of contact surfaces. Accuracy of measurement depends on the untightness of the rotors.

Rotary piston flow meters

It is used in metallurgical plants to measure the flow rate of liquids, particularly for measuring and dispensing of fuel oil during intensification of the process of heating in blast or steelmaking furnaces. They have high accuracy and long term stability of accuracy. The disadvantage is a low accuracy at low flow rates.

Velocity flow meters

They are based on a dynamic force effect of the flowing medium on the rotating element of the meter. The rotational speed of the rotating element is proportional to the mean flow velocity, and thus the amount flowing through.

The advantage of velocity flow meters is their high accuracy, the possibility to construct meters for a wide range of measured quantities, low pressure drop and long-term preservation of parameters of the meter.

The disadvantage is their high sensitivity to mechanical impurities contained in the gas or liquids. It is necessary to use filters that need to be checked and cleaned regularly.

Induction flow meters

They are based on Faraday's induction law. This law says that electrical voltage is induced in an electrical conductor moving perpendicular to the lines of force of the magnetic field. For an induction flow meter, the column of liquid (in the pipeline) between two electrodes is considered a conductor, which moves in the magnetic field through the influence of flowing.

It consists of a pipeline of non-conductive and non-magnetic material, possibly metal, but the inner surface must be insulated. The advantage is the independence of measurement on the density of the measured substance, its viscosity, pressure and temperature. Neither the Reynolds number has any effect. They are used in sewage treatment plants and sludge management.

Gas and flue gas analysers

It is not possible to control metallurgical processes without complete chemical analysis. Chemical analyses performed in metallurgical plants can be distinguished as follows:

- analyses in chemical laboratories - chemical analyses of substances entering the production processes, analyses of finished metallurgical products, semi-finished products and by-products;
- operational analyses - analyses of gaseous media, flue gases and gases produced during metallurgical processes (analysis of blast furnace gas, waste gases, flue gases, etc.).

The content of a specific gas component in the flue gases, waste gases and other gaseous mixture is referred to as the concentration.

Analysers based on the thermal conductivity of the gas

The measurement is performed by comparing the thermal conductivity of the gas being measured with the thermal conductivity of the reference gas. Most often air is chosen as the reference gas. Analysers using the thermal conductivity are preferably used for measuring the content of H₂ and CO₂, or SO₂.

Analysers based on heat of combustion (gross calorific value)

They use different heat of combustion of gases. In metallurgy, this analyser is used for analysing the blast furnace gas.

Analysers for determining the oxygen content

They are based on the magnetic properties of oxygen. Substances can be divided by their magnetic permeability to ferromagnetic, paramagnetic and diamagnetic. Gases are generally diamagnetic, except for oxygen, and some other gases, which are paramagnetic.

Infrared gas analysers

It uses a method based on the absorption of infrared radiation by certain gaseous substances. Infrared rays only absorb those gases which contain at least two different kinds of atoms in a molecule. This method is therefore not suitable for measuring substances such as oxygen, nitrogen, hydrogen, etc. Most often this method is used for the measurement of content of CO, CO₂, CH₄, and C_nH_m. Every substance absorbs infrared radiation in a narrow, precisely defined band.



Questions to Chapter 9

88. On what principle does the thermocouple work ? Explain it.
89. What types of thermocouples do you know?
90. What types of electromagnetic radiation do you know?
91. Classify pyrometers into groups and briefly describe them.
92. For what U-shaped tube is used?
93. Is it possible to increase the sensitivity of the inclined manometer and how?
94. Enter the disadvantages of using Prandtl tube.
95. Name the positive displacement flow meters.
96. On what law is principle of induction flow meter based? Explain it.
97. What analyses we distinguish in metallurgical processes and what is done during them?
98. What analysers of gas and flue gas do you know?

10. INDUSTRIAL FURNACES – PART ONE

Furnace is a technological device whose main objective is to create optimum conditions for the course of a specific technological process. What is important is the shape of the furnace chamber. The economy of operation is influenced by the use of waste heat from flue gases.



Study time: 15 hours



Objective After reading this section, you should be able to

- Classify industrial furnaces according to various criteria.
- Determine the thermal and temperature regime of the furnace.
- Calculate the efficiency and capacity of the furnace.
- Describe the blast furnace, cupola furnace, converter and arc furnace.



Presentation

There are different criteria applied to the classification of industrial furnaces. Most frequently they are divided by the following characteristics:

1. According to the technological purpose:

- melting – intended for melting materials (blast furnaces, cupola furnaces, glass melting bath),
- heating – intended for heating the material before rolling, forging, pressing, etc. (forge furnaces, rolling mill furnaces),
- heat treatment – intended for heat treatment such as hardening, annealing, tempering,
- burning – intended for firing products (kilns for firing refractory ceramic materials, lime kilns),
- drying – to remove moisture from the material (drying of moulds and cores in foundries),
- distillation – a new product is formed from the charge by distillation (coke oven batteries).

2. According to the heat source:

- flame - heat energy is obtained by combustion of solid, liquid or gaseous fuels,
- electrical - thermal energy is generated from electricity (arc furnaces, resistance furnaces, plasma furnaces, induction furnaces, electron furnaces)
- no external source – they use internal chemical energy of the processed metal and its additives.

3. According to the shape of working space (chamber):

- shaft - the entire volume is filled with charge, the counter-current principle,
- tank – only part of the working chamber is filled with charge,
- continuous – either horizontal (pusher-type kilns, walking beam furnaces) or vertical (tower furnaces), the charge moves from the charging window to the withdrawal window,
- rotary-hearth furnace – charge moves together with the hearth, which has a circular ring shape,
- pipe - cylindrical shape, diverted from the horizontal plane by a small angle, turns while the charge is constantly stirred,
- tunnel – charge moves in a straight line along with the hearth consisting of a series of carriages,
- chamber – charge lies on the hearth during the whole technological process, the design can be either fixed hearth or bogie type, temperature of the working space is at all points practically the same,
- hood-type (muffle) – charge is protected from the furnace atmosphere by a hood - muffle.

4. According to the way of using the waste heat from flue gases:

- recuperative – the use of a recuperator for preheating the combustion air or gas,
- regenerative – the use of a regenerator,
- without heat exchanger.

The above classification of furnaces is, of course, not complete. Furnaces can be divided according to additional criteria, such as by the dependence of power on time (steady and non-steady), by mode of charge transport (walking-beam, roller, pneumatic, etc.) or

according to the level of temperature in the working chamber (low temperature, high temperature).

Thermo-technical characterization of the work of the furnace

The main indicators of the work of furnace are the temperature and thermal regimes, efficiency and capacity.

Temperature regime

Under this concept, we can imagine the temperature of the furnace as a function of time. The furnace temperature is dependent on the combustion temperature of the fuel, the amount of heat absorbed by the walls of the furnace and the furnace charge, the shape of the working space and the size of the other heat losses. Theoretical determination of the furnace temperature is extremely difficult, for indicative calculations we derive the temperature of the furnace from the practical combustion temperature.

$$t_p = t_t \cdot \eta_{pyr} \quad (^\circ\text{C})$$

where:

η_{pyr} is the pyrometric effect characterizing the furnace design; its size ranges from 0.65 to 0.85.

The furnace temperature is determined by its technological purpose. High temperatures occur in melting furnaces, in furnaces for heat treatment the difference is less. The greater the difference between the furnace temperature and the temperature of the charge, the more quickly the process proceeds, which may lead to adverse effects, i.e. higher melting loss, melting of the surface near the heating point, uneven heating etc. Lower furnace temperature causes prolongation of the entire process and greater energy losses.

Thermal regime

Thermal regime can be defined as the functional dependence of the heat input on time. Heat input is an amount of heat introduced into the furnace over a unit of time. The largest possible amount of heat introduced into the furnace chamber is called maximum heat input. With non-stationary working furnaces, the thermal regime is a function of time, while with the stationary furnaces it is constant.

In the older literature, the input of the furnace is given using the specific fuel consumption (B_{mp}). Specific fuel is a fictitious fuel with efficiency of $29.3 \text{ MJ}\cdot\text{kg}^{-1}$.

$$B_{mp} = \frac{P}{29,3 \cdot 10^6} \quad (\text{kg}\cdot\text{s}^{-1}, \text{m}^3\cdot\text{m}^{-3})$$

In the furnace practice, we can come across an indicator called the specific heat load (p) of the working space of the furnace. It determines the heat input per unit of the working space volume:

$$p = \frac{P}{V} \quad (\text{W}\cdot\text{m}^{-3})$$

Furnace capacity

It indicates how much material we melt out, dry, warm up and produce in general in a given unit per unit of time. According to the type of furnace, the mass and time units are chosen, and so the capacity is measured in $\text{kg}\cdot\text{s}^{-1}$ or $\text{t}\cdot\text{h}^{-1}$.

The capacity of the furnace depends on a number of factors, such as temperature of the working space, temperature of discharged flue gases, the method and intensity of heat transfer to the charge, etc.

To compare the productivity of the same kinds of furnaces of different sizes, we use the specific capacity. In most furnaces, the specific capacity (g) refers to one square metre of hearth (S_N) and one hour.

$$g = \frac{G}{S_N} \quad (\text{kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1})$$

Efficiency of the furnace

The heat balance is used to analyse the thermal work of the operated furnace, during which we analyse the items of heat intake and output. The ratio of heat usefully consumed (Q_u) to the furnace input is called the efficiency of the furnace.

$$\eta_p = \frac{Q_u}{P} \cdot 100 \quad (\%)$$

In case of heating furnaces, the item Q_u includes the heat of the hot metal and scale, in case of melting furnaces it is the heat of the molten metal, slag and heat for the decomposition of slag-forming additives. The higher the furnace efficiency, the more superior unit is the furnace from a thermo-technical viewpoint.

The fuel consumption in the furnace is characterized by an indicator called the specific energy consumption (e), which indicates the amount of energy consumed per unit of production.

$$e = \frac{P}{G} \quad (\text{J}\cdot\text{kg}^{-1})$$

Blast furnace

Blast furnace is the largest melting unit in which pig iron is acquired from iron oxides through the reduction processes.

An iron-bearing charge (iron ore, sinter, pellets, etc.) is charged into a blast furnace, plus slag-forming additives and coke. To burn the fuel, the preheated air (blast) is blown into the furnace from Cowper stoves, sometimes enriched with oxygen.

The main product of the process is pig iron; by-products are blast furnace slag and blast furnace gas. Tuyeres bring to blast furnaces also the substitute fuels that can be gaseous, liquid or powder.

The working space (chamber) of the furnace consists of a high shaft of circular cross-section, which is lined with refractory material. The furnace stands on a concrete base; the bottom part is disposed below ground. The upper cylindrical part is the throat and

downwardly, the furnace gets wider and this part is called the shaft. The widest part of the furnace is the belly and the conical tapered part is the saddle. The lower part is called the hearth, may be of cylindrical or slightly conical shape, and it is closed by the bottom from below. Tuyeres blowing the heated air are situated in the upper part of the hearth. Pig iron and slag are discharged through the tap hole, which is located 0.5 - 2 m above the hearth. The number of tap holes depends on the richness of the charge.

The furnace lining and shell must be protected from the effects of high temperatures by cooling. Mostly water or evaporative cooling is used. Coolers are usually of a plate type and they are placed between the steel shell and furnace lining. Between the bottom and concrete base, cast iron slabs are laid with embedded steel tubes that carry the cooling air.

Blast furnaces are built with a thin-walled or thick-walled lining. Material of the lining is chosen according to the main causes of wear of the brickwork at a given point of the furnace. Fireclay materials are used for the upper and middle part of the shaft, while fireclays of the finest grade, high alumina fireclay and mullite materials are used for the lower part, belly and saddle.

Cupola furnaces

Cupola furnace is a shaft furnace for the production of cast iron from pig iron. It uses coke as a fuel and fluorite and limestone are added for the formation of an easily meltable slag.

The bottom of the cupola furnace has a circular opening which is closed by a door. At the bottom, there is the tap hole for cast iron; the tap hole for slag is placed above. In terms of the temperature progression in the charge, cupola furnaces can be divided to preheating, melting, superheating and hearth zones.

In the preheating zone, all materials are in the solid state. Gradually they sink down and warm up. At a temperature of 800°C, limestone decomposes and coke loses moisture and volatile matter. In the melting zone, slag is formed by melting the metal-bearing charge. Coke is still in the solid state. Drops of molten metal and slag flow down, where they pass through the superheating zone and their temperature rises. They are mainly heated by the hot coke. In the hearth zone, coke is not burning any more. The temperature of the filling layer is downwardly declining.

According to the nature of the slag, furnaces are lined with:

- acidic linings – semi-hard fireclay, ramming materials with ceramic binder,
- basic linings – magnesite,
- neutral materials based on Al_2O_3 , Zr_2O_3 , SiC – in water-cooled cupola furnaces.

Converters

Converters are aggregates which produce steel from molten pig iron and other ingredients. The heating and melting of the charge make use of the heat generated by oxidation of the elements contained in the pig iron (carbon, silicon, manganese, and phosphorus). Air or oxygen is used as the oxidant, and accordingly converters are divided

into air converters and oxygen converters. Approximately 50% of the heat is introduced into the process by exothermic reactions and other 50% by the enthalpy of the liquid pig iron.

a) Air converters

Today, they are no longer in use.

b) Oxygen converters

Technically pure oxygen having a content of 99.5% O₂ is used as the oxidizing gas, thereby the volume of gases blown into the converter is reduced and the amount of heat needed for their heating decreases. The excess energy is used to heat and melt the scrap and solid oxidants (iron ore, sinter, and scale). Lime is added for the formation of slag. Thermal efficiency is 75%. By way of oxygen blowing, converters are divided into LD process (oxygen top-blowing) and OBM process (oxygen bottom-blowing).

LD converters

Converter consists of a vessel, carrying ring, pins, bearings, and tilting device with a drive and stand. The shell is made of sheet steel. They are lined with refractory materials in multiple layers. Basic materials are magnesite or dolomite with ceramic or tar-based bond. The most common way to repair the lining is guniting, i.e. applying refractory material with a binder under pressure to the areas being repaired.

OBM converters

They were developed for processing phosphatic pig irons, which can only be processed in LD converters with great difficulties. The nozzles at the bottom blowing consist of two concentric tubes. The inner tube drives in oxygen, while annulus drives in gaseous or liquid hydrocarbon refrigerant (natural gas). They are lined with dolomite and magnesite materials, either tar-based or burnt. Material based on MgO-C is used in the vicinity of the nozzles, where the lining is stressed by large temperature variations.

The main advantages of OBM process when compared with the LD process:

- lower iron content in slag and lower fly ashes → higher yield of iron from the charge,
- lower nitrogen and oxygen content in the steel → lower consumption of alloying and deoxidising ingredients (Mn, Al,...),
- better steel desulfurization at the same basicity of slag → lower consumption of lime,
- lower investment cost,
- the possibility of using untreated steel waste with greater weight of individual pieces.

The OBM process has, however, also disadvantages against the LD process:

- higher hydrogen content in steel,
- higher share of steel waste in the charge (by 2 – 5 %),
- reduced service life of lining (especially at the bottom).

Electric arc furnaces (EAFs)

Electrical energy is converted into heat in an electric arc, from which heat is transferred to the charge by radiation. We divide arc furnaces to:

- a) furnaces with a dependent arc - the charge is part of the electrical circuit and the current passes through the electrode, arc and charge on the adjacent arc and electrode,
- b) furnaces with an independent arc – the arc is not bound to the charge, it burns between electrodes,
- c) covered-arc furnaces – the arc is covered with molten charge.

The electric arc is a type of electrical discharge in the gas. A prerequisite for discharge is the ionization of the gas, which can occur either by impact or influence of electromagnetic waves. The ionization of the gas in the arc occurs through collisions of electrons with neutral atoms.

EAF is composed of the furnace itself with a lining, tilting mechanism, electrodes with holders, sliding mechanism, and electrical accessories. The working space consists of the bottom, walls and roof. Electrodes are placed vertically and are fastened in holders, moving on supporting posts.

An advantage of electric arc furnaces is that, unlike oxygen converters, they are not dependent on the production of pig iron. Making steel by this method is characterized by low raw material demands and specific energy consumption. They can make steels in a wide range of quality grades. A disadvantage of these furnaces is lower producibility and productivity of labour when compared with oxygen converters, as well as the use of expensive electrodes.



Questions to Chapter 10 – Part One

99. How we divide industrial furnaces?
100. How to calculate the efficiency of the furnace?
101. What is the temperature and thermal regime of the furnace?
102. Describe the charge into the blast furnace.
103. How the cupola furnaces are lined?
104. Enter the by-products of producing pig iron in a blast furnace.
105. How we divide converters? Describe them.
106. What are the advantages of electric arc furnaces?

10. INDUSTRIAL FURNACES – PART TWO



Study time: 24 hours



Objective After reading this section, you should be able to

- Define different kinds of furnaces that are commonly used in metallurgical or machine works and other plants.
- Describe the different types of furnaces - their advantages and disadvantages, suitability for use.
- Define the structural characteristics of induction furnaces, electron furnaces, plasma furnaces, heating furnaces - soaking, pusher-type, chamber, walking-beam, rotary-hearth; heat treatment furnaces, and furnaces with microwave and dielectric heating.



Presentation

Induction furnaces

Induction furnaces use the induction heating method as previously mentioned. Induction furnaces are divided to:

Furnaces with an iron core – channel-type furnaces

Furnaces without an iron core - crucible furnaces.

Induction furnaces are used for melting materials, heating materials for hot forming and thermal processing of materials. Furnaces are powered by a current of low or medium frequency.

The following sections describe the different types of induction furnaces.

Induction furnaces with an iron core

Induction furnace with an iron core is a device based on a closed-core transformer and the primary coil is connected to the network with the appropriate frequency. The secondary part of the transformer is made up of a channel which is filled with molten metal and forms a short-circuited thread.

These furnaces are used for melting ferrous metals - copper and its alloys, nickel, aluminium or cast iron, but also in the steel making process - steel vacuum degassing, or may

preheat pig iron before further processing (e.g. in an oxygen converter). The advantages of induction furnaces with an iron core are as follows:

- No carburizing of the molten bath (as occurs in arc furnaces, which use electrodes for melting).
- The charge swirls, therefore, more efficient mixing of materials takes place - better homogeneity.

Induction furnaces with an iron core are supplied from a single-phase generator with a low frequency (5-10 Hz). Furnace coil is connected to the phase or mesh voltage. During the process, the level of melting charge is not horizontal, but inclined (higher) at the outer edge of the groove. Thus the movement of charge is caused and leads to mixing of the material. Power input of the furnace must be sufficient for the charge to be melted and agitated. If the furnace input is incorrectly set, it reaches the critical value of current and the side effect, known as the “pinch” effect takes place. When this effect happens, the continuous ring of molten metal is disrupted, electrodynamic forces (which cause mixing of the charge) cease to operate and the ring of the molten charge joins together and current surges are generated, which prevent correct operation of the furnace. Therefore, induction furnaces with an iron core are constructed with a concealed channel embedded on the bottom of the furnace.

Schematic representation and description of the channel furnace is in Figure 11.1. The melt is placed in a pot with refractory lining (5). Under the pot, a primary coil (4) is placed which is wound on a ferromagnetic core (2). Inductor made of refractory material is encircled by one or more channels (3), which open into the melt. The molten metal within the channel creates a secondary short-circuited thread and owing to electrodynamic forces it flows from the channel into the melt. And due to hydrostatic pressure, a new metal flows into the channel. In this manner, the charge is intensely mixed up.

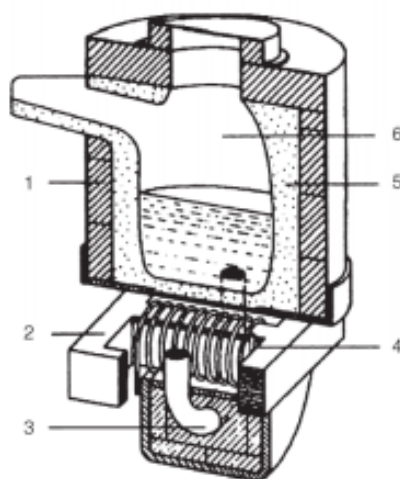


Fig. 11.1 Channel-type induction furnace

- 1 - Insulation 4 – Primary coil 2 – Core of the transformer 5 – Refractory lining
3 - Channel 6 – Melting chamber

The heat for melting of the charge is generated only in the charge located in the channel. Through the effect of electrodynamic pressure, the metal is continuously discharged from the channel into the hearth, and the colder metal from the hearth flows into the channel. By this, heat is transferred from the channel to the whole charge in the hearth.

The charge for these furnaces must include both a solid part and a prepared melt. The melt is prepared in advance in another device or portion of the "previous" melt is retained. Liquid charge then constitutes 10-30% of the capacity of the furnace.

The electromagnetic energy generated by the activity of an induction furnace with iron core is converted into thermal energy in the channel. Heat to the other charge is passed on through convection and conduction.

Furnaces are lined with a lining that prevents the reduction of life of the furnace. Furnace lining is thick, as this will reduce the heat losses and improve the working conditions of the furnace - for example, the charge will remain longer warm during a power outage lasting several hours. Proper lining extends the life by several months. Lining of the channel around the inductor is on the other hand as thin as possible, to not reduce the electrical efficiency of the furnace. The channel is highly stressed part of the furnace, so the life of lining is less than the life of the lining in the whole furnace. Therefore ducts are constructed removable to allow for the replacement of the lining.

Induction furnaces with an iron core have good electrical efficiency (about 85-95%) and low losses by burning (below 1%). The overall efficiency of channel-type induction furnaces is between 70 and 80%.



Fig. 11.2 Induction medium-frequency melting furnace for melting grey cast iron, Roučka Slévárna, a.s.

Induction furnaces without an iron core

Induction furnaces without an iron core are called crucible furnaces. The crucible of a refractory ceramic material is located inside the cylindrical inductor. The furnace has no iron core, the magnetic lines of force are closed by air, energy gets lost in the process and the efficiency of the furnace is lower.

Induction crucible furnace with non-conductive crucibles

This induction furnace can be made in three variants

- with a conductive shielding jacket,
- without shielding jacket,
- with an iron core outside the coil.

Induction crucible furnace with non-conductive crucibles is shown in Figure 11.3. A crucible (of ceramic material) is placed within the coil. Shielding jacket is made of sheet copper or steel casing with packs of transformer sheets. A current with a frequency of 500 to 10 000 Hz plus current with the mains frequency passes through the coil (Cu material). The coil radiates electromagnetic waves into the inner cavity, which strike perpendicularly upon the charge that is disposed in the crucible. The charge heats due to the absorption of electromagnetic waves. Through the coil cavity, a magnetic flux passes that closes outside the coil. It is necessary that the magnetic field intensity outside the furnace is minimized in order to avoid heating of the load-bearing structure. Therefore, the entire device is protected by the shielding jacket.

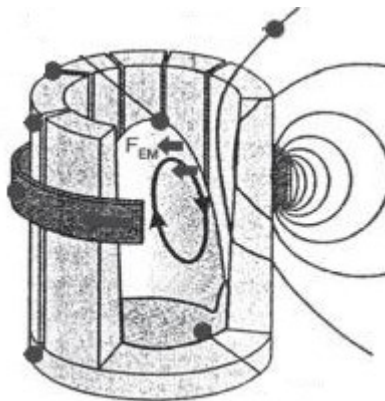


Fig. 11.3 Crucible induction furnace of Stinchcombe Furnaces Group, s.r.o.

Induction crucible furnace with conductive crucibles

Induction furnace having a non-conductive crucible has low electrical efficiency in melting good-conducting materials such as copper and its alloys, aluminium and its alloys. But electrical efficiency increases when the furnace is equipped with a conductive crucible. Crucibles are made of different materials. E.g. for lower melting points, such as aluminium and its alloys, the crucible is made of cast steel, while for higher melting points graphite crucibles are used - a mixture of fireclay and graphite.

There is a ceramic insulating layer between the coil and the crucible that reduces the lost heat flux from the hot crucible into the cooling water.

If we insert current into the coil, an electromagnetic wave occurs, which attacks the surface of the conductive crucible, enters its wall, and induces a current in the wall, through the passage of which the crucible is heated. The heated crucible transfers heat to the charge.

Comparison of induction furnaces

The efficiency of the furnace with an iron core is about 5% higher than in the furnace with the shielding jacket. Every increase in efficiency leads to electricity savings, particularly for large furnaces designed for continuous operation. The crucible induction furnace with an iron core is technically a "more perfect" solution, but its production is more expensive. Also its operation is more costly, especially when the crucible breaks out, which may cause damage or destruction of the furnace.

STRENGTHS AND WEAKNESSES OF INDUCTION FURNACES

Strengths:

1. Melting in any atmosphere or vacuum – i.e. production of various steel grades
2. Minimum loss of alloying elements
3. Chemical homogeneity and uniform temperature of the molten material
4. Melting without electrodes
5. Silent operation, operation without emissions.

Weaknesses:

1. Slag has a lower temperature than the melt (by up to 200 K), because it only heats up from the metal
2. Reduced life of the lining
3. Higher costs of electrical equipment
4. Lower capacity

Electron furnaces

We use electron furnaces for melting materials. Electrical energy is converted into the kinetic energy of electrons emitted by the cathode and accelerated by an electric field between the cathode and anode. The kinetic energy of electrons when they hit the surface of the heated material is converted into thermal energy. After hitting the surface of the heated material, electrons penetrate into its crystal lattice, and collide with atoms and free electrons. The depth of penetration is then about 10^{-6} m to 10^{-7} m. The energy of electrons is absorbed in a thin surface layer and the generated heat propagates into the material by conduction. As far as the molten mass is concerned, besides conduction, also convection or radiation is applied.

Electrons, which have penetrated first into the charge, are accelerated from their trajectories by the action of metal atoms. It may happen that the electron can leave the metal without passing to it all its initial energy. The ratio between the quantity of reflected (secondary) electrons and the amount of incident (primary) electrons is defined by the

reflection coefficient k_N . The coefficient ranges from 0.2 to 0.5; it is a function of the atomic number of a particular given metal.

Energy of reflected electrons is by order comparable with the energy of primary electrons. However, since some electrons do not pass all their energy, the mean value of energy of reflected electrons E_{OD} is introduced, as well as coefficient k_E , which is also a function of the atomic number of particular metals and does not exceed 0.35 to 0.45.

The total energy losses due to the reflection of electrons for metals having an atomic number less than 75 range up to 0.2.

Electron gun

This is a device in which an electron beam is emitted by cathode; it gets accelerated in the electric field and directed in the magnetic field to the metal being heated. The cathode is made of tungsten and is directly or indirectly heated; her life is between 10 and 100 hours of operation.

Structural design of electron guns:

- axial system,
- annular cathode system, near or distant,
- with transverse electron beam.

Axial electron gun

The main cathode is disk-shaped and is heated by the electrons, which strike from the fibres of the auxiliary cathode. The voltage between the cathode and anode accelerates the flow of thermally emitted electrons. For steady gun operation, an underpressure of 10^{-3} Pa must be ensured in the zone where beam is formed. The cathode, anode and the focusing electrode form an electron beam, which then gets out through an opening in the anode. The first magnetic coil allows the electron beam to pass through the chamber of the vacuum closing without loss. The closing allows opening the furnace without loss of vacuum in the electron gun system. At the lower part of the gun, there are other rectifier coils and a deflecting device. The electron beam is deflected in order to avoid overheating of the charge, due to the large value of heat flux density - for melting steel - 5 MW.m^{-2} .

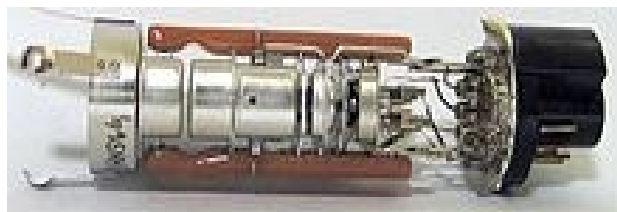


Fig. 11.4 Electron gun

Electron melting furnaces

These furnaces are used for remelting metals. In general, the furnaces consist of the following parts: electron gun - working chamber - crystallizer - mechanisms for feeding

remelted material and pulling out ingots - vacuum system - water cooling - opening for the observation of charge.

The initial material intended for remelting (refining) metals (materials) may be an ingot or bar. After necessary vacuum is created, the emission of electrons occurs and the electron beam is directed on the remelted material and surface of the ingot. The material starts to melt and falls dropwise into a copper, water-cooled crystallizer. These drops produce an ingot which is continuously pulled out from the bottom of the crystallizer. This method is used for high-melting materials, such as tungsten, molybdenum, tantalum, niobium, or for high-purity semiconductors.

There are furnaces having two electron guns, the first is used for melting the feed material and the second gun heats the surface of the melt in the crystallizer. These furnaces, usually, have power output of 7.5 MW, and the charge is around 100 tons.

Advantages of electron remelting:

- high vacuum on the surface, i.e. we achieve high purity,
- melting is controllable and adjustable, particularly adjustable is the feed of charge,
- melting can be maintained at any operating temperature,
- melting as a process can be monitored optically.

Disadvantages:

- increased evaporation of metals,
- low efficiency, high specific energy consumption,
- X-ray radiation generated during the process.

Electron furnace efficiency

Efficiency is determined by the electrical and thermal efficiency. The electrical efficiency includes efficiency of the high voltage source (85-95%), electron gun (96-98%) and conversion of the kinetic energy of electrons into thermal energy (80-90%). The total value of electrical efficiency is 60-80%. Thermal efficiency includes heat losses by radiation and evaporation from the surface of the bath and the loss of heat by being conducted through the ingot. All losses increase with the temperature of the melt and remelting time. Therefore, it is ideal to set the appropriate time of remelting and optimum temperature in accordance with technological requirements, but also with the requirements of energy. The thermal efficiency of the furnace is not higher than 15%, so the overall efficiency is in the range between 8% and 12%.

Plasma furnaces

As a source of energy in plasma furnace, plasma is electrically conductive, has high thermal capacity and conductivity and is influenced by effects of electric and magnetic fields.

We distinguish between **low-temperature** plasma (temperature of 10^3 K to 10^4 K) and **high-temperature** plasma (temperature of 10^5 K to 10^8 K). Devices for converting electrical energy into thermal energy for low-potential plasma are called **plasma torches** (plasmatrons). The plasma torch makes use of an electric arc concentrated by a nozzle and aerodynamic effect of plasma-forming gases. The essence of ionization in the discharge is the formation of electron avalanches in a chain effect. Plasmatrons with a gas stabilization of electric arc work with direct current of high intensity, or alternating current.

Plasma-forming gas may be argon, helium, nitrogen, hydrogen, or a mixture of gases - argon and hydrogen, argon and helium, argon and nitrogen, air, air and natural gas. These gases or their mixtures are selected according to the technology and requirement of protective and technological atmospheres (oxidizing, reducing or neutral).

Types of plasma torches:

- with independent electric arc – melts even electrically non-conductive materials,
- with dependent electric arc – most commonly used in metallurgy.

The body of the torch must be continuously and intensely cooled with water. Electrodes are made of tungsten.

Technical application of plasma torches

These torches can also be used in following areas:

Coating of material - filler material is fed in the form of wire or powder. Powders are applied to metal surfaces. Both the torches with dependent and independent arc are used. Torches operate with an auxiliary gas. Auxiliary gas supplies still new particles and forces the discharge to burn on the axis of the plasma torch. A condensed discharge is formed, with smaller diameter, and higher voltage and temperature. An example may be argon or diatomic gases.

Welding – If the plasma hits the material, atoms are merged, while releasing large amounts of heat. High frequency ignition device ignites the torch, which ignites the auxiliary arc. This will ionize the gas column between the nozzle and the material. Then the main arc is created between the tungsten electrode and the material. The weld is performed by targeting the torch head along the welding surfaces. The plasma flow must pass freely from the material. The weld is formed by the merger of the molten metal only after removal of the plasma torch. This method of welding is used mainly for welding thin metal and alloy sheets. In this method, only small areas of the sheet are heated, thus creating little stress and strain in the material.

Cutting – is analogous to the welding of material. The difference is that the flow of gas from the torch nozzle has a higher speed. Thus the liquid metal is removed from the cut and it prevents its merger after the plasma torch is removed. Nitrogen is used as an auxiliary gas, which is guided helically around the arc. The arc gets more concentrated and stabilized. The thermal stress of the material is smaller than in conventional cutting (separation) of the

material. The width of cut is small and there is no need to count with material allowance for reworking.

For chemical reactions, which normally proceed at atmospheric pressure, it is possible to use plasma heating, where high temperature is required. This is used in the synthesis of chemical compounds, in the manufacture of acetylene, hydrogen cyanide, etc.

Material melting – takes place in the plasma furnaces, which are described in the following sections.

Plasma melting furnaces with refractory ceramic lining

These furnaces operate like arc furnaces - electrodes are replaced by a plasma torch. A water-cooled plasmatron cathode made of a tungsten-based alloy is protected from slag and hot metal by a copper nozzle, which is also cooled by water. The cooled electrode (anode) is situated in the furnace hearth. The furnace space is sealed by a sand seal to make it possible to melt in an inert atmosphere. The shape and lining of the working space is similar to that of arc furnaces. The furnace is equipped with an electromagnetic stirring of the charge in order to avoid local overheating of the resultant melt.

Torches of plasma furnace, which are built into the side walls, may be positioned at an angle (e.g. 45 °). The furnace has two times smaller losses of heat from cooling water and higher efficiency.

Efficiencies of furnaces depend on the mode of operation, typically they are around 20%, with the losses from cooling water moving around 40% of the total input of the furnace.

Plasma furnaces with a water-cooled crystallizer

These furnaces are similar to electron furnaces. Plasmatrons are used instead of electron guns and furnace operates at a pressure close to atmospheric pressure. These furnaces are suitable for remelting grade steels, as well as metals and alloys with high melting point.

The furnace consists of the melting chamber itself and a copper crystallizer and plasmatron. Above it, there is a chamber for placing the remelted material, while in the lower part there is a space for cooling down metal. The remelted metal is fed by means of a mechanism with axial and rotary movement. The furnace has systems for creating a vacuum, cooling-through of the crystallizer and other parts of the furnace and other facilities for the auxiliary gas (circulation cleaning, distribution).

Advantages of plasma furnaces:

- the use of any working atmosphere,
- no electrodes are used for remelting,
- less evaporation of metal,
- high and easily adjustable temperature

- fast melting, high concentration of energy.

Disadvantages of plasma furnaces:

- short life of plasma torches,
- risk of the cooling water penetrating into the furnace chamber upon ignition of the nozzle.

Heating furnaces

Heating furnaces are used in industrial plants wherever it is needed to heat the material to a certain temperature before technological processing. They are mostly metallurgical plants, rolling mills and forging shops. By heating, the material (metal) becomes more plastic, has lower deformation resistances. Temperature prior to the forming processes must be high enough to ensure that during transport from the heating furnace to the device no significant temperature drop takes place. At the same time, heating must not cause any excessive oxidation of the material. Therefore, every material has its own technological conditions of heating in the context of the construction of the heating furnace and its subsequent use.

Soaking furnaces

Soaking furnaces are structurally adapted for heating ingots before rolling. Ingots have varying thicknesses - most often 0.4 m. The ingot weighing about 10 tons is to be heated symmetrically from all sides. Heating should be uniform in order to avoid internal stresses.

Soaking furnaces have different structural design, different sources of heat (gas, resistance heating) and may have a device for preheating the combustion air or fuel.

Types of soaking furnaces:

- a) one-way – the burners are located on the front side, along with the flue gas exhaust,
- b) two-way – the burners, along with the exhausts are located on the opposite sides. When two burners are located, they are referred to as double-loop, with four burners as tetra-loop.

Structural design:

Soaking furnace consists of two chambers, placed side by side. The chamber, into which material is charged for heating, should always contain the same brand of steel material and should be filled up completely. The weight of ingots, which are charged into the soaking furnace, is dependent on the size of the hearth area. It is desirable that the shading coefficient of the hearth is between 35% and 45%. If the coefficient is less than 35%, the furnace capacity is not fully utilized and its specific capacity is low. When the coefficient is higher than 45%, ingots are heated unevenly, in particular over the cross section.

Usually, the size of the hearth area is in the range between 15 m² and 30 m², the charge size moves from 60 t to 150 t, with power input up to 12 MW. Specific heat consumption and specific capacity is correlated with the temperature of the charge. The temperature of the charge is related to the enthalpy of that charge. If the charge is hot, the capacity of the furnace

increases, because the specific consumption of heat for its heating directly in the furnace decreases.

Soaking furnace regimes

The temperature and thermal regime of the soaking furnace is variable, non-stationary. The course of temperatures – of the furnace, of the ingot surface and centre, and the furnace power input. Furnaces use two-stage heating of material. In the first phase – the maximum amount of heat is supplied and the furnace temperature increases. The second phase is an equalizing phase, the furnace temperature does not change, and gradually the power input decreases. Power input of the furnace must be chosen so as to ensure a sufficiently rapid heating of both the lining of the chamber and surface of the ingot. At small power input, the heating phase becomes unreasonably prolonged. Likewise, too high a value of input is unsatisfactory, because losses of material by burning occur. Most often, the power values varies between 0.33 to 0.55 MW.m⁻² of the hearth area.

In case of a cold charge, the difference of temperatures between the surface and centre of the material increases and internal stresses occur. Therefore, e.g. cold ingots of special (high alloyed) steels are heated in three phases. During the first phase, preheating, the power input is reduced in order to avoid stresses. At temperatures above 600°C, steel is in a plastic state, the material cannot be disrupted and the heating rate increases.

When heating the material in the soaking furnace, oxidation occurs which can reach up to 2%. The formed scale falls off on the furnace hearth and must be removed. If the hearth is not regularly cleaned from scale, the deposit may reach up to 1.2 m high. Then, the furnace is shut down and scale (slag) is removed. The hearth is also lined with a refractory material that does not react with the scale. In the hearth, there is a furnace where the scale (slag) is continuously being removed beneath the furnace.



Fig. 11.5 Soaking furnace with resistance heating

Soaking furnace lining:

The hearth is lined with magnesite, chromium magnesite or corundum. Furnace walls are made of silica, the transition between silica and magnesite is formed by fireclay. The refractory lining is made up of two or three layers. Under the working layer, there is a fireclay layer, and below it an insulation from expanded fireclay. The most thermally and mechanically stressed part of the furnace is the cover, whose life is significantly lower than that of the furnace itself. The cover is lined with fireclay. The seal between the cover and walls is made with a channel filled with silica sand. Currently, you can also find other types of linings – refractory concrete with a hydraulic binder, chemical or fibrous materials, etc. Brickwork needs to be maintained.

Chamber furnaces

Chamber furnaces are used in works processing charge of various shapes and dimensions, as in the forges and rolling mills. They heat the material of a weight ranging from tenths of kilograms to hundreds of tons. Diversity of the charge led to the construction of different types of chamber furnaces.

We distinguish between two basic versions:

- with fixed hearth,
- with movable-hearth /bogie-hearth furnaces/. The movable hearth, which goes out from the furnace on rails, serves for easier charging and pulling out of the charge. This means that furnaces with running-out hearth may have a larger ground plan; length up to 20 m, width up to 6 m. The height of chamber furnaces does not exceed 5 m.

In the chamber furnace, the charge of varied quality, shape and weight is heated and therefore the specific heat consumption is high and fluctuates from 3 to 7 MJ . kg⁻¹. Specific capacity is usually not more than 150 to 250 kg . m⁻² . h⁻¹.

Flue gases have approximately the same temperature in the entire working space of the furnace. It is therefore not possible to use adequately their enthalpy during heating and temperature of the waste flue gases is high. It follows that the thermal efficiency of the chamber furnace is low (10-30%), particularly if the preheating of combustion components not utilized. Flue gases take away up to 65% of the total amount of the applied chemical heat.

Division by thermal regime:

These furnaces work as stationary or non-stationary. *Stationary furnaces* heat large quantities of smaller material. They are fixed-hearth furnaces, the material is charged in manually. Into a *non-stationary furnace*, the material is charged together and together it is also pulled out.

Chamber furnace lining:

Lining is most frequently fireclay with sufficient thermal capacity. Lining must be completely insulated to avoid large losses of heat to the surrounding area. Blocks made of fireclay can be replaced by refractory concrete.

Chamber furnace heating regime:

Chamber furnaces are heated by gas. The burners in the furnace are chosen so as to avoid overheating of the charge and thereby its damage. In addition, even distribution of the temperature field in the furnace must be ensured, so burners with low outputs are installed, which are located just above the hearth. In larger furnaces, burners are also under the roof of the furnace.

The material is deposited on rests such for the flue gases to be able to flow around the charge; therefore we leave spaces between 100 mm and 200 mm.

Pusher-type furnaces

Pusher furnaces are used in rolling mills for heating billets and slabs weighing up to 40 tons. The furnaces can be also used for small ingots.

The pusher furnace uses the counter-current system of the charge and flue gases motion. Blooms (material) are pushed close to each other using a pusher. Flue gas outlet is near the charging door. This means that the furnace acts as a counter-current heat exchanger - heat transfer is then the highest and efficiency of furnaces is 40% to 60%.

Thermal regime of furnaces:

Pusher furnace operates with a constant thermal and temperature regime, however, the temperature varies along the length of the furnace. The furnace is divided lengthwise into several zones (sectors). The material is usually heated in three phase - preheating, heating, and equalizing. Same names then apply for the parts of the furnace.

Preheating zone - is at the beginning of the furnace, where the material enters the process. The flue gas temperature increases from the beginning of the furnace. Heating of billets is slower, without thermal stresses. Then the heating is performed so that the optimum difference (temperature gradient) between the material surface and its centre is not exceeded.

The second function of the preheating zone is a perfect use of the flue gas heat. Only a small portion of the total heat input is fed to the zone, or no heating takes place in this zone. Cold metal takes heat from the flue gases and their temperature sharply drops. Convection dominates at the beginning of the zone, while radiation dominates at the end. So the correct choice of the temperature of the departing flue gases is very important. At lower value, the overall coefficient of transfer of heat to the charge decreases and the residence time of the material in the furnace in this zone gets longer.

The task of the **heating zone** is the rapid heating of the surface of billets to the desired temperature. The flue gas temperature in this zone exceeds the temperature of heating by about 150 K, while the furnace temperature in this zone can be up to 1400°C.

When leaving the heating zone, billets are heated up unevenly, because the temperature difference between the centre and the surface is considerable. Therefore billets go to the equilibrium zone. There the equalization of temperatures between the centre and the surface take place, so the billets can be rolled.

Transport of material within the furnace:

In the furnace, the material moves over the skids by a pusher. Skids work in difficult conditions – they must withstand high temperatures in the furnace, mechanical shock, they are exposed to the chemical effect of scale and furnace atmosphere and must be wear resistant. Ceramic or metal skids are used.

Ceramic skids are electro-melted stones with a high content of aluminium oxide, mullite-corundum or zirconia corundum materials. They are cooled with water.

Metal skids are the most widely used. They consist of a pipe with wall thickness up to 2 cm, of round, square, or rectangular cross section. There flows the cooling water inside the tube.

Cooling water temperature should not exceed 40°C, otherwise scales settle down. There should also be an optimum velocity of flowing of the cooling water, as in the slow water flow rate steam membranes are formed, thereby preventing transfer of the heat from the skids. Interruption in the supply of cooling water is the cause of deformation of the skid.

Heating of the pusher furnace:

Furnaces are heated with natural gas, mixed gas or fuel oil. If the fuel oil is used, the heat transfer is more intense, but it can lead to local overheating of the charge, the wear of the lining increases, and since the fuel oil contains a certain percentage of sulphur, also the burn-off is higher. So only use the fuel oil in the preheating and heating zone. The equilibrium zone is heated with natural gas.

The burners are placed on the front sides, on the roof, sometimes on the side walls. Each zone has its specific location of burners.

The pusher furnace lining:

The walls and roof of the furnace are lined with fireclay, which is applied by guniting. In the past, hearth lining in the equilibrium zone was done by chromium magnesite, now it's the electro-melted corundum. The hearth is lined with corundum blocks, which are the continuation of skids.

Method of charging material to the furnace:

Billets are charged to the furnace in one or more rows, the gap between the rows is about 30 cm. Material is pulled out of the furnace either through front or side door.

Walking beam furnaces

The construction of the walking beam furnaces and pusher furnaces is similar. Today, walking beam furnaces are driving out the pusher furnaces from rolling mills. The range of

the charge is the same as for pusher furnaces. The primary difference is in the way of movement of the heated material.

Movement of material is effected via a walking device, which has movable and immovable parts. When heated, the charge lies on the immovable longitudinal beams. During transposing, the charge is lifted by movable beams, transferred forward and released back on the immovable beams. Movable longitudinal beams then do the return movement under the billets. Kinetic scheme is rectangular: lifting, moving forward, dropping down, and moving back. Walking device is driven by electric motors or hydraulic cylinder drive systems. With a hydraulic drive, the size of a “step” can be changed more easily.

Walking beam furnace lining:

Lining is rammed or composed of segments. Blocks are not used, because they have less durability and resistance to scale. Lining may be a double layer, wherein the upper layer is of a superior material. For preheating zone of the furnace, materials with content of aluminium oxide about 40% are used. For sections with a higher temperature, it is 70% or chromite is used.

Method of charging material to the furnace:

Charging is from side or frontal. When charging from the front, the pusher is used that transfers the billet from the furnace grate to fixed beams. Or the charge is taken directly from the conveyor by means of moving beams. Frontal charging allows you to control the position of the charge. The lateral charging takes place via a roller conveyor situated in the furnace. Roller conveyor is driven by a motor. The whole system is controlled by the length of the billet. The heated material is pulled out from the furnace exclusively through the side wall by means of the outgoing roller conveyor.

Comparison of walking beam furnaces against pusher furnaces:

Advantages:

- Possibility to heat subsequently dimensionally heterogeneous material
- Easy to distinguish the different steel brands
- The charge neither superimposes, nor adheres
- The surface material is not mechanically damaged, hearth does not rub
- Lower temperature difference between the surface and the centre of the material
- Low burn-off and decarburization of charge
- Easy to empty the furnace

Disadvantages:

- Higher specific heat consumption
- Higher investment cost

- Demanding maintenance
- Higher need for cooling water

Rotary-hearth furnaces

Rotary-hearth furnace is a heating device used in rolling mills for heating tubes. The charge (tubes) is deposited on a rotary hearth of annular shape and gradually passes through each heating zone of the furnace.

Construction of the rotary-hearth furnace:

Flue gas exhausts are located near the charging door. The counter-current system of movement of the charge and flue gases is used. Door to pull out the heated charge is located near the charging door. The angle between axes of the charging and pulling out openings ranges from 10° to 35° and there must be a dividing partition between them. Material handling is performed automatically using the arms or tongs in accordance with the moving hearth. Semi-finished products are therefore distant from each other and so the heating takes place evenly. The charge does not move.

The size of the working space is given by the furnace capacity, heating mode, way of placing and dimensions of the charge, and by the type of burners. The height of the furnace is not more than 2 m. Individual zones are separated by hanging partitions.

On the lower side, the hearth is equipped with wheels moving along the rails mounted on a structure below the furnace.

Type of heating:

Rotary hearth furnaces are heated with gaseous and liquid fuels. The burners are positioned on the outer side wall, or on both sides. The burners are turbulent or high-speed, or burners with radial spread of flame.

Rotary-hearth furnace lining:

Lining of the walls and roof of the furnace is not too stressed thermally, neither mechanically. Design is a double layer - fireclay and insulation. It is composed of segments. Hearth lining must resist the scale and impacts of the material, as well as temperature changes. Basic linings are used – magnesite and chromium magnesite.

Advantages of rotary-hearth furnaces:

- Uniform heating of material
- Stationary charge, low burn-off
- Good pressure control in the furnace
- Low maintenance, long life

Disadvantages of rotary-hearth furnaces:

- The final length of the heated semi-finished products

- The need for more space for the furnace location,
- Charging and pulling out doors close to each other, the travelling of material is complicated due to technology
- Charging and pulling-out machines (mechanisms) are additional costs.

Specific heat consumption is between 1450 and 2000 kJ.kg⁻¹. Maximum capacity of rotary-hearth furnaces is approximately 150 t.h⁻¹.

Furnaces for heat treatment

Furnaces for heat treatment differ according to the technology of processing of individual semi-finished products. Heat treatment (annealing, hardening, tempering) is characterized by the temperature of heating, exposure time at this temperature and method of cooling the material. Each phase of heating, holding and cooling can be repeated several times (polyphase heating). During the heat treatment, the material is also subject to chemical effects and therefore the furnace must also have a device for the controlled atmospheres.

The temperature in the furnaces for heat treatment depends on the method of this heat treatment. It ranges from hundreds of °C to 1300°C; however, in most furnaces the working temperatures do not exceed 1000°C. Holding time ensures the equalization of temperatures in the charge with modification changes or diffusion processes taking place. Equalization phase may last several hours. The cooling phase is determined by the cooling medium (air, water, oil, controlled atmosphere, etc.).

Furnaces for heat treatment are therefore very different. We distinguish between furnaces with *direct* and *indirect* heating. In **furnaces with direct heating**, the charge is in a direct contact with the furnace gases. Flue gases can affect the surface of the heated material. Therefore, this heating is only used for some materials (open annealing, "black" annealing). If the combustion is incomplete, the material can be heated directly without the formation of scales.

In furnaces with **indirect heating**, the material is enclosed in the muffle and thus protected from the furnace atmosphere (undesirable). Flue gases are transmitting their heat indirectly. Also, the furnaces can be heated with radiant tubes or by electrical resistance. Then a controlled atmosphere can be used.

According to the temperature and thermal regime, we further divide the furnaces to furnaces working intermittently or continuously. With intermittently working furnaces, the charge does not move, the temperature and thermal regimes are non-stationary.

Hood-type (muffle) furnaces

In these furnaces, the charge is placed on a stationary hearth and covered with a protective muffle of corrosion-resistant steel. Controlled atmosphere can be fed through this muffle. A lined heating hood and burners (for fuel-burning furnaces) or resistive heating elements are put on the protective muffle.

In reverberatory muffle furnaces, the burners are placed around the perimeter of the bottom part of the hood along with the distribution of combustion media. The burners have fans for combustion air. Flue gases flow in the direction of a tangent to the surface of the protective muffle. The flue gases are drawn off from the working space by fan. The heat exchanger for preheating the combustion air can be deposited in the muffle. These furnaces can also have vertically placed radiant tubes. With resistance heating muffle furnaces, the resistive elements are distributed over the whole lateral surface of the heating muffle. The advantage of electric heating is uniform and rapid heating and precise temperature control.

Muffle lining:

Lining must have a minimum weight and small heat losses to the surroundings. Fireclay or expanded fireclay is used. It can be made of precast refractory concrete. It is not lined with fibrous materials.

The yield of muffle furnace is about several tons per hour. Efficiency goes hand in hand with slow equalization of temperatures in the material.

Continuous furnaces

According to the structural arrangement, we divide continuous furnaces to horizontal and vertical. In horizontal furnaces, the strip (material/charge) extends in a horizontal direction along the support rollers. In the tower continuous furnaces, the strip is moving alternately up and down, with return rollers changing the direction.

Comparison of continuous and muffle furnaces. Continuous furnaces have the following advantages:

- Uniformity of mechanical properties and structure along the length and width
- Better surface quality
- Improved flatness of belts
- High capacity of furnaces

Design layout

The furnaces consist of entrance and exit parts and the furnace itself. In the entrance part, there is a mechanism for conveying strips into the furnace and surface treatment. This part includes decoilers of rolls for the process to run continuously. The end of one strip is connected with the beginning of the other. The joints between the strips are welded together. The exit part contains the loop device, dividing shears and two strip coilers.

The number of individual sections of the furnace itself is chosen according to the type of heat treatment. Usually, it includes following sections (zones) - heating, holding, controlled cooling and rapid cooling.

Horizontal furnaces:

The burners are positioned above and below each of these zones. They operate in protective atmosphere. The furnaces are heated by two rows of radiant tubes.

Tower furnaces:

These furnaces also contain radiant tubes, which are placed horizontally.

Holding section of the furnace for black annealing is identical to the heating section. Output of burners in the holding section is smaller. If controlled atmosphere is in this section, electric resistance heating is used.

The controlled cooling section ensures the drop of temperature according to the requirements of a particular technology. Strips are cooled with air. The heated air is not further processed. The rate of cooling depends on the speed of the airflow. Also this section has a resistive heating to heat up the zone to an operating temperature.

Rapid cooling sections use water-cooled panels placed instead of the furnace walls in horizontal furnaces, and between individual runs of the strip in horizontal furnaces.

Furnaces for dielectric heating

Devices using dielectric heating for processing are used for:

- wood drying,
- welding of thermoplastic materials,
- preheating, hardening of rubber materials,
- drying of various products and materials, heating of electrically non-conductive bodies,
- heating of electrically non-conductive bodies of large thicknesses.

a) Drying of wood, plywood production

An example may be made beech wood veneers sized 1 x 2 m, which are coated with synthetic resin and inserted into the press in a layer up to 40 cm high. An electrode of a high-frequency voltage U_{ef} is inserted in the central plane of the layer. The two jaws of the press represent the second electrodes and are grounded. The layers of plywood on both sides of the centre electrode (hot) with a voltage U_{ef} represent layers cut electrically in parallel. With respect to the distance $d = 0.2$ and area $S = 4\text{m}^2$, we choose the supply high-frequency output $P = 100$ kW.

The required voltage is then $U_{ef} = 13.3$ kV. It can also be possible to easily determine the total amount of heat that is needed to heat up a unit volume $V = 1$ dm³ from the ambient temperature of 20°C to the hardening temperature of 130°C. In so doing, it is necessary to evaporate from this unit volume about 3% of water from the total weight. Thermal energy consumption is $Q_1 = 170\text{kJ} \cdot \text{dm}^{-3}$. For the total volume $V_p = 800$ dm³, total quantity of heat $Q_c = 141\ 000$ kJ will be needed, i.e. work or energy of 39.2 kWh. At high-frequency output of 100 kW, this amount of heat is generated over the time $\tau = 23.2$ min.

After this period, it is possible to remove the finished dried-up and hardened plywood from the press.

b) Preheating of plastics, processing of thermosets

Dielectric devices can be advantageously used in the processing of thermosets. Thermosetting powder is premoulded into tablets which are then inserted into the mould. Preheating time is about 1 minute. The curing itself, i.e. polymerization occurs after some time. The polymerization temperature is about 100°C and depends on the type of filler. The high-frequency input is 1 kW. It is sufficient to perfectly heat 28 decagrams of component weight during heating up from 20°C to 120°C in 1 min.

In a dielectric device, preheated tablets are inserted into a die in the press. Both parts of the die are electrically heated and the temperature increases to about 140°C, when polymerization takes place. If the thermoset is premoulded and dielectrically preheated, the total time for making the compact is 2 to 3 times shorter. The pressure required for pressing is decreased and the quality of the compacts rises. As far as energy is concerned, this solution represents considerable energy savings.



Fig. 11.6 Device using dielectric heating for drying wood

Furnaces for microwave heating

Microwave heating has been successfully applied in many industries. In the *food* and *pharmaceutical* industry, it allows modernizing and using new production processes. Microwave heating is advantageous when defrosting deep-frozen materials, pasteurization and sterilization of packaged foods (such as meat and dairy products, juices and sliced bread). Pasteurization of packaged foods ensures durability without the use of preservatives. When the sliced bread is pasteurized, it passes through a tunnel furnace and within a few minutes it is heated to pasteurization temperature without overheating of the surface crust or change in its taste properties.

Microwave apparatus for pasteurizing occupies only about 10% of the space in comparison with a gas furnace. Within one hour, the microwave defrosting equipment with

power output of 120 kW can warm up 3 tons of packaged food from a temperature of -18°C to -2°C .

In the production of plastics and in the rubber industry, the microwave heating is used, for example, for heating plastic granulates before entering the extrusion presses, for preheating rubber before vulcanization, and in curing glassfibre products. In the manufacture of epoxy high-voltage insulators, the microwave heating to a temperature between 80°C and 100°C shortens the moulding process by 15% up to 45%. At microwave heating of ceramic materials, the sintering time is reduced by 5% to 30%.

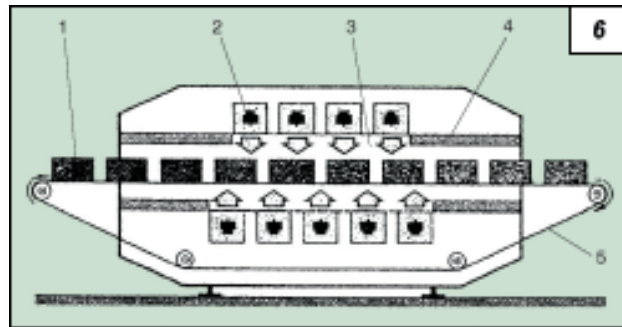


Fig. 11.7 A schematic arrangement of tunnel microwave heating facility: 1 – heated material, 2 – microwave module, 3 – heating tunnel, 4 – microwave absorber, 5 – conveyor belt

Current microwave devices have an output of 100 kW or more, have very good efficiency, can be adapted to various production processes and enable an optimal combination with conventional heating methods.

Design layout

Microwave belt driers are produced for outputs between 8 KW and 150 kW, the length of the conveyor belt from 5 m to 30 m and belt width from 0.2 m to 1 m. The maximum drying temperature is 230°C . The microwave energy is supplied from four sides to guarantee homogeneous heating of the material to be dried. As a source of microwave radiation, robust air-cooled magnetrons are typically used with an output of 800 kW. The function of magnetrons and high-voltage transformers is separately protected. Optionally available is e.g. a continuous power control and continuous control of air humidity.

Figure 11.7 shows schematic layout of the tunnel microwave heating facility. Heated objects pass through the tunnel on a conveyor belt. Heating equipment consists of several microwave modules that enable the desired temperature increments. The modules are designed so that the leakage between them is limited to acceptable values and radiation cannot penetrate into the surrounding area.



Questions to Chapter 10 – Part Two

107. Describe the principle of an induction furnace.
108. What is the difference in the method of heating between the induction furnace with an iron core and without it?
109. What type of charge is used in induction furnaces?
110. What is the function of a crucible in the induction furnace?
111. List the advantages and disadvantages of induction furnaces. Justify your claims.
112. Describe the principle of an electron furnace.
113. How the charge is heated in electron furnaces?
114. List the advantages and disadvantages of electron furnaces. Justify your claims.
115. Describe parts of a plasma furnace.
116. How the material is heated in plasma furnaces?
117. Explain where you can further use the plasma torches (outside of metallurgy).
118. List the advantages and disadvantages of plasma furnaces. Justify your claims.
119. What is the most common use of a soaking furnace?
120. Describe the soaking furnace design.
121. How can we control the loss by burning amount in the soaking furnace?
122. For what purposes the chamber furnace is used?
123. Explain the differences in the design and use of a chamber furnace and a pusher furnace.
124. Describe the movement of material (charge) in a rotary-hearth furnace, pusher-type furnace, chamber furnace, and walking-beam furnace.
125. List the advantages and disadvantages of heating furnaces. Justify your claims
126. Describe the charge heating regime in furnaces for heat treatment.
127. Explain the method of heating the charge in hood-type furnaces and continuous furnaces.
128. How and by what the heating furnaces are heated?
129. Every industrial furnace has its lining - name the most commonly used refractory materials for various types of industrial furnaces.
130. Give examples of the use of furnaces with dielectric and microwave heating.



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