THEORETICAL FOUNDATIONS OF TRANSFER

LEARNING OBJECTIVES

After studying:

- You will understand the issue of heat propagation.
- Understand the relationship between thermal and mechanical energy.
- Can you explain heat transfer by conduction, convection and radiation.
- You will be able to apply your theoretical knowledge in practical calculations.
- Understand the analogy between temperature and electric fields

KEYWORDS

temperature, temperature difference, heat capacity, heat output, heat loss.

TIME NEEDED TO STUDY

180 minutes

📖 **TEXT TO READ**

1. PHYSICAL BASIS OF HEAT TRANSFER

1.1 Quantities, symbols, units

Temperature, temperature difference

ϑ .... temperature °C .... degree Celsius
Θ .... thermodynamic temperature K .... kelvin
$\Delta\vartheta = \vartheta_2 - \vartheta_1$ .... temperature difference °C, K
$\Delta\Theta = \Theta_2 - \Theta_1$ .... temperature difference °C, K

Both temperature and temperature difference are scalar quantities. The temperature field is a scalar field. Relationships between temperatures:

$$°C + 273.15 = K$$

Heat

Q .... heat J .... joule

Heat is a form of energy. The relationships between the units are shown in Table 1.1.

Unit	**J**	**Wh**	**cal**	**Kpm**	**erg**
J	1	$2.778 \cdot 10^{-4}$	0.239	0.102	10^{7}
Wh	3600	1	860	367.1	$3.6 \cdot 10^{10}$
Cal	4.186	$1.163 \cdot 10^{-3}$	1	0.427	$4.186 \cdot 10^{7}$
Kpm	9.807	$2.724 \cdot 10^{-3}$	2.343	1	$9.807 \cdot 10^{7}$
Erg	10^{-7}	$2.778 \cdot 10^{-11}$	$2.389 \cdot 10^{-8}$	$1.020 \cdot 10^{-8}$	1

Table 1.1 Relationships between units

Heat capacity (accumulated heat)

$$Q = m\, c \cdot \Delta\vartheta \qquad (J\ ;\ kg\ ,\ J \cdot kg^{-1} \cdot K^{(-1)}\ ,\ K)$$

m .... weight of the body
c .... specific heat capacity (specific heat)
$\Delta\vartheta$ .... temperature difference

Specific heat capacity

c .... specific heat capacity ($J \cdot kg^{-1} \cdot K^{(-1)}$)

The conversion relationships between units are shown in Table 1.2.

unit	**$J \cdot kg^{-1} \cdot K^{(-1)}$**	**$kJ \cdot kg^{-1} \cdot K^{(-1)}$**	**$cal \cdot kg^{-1} \cdot K^{(-1)}$**	**$kcal \cdot kg^{-1} \cdot K^{(-1)}$**
$J \cdot kg^{-1} \cdot K^{(-1)}$	1	10^{-3}	0.2389	$0.2389 \cdot 10^{-3}$
$kJ \cdot kg^{-1} \cdot K^{(-1)}$	10^{3}	1	238.9	0.2389
$cal \cdot kg^{-1} \cdot K^{(-1)}$	4.186	$4.186 \cdot 10^{-3}$	1	10^{-3}
$kcal \cdot kg^{-1} \cdot K^{(-1)}$	4186	4.186	10^{3}	1

Table 1.2 Transfers between units

Heat output

Heat output is heat per unit time. It is a scalar.

P .... heat output W .... watt

Heat flux density

Heat flux density is the heat output per unit area. It is a vector - it has a direction given by the normal to the area element dA under consideration.

q .... heat flux density ($W \cdot m^{(-2)}$)

$$q = dP / dA$$

EXAMPLES

Example 1:
How many kcal/hour is 10 W?

(8.6 kcal/hr)

Example 2:
How many cal is 5 Wh?

(4300 cal)

Example 3:
What will be the specific resistance of aluminium in $\Omega \cdot m$ if it is equal to 0.03 in $\Omega \cdot mm^2/m$?

($3 \cdot 10^{-8} \Omega \cdot m$)

Example 4:
What will be the current density in A/m^2 , if A/mm^2 is equal to 5?

($5 \cdot 10^{6}\ A/m^2$)

Example 5:
How many kpm is 3 cal?

(1,278 kpm)

Rating: 2 points per example.

1.2 Relationship between thermal and mechanical energy

For practical purposes, it is useful to realise the relatively significant mechanical work involved in heat energy of the order of one kilocalorie. The following examples will document this:

EXAMPLES

Example 1:

How much cement could be loaded onto a 2m high truck using the energy required to heat 1 litre of water by 20°C? The loading efficiency is η =

a) 100 %

b) 50 %

Solution:

Thermal energy required:

$Q = m\ c \cdot \cdot \Delta\vartheta = 1 \cdot 4.186 \cdot 10^3 \cdot 20 = 8.372 \cdot 10^4$ J

Energy required for loading:

$W = m\ g \cdot \cdot\ h / \eta$

g .... gravitational acceleration
h .... loading height
η .... loading efficiency

From the equation Q = W, determine the mass of the load:

a, $m = Q \cdot \eta / (g \cdot h) = 8.372 \cdot 10^4 \cdot 1 / (2 \cdot 9.806) = 4.267 \cdot 10^3$ kg

b, $m = 8.372 \cdot 10^4 \cdot 0.5 / (2 \cdot 9.806) = 2.134 \cdot 10^3$ kg

The results show that the energy required to brew a few cups of tea would be enough to load a few tens of cents of cement onto a car or wagon.

Example 2:

How many times more energy intensive is a litre of hot tap water than a litre of cold water? Both waters are drawn from the same source at a temperature of ϑ_1 = 10 °C up to a height of h = 100 m. The cold water is taken directly at the point of consumption, the hot water is heated at the point of consumption to ϑ_2 = 70 °C.

Solution:

We consider the efficiency of pumping by pump with electric motor in relation to the primary energy η_{no} = 0.15 (η power plant = 0.3 ;η motor with pump = 0.5). We consider heating by coal with efficiency η_o = 0.5.

Energy required for cold water (based on 1 litre):

$W_s = m\, g \cdot h / \eta_{no} = 1 \cdot 9.806 \cdot 100 / 0.15 = 6538$ J

Energy required for hot water (based on 1 litre):

$W_t = m\, g \cdot h / \eta_{no} + m\, c\, (\vartheta_2 - \vartheta_1) / \eta_{(o}$
$W_t = 1 \cdot 9.806 \cdot 100 / 0.15 + 1 \cdot 4.186 \cdot 10^3 \cdot (70 - 10) / 0.5 = 6\,538 + 502\,320 = 508858$ J
$n = W_t / W_s = 508\,858 / 6\,538 = 77.8$

Hot water is almost 78 times more energy intensive than cold water.

EXAMPLES TO PRACTICE

Example 1:

What wattage would a direct-fired electric instantaneous heater need to have to make hot water $\vartheta_2 = 60$ °C flow out of a 10 mm diameter tap at v = 2 m/s? The water is heated from a temperature of $\vartheta_1 = 10$ °C. The heating efficiency is 97%. How many fluorescent lamps of 40 W could shine at this wattage?

(33.5 kW , 838 fluorescent lamps)

Example 2:

How many times more energy does it take to heat 10 litres of water by 10°C than to raise that 10 litres of water to a height of 10m? Consider both the heating efficiency and the lifting efficiency to be 100% .

(427 times more)

Rating: 3 points per example.

1.3 Warming and cooling processes

The dependence of temperature on heating time is represented by the warming curve (Figure 1.1):

$$\Delta\vartheta = \Delta\vartheta_{max} \cdot (1 - e^{-\frac{t}{\tau}}) \qquad (1.1)$$

The dependence of temperature on cooling time is represented by the cooling curve (Figure 1.2)

$$\Delta\vartheta = \Delta\vartheta_{max} \cdot e^{-\frac{t}{\tau}} \qquad (1.2)$$

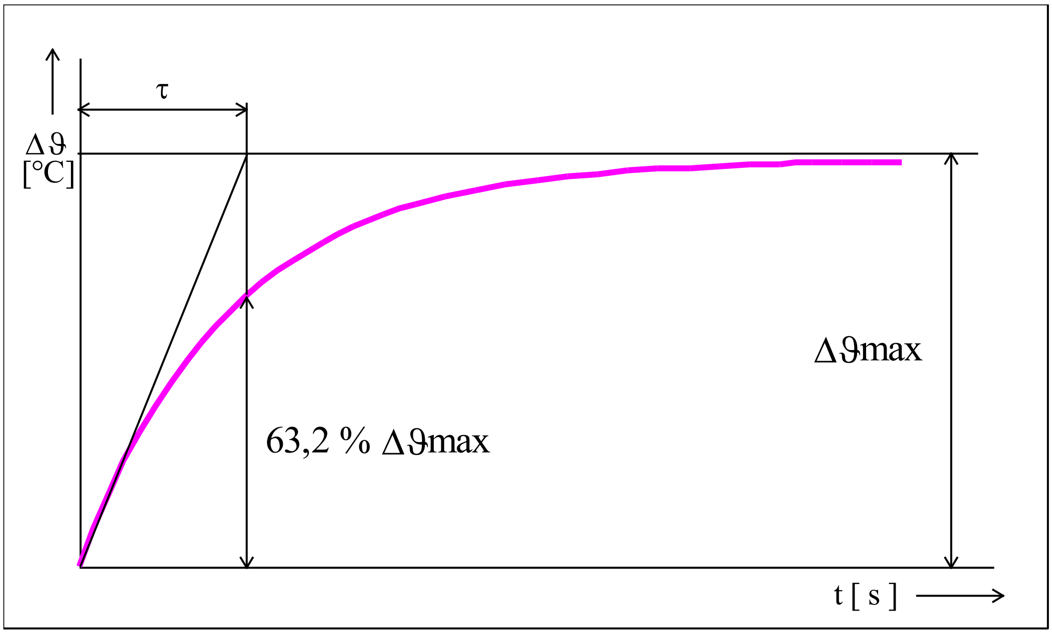


Fig. 1.1 Temperature versus time - warming curve

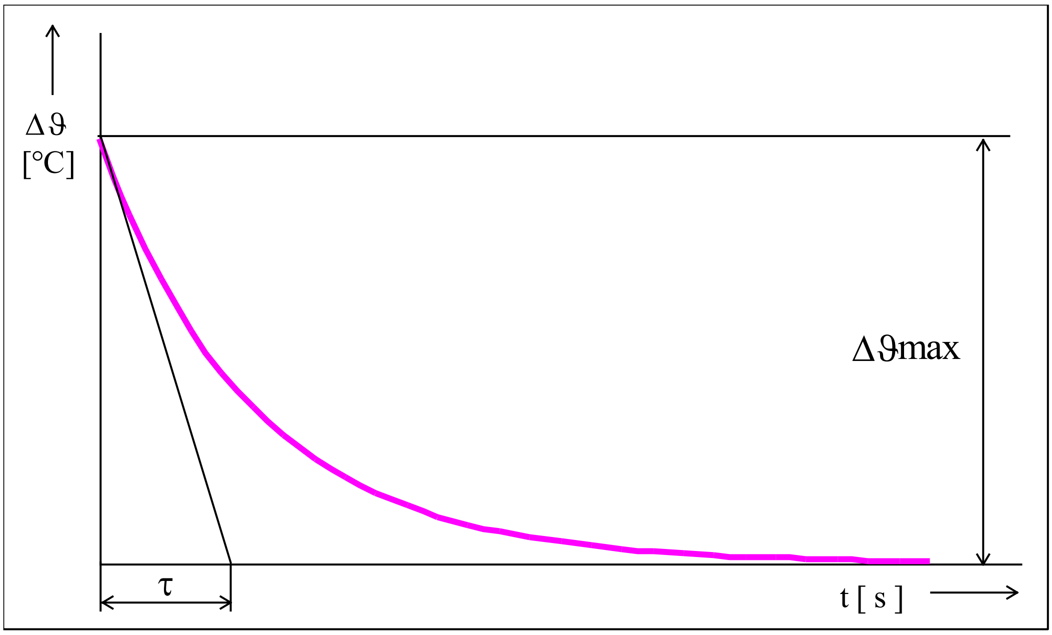


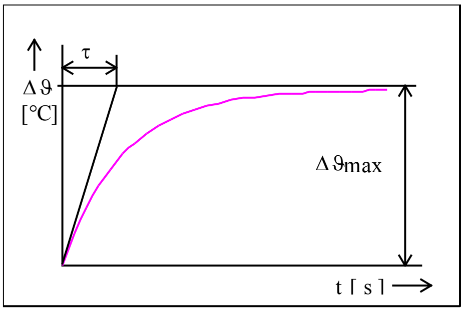
Fig. 1.2 Temperature versus time - cooling curve

EXAMPLE

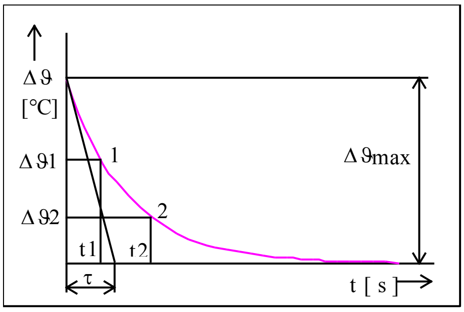
How long does it take for water to heat from 20 °C to 100 °C if it cools from 40 °C to 30 °C in 10 minutes? The cooling process takes place between 100 °C and 20 °C, the time constant of warming is equal to the time constant of cooling. Consider the completed process in terms of three time constants.

Solution:

Warming curve:



Cooling curve:



We know two points on the cooling curve that must satisfy its equation:

$$\Delta\vartheta = \Delta\vartheta_{max} \cdot e^{-\frac{t}{\tau}}$$

Point 1: $$\Delta\vartheta_1 = \Delta\vartheta_{max} \cdot e^{-\frac{t_1}{\tau}} \qquad (1.a)$$

Point 2: $$\Delta\vartheta_2 = \Delta\vartheta_{max} \cdot e^{-\frac{t_2}{\tau}} \qquad (1.b)$$

Dividing equation (1.a) by equation (1.b) gives an equation with one unknown:

$$\frac{\Delta\vartheta_1}{\Delta\vartheta_2} = \frac{\Delta\vartheta_{max} \cdot e^{\frac{t_1}{\tau}}}{\Delta\vartheta_{max} \cdot e^{\frac{t_2}{\tau}}} = e^{\frac{t_2 - t_1}{\tau}}$$

We logarithm this equation and calculate the unknown from it:

$$\ln\frac{\Delta\vartheta_1}{\Delta\vartheta_2} = \frac{t_2 - t_1}{\tau}$$

Where $\Delta\vartheta_1 = \vartheta_1 - \vartheta_0 = 40 - 20 = 20$ °C

$\Delta\vartheta_2 = \vartheta_2 - \vartheta_0 = 30 - 20 = 10$ °C

$t_2 - t_1 = 10$ min $= 600$ sec

$$\tau = \frac{t_2 - t_1}{\ln \frac{\Delta\vartheta_1}{\Delta\vartheta_2}} = 865.6 \quad \text{sec}$$

$3 \cdot \tau = 3 \cdot 865.6 = 2596.9$ sec

1.4 Heat transfer by conduction

Inside solid bodies or in close contact with them, heat is transferred by conduction. Heat, like magnetic or electrical energy, creates a so-called thermal field around itself. The heat field is the set of instantaneous temperatures of all points in the part of space under study and is a scalar field:

$$\upsilon = f(x,y,z,\ )\tau \qquad (1.3)$$

If:

$$\frac{\partial \vartheta}{\partial t} = 0 \qquad (1.4)$$

then it is a stationary field:

$$\upsilon = f(x,y,z) \qquad (1.5)$$

In the calculation of heat losses and thermal comfort of the environment, a steady state is assumed, i.e. the case of a stationary thermal field is considered. Actual temperature variations over time are taken into account in the additional coefficients applied in the relations used.

Connections of places with the same level of thermal energy are called isotherms (Fig. 1.3), or isothermal surfaces, and they are also places with the same temperature. The largest temperature changes occur in the direction normal to the isothermal surface. The limiting value of the temperature gradient is the temperature gradient:

$$-grad(\upsilon r = \lim_{n \to 0} \frac{\Delta\upsilon}{\Delta n} \bar{n}_0 \qquad (1.6)$$

It is a vector perpendicular to the isothermal surface. The set of temperature gradients forms a vector field. The existence of a field (if non-zero) means that heat propagates in space. Thus, heat does not propagate when:

$$\upsilon = \text{const.} \Leftrightarrow \text{grad}(\upsilon\ ) = 0 \qquad (1.7)$$

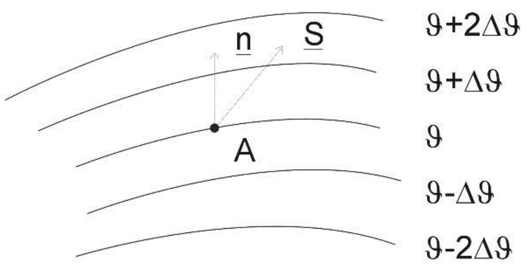


Fig. 1.3 Isotherms

In most technical applications, the heat conduction problem can be simplified. The most frequently solved cases are:

- heat transfer through a plane wall
- heat transfer through the cylindrical wall

1.4.1 Heat conduction through a plane wall

Heat flux through a homogeneous plane wall at a constant surface temperature difference (Fig. 1.4):

$$\Phi = \frac{\lambda}{s} \cdot S \cdot (\upsilon_1 - \upsilon_2) \qquad [W] \qquad (1.8)$$

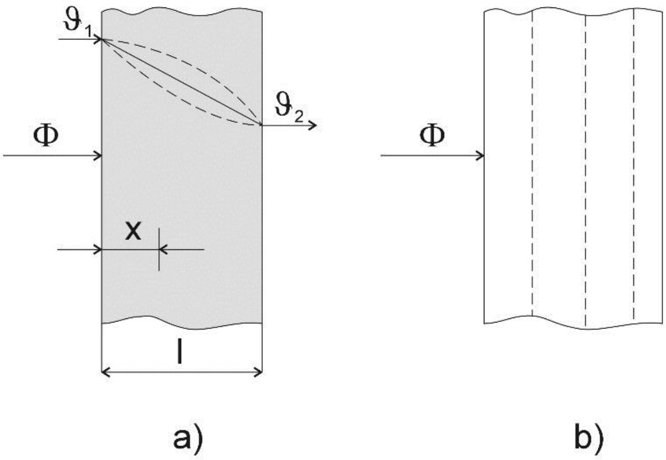


Fig. 1.4 Heat conduction through a plane wall

The temperature υ decreases linearly with distance *x* from the value υ_1 on the left interface to the temperature υ_2 on the right interface.

$$\vartheta = \frac{\vartheta_2 - \vartheta_1}{l} \cdot x + \vartheta_1 = \vartheta_1 - \frac{\vartheta_1 - \vartheta_2}{l} \cdot x \qquad (1.9)$$

If the wall is composed of several layers of materials of different thermal conductivity (Fig. 1.5), then the heat flow through the structure:

$$\Phi = \frac{l}{\frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} + \ldots + \frac{s_n}{\lambda_n}} \cdot S \cdot (\upsilon_1 - \upsilon_2) \qquad [W] \qquad (1.10)$$

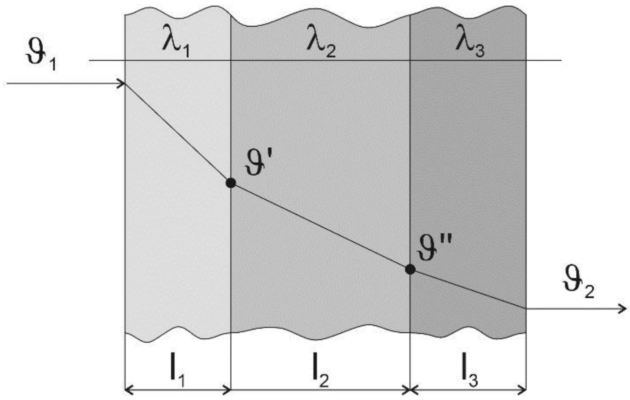


Fig. 1.5 Heat conduction through a composite plane wall

1.4.2 Heat conduction through the cylindrical wall

As heat is conducted from the inner surface of a thick-walled cylindrical tube to the outer surface, the area through which the heat passes increases with increasing diameter. The temperature versus radius curve is therefore a logarithmic curve. The relationship holds:

$$d\Phi = \frac{\lambda}{dr} \cdot \pi \cdot 2 \cdot r \cdot l \cdot dt \qquad (1.11)$$

By integrating from r_1 to r_2 we obtain the relation:

$$\Phi = \frac{2 \cdot \pi}{\frac{1}{\lambda} \cdot \ln \frac{r_2}{r_1}} \cdot l \cdot (\upsilon_1 - \upsilon_2) \qquad [W] \qquad (1.12)$$

For a composite cylindrical wall, the relation applies similarly:

$$\Phi = \frac{2 \cdot \pi}{\frac{1}{\lambda_1} \cdot \ln \frac{r_2}{r_1} + \frac{1}{\lambda_2} \cdot \ln \frac{r_3}{r_2} + \ldots + \frac{1}{\lambda_n} \cdot \ln \frac{r_{n+1}}{r_n}} \cdot l \cdot (\upsilon_1 - \upsilon_2) \; [W] \qquad (1.13)$$

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

$$\vartheta' = \vartheta_1 - \frac{\Phi}{\pi \cdot l} \cdot \frac{1}{2\lambda_1} \cdot \ln \frac{d'}{d_1}$$
$$\vartheta'' = \vartheta_2 - \frac{\Phi}{\pi \cdot l} \cdot \frac{1}{2\lambda_3} \cdot \ln \frac{d_2}{d''} \qquad (1.14)$$

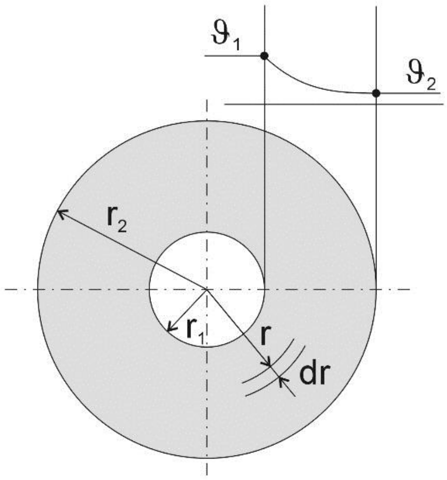


Fig. 1.6 Heat conduction through the cylindrical wall

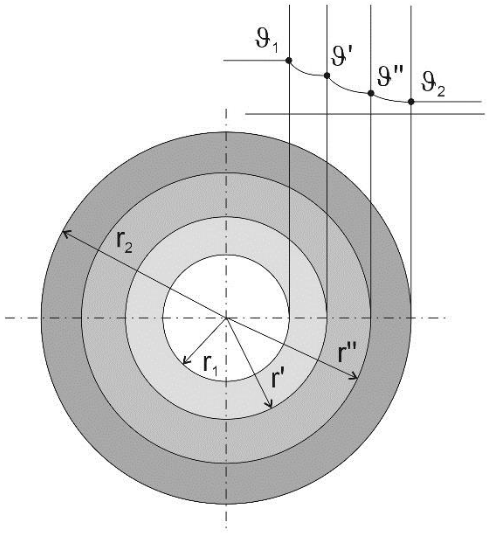


Fig. 1.7 Heat conduction through a composite cylindrical wall

EXAMPLES FOR CHAPTER 1.4

Example 1:

Determine the heat output through a wall of thickness l = 50 mm and area S = 1 m^2. The temperature on the outer surface of the wall is ϑ_1 = 100 °C , on the inner surface ϑ_2 = 90 °C. The wall is:

a, steel , λ = 40 W . m^{-1} . K^{-1}
b, concrete , λ = 1.1 W . m^{-1} . K^{-1}
c, diatomaceous earth , λ = 0.11 W . m^{-1} . K^{-1}

Solution:

$$P = \lambda \cdot \frac{S}{l} \cdot \Delta\vartheta \qquad (W ;\ W.m^{-1}.K^{-1},\ m^2,\ m\ ,\ K)$$

a, $P = 40 \cdot \frac{1}{0,05} \cdot (100 - 90) = 8\,000$ W

b, $P = 1.1 \cdot \frac{1}{0,05} \cdot (100 - 90) = 220$ W

c, $P = 0.11 \cdot \frac{1}{0,05} \cdot (100 - 90) = 22$ W

Example 2:

Determine the heat flux through the boiler wall. The wall is covered with a layer of soot with a thickness of l_1=1 mm,λ_1=0.08 W.m^{-1}.K^{-1} and on the water side there is a boiler stone with a thickness of l_3=2 mm,λ_3=0.8 W-m$^{(-1)}$)-K^{-1}. The boiler wall has a thickness of l_2=12 mm,λ_2=50 W-m$^{(-1)}$)-K^{-1}. The wall temperature on the water side isϑ_4=206°C , on the heating sideϑ_1=685°C. Determine the heat flux density q, the temperatures at the interface of the layers and the mean temperatures of the layers. The boiler wall has an area S=10 m^2.

Solution:

Heat flux density:

$$\bar{q} = \frac{\vartheta_1 - \vartheta_4}{\frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + \frac{l_3}{\lambda_3}} = \frac{685 - 206}{\frac{0{,}001}{0{,}08} + \frac{0{,}012}{50} + \frac{0{,}002}{0{,}8}} = 31\,430 \text{ W. m}^{-2}$$

Interface temperatures:

soot - boiler

$$\vartheta_2 = \vartheta_1 - q \cdot \frac{l_1}{\lambda_1} = 685 - 31\,430 \cdot \frac{0{,}001}{0{,}08} = 292.12 \text{ °C}$$

water stone - boiler

$$\vartheta_3 = \vartheta_4 + q \cdot \frac{l_3}{\lambda_3} = 206 + 31\,430 \cdot \frac{0{,}002}{0{,}8} = 284.58 \text{ °C}$$

Mean layer temperatures:

soot

$$\vartheta_S = \frac{\vartheta_1 + \vartheta_2}{2} = \frac{685 + 292{,}12}{2} = 488{,}56 \text{ °C}$$

boiler wall

$$\vartheta_{SK} = \frac{\vartheta_2 + \vartheta_3}{2} = \frac{292{,}12 + 284{,}58}{2} = 288{,}35 \text{ °C}$$

boiler stone

$$\vartheta_{KK} = \frac{\vartheta_3 + \vartheta_4}{2} = \frac{284{,}58 + 206}{2} = 245{,}29 \text{ °C}$$

Heat flux:

$$P = q \cdot S = 31\,430 \cdot 10 = 3{,}143 \cdot 10^5 \text{ W}$$

EXAMPLE TO PRACTICE FOR CHAPTER 1.4

Determine the heat flux density q ($W \cdot m^{(-1)}$) through the wall of a refractory steel pipe with dimensions d_1 = 32 mm, d_2 = 42 mm. The thermal conductivity coefficient of the material of which the pipe is made λ = 14 $W\text{-}m^{(-1)}\text{-}K^{-1}$. Outer wall temperature of the pipe ϑ_1 = 580 °C, inner wall temperature of the pipe ϑ_2 = 450 °C.

(42 052 $W\text{-}m^{-2}$)

Rating: 3 points

1.5 Heat transfer by flow

Let us introduce the heat transfer coefficient α_p with unit $W \cdot m^{(-2)} \cdot K^{(-1)}$, which determines how much heat flux (power) flows through a unit area at a temperature difference of 1 °C. Heat transfer in this way is applied when heat is transferred from a solid surface to the surrounding environment or vice versa (usually in combination with radiation).

Heat propagation by flow is one of the most difficult computational problems in thermal engineering. It is dealt with in many scientific literatures. In important cases, it is best to determine the heat transfer coefficient α_p ourselves by measuring it on a model as close as possible to our case using the given relations in which α_p occurs.

Newton's law applies to the transfer of heat by flow (Fig. 1.8):

$$\Phi = \alpha_1 \cdot (\vartheta_{p1} - \vartheta_1) \cdot S \quad [W; W\text{-}m^{(-2)}\text{-}K^{-1}, K, m^2] \qquad (1.15)$$

$$\Phi = \alpha_2 \cdot (\vartheta_2 - \vartheta_{p2}) \cdot S \quad [W; W\text{-}m^{(-2)}\text{-}K^{-1}, K, m^2] \qquad (1.16)$$

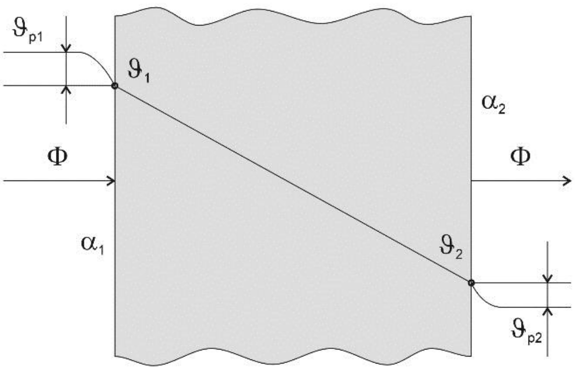


Fig. 1.8 Heat transfer by flow

In liquid and gaseous environments, heat is shared by the flow of the liquid or gas. The movement can be caused by external influences (forced flow) as well as by the dependence of specific gravity on temperature, i.e. gravity.

The heat transfer coefficient of the flow α_p, depends on the pressure, temperature and velocity of the fluid flow, the type of flow (laminar or turbulent), and the physical properties of the fluid (density, specific heat capacity, specific thermal conductivity and viscosity), as well as the shape, dimensions and roughness of the body to be circulated. In practice, α_p can be as high as 3÷ 20 $W\text{-}m^{(-2)}\text{-}K^{-1}$ for still air and 1000÷ 60000 $W\text{-}m^{(-2)}\text{-}K^{(-1)}$ for condensing water vapour. For this considerable range, the empirical relations for calculating α_p can only be valid over a limited range of independently variable parameters.

	α_{min} [$W.m^{-2}.K^{-1}$]	α_{max} [$W.m^{-2}.K^{-1}$]
Calm air	3,5	35
Flowing air	11	584
Flowing liquid	2300	5800
Boiling liquid	4660	6970
Condensing vapours	8055	13580

Table 1.3 Coefficient values α

EXAMPLE

Determine the heat loss through a vertical wall of area S = 1 m^2. Wall temperature ϑ_1 = 60 °C, ambient temperature ϑ_2 = 10 °C.

a) natural convection $\alpha = 4\cdot (\Delta\vartheta)^{(0.13)}$, $v_0 = 0\ m\cdot s^{(-1)}$
(b) by blowing $\alpha = 5.8 + 3.95\cdot v_0$, $v_0 = 5\ m\cdot s^{(-1)}$

v_0 is the flow velocity of the medium at the wall

Solution:

a) $P = \alpha_p \cdot \Delta\upsilon \cdot S$

(332,6 W)

b)

(1277,5 W)

Rating: 2 points

1.6 Radiant heat transfer

The last principle of heat sharing is radiation. Any body with a temperature greater thanΘ =0 K radiates energy into its surroundings in the form of electromagnetic waves, which propagate in a transparent medium in a straight line and in all directions. The body also receives heat flux from other bodies in space. Of course, heating of a body occurs when it receives more energy from its surroundings than it radiates and vice versa. The amount of energy radiated is proportional to the active surface area of the body and to the fourth power of its thermodynamic temperature. It also depends on the nature of the surface of the body. The energy flux incident on a body can be divided into three parts:

- reflected flow
- pervasive flow
- absorbed flux

It must be true that:

$$a+b+c=1 \qquad (1.17)$$

The following extremes can be defined:

- a = 1 ...absolutely black surface (all heat flux energy is absorbed by the body)
- b = 1 ...absolutely white surface (all energy is reflected by the body)
- c = 1 ...clear (transparent) environment - diatomic gases and air
- c = 0 ...thermally opaque environment - e.g. metals

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

$$a_\lambda + b_\lambda + c_\lambda = 1 \qquad (1.18)$$

Radiative heat transfer is governed by the laws of physics:

Laws of radiation of an absolutely black surface

The surface of a heated absolutely black body emits a continuous spectrum of radiation at different wavelengths (Fig. 1.9).

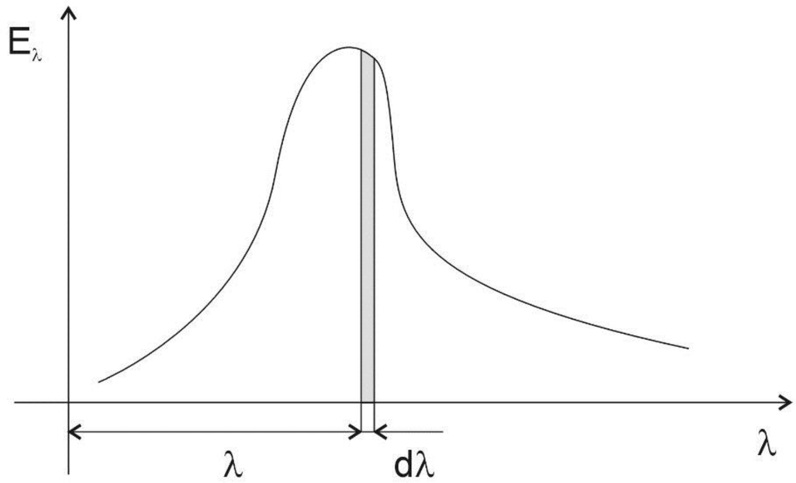


Fig. 1.9 Spectral radiance versus wavelength λ

Kirchhoff's Law

$$\frac{E_{\check{S}}}{A_{\check{S}}} = f(\Theta) = \frac{E_{\check{C}}}{A_{\check{C}}} = E_{\check{C}} \qquad (1.19)$$

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

$$\frac{E_{\lambda\check{S}}}{A_{\lambda\check{S}}} = f(\Theta;\lambda) = E_{\lambda\check{C}} \qquad (1.20)$$

Stefan-Boltzmann law

$$E_{\check{C}} = \sigma_{\check{C}} \cdot \Theta^4 \qquad (\text{W-m}^2) \qquad (1.21)$$

whereσ_{no} = 5.67.10^{-8} W-m$^{(-2)}$-K^{-4}

The luminosity of a black body is proportional only to the fourth power of the absolute temperature.

Planck's radiation law

$$E_{\lambda\check{c}} = f(\Theta;\lambda) = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda\cdot\Theta}} - 1\right)} \qquad (\text{W-m}^{-3}) \qquad (1.22)$$

where the constants c_1, c_2 are calculated from the Planck constant (c_1 = 5.95.10^{-17} W-m^{-2} ,
c_2 = 1.4388.10^{-2} m-K.
Planck's law describes the dependence of the spectral intensity of radiation from an absolutely black body on its surface temperature.

The law of Wien

$$\lambda_{\max} = \frac{2{,}892 \cdot 10^{-3}\, E_{\check{C}}}{\Theta} \qquad \text{(m)} \qquad (1.23)$$

The spectral radiation E_λ is most intense at a given temperature for a wavelength λ_{max} that is inversely proportional to this temperature Θ . It follows that a body emits only longwave (infrared) radiation through its surface at low temperature. Thus, not only does the radiance of the body increase with increasing temperature, but the maximum of the emitted spectrum also shifts to shorter wavelengths - Wien's shift law (Fig. 1.10).

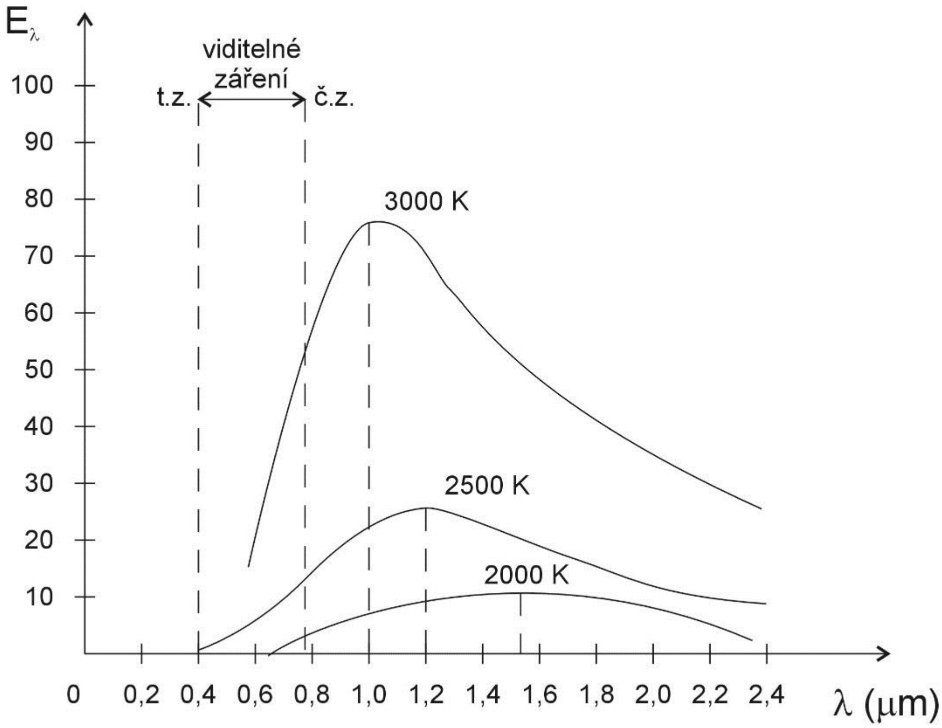


Fig. 1.10 Wien's displacement law

For the heat power transferred by two parallel, differently sized surfaces A_1, A_2, one of which has temperature Θ_1 and emissivity ε_1 and the other has temperature Θ_2 and emissivity ε_2 , the following holds:

$$P = \frac{A_1 \cdot \sigma_{\check{c}}}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2} \cdot (\frac{1}{\varepsilon_2} - 1)} \cdot \left[\left(\frac{\Theta_1}{100} \right)^4 - \left(\frac{\Theta_2}{100} \right)^4 \right] \qquad \text{(W)} \qquad (1.24)$$

EXAMPLE

Determine P_{no} ,λ_m , $E_{\lambda\,(m\check{c})}$ of an absolutely black body of area S = 300 cm^2 and temperature ϑ=1200°C

Solution:

Heat flux (power)

$$E_{No} = \sigma_{No} \cdot \Theta^4 \cdot S = 5.6697 \cdot \left(\frac{1200+273.15}{100}\right)^4 \cdot 300.10^{-4} = 8000 \text{ W}$$

The wavelength at which the maximum spectral density of the intensity of the radiation is found:

$$\lambda_m = 2892 / \Theta = 2892 / (1200 + 273.15) = 1.96 \text{ m}\mu$$

Spectral intensity density of radiation at wavelength 1.96μ m:

$$E_{\lambda\, m\check{c}} = \frac{c_1}{\lambda_m^5 \cdot \left(e^{\frac{c_2}{\lambda_m \cdot \Theta}} - 1\right)} = \frac{3.73 \cdot 10^{-16}}{\left(1.96 \cdot 10^{-6}\right)^5 \cdot \left(e^{\frac{1.438 \cdot 0.01}{1.96 \cdot 10^{-6} \cdot 1473.15}} - 1\right)} = 8.9 \cdot 10^{10} \text{ (W} \cdot \text{m}^{-3})$$

EXAMPLE TO PRACTICE

Determine the heat output radiating from a body of area A_1= 1 cm^2 , temperatureϑ_1= 1000 °C, emissivityε_1= 0.9 to a body of area A_2= 10 cm^2 , temperatureϑ_2= 0 °C, emissivityε_2= 0.9. The second body completely surrounds the first in space.

(13.25 W)

Rating: 3 points

? THEORETICAL CONTROL QUESTIONS

1. (2 points) What is heat capacity and specific heat capacity?
2. (2 pts) What is the dependence of the temperature in the cylindrical wall on the radius?

3. (1 point) What does the coefficient *b=1* represent for radiative heat transfer?
4. (2 points) What does Planck's law describe?
5. (2 pts) What is the wavelength and spectral density of radiation intensity?

SUMMARY

New findings:

- the relationship between thermal and mechanical energy
- cooling and warming processes
- calculation of heat flux and power
- Calculation of heat losses during heat transfer through a composite plane and cylindrical wall

New concepts:

temperature, temperature difference, heat capacity, heat output, heat loss.

KEY TO THEORETICAL QUESTIONS

1. Chapter 1.1
2. Chapter 1.4.2
3. Chapter 1.6
4. Chapter 1.6, equation 1.18
5. Chapter 1.6

AUTOCONTROL

If you have obtained at least 15 points in the examples and 6 points in the theoretical questions, you can continue your studies. Otherwise, repeat the chapter in a shorter time.

2. ANALOGY BETWEEN TEMPERATURE AND ELECTRIC FIELD

The analogy between the electric field and the temperature field is very strong and useful for the electrical engineer. It facilitates heat calculations in simpler systems and at steady state. Table 2.1 lists the basic analogies:

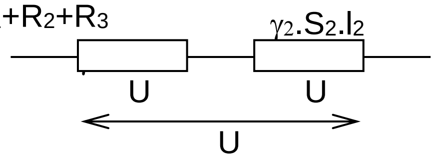
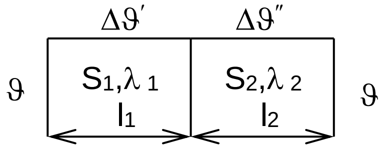
Electric field	**Temperature field**
1. Potential V [V]	1. Thermodynamic temperature Θ [K]
2. Voltage $U = V_1 - V(_2$ [V]	2. Temperature difference $\Delta\Theta = \Theta_1 - \Theta_2$ [K]
3. Conductivity (specific conductance) γ [S.m^{-1}]	3. Heart rate coefficient. Conductivity λ [W.m^{-1}.K^{-1}]
4. Electrical conductivity $G = \frac{\gamma.S}{l}$ [S]	4. Thermal conductivity $G = \frac{\lambda.S}{l}$ [W.K^{-1}]
5. Current density $\bar{J}$ [A.m^{-2}]	5. Heat flux density $\bar{q}$ [W.m^{-2}] Heat flow per unit time per unit area
6. Electric current $I = \int_S \bar{J}.d\bar{S}$ [A]	6. Heat flux $= \int_S \bar{q}.d\bar{S}$ [W]
7. Resistances in series R=R_1+R_2+R_3 	7. Heat conduction through a composite wall R=R_1+R_2+R_3 

Table 2.1 Analogy between temperature and electric field

LEARNING OBJECTIVES

After studying:

- You will understand the issue of temperature measurement.
- You will understand the principles of its measurement.
- You will learn the basic properties and principles of temperature sensors.
- Understand the advantages and disadvantages of each type of sensor.

TEMPERATURE MEASUREMENT

KEYWORDS

thermodynamic temperature, temperature sensor, thermocouple, thermovision.

TIME NEEDED TO STUDY

240 minutes

Text to read

3. BASIC CONCEPTS

Correct temperature measurement is of crucial importance in all cases of electric heat use. Every heat process has a certain optimum temperature at which the product is obtained or at which the production process is carried out in the fastest and most optimal way, i.e. with the minimum consumption of electrical energy.

Size, name	Brand	basic name	unit mark	secondary name	unit mark
thermodynamic temperature	Θ	kelvin	K		
Celsius temperature	t			Celsius degree	°C

Table 3.1 Basic variables

The Kelvin as the basic unit of thermodynamic temperature is 273.16 part of the triple point thermodynamic temperature of water. In addition to the thermodynamic temperature, the Celsius temperature defined by the equation

$$t = T - T_{(0} \qquad [°C] \qquad (3.1)$$

where $T_0 = 273.15$ K

Both units (°C, K) can be used to express the temperature difference, with the following

$$\Delta t = T\ \Delta \qquad [°C, K] \qquad (3.2)$$

The thermodynamic temperature scale is theoretically defined on the basis of the laws of thermodynamics independently of the properties of real substances. The following relations can be used to define the thermodynamic scale:

(a) from the Carnot reversible cycle effects

$$\frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1} \quad \text{platí} \quad \frac{Q_1}{Q_2} = \frac{T_1}{T_2} \qquad (3.3)$$

where $Q1$ is the heat input and $Q2$ is the heat output from the Carnot machine storage tank operating between temperatures $T1$ and $T2$.

b) the equation of state for a constant volume of ideal gas is

$$\frac{p_1}{p_2} = \frac{T_1}{T_2} \qquad (3.4)$$

(c) for the speed of sound in an ideal gas

$$\omega^2 = \frac{c_p}{c_v} - \frac{R \cdot T}{M} \qquad (3.5)$$

where c_p , c_v are specific heats, R is the gas constant, M is the molecular weight of the gas.

In 1927, the International Practical Temperature Scale was established. This scale has been progressively added to and modified by the General Conferences on Weights and Measures. The latest version is from1990 a and is designated ITS-90 (The International Temperature Scale of 1990).

The ITS-90 is an empirical temperature scale set at 17 fixed temperature points.

	temperature			
T_{90} (K)	t_{90} (°C)	substance	Status	$W_r(T_{90})$
3 to 5	-270.15 to -268.15	He	saturated steam pressure	
13,8033	-259,3467	e-Hz	triple point	0,00119007
~17	~ -256,15	e-H_2 (He)	saturated steam pressure	
~20,3	~ -252,85	e-H_2 (He)	saturated steam pressure	
24,5561	-248,5939	No	triple point	0,008 449 74
54,3584	-218,7916	O_2	triple point	0,091 71804
83,8058	-189,3442	By	triple point	0,215 85975
234,3156	-38,8344	Hg	triple point	0,844 142 11
273,16	0,01	H_2O	triple point	1,00000000
302,9146	29,7646	Ga	melting point	1,118 13889
429,7485	156,5985	And	freezing point	1,609801 85
505,078	231,928	Sn	freezing point	1,892 797 68
692,677	419,527	Zn	freezing point	2,56891730
933,473	660,323	Al	freezing point	3,376008 60
1234,93	961,78	Ag	freezing point	4,286 420 53
1337,33	1064,18	Au	freezing point	
1357,77	1084,62	Cu	freezing point	

Table 3.2 ITS-90 defining fixed points

The ITS-90 is divided into four ranges according to the interpolation instruments:

a) Range from 0.65 K to 5.0 K
The temperature T90 is defined by the vapour pressure ^{3}He or ^{4}He.

b) Range from 3 K to 24,556 K
is defined by the pressure of the gas thermometer.

c) Range from 13,8033 K to 961.8 °C
is defined by the equations for a platinum resistance thermometer. This range is further subdivided into four ranges in the band from 13.8033 K to 273.16 K and into six more

ranges in the band from0°C to 961.8°C. For these ranges, the resistance ratio $W(T_{90})$ is introduced by the relation.

$$W(T_{90}) = \frac{R(T_{90})}{R(273{,}16)K} \tag{3.6}$$

where $R(T_{90})$ is the resistance of the platinum thermometer.

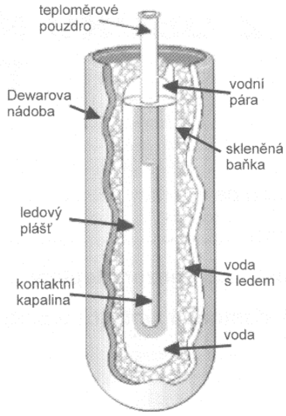


Fig. 3.1 Realization of the triple water point

d) Scope above 961,8 °C
is defined by Planck's radiation law.

4. THERMOMETERS (TEMPERATURE SENSORS)

These are functional elements that form the input block of the measurement chain - it is in direct contact with the measured environment. The basic breakdown is shown in Table 4.1.

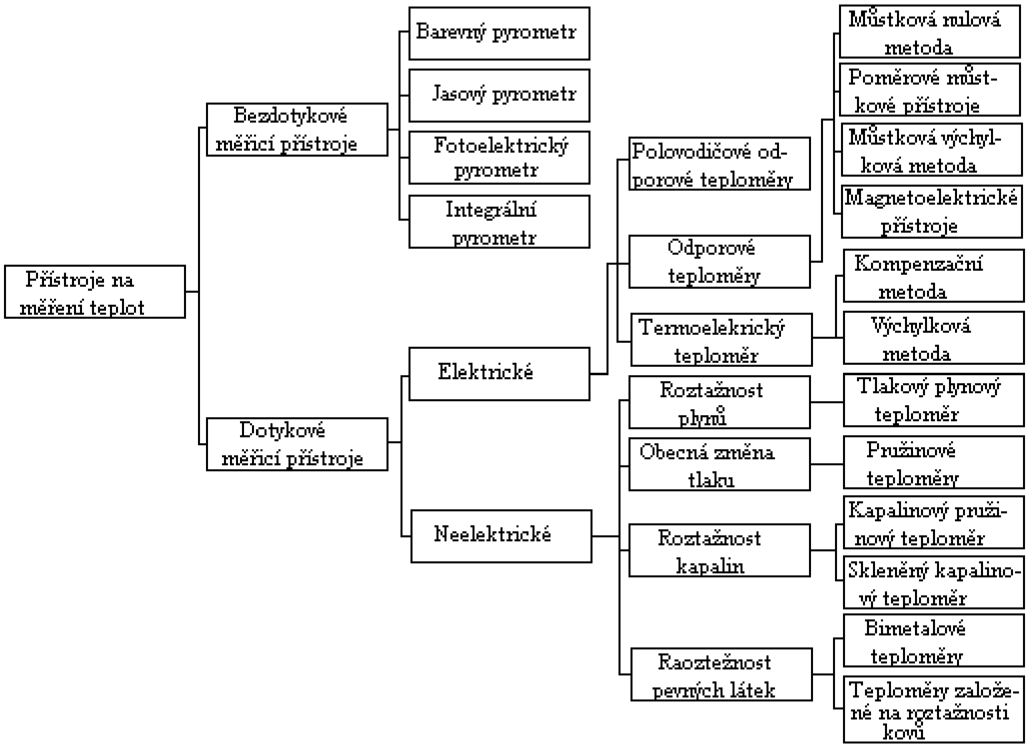


Table 4.1 Basic distribution of thermometers

Fig. 4.1 shows the range of measured temperatures for each type of thermometer

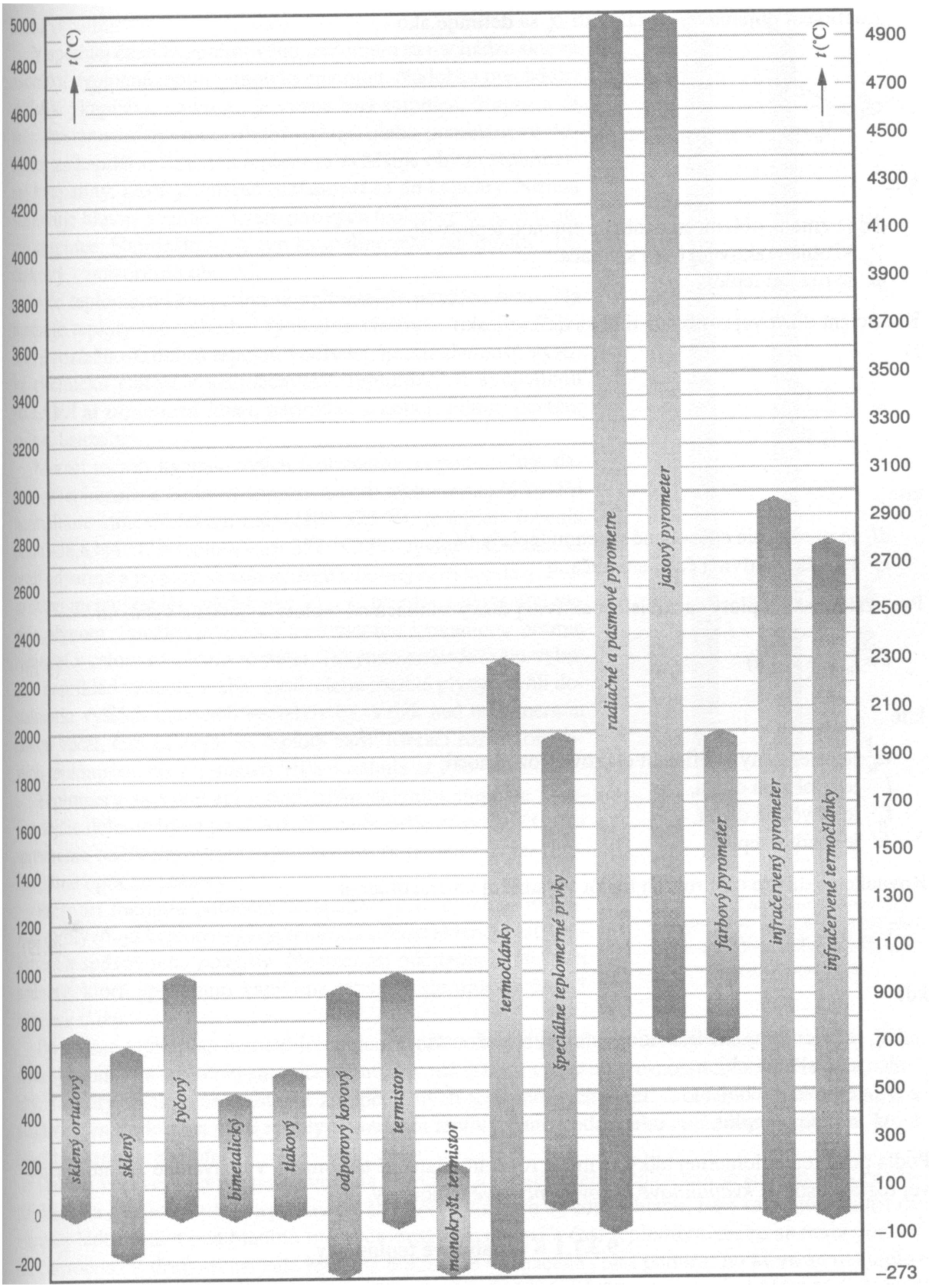


Fig. 4.1 Thermometer temperature ranges

4.1 Static properties of temperature sensors

Static characteristics
is given by the functional dependence $Y = f(X)$ between the measured quantity (temperature) and the transformed quantity *Y* in the time steady state.
The ideal static sensor characteristic is

$$Y = K \cdot X \qquad (4.1)$$

where *K* is the sensitivity of the sensor.

Sensitivity threshold
is given by the value of the measurand at which the sensor output has a signal corresponding to the root mean square deviation of the sensor noise. For a voltage output signal, it is given by the standard deviation of the noise voltage u_s.

$$u_t = \sqrt{\overline{u_s^2}} \qquad (4.2)$$

Dynamic range
is given by the interval of permissible values of the sensed variable, bounded by the sensitivity threshold and the maximum value of the measured variable.

Reproducibility
is given by the deviation of measured values at short-term unchanging measured variable and unchanging environmental disturbances.

Distinguishability
is the ratio of the reliable measurand to the sensitivity threshold.

4.2 Dynamic properties of temperature sensors

The measured temperature is constantly changing with time. The dynamic properties are necessary to know for the analysis and synthesis of measurement and control systems. They can be described by differential equations1. a of 2nd order. Graphically, the dynamic properties are represented by a transient characteristic, i.e. the response to a unit temperature jump, or by a rate characteristic, i.e. the response to a temperature change at a constant rate. Temperature sensors have no inertial mass > both characteristics are always aperiodic or at intermediate aperiodicity. The progression of typical1. a 2nd order transient characteristics is Fig. 4.2.

The time constantτ is the time it takes for the response to a step change to reach 63.2% of the steady state value. Sensor manufacturers quote either the time constantτ or the so-called response time, i.e. the time for the response to reach 90% or 95% of the steady state value, independent of the order value.

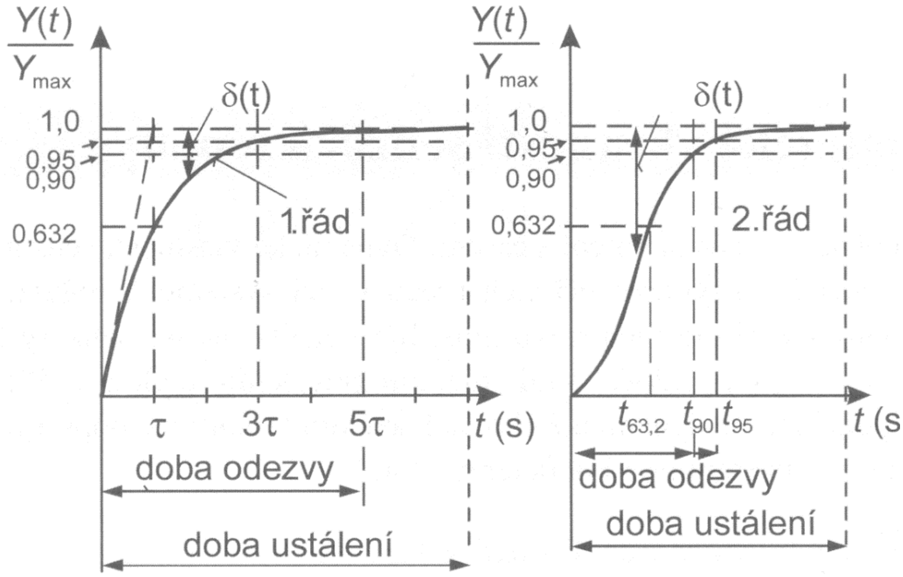


Fig. 4.2 Transition characteristics1. a 2nd order

5. METAL RESISTIVE TEMPERATURE SENSORS

The principle of resistive metal temperature sensors is the temperature dependence of the metal resistance. A metal can be thought of as a collection of positive ions located at lattice points in a crystal lattice and a so-called electron gas consisting of a collection of chaotically moving electrons.

For metals, the only temperature-dependent parameter is the relaxation time, whose value is of the order of 10^{-13} s. For a small temperature range0°C to100°C a linear relationship can be used with some uncertainty:

$$R_t = R_0(1+\alpha t) \tag{5.1}$$

where R_0 is the resistance of the sensor at temperature0°C . The mean value of the temperature resistance coefficientα can thus be determined:

$$\alpha = \frac{R_{100} - R_0}{100 R_0} \tag{5.2}$$

where R_{100} is the resistance of the sensor at temperature .100°C

Another basic parameter of resistive temperature sensors is the ratio of sensor resistances R_{100} at temperature100°C and R_0 at temperature 0°C . This ratio is denoted by the letter W according to the relation:

$$W_{100} = \frac{R_{100}}{R_0} \tag{5.3}$$

For larger temperature ranges, linear relationships can no longer be used. The temperature dependencies of the basic materials are shown in Fig.5.1 a in Table 5.1.

materiál	$\alpha \cdot 10^2$ (K^{-1})	teplotní rozsah (°C)	poměr odporů W_{100}
platina	0,385 až 0,391	–20 až 850	1,3850
nikl	0,617 až 0,675	–70 až +150 (+200)	1,6180
Ni-Fe	0,518 až 0,527	–100 až +200	1,462
měď	0,426 až 0,433	–50 až +150	1,4260

Table 5.1 Materials for metal temperature sensors

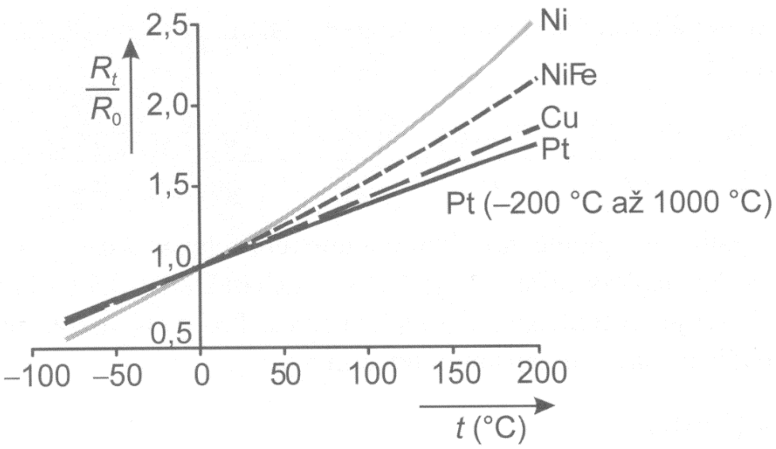


Fig. 5.1 Temperature dependencies of resistive temperature sensors

In addition to the basic resistance value of $R_{100} = 100\Omega$, sensors with a basic resistance value of 50, 200, 500,1000 a 2000Ω are produced. For platinum resistance temperature sensors, $W_{100} = 1.385$ is prescribed. The nonlinearity of Pt_{100} is shown in Fig. 5.2.

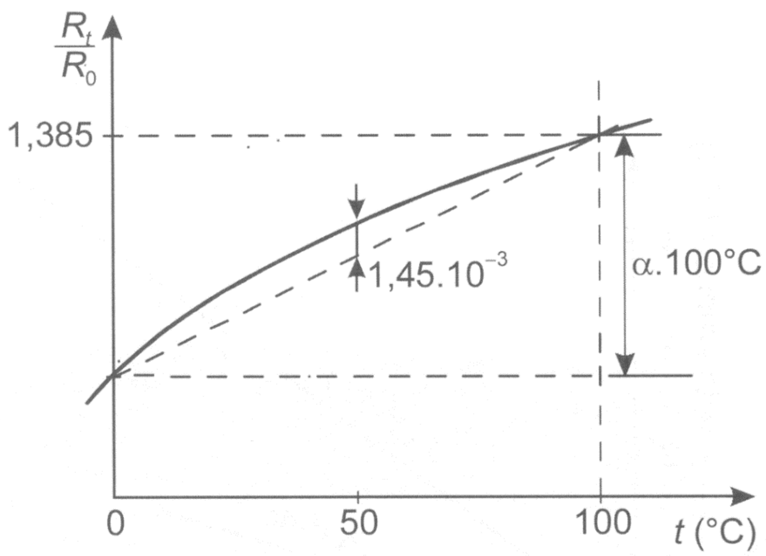


Fig. 5.2 Non-linearity of Pt_{100}

5.1 Measuring circuits for metal resistive temperature sensors

Requirements

- minimizing the influence of the current passing through the sensor
- minimum time constant
- minimal influence of the line resistance to the measuring resistance
- linearization of the temperature dependence of the sensor resistance

The classic circuit for evaluating resistive sensors is the Wheastone bridge (Fig. 5.3)

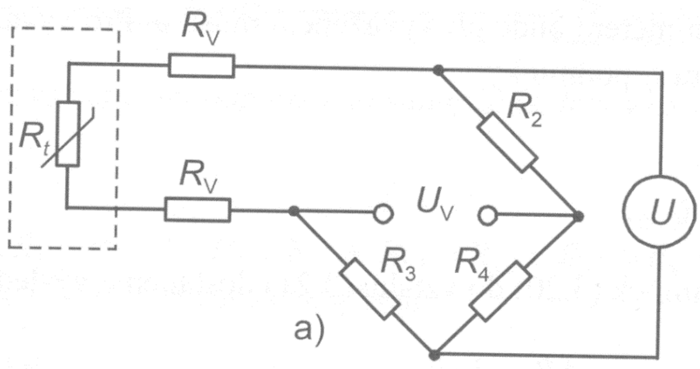


Fig. 5.3 Two-wire connection

In order to balance the bridge, a condition must be met:

$$R_3 = R_2 = R \tag{5.4}$$

$$R_4 = R_{tz} = 2R_{Cu0} \tag{5.5}$$

where R_{tz} is the resistance at the initial temperature. When these conditions are met, the sensitivity of the bridge is highest. In practice, a three-wire active-bridge circuit is used (Fig. 5.4), where the resistive network of the operational amplifier provides the current supply to the temperature sensor.

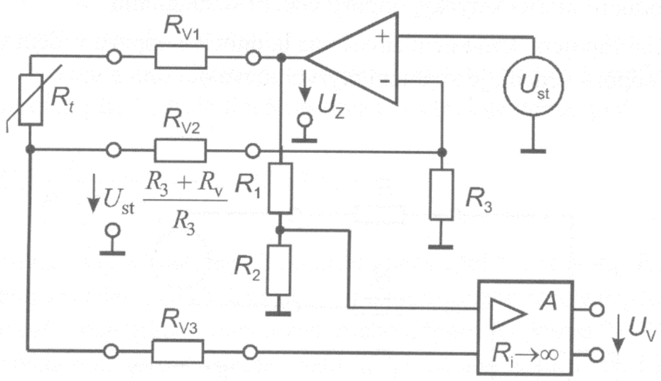


Fig. 5.4 Three-wire circuit with active bridge

6. SEMICONDUCTOR TEMPERATURE SENSORS

They use the temperature dependence of resistance as metal sensors. They can be divided into:

thermistors
- negastory
- posistory

monolithic resistive sensors

A thermistor (from the English description *thermally sensitive* **resistor**) is a temperature-dependent resistor made of semiconductor ferroelectric ceramic materials. Ceramic technology allows the production of thermistors in the shape of a disk, plate, drop, cylinder, etc. (Figure 6.1).

The advantages of the thermistor are its high temperature sensitivity, small size, simple conversion of resistance to electrical voltage or current, and the ability to directly measure the resistance of the thermistor over a longer distance. The disadvantage is the non-linear characteristic.

Thermistors are divided according to their structure into amorphous and polycrystalline. Depending on the material, a thermistor has either a large negative temperature coefficient of resistance, called a negastor or NTC thermistor (Negative Temperature Coefficient) or a large positive temperature coefficient of resistance, called a posistor or PTC thermistor (Positive Temperature Coefficient). The temperature dependence of the resistance of a non-gastor and a posistor compared to the temperature dependence of metal resistive sensors (Pt, Ni) is shown in Figure 6.2.

6.1 Negastors (NTC thermistors)

Negastors are produced by powder technology from metal oxides such as chromium oxide, cobalt, copper, iron, manganese, nickel and titanium, e.g. Fe_2O_3 + TiO_2, MnO+CoO. The sintered sensors are hardened by sintering at high temperatures. The temperature ranges of the negastors are from the normal -50°C to +150°C to extreme ranges in the low temperature region from +4,2°C to high temperatures up to 1000°C

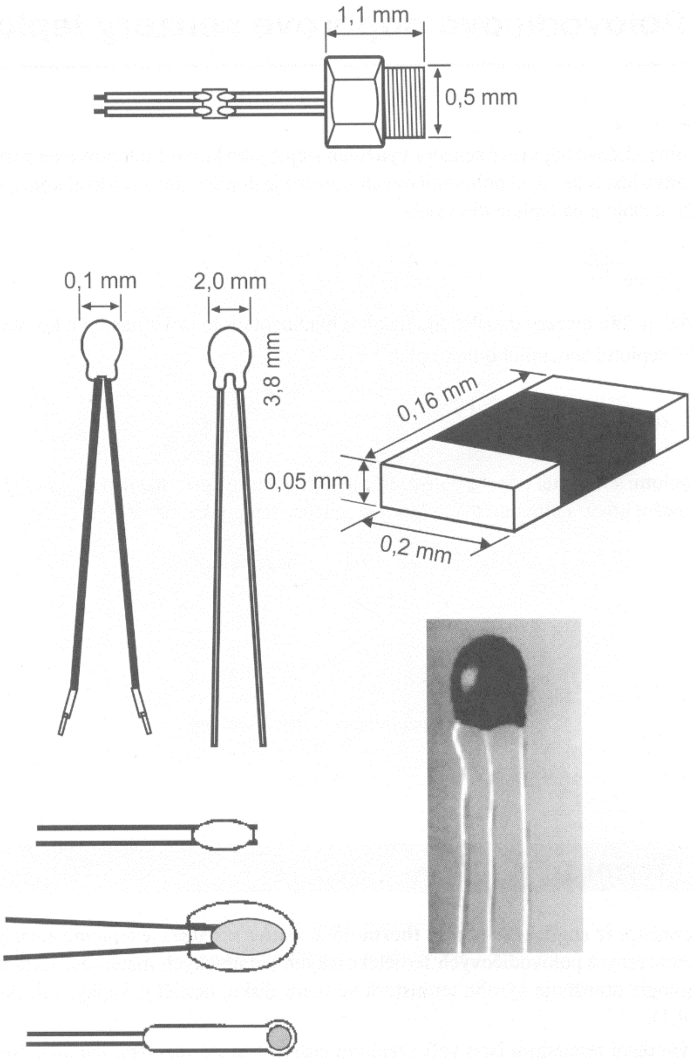


Fig. 6.1 Shapes of miniature thermistors

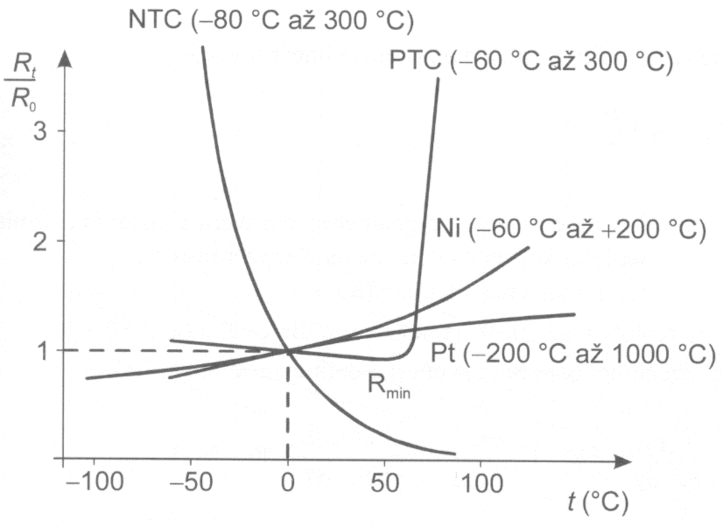


Fig. 6.2 Comparison of temperature dependencies of NTC and TPC thermistors with metal sensors

6.2 Monocrystalline Si sensors

They are designed for temperature ranges from -50°C to 150°C . The sensor is based on a non-proprietary semiconductor of type N. Its layout is shown in Fig. 6.3, typical characteristics in Fig. 6.4.

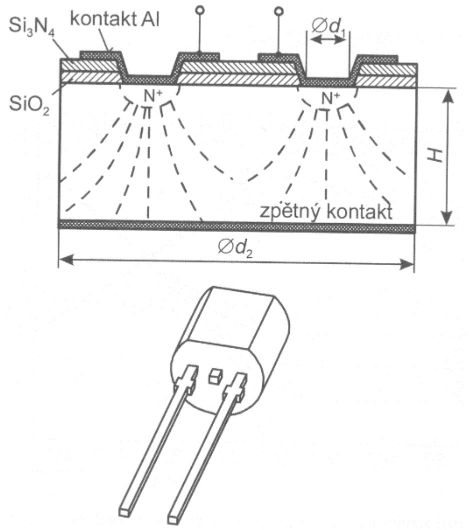


Fig. 6.3 Single crystal Si sensor arrangement, TO-92 housing

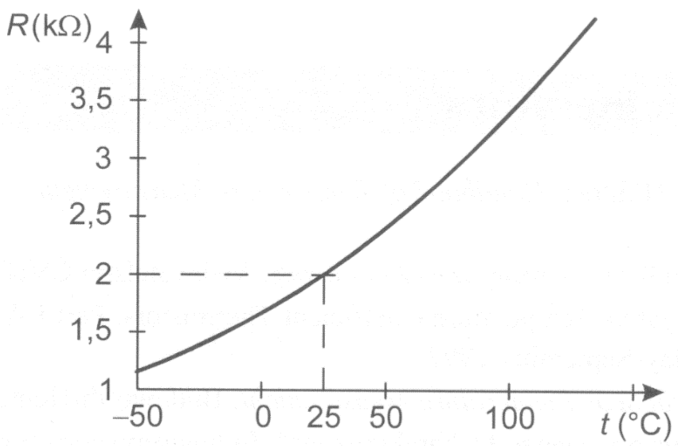
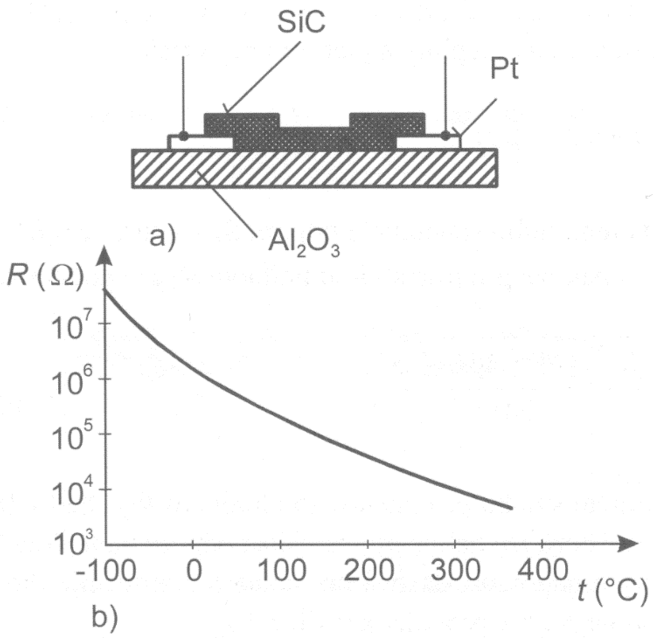


Fig. 6.4 Characteristics of the Si sensor (KTY 10, KTY 81 Philips)

6.3 SiC sensor

They can be used for a larger temperature range, from -100°C to 450°C . The characteristic corresponds to non-gastors (Fig. 6.5).



Senzor SiC (a – struktura, b – charakteristika)

Fig. 6.5 SiC sensor

7. MONOLITHIC PN TEMPERATURE SENSORS

Integrated monolithic temperature sensors are most often based on the temperature dependence of the PN transition in the transmittance direction. They have a temperature range from -55°C to +150°C and a measurement uncertainty of up to 2%. The temperature dependence of the PN transition voltage of the diode can be seen in Fig. 7.1.

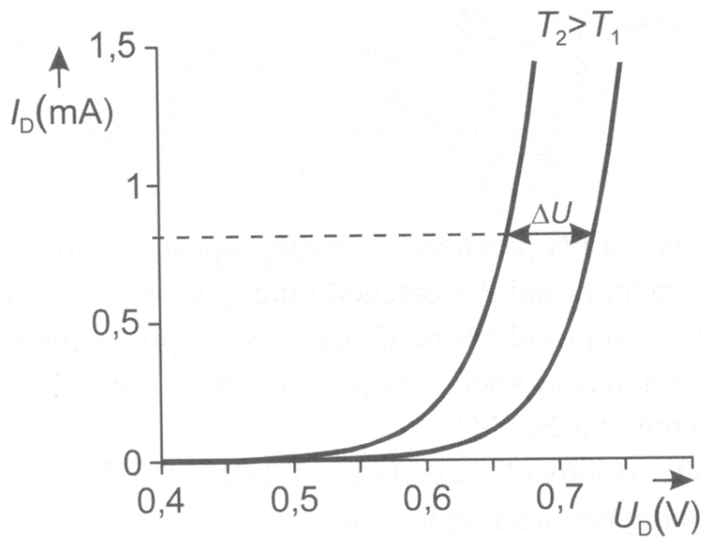


Fig. 7.1 Temperature dependence of PN diode transition characteristic

7.1 Transistor PN temperature sensors

They are based on a similar principle as PN-diodes.

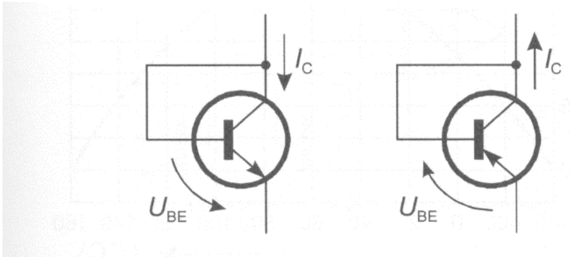


Fig. 7.2 Transistor diode

Fig. 5.3 shows the deviation from the linear function $U_{BE} = kt$

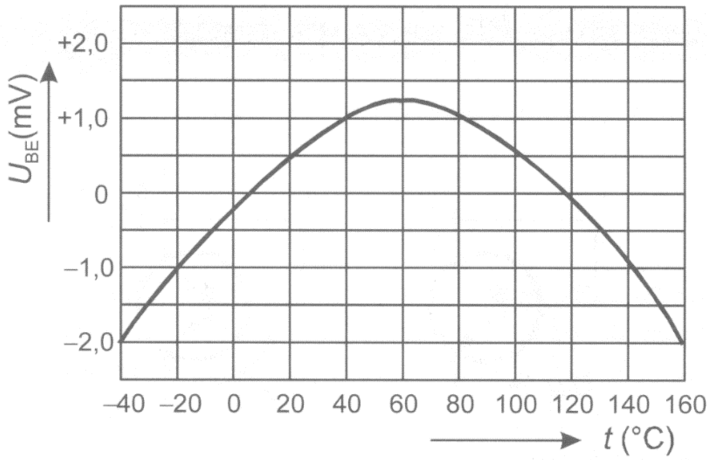


Fig. 7.3 Nonlinearity of the transition voltage U_{BE} versus temperature at I=0.1 mA

8. THERMOELECTRIC CELLS

The essence of the thermoelectric phenomenon is the direct conversion of thermal energy into electrical energy and vice versa. The thermoelectric phenomenon was discovered in 1758 by the Russian scientist Epinus, who discovered that in a circuit composed of two different conductors, a voltage is generated when the junctions of the conductors have different temperatures.

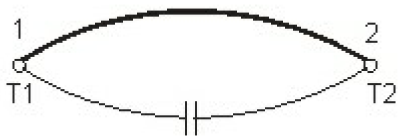


Fig. 8.1 Seebeck effect

A thermoelectric cell converts a temperature change in the environment into a change in electrical voltage. This takes advantage of the fact that if two conductors of different metals are used in a simple electrical circuit, see. Fig. 8.1, their two junctions1 a 2 are placed in an environment with two different temperatures T1 and T2, an electric current will start to flow through the circuit. If we break the circuit at the indicated point and include a suitable measuring instrument, we measure a small difference in electrical potential which is a function of the temperature difference T2 - T1. This potential difference is called the thermoelectric voltage. This is a simplified description of the so-called Seebeck effect, which is the basis of temperature measurement by thermoelectric cells (thermocouples).

There is an opposite phenomenon to the Seebeck effect, which is called the Peltier effect. It manifests itself in such a way that when an electric current passes through the mentioned electric circuit, one of its connections heats up and the other one cools down. This phenomenon can also be encountered in temperature measurements due to the fact that some manufacturers use it for cooling, e.g. in devices for realizing the melting point of ice, i.e. 0 °C.

We have stated that thermoelectric voltage is generated when we connect conductors made of two different metals to each other. Then, at different temperatures between the joined and free ends of the wires, a voltage is generated at the free ends of the wires which is proportional to the temperature difference. The ends of the wires, welded together and insulated from each other, are placed in the space whose temperature is to be measured, and a millivoltmeter, usually calibrated in degrees Celsius, is attached to the free ends. The measured voltage indicates the temperature difference between the hot and cold junction of the thermoelectric cell. It is therefore important that the cold junction is kept at a constant temperature. The relationship between voltage and temperature depends solely on the composition of the metals used and does not depend on the cross-section or length of the wires.

However, from a measurement point of view, it is necessary that the thermoelectric voltage generated is as large as possible and that both metals are as resistant as possible to environmental influences so that their properties change as little as possible over time. Only a few pairs of materials meet this requirement and their composition is therefore standardised so that the properties of identically labelled thermocouples made by different manufacturers are identical.

At present, it is recommended to use thermocouples according to IEC 584-1, or EN 60584-1. This standard contains tables of basic thermoelectric voltage values for individual thermocouples and polynomials for calculating their characteristics. Less commonly used are thermocouples according to DIN 43710. It should be noted that the standards give basic thermoelectric voltage values for a reference temperature of 0° C. In practice, however, other reference temperatures are usually used (in thermostats of comparison junctions), such as 20° C, 50° C, but also 70° C, and the measured thermoelectric voltage values must be corrected to these reference temperatures.

Thermocouple marking according to IEC 584	**Original**	**Measuring range [° C]**
T	Cu-CuNi,	- 200 to 350
J	Fe-CuN	- 200 to 750
E	NiCr-CuNi,	- 100 to 900
K	Ni-Cr-Ni, ch-a	- 200 to 1200
N	NiCrSi-NiS	- 200 to 1200
S	PtRh10-Pt	0 to 1600
R	PtRh13-Pt	0 to 1600

B	PtRh30-PtRh6	300 to 1700
Thermocouple marking according to DIN 43710	**Original**	**Measuring range [°C]**
L	Fe-CuNi,	- 200 to 900
U	Cu-Ni,	- 200 to 600

Table 8.1 Measuring ranges of thermocouples

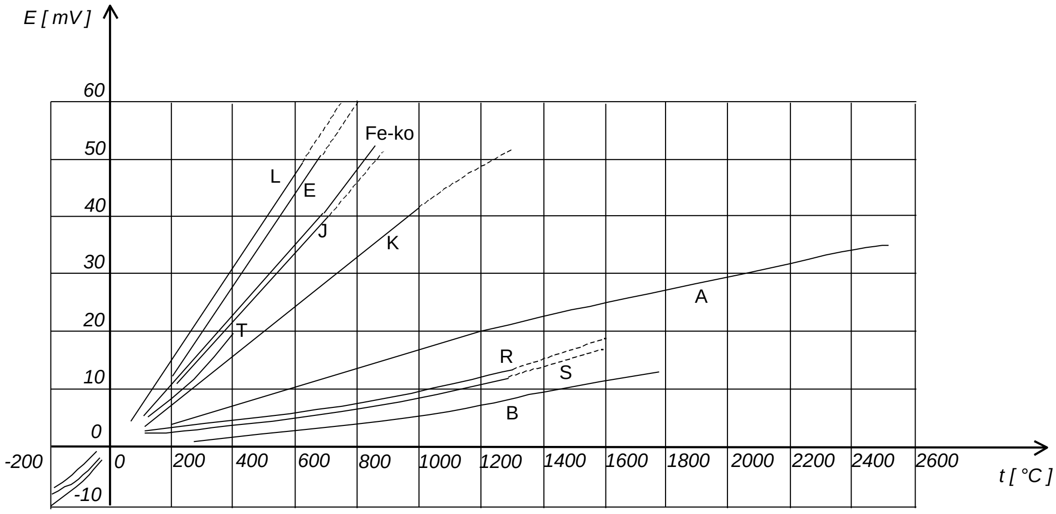


Fig. 8.2. Temperature dependence of thermoelectric voltage of the most used thermoelectric cells

The permissible tolerances for thermocouples are specified in IEC 584-2 or IEC 584-2.

Mark Thermocoupl	**Class Accuracy**	**Permissible deviations (tolerances) [°C]**
J	1	± 0.004 . │ t│ or± 1.5° C in the range (-40 to 750)° C
	2	± 0.0075 . │ t│ or± 2.5° C in the range (-40 to 750)° C
K and N	1	± 0.004 . │ t│ or± 1.5° C in the range (-40 to 1000)° C
	2	± 0.0075 . │ t│ or± 2.5° C in the range (-40 to 1200)° C
	3	± 0.015 . │ t│ or± 2.5° C in the range (-200 to 40)° C
S	1	±[1 + (t-1000).0.003] or± 1.0° C in the range (0 to 1600)° C
	2	± 0.0025.│ t│ or± 1.5° C in the range (-40 to 1600)° C

B	2	± 0.0025 . ∣ t ∣ or± 1.5° C in the range (600 to 1700)° C
	3	± 0.005 . ∣ t ∣ or± 4° C in the range (600 to 1700)° C
L		± 3° C in the range (100 to 400)° C
		± 0.75° C in the range (400 to 900)° C

Table 6.2 Tolerances according to IEC 584-2 a DIN 43710

Note: The larger of the specified tolerance values is always valid! Absolute temperature value in degrees Celsius regardless of the sign.

The deviations from the linear characteristic are shown in Fig. 6.3.

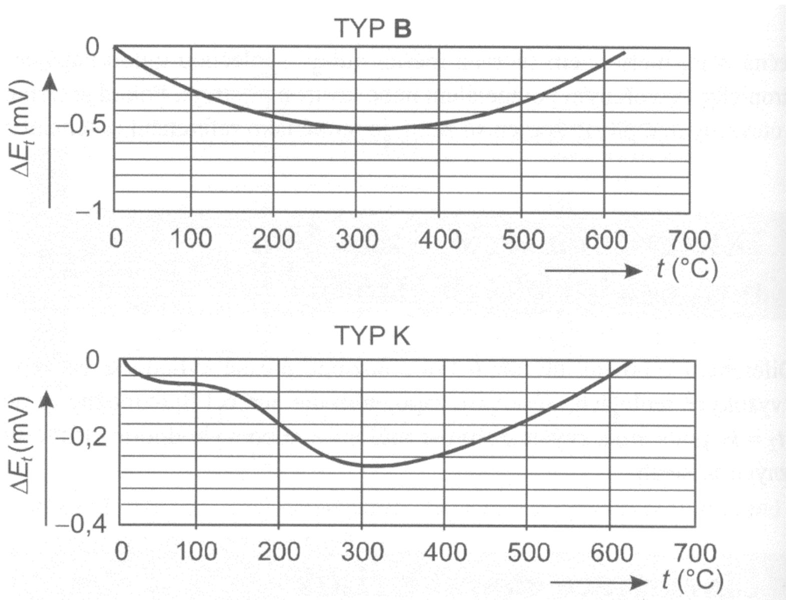


Fig. 8.3 Deviations from the linear characteristic of type **B** and **K** thermoelectric cells

8.1 Thermocouple wiring

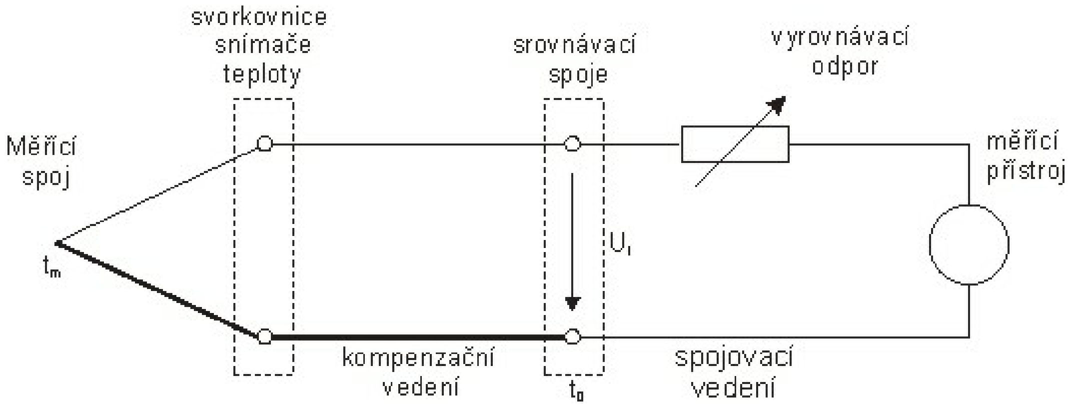


Fig. 8.4 Thermoelectric cell measurement chain

Fig. 6.4 shows the individual functional locations of the circuit. The thermoelectric voltage U_t, the value of which is proportional to the difference between the temperature t_m at the measuring junction (warm end) and the temperature t_o at the comparison junction (cold end), is applied via a compensation (extension) line and a copper connection line to the measuring instrument. In order to assign a temperature to each value of the thermoelectric voltage, it is necessary to maintain the comparison junctions at a known and constant temperature, the so-called reference temperature.

8.2 Extension lines

Extension and compensation lines extend the actual thermoelectric cell from the thermoelectric sensor terminals to a location with a known and guaranteed junction temperature. Such a location is a junction thermostat, compensation box, or other auxiliary device. According to IEC terminology, we distinguish between extension lines (made of the same materials as the thermoelectric cell) and compensation lines (made of substitute materials). Compensation lines are used for thermoelectric cells made of precious metals. Both lines are characterised by the fact that over a certain temperature range (usually 0 to 200 °C) they have the same characteristics as the respective thermoelectric cell. Most often each of the branches has the same characteristic, sometimes (for less accurate measurements) only the pair as a whole has the same characteristic.

Tolerances for extension and compensation lines are specified in the relevant standards. In general, they correspond to approximately (1,5 to 2,5) °C for class A and (2,5 to 5) °C for class B. Substitution of similar thermoelectric cells results in an additional measurement error - e.g. substitution of thermoelectric cell J for Fe-Ko results in an error of approx. 3 °C

The following mistakes are often made when connecting the extension line:
- replacement of the extension line type
- wrong polarity of the connected wiring (if the polarity is switched at both ends, it is very difficult to recognize it when the wiring is "cold")
- the view that the compensation line compensates for the influence of the temperature of the comparison junction is completely wrong (but common) and therefore the thermostat of the comparison junction cannot be omitted
- the extension line does not have sufficient insulation resistance
- any pair of wires can be used as an extension lead
- for a type B thermoelectric cell, a compensation (extension) line for a type S thermoelectric cell is used.

8.3 Thermoelectric sensor materials

When selecting the material for the thermoelectric sensor, we try to meet some basic requirements. First of all, the dependence of the thermoelectric voltage on temperature must be close to linear. The material should be resistant to chemical, mechanical and corrosive influences. The output thermoelectric voltage should be as high as possible. The smaller the value of the voltage, the lower the accuracy, the more sensitive the measuring instrument must be and the more delicate it is. In the case of sensors made of brittle metals (bismuth, antimony, etc.), these have to be sprayed or sintered onto each other under vacuum.

The material is selected in terms of the required temperature range and the required accuracy of the measurement. The time stability or the mean lifetime of the sensor is also important. The stability of the characteristic should be invariant with time. This condition is difficult to meet, especially at higher conditions. Recrystallisation at the junction or ageing occurs. The sensors then have to be renewed and occasionally resealed. Pairs of materials have been developed for the construction of thermoelectric sensors. Their parameters are given in the standards.

8.4 K-type thermocouple

The K-type thermocouple is the most important representative of nickel alloy thermocouples and the most widely used industrial thermocouple. It came under a number of names: nickel-chromium-nickel, nickel-chromium-nickel-aluminum, tophel, Hoskins, thermokanthal, chromel-alumel. These were always the same basic materials in alloys with different additives. Even today, individual manufacturers supply different materials but with the same resulting characteristics. It is therefore not recommended, for example, to combine materials from different manufacturers. The thermoelectric cell K has an almost linear characteristic - the sensitivity is in the whole range of approx. 40μ V/°C. The thermocouple is suitable for measurements in neutron flux. During deformations the thermocouple becomes inhomogeneous and the thermoelectric voltage changes (the measurement error can be up to tens of degrees). Thermocouples are characterized by instability of values in the temperature range 200 to 600 °C . These so-called K - states are caused by the state of atoms in the crystal lattice of nickel materials and cause measurement errors of several degrees. The magnitude of the error depends on the temperature gradient and cannot be removed by conventional heat treatment of the material. It is a reversible change in characteristic. Therefore, it is recommended to use J-type thermoelectric cells in the temperature range up to600 °C .

8.5 Limiting the influence of temperature fluctuations of the comparison joint

The effect of temperature fluctuations of the comparator junction can be eliminated by placing the comparator junctions in a thermostat (in the laboratory at 0 °C , for industrial applications at 50 °C) or by using compensation circuits. In digital measuring systems, the most common isotherm is the so-called isothermal terminal block, whose temperature is sensed e.g. by a semiconductor resistance thermometer. The corresponding correction is evaluated digitally.

The use of thermocouples is particularly suitable when monitoring a large number of measuring points. In these cases, different types of thermocouples can also be used, whose comparison connections are connected to an isothermal terminal block. Compensation for the effect of temperature changes in the reference junction is done by software using a computer (Figure 6.4). The computer controls the signal evaluation and, via a multiplexer, the serial acquisition of data from the individual sites. The multiplexer is actually a multi-position switch that provides sequential connection of individual thermocouples to the evaluation device. A certain disadvantage of this arrangement is the longer time required for data processing. If a fast response is required, hardware compensations specific to each thermocouple must be used.

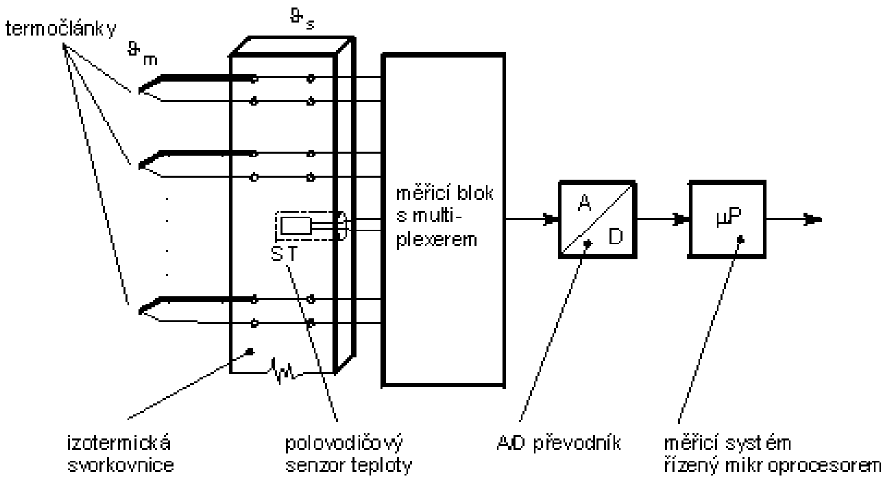


Fig. 8.5 Temperature monitoring

8.6 Design of thermoelectric sensors

There are two basic designs of thermoelectric temperature sensors. The classic design consists of the thermoelectric cell itself, placed in a protective armature that prevents mechanical damage and protects it from adverse physical and chemical influences. The thermoelectric cell itself is inserted into a stem tube terminating in a terminal block, which is inserted into a protective tube with a head. The material of the outer protection tube varies according to the nature of the environment and the magnitude of the temperature to be measured. The protection tube protects the thermometer from the adverse effects of the environment but degrades its dynamic properties.

A modern type of compact sensors are so-called sheathed thermocouples, in which the wires are housed in a nickel tube filled with powdered MgO or Al_2O_3 (Fig. 6.6 b). The diameter of the metal sheath is (0.15 to 10) mm. The sheathed thermoelectric cell is a "sheathed cable" where the actual thermoelectric pair is tightly crimped in the insulation in the metal sheath. Sheathed thermoelectric cells are supplied as a cable (in lengths, e.g.100 m) or as a "assembly" in the required length. The user should always order this assembly, as the fabrication of the measuring junction and cable leads is a demanding operation requiring special equipment. The measuring junction of these thermoelectric cells can be made as insulated (from the sheath), connected to the sheath (grounded) or 'exposed' (measuring junction is outside the sheath). The insulated joint design is recommended. The termination of the sheathed thermoelectric sensor is either standard (hemispherical cable termination) or with a reduced diameter (about 1/3), flat or otherwise shaped termination. Sheathed thermocouples can be bent, have a small time constant and allow measurements even in hard-to-reach places.
Thermoelectric measuring inserts are manufactured with one or two cells.

The thermocouple wires are electrically insulated by ceramic tubes (Fig. 8.6).

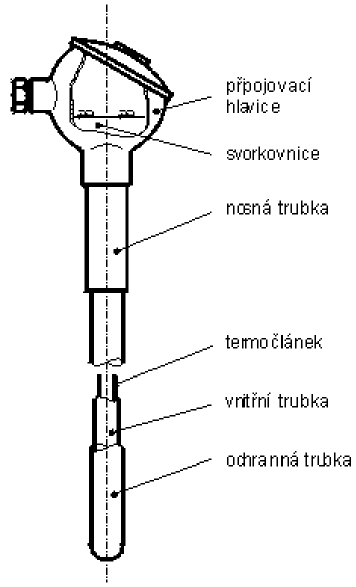


Fig. 8.6 Detail of the thermocouple

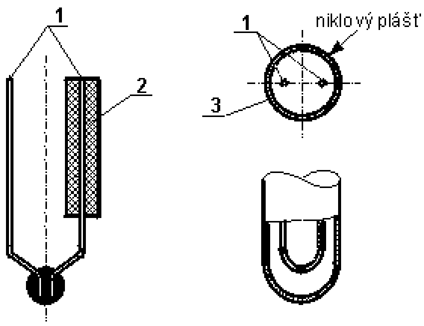


Fig. 8.7 Sheath thermocouple
1-terminal wires, 2-ceramic insulation
3-ceramic powder

9. SPECIAL TOUCH TEMPERATURE SENSORS

9.1 Acoustic thermometers

They are based on the temperature dependence of the speed of sound propagation in a gaseous or solid medium.

Fig. 9.1 shows:
1... transmitter,
2... receiver,
3... feedback amplifier,
4... the flowing gas whose temperature is being measured,
5... the object whose temperature is being measured

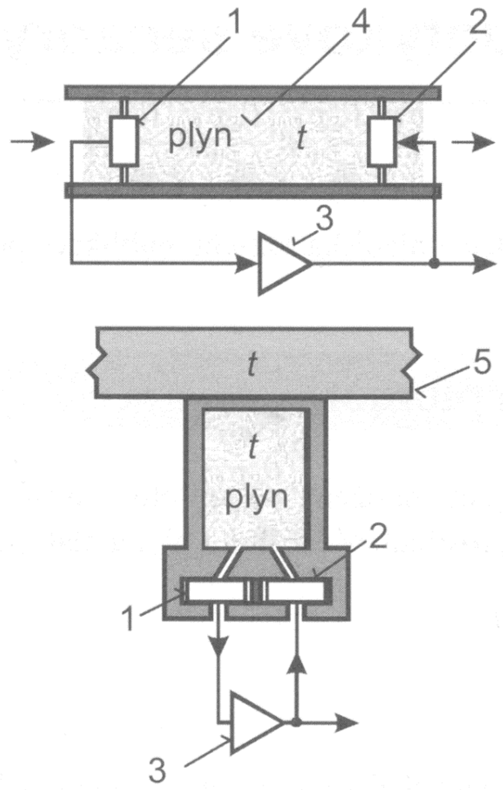


Fig. 9.1 Resonant acoustic thermometer

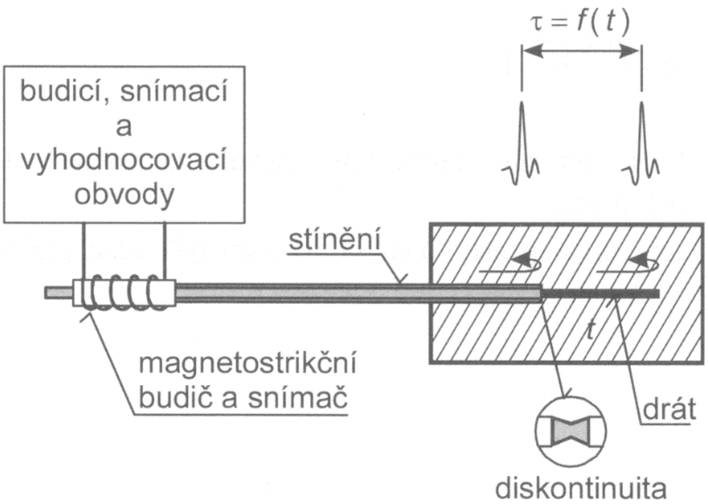


Fig. 9.2 Pulse acoustic thermometer

Various methods can be used to evaluate the speed of sound propagation:

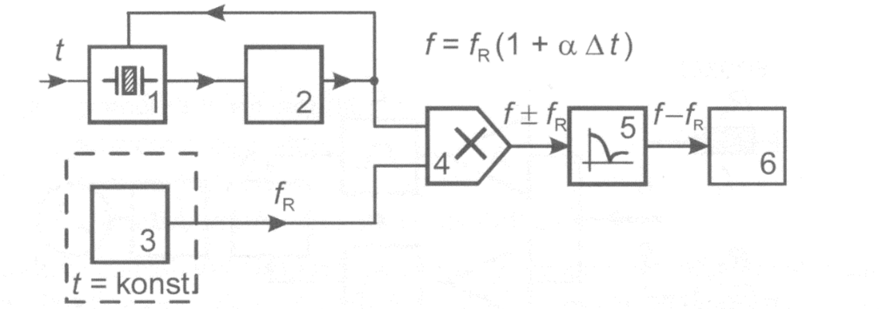
- the resonance method with feedback oscillator in Fig. 9.1 uses the temperature-dependent sound propagation velocity in a gaseous medium,
- The pulse method uses the temperature dependence of the sound propagation velocity in a solid medium and is based on the evaluation of the transit time of the acoustic pulse passing through the rod from the transmitting acoustic transducer to the receiving one or from the discontinuity to the end of the sensor according to Fig. 9.2.

Acoustic thermometers are used for both very low (2 K to 20 K) and high temperatures. The arrangement of the pulsed acoustic thermometer in Fig. 9.2 is based on a measuring rod (aluminium, steel, sapphire, ruthenium, molybdenum, tungsten, tungsten/rhenium) with a diameter from0,03 mm to3 mm , length from1,3 cm to3 m . Through a magnetostrictive exciter, an ultrasonic pulse is transmitted to the rod, which is first partially reflected from the discontinuity and then reflected from the end of the rod. Both reflected pulses are again sensed by the magnetostrictive transducer and the time difference is processed in the evaluation unit. The temperature range according to the material used is from750 °C to3000 °C with a measurement uncertainty of ± 20 °C.

9.2 Crystal thermometers

The temperature dependence of the resonant frequency of the quartz cut can be used to measure the temperature. The principle is evident from the measurement chain in Fig. 7.3.

For example, if for the range from -80 °C to +250 °C the temperature coefficient of the oscillator frequencyα = 35.4.10^{-6} K^{-1} a the reference frequency f_R = is 28.2 MHz, the sensitivity of the crystal thermometer will be 1 kHz/K. Thus, a resolution of 10^{-4} °C can be achieved, which corresponds to the short-term frequency stability of the crystal. The measurement uncertainty due to nonlinearity is of the order of + 0,05 °C.



Krystalový teploměr (1 – krystal, 2 – oscilátor řízený krystalem, 3 – oscilátor řízený krystalem umístěným v termostatu, 4 – směšovač, 5 – nízkofrekvenční filtr, 6 – čítač s displejem)

Fig. 9.3 Crystal thermometer

9.3 Noise thermometers

At the pins of each resistor, due to the temperature-dependent free movement of electrons in the conduction band, there is a measurable electrical voltage, which has a stochastic character. This voltage is referred to as Johnson or Nyquist or simply as thermal noise. The energy of this summation is uniformly distributed over the entire frequency band or corresponds to the white noise specification.

The advantage of a noise thermometer is its independence from the environment, including ionizing radiation, highly aggressive atmospheres, neutron flux, and high temperature (>1000 °C). Any effects that cause a change in resistance can be eliminated either by accurate resistance measurement or by ratio evaluation (Fig. 7.4). A significant disadvantage of noise thermometers is the very small output electrical voltage. For example, if the resistance is R = 100 ,$\Omega\Delta$ f = 100 kHz and the temperature is 300 K, then $u_{ef} = 4.10^{-7}$ V. This example implies the requirements for electronic signal processing. A ratio circuit with sensing resistor R_S *and* reference resistor R_R is shown in Fig. 9.4.

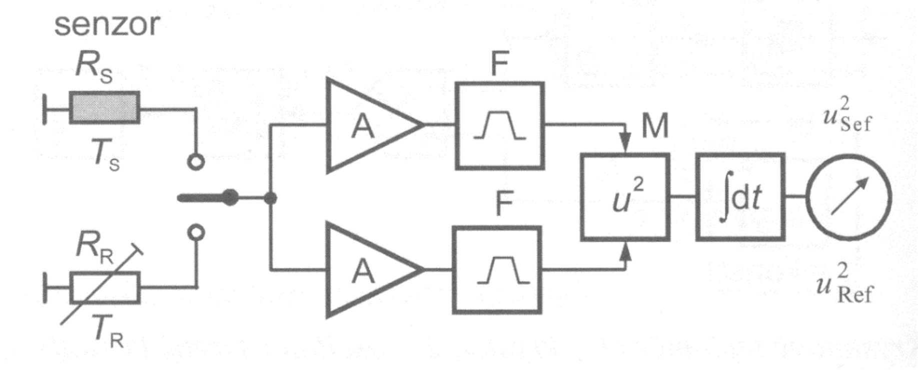


Fig. 9.4 Noise thermometer block diagram

Fig. 9.4 shows:
A... amplifier,
F... filter,
M... multiplier

9.4 Fiber optic temperature sensors

Optical fibre sensors (OFS) were developed by exploiting the undesirable effects of the surrounding environment on the parameters of optical communication cables. The basis of OFS temperature is to exploit the effect of temperature on the properties of optical fibers. The measured temperature modulates an optical signal that is transmitted to the optical fiber by a radiation source (semiconductor electroluminescent diode LED or semiconductor laser) and detected by a PN, PIN or avalanche type semiconductor diode).

The optical fibre used for OFS consists of a cylindrical core with a refractive index n_j *and a* cladding with a refractive index n_p as shown in Fig. 9.5. Or the condition must be satisfied:

$$\frac{n_p}{n_j} < 1 \tag{9.1}$$

A relationship can be derived:

$$NA = \sin\Phi_{1C} = n_j \sin\Phi_{2C} = \sqrt{n_j^{\,2} - n_p^{\,2}} \tag{9.2}$$

where *NA* is the numerical aperture of the fibre, which determines the angle at which the waveguide is able to receive the radiant flux and emit the flux at the output side. A typical aperture value is *NA* = 0.15-0.5.

One possible application is shown in Fig. 9.6. The phosphor layer in the sensor head is excited (the process of transition to a higher energy level) by ultraviolet radiation. During de-excitation, the sensor head fluoresces and the return optical beam e split into red and green components in an interference filter. By evaluating the ratio of the intensities of the light beams, the temperature of the sensor head is clearly defined. The measured temperature range is from -50 °C to +200 °C . The measurement uncertainty is ± 0,1 °C.

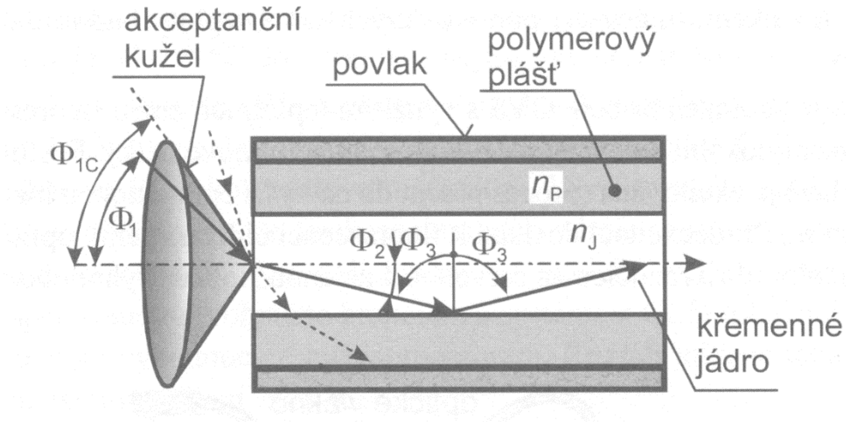


Fig. 9.5 Double-layer optical fibre waveguide

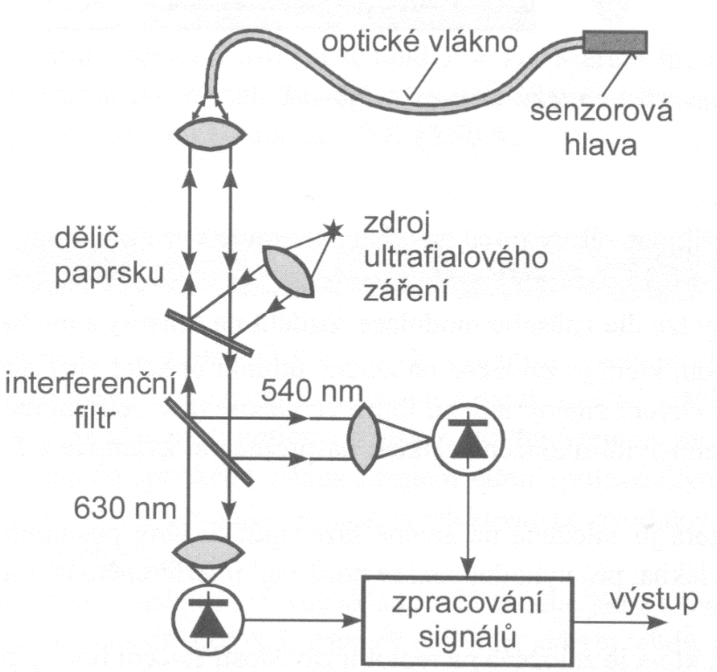


Fig. 9.6 Fiber optic fluorescence thermometer

10. NON-CONTACT TEMPERATURE MEASUREMENT

Non-contact temperature measurement (also referred to as *infrared pyrometry)* is the measurement of the surface temperature of bodies based on the electromagnetic radiation emitted by the body and received by a sensor (detector) of radiation wavelengths from 0.4 μm to 25μm. This range covers the visible spectrum from 0.4μm to 0.78 μm, the near-infrared spectrum from 0.78 μm to 1μm, the short-wave infrared spectrum from 2μm to 3μm, the mid-wave infrared spectrum from 3 μm to 5 μm and finally the long-wave infrared spectrum from 5 μm to 25 μm. Electromagnetic radiation with wavelengths from 2 μm to 25 μm is referred to as *thermal radiation.* These ranges cover temperature measurements from -40 °C to + 10000 °C.

Non-contact temperature measurement is advantageous for:

- negligible influence of the measuring technique on the measured object,
- the ability to measure temperature on rotating or moving objects,
- temperature measurement from a safe distance (electrical installations, metallurgical objects, etc.),
- the ability to measure very rapid temperature changes,
- the ability to measure and further digitally process the temperatures of entire body surfaces (thermography, thermovision).

However, it is necessary to point out the disadvantages of non-contact temperature measurement:

- measurement uncertainties caused by not knowing the correct value of the emissivity of the surface of the body,
- measurement uncertainties caused by not knowing the correct value of the permeability between the sensor and the object,
- measurement uncertainties due to inaccurate correction of parasitic reflected radiation from the ambient environment to the measured object.

Basic division of pyrometers:

- **aggregate -** according to Stefan-Boltzmann law
- **monochromatic** - according to Planck's (Wien's law)
- **zonal** - according to Stefan-Boltzmann law
- **Proportional**

Fig. 10.1 shows the principle of the ratio pyrometer.

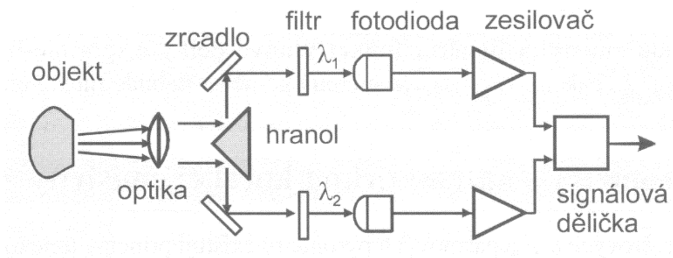


Fig. 10.1 The principle of the ratio pyrometer

10.1 Sensing temperature fields

The systems for non-contact measurement and display of temperature fields can be divided into systems without decomposition and with image decomposition. Systems based on direct conversion of the radiant flux to an image are vacuum photodiodes, where the thermal image is formed by the optics on the photocathode. Irradiation of the photocathode causes photoemission of electrons, whose flux is amplified by a photomultiplier tube and then directed by an electric field to a luminescent screen where the corresponding visible image is formed. In the system described herein, a microchannel plate (MCP) is currently used, which amplifies the electron flow behind or without the photomultiplier, based on the principle of a large number of parallel photomultipliers implemented in individual microchannels. The channels are connected to a high voltage (HV) source so that the electric field strength vector has an axial direction. The emitted electrons are accelerated in the channels, with reflections on the inner resistive layer followed by secondary emission. The accelerated and multiplied electrons are incident on the output screen of the multianode, and from there the visible image is fed through the optics to a CCD (Charge Coupled Devices) chip used in digital cameras or camcorders (Fig. 10.2).

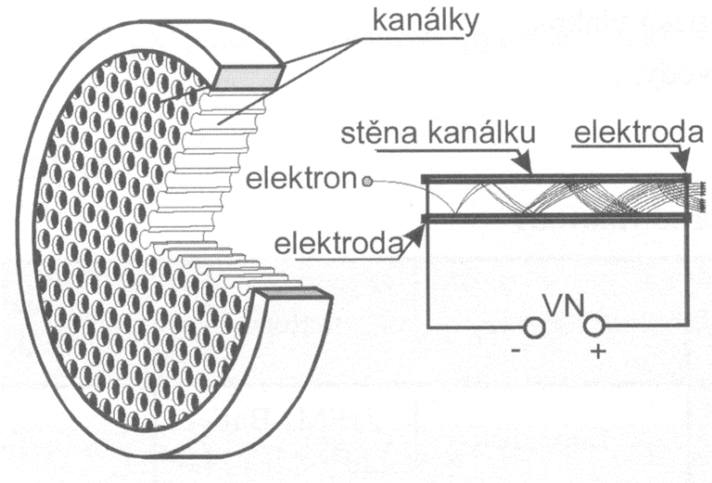


Fig. 10.2 Microchannel image intensifier

The principle described is limited to wavelengths up to 1μ m. Systems with image decomposition are referred to as thermal imaging.

10.2 Thermovision

Thermal imaging systems are divided into
- thermal imaging systems with optical-mechanical image decomposition,
- thermal imaging systems with matrix detector.

Optical-mechanical image decomposition is realized by scanning individual points of the object by a controlled optical axis. The instantaneous field of view of the thermal imaging system is gradually focused on all points (surfaces) of the measured object. The decomposition path is performed by moving optical parts of the camera (rotating prisms or mirrors). Since the production of these systems for civilian purposes has ceased, the optical-mechanical principle will not be described in detail.

For thermal imaging cameras, cooled and uncooled matrix microbolometer and quantum (QW1P) FPA detectors (1D-row and 2D-area) are now used. Cooling of the FPA matrix is performed by a Stirling cooler (hermetically sealed cooling system with two helium gas pistons, operating on the principle of a compressor microcooler) or a thermoelectric cooler operating on the principle of the Peltier effect. Signal processing is implemented directly on-chip via multiplexers and 14-bit A/D converters in each row of the matrix. Two main wavelength bands are used in thermal imaging technology, namely shortwave (2μ m to 5μ m) and longwave (7μ m to 13μ m).

Thermal imaging is the basic measuring device for infrared diagnostics. Based on the knowledge of the temperature field distribution of the object to be diagnosed, it is possible to check the function of devices whose operation is related to the generation or absorption of heat. Various material defects, frictional wear (e.g. in bearings) and other defects in the internal parts of the object that affect the surface temperature distribution can be located.

In the power industry, it is possible, for example, to diagnose under high voltage during operation the insulation conditions of insulators, contact terminals, switch conditions, etc. In the metallurgical industry, it is possible to detect damage to furnace linings, in electrical engineering to monitor the temperature of the electric motor casing, etc. There are two methods that also allow the diagnosis of defects within the material:

Pulse thermography, which is based on irradiation of the diagnosed object from an external emitter with thermal stimulation pulses and subsequent sensing of the temperature of the object surface with a thermal imaging camera. The thermal pulses last from a few milliseconds for materials with high thermal conductivity to a few seconds for low thermal conductivity layers such as plastics, laminates, etc. A short duration warming of a few degrees will not cause damage to the object. After the heat pulse hits the surface of the material, the heat spreads by thermal diffusion through the material. Thermal diffusion (the scattering of thermal radiation in a body)ξ depends on the thermal conductivityλ_{heat}, densityρ and specific heat capacity *c* of the material and is given by the relation:

$$\xi = \frac{\lambda_{tep}}{\rho \cdot c} \tag{10.1}$$

The temperature inside the material increases, and after the heat pulse is over, the inside of the material cools again by diffusion. If there is an inhomogeneity in the material with different specific heat capacity and thermal conductivity, the defect will be reflected in the thermal image of the surface of the object at a certain point in time. Heating can also be achieved with hot air. The pulse thermography method is used, for example, in tomography for aircraft propellers made of composite materials.

Lock-in thermography is based on heat flux modulation. The heat wave (usually sinusoidal with angular frequencyω) penetrates inwards after striking the surface of the body and is reflected back to the surface at the point of environmental change (defect). Interference with the primary wave then occurs at the surface. The images captured by the thermal imaging camera are digitally processed by Fourier Fast Transform (FFT) so that the amplitude and phase shift can be determined from each pixel. The amplitude of the signal is affected by the absorption, emissivity of the body surface and the irradiance distribution. However, in the phase of the signal, these effects are eliminated and only the temperature information both just below the surface and up to a certain depth in the material is revealed. The diagnosed depth is given by the so-called penetration depth of the thermal waveμ , at which the relative decrease in amplitude is given by a multiple of 1/e = 0.37.

11. SUMMARY

The properties of the individual sensors are clearly shown in Table 11.1

Note

Literal quotations and figures from the literature are used in this section:
Kreidl, M.: Sensors of non-electrical quantities - Temperature measurement. BEN, Prague 2005.

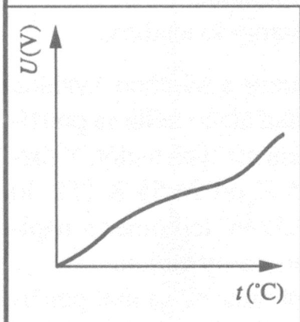
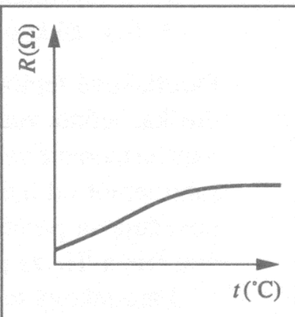
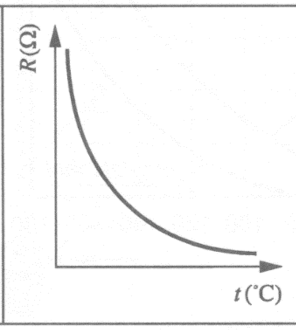
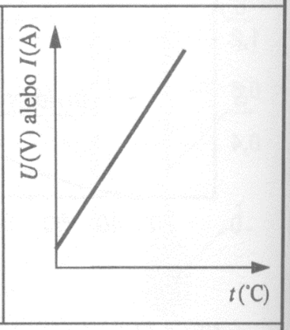
Termočlánky	**Kovové odporové snímače**	**Polovodičové odporové snímače (termistory)**	**Infračervené snímače**
Statická charakteristika			
			
Vyhodnocuje sa			
• napäťový výstupný signál	• zmena odporu snímača	• zmena odporu snímača	• napäťový alebo prúdový výstupný signál
Výhody			
• vlastné napájanie • jednoduché • robustné • lacné • široká paleta vyhotovení • veľký teplotný rozsah	• najstabilnejšie • najpresnejšie • lineárnejšie ako termočlánky	• veľký výstupný signál • rýchle • dvojvodičové meranie odporu	• najlineárnejšie • najväčší výstupný signál • lacné
Nevýhody			
• nelineárne • nízke napätie • vyžaduje sa referenčná hodnota teploty • najmenej stabilné • najmenej citlivé	• drahé • vyžaduje sa prúdový zdroj • malá zmena odporu v závislosti od teploty • malý merný odpor • zohrievajú sa	• nelineárne • obmedzený teplotný rozsah • krehké • vyžaduje sa prúdový zdroj • zohrievajú sa	• vyžaduje sa zdroj napätia • pomalé • zohrievajú sa • obmedzené množstvo vyhotovení

Table 11.1 Key characteristics of temperature sensors

? THEORETICAL CONTROL QUESTIONS

1. (2 pts) What does the International Temperature Scale ITS-90 define?
2. (2 points) Explain the concept of a triple point.
3. (5 pts) What is the basic division of temperature sensors.
4. (4 pts) For which temperature range are each sensor suitable?
5. (4 pts) What are the static and dynamic properties of temperature sensors?
6. (2 pts) Which material is most suitable for metal temperature sensors and why?

7. (3 pts) Which semiconductor temperature sensors do you know, what are their characteristics?
8. (2 pts) What are monolithic temperature sensors based on?
9. (6 pts) Describe the measuring circuit with thermoelectric cells, what are their basic types?
10. (6 pts) Describe the basic principles of special temperature sensors.
11. (2 pts) What are the advantages and disadvantages of non-contact temperature measurement?
12. (2 pts) Name and briefly describe the basic thermal imaging systems.

SUMMARY

New findings:

- temperature sensors
- individual types of temperature sensors
- Physical principles of temperature sensors
- temperature measuring chain
- the advantages and disadvantages of individual sensors and measuring circuits

New concepts:

thermodynamic temperature, temperature sensor, thermocouple, touch and non-contact temperature measurement, thermovision

KEY TO THEORETICAL QUESTIONS

1. Chapter 1
2. Fig. 1.1
3. Chapter 2, Fig. 2.1
4. Chapter 2, Table 2.1
5. Chapters 2.1, 2.2
6. Chapter 3, Fig. 3.1
7. Chapter 4
8. Chapter 5
9. Chapter 6, Fig. 6.2, Fig. 6.4
10. Chapter 7
11. Chapter 8
12. Chapter 8.2

AUTOCONTROL

If you have earned at least 20 points, you can continue your studies. Otherwise, review the chapter thoroughly.

LEARNING OBJECTIVES

After studying:

- Understand the concept of thermal comfort and the influences that contribute to it.
- You will know the different heating methods.
- You will learn how to assess and calculate heat loss.
- You will understand the different methods of electric heating.
- You will learn about the basic heating control options.

KEYWORDS

thermal comfort, heat loss, storage heating, hybrid heating.

ELECTRIC HEATING

TIME NEEDED TO STUDY

240 minutes

12. INTRODUCTION

Electricity, as in most other countries, will be used for heating, especially in suburban and rural areas where there is no CHP and gas and because of its absolute ecological purity at the point of consumption it has an irreplaceable role, e.g. in unventilated boiler rooms and mountain areas.

A properly designed direct-fired heating system has the lowest losses , is the best and fastest to control and has the lowest installed power, but loads the grid for up to 20 hours. Accumulation systems, on the other hand, have a power input 2 to 3 times higher, but the operating time is only 8 hours per day. Combined systems are therefore the most advantageous.

The limiting factor must be the satisfactory thermal insulation properties of the heated buildings. And the thermal technical properties of existing buildings in particular usually do not suit the use of such noble energy.

In the Czech Republic in 1999 there were 353 870 fully electrified points of consumption, i.e. 8%. From a macroeconomic point of view, the number is relatively small. The total of 5,452 GWh consumed represents 24.4% of all consumption from the LV network. The average consumption per fully electrified point of consumption was 15 406 kWh.

These facts show that, even though we are behind the peak of the curve in the number of direct connection heaters, the development of heating and hot water production by electricity must be directed and controlled. The most optimal way is to complement the direct heating and storage systems so that the grid is used efficiently throughout the 24 hours.

On the basis of the above data, it is possible to consider 10% of households and holiday homes using electricity for heating and DHW. There is therefore room for about 60 000 new users of electricity heating. In view of the energy price adjustments under consideration, there will be a decline in interest in electric heating, which will always be slightly more expensive than other heating media, but more comfortable.

Different European countries have different targets for electricity heating. These are mainly based on the different structure of primary energy sources.

In general, electric heating is not promoted where oil and natural gas have a significant share in electricity generation. Conversely, where nuclear power is developing or coal is a major primary energy source, it is advantageous to replace coal heating with electricity in certain areas. The shape of the electricity grid and its renewal also have a fundamental influence on the development of electric heating. The management of electricity consumption for heating purposes is then linked either to storage appliances or to interruptions of supply at times of energy peaks. The HDO system is generally a prerequisite for successful and, above all, flexible demand management. Another non-negligible fact is the requirements for the design of heating systems.

The measurements made so far show that if semi-continuous heating is used (with consistently applied automatic control), costs are reduced by 10 to 25% compared to direct-fired heating.

There are many other options and ways to use electricity efficiently. Switching to green heating has been and is of great importance for the environment. There are a number of very efficient ways to use electricity sparingly for heating and hot water.

12.1 Issues of human thermal comfort in the room

The main task of heating is to ensure favourable thermal conditions in closed rooms during the cold winter period, when the outside temperature is lower than the desired room temperature and when other weather influences (e.g. wind) cause the rooms to cool down. It is about ensuring so-called **thermal comfort**. This means that thermal conditions must be achieved in such a way that people feel comfortable.

A person's thermal comfort is influenced by their health, age, and the type of activity they perform. The feeling of good thermal comfort is basically determined by the balance of the thermal regime of a person, necessary to maintain a constant body temperature of 37 °C. An important component of the human thermal regime is the sharing of heat from the body surface to the environment, which is governed by precise physical laws and can therefore be expressed mathematically.

During the metabolic transformations taking place in the human body, a certain amount of heat is released, which depends mainly on the intensity of physical exertion and the weight of the person. This heat must be dissipated into the environment. Thermal equilibrium, i.e. a state in which the environment removes as much heat from the human body as the person is currently producing, is therefore the first and essential prerequisite for thermal comfort. The human body is cooled by conduction, convection, radiation and, in addition, by evaporation of sweat and respiration. With little physical exertion, most of the heat is removed from the surface of the body by convection and radiation - dry cooling of the body.

Achieving thermal equilibrium during dry cooling, without excessive sweating, is the second prerequisite for human thermal comfort.

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

The thermal equilibrium condition can be expressed in general as follows:

$$Q_M = Q_V + Q_D + Q_K + Q_S \ (w) \qquad (12.1)$$

In equation (1.1):

Q_M .... heat produced by the human body
Q_V.......... heat dissipated by evaporation
Q_D.......... heat dissipated by respiration
Q_K.......... heat dissipated by convection (flow)
Q_S.......... heat dissipated by radiation

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

$$Q_M - Q_V - Q_D = \tau \cdot S \cdot (t_h - t_r) = Q_K + Q_S \ (w) \qquad (12.2)$$

where it is:

τ .... permeability of the garment ($W.m^{-2}.K^{-1}$)
S............ total body surface area
t_h............ body surface temperature

t_r ....temperature of the surface of the garment

12.1.1 Thermal state of the environment

Several factors determine the thermal sensations of people in closed rooms:

- Degree of physical exertion (internal heat production Q_M)
- Thermal insulation capacity of clothing (thermal transmittance)τ
- Ambient air temperature t_v
- effective temperature of surrounding surfaces t_p
- ambient humidity (relative humidity)
- air velocity

The factors t_v, t_p, humidity and air velocity characterise the thermal state of the environment, which is reflected in the resulting thermal effect of the environment on humans. However, we usually try to express the thermal state of the environment in a single, easily measurable quantity.

12.1.2 Room air temperature

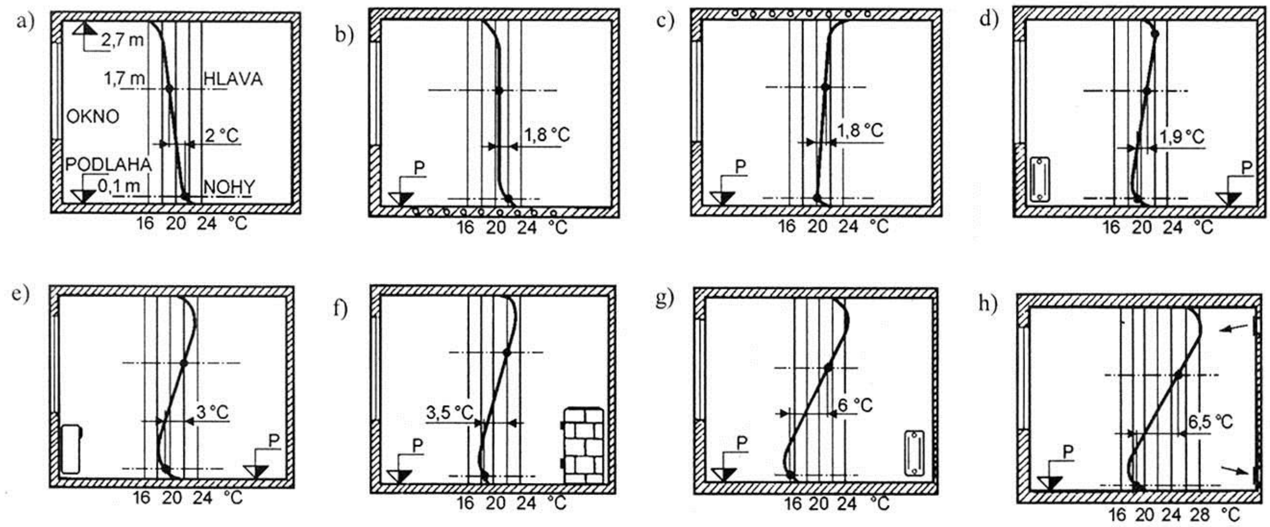
The air temperature t_v, measured in the area of human residence, is the main tool for assessing the thermal state. The air temperature can be considered a satisfactory measure of the thermal state of the environment where it is an environment of almost still air and where the temperature of the surrounding surfaces differs only slightly from the air temperature. In these circumstances, the air temperature also coincides with the resulting temperature t_i. The air temperature t_v is usually not the same throughout the room and therefore the local variation, the non-uniformity, must also be considered.

Vertical unevenness of air temperature in heated rooms is very important, which is caused by uneven heat supply and uneven cooling of individual walls, floors and ceilings of rooms. The vertical distribution of room temperatures for different heating methods is shown in Figure 12.1.

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

Ideal heating (Figure 12.1 a) is when the temperature at the foot level is approximately 21°C and at the head height of a standing person approximately 19°C. Thus, from the point of view of thermal comfort, the temperature difference between the head and foot areas should be no greater than 2.0 °C for a standing person and 1.5 °C for a seated person.

The respective temperature difference for the different heating methods is always indicated in Figure 12.1. From the figure it is clear that underfloor heating is the most advantageous in terms of vertical temperature distribution - Figure 12.1 b.



a) ideální vytápění

b) podlahové

c) stropní

d) teplovodní

e) konvektorové

f) lokální vytápění kachlovými kamny

g) teplovodní (radiátor na vnitřní stěně)

h) teplovzdušné

Fig. 12.1 Vertical distribution of room temperatures for different heating methods

12.1.3 Effective ambient temperature

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

$$t_p = \sum_{j=1}^{n} \varphi_j \cdot t_j \ (°C) \qquad (12.3)$$

where it is:

φ_j .... ratios of the area of the human body to the area of the surrounding surfaces

t_j .... temperatures of surrounding surfaces

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

12.1.4 Resulting room ambient temperature

If we start from the relation for thermal equilibrium expressed in terms of heat fluxes to the body surface S and use the simplification for the heat transfer coefficients by convection and radiation $\alpha_k = \alpha_s$ (for air flow velocities less than 0.3 m.s^{-1}), we obtain an equation of the form:

$$t_i = 0{,}5 \cdot t_v + 0{,}5 \cdot t_p \ (°C) \qquad (12.4)$$

It follows that the thermal comfort of a person depends only on the air temperature and the effective temperature of the surrounding surfaces for a given internal heat production and a given thermal transmittance of the garment. However, the ratio of the two temperatures t_v and t_p cannot be completely arbitrary. If the air temperature $t_{(v)}$ is assumed to be between 15 °C and 25 °C in rooms where a resulting temperature t_i = 18,5 °C and 21,5 °C is required, the effective temperature of the surrounding surfaces t_p may vary between 12 °C and 28 °C. This 'thermal comfort zone' is illustrated by the shading in Figure 1.2.

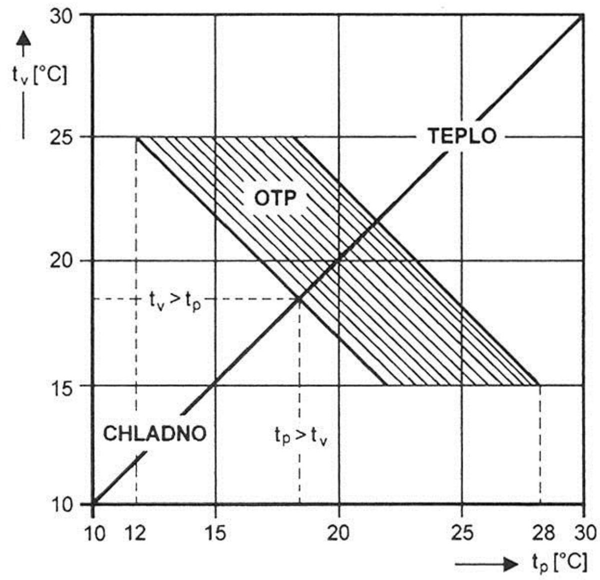


Fig. 12.2 Thermal comfort area

12.2 Heat transfer through the wall

If a wall of a certain thermal resistance separates a higher temperature environment from a lower temperature environment, heat is first transferred from the warmer environment to the separating wall. The surface of the wall heats up. Heat is then conducted through the wall and eventually heat is transferred from the cooled wall surface to the cooler environment. Together, these phenomena can be called heat transfer through the wall.

In the case of heat transfer through walls in room heating (heat transfer from rooms to the outside environment), in terms of the local distribution of the ambient temperature around the wall, this is heat transfer at constant ambient temperatures, in steady state. (See "Theoretical basis of heat transfer".)

13. PRACTICAL CALCULATION OF HEATING DEVICES

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

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

- A site plan showing the location of the building in relation to cardinal points, the height and distance of surrounding buildings, the elevation of the site and the prevailing wind direction and intensity
- Floor plans of each floor of the building with all main dimensions, including window and door dimensions, at a scale of at least 1:100
- Sections through the building indicating all main heights (clear and structural height of rooms, height of parapets, etc.)
- Data on materials and construction of walls, floors, ceilings and roofs for the determination or calculation of the heat transfer coefficient
- Data on the material and construction of windows and doors required for the calculation of heat loss through penetration and infiltration
- Room usage data for determining the internal temperature t_i
- Description of the intended method of heating individual rooms

13.1 General procedure for calculating heat losses

The total heat loss of a room Q_c according to ČSN 06 0210 is equal to the sum of the heat loss through walls Q_p and the heat loss through ventilation Q_v minus the permanent heat gains Q_z:

$$Q_c = Q_p + Q_v - Q_z \ (W) \qquad (13.1)$$

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

$$Q_p = Q_o \cdot (1 + p_1 + p_2 + p_3) \ (W) \qquad (13.2)$$

In equation (2.2):

Q_o.......... basic heat loss through heat transfer (W)
p_1........... allowance for compensating the effect of cold structures
p_2........... surcharge for acceleration of bay
p_3........... mark-up on the world side

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

$$Q_o = k_1 \cdot S_1 \cdot (t_i - t_{e1}) + k_2 \cdot S_2 \cdot (t_i - t_{e2}) + ... + k_n \cdot S_n \cdot (t_i - t_{en}) =$$

$$= \sum_{j=1}^{n} k_j \cdot S_j \cdot (t_i - t_{ej}) \, (W) \qquad (13.3)$$

In equation (2.3):

S_j .... cooled wall area (m^2)
k_j .... heat transfer coefficient ($W.m^{-2}.K^{-1}$)
t_i .... calculated internal temperature (°C)
t_{ej} .... temperature on the outside of the jth wall (°C)

If the temperature on the outside of one of the walls is higher than the temperature in the heated room, the heat flux through this wall is negative. In this case it is the heat gain Q_z which reduces the basic heat loss Q_o. Table (13.1) shows the values of the design internal temperature t_i for different room types:

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

Table 13.1 Values of the calculated internal temperature t_i

The cold wall allowance p_1 allows the indoor air temperature to be increased so that the desired indoor temperature t_i, for which the basic heat loss is calculated, is achieved in the heated room at the lower surface temperature $t_{(p)}$ of the cooled walls. This allowance depends on the average heat transfer coefficient of all the walls of the room k_c, which can be expressed by

$$k_c = \frac{Q_o}{\sum S \cdot (t_i - t_e)} \, (W \cdot m^{-2} \cdot K^{-1}) \qquad (13.4)$$

where it is:

ΣS .... total area of all structures enclosing the heated room (m^2)
$t_{(e}$ .... design outdoor temperature for a certain area given by the standard (table in ČSN 06 0210)

The surcharge to compensate for the effect of cold structures p_1 can then be determined from the relation $p_1 \approx 0.15.k_c$ or approximately determined from the following table:

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

Table 13.2 Compensation for the influence of cold structures

The surcharge for acceleration of the flooding p_2 is only taken into account in residential construction, hospitals, etc. in cases where uninterrupted heating operation cannot be ensured even at the lowest outside temperatures. Normally, the p_2 surcharge is not taken into account. For intermittent operation, it is selected according to the heating period as follows:

- $p_2 = 0.1$ for daily heating times longer than 16 hours
- $p_2 = 0.2$ for daily heating time less than 16 hours

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

St. p.	J	JZ	Z	SZ	S	SV	V	JV
p_3	-0,05	0	0	0,05	0,1	0,05	0,05	0

Table 13.3 Balancing the influence of the world side

The ventilation heat loss Q_v expresses the heat loss due to natural ventilation by infiltration or forced ventilation by negative pressure and is calculated from the relation:

$$Q_v = c_v \cdot V_v \cdot (t_i - t_e)\ (W) \qquad (13.5)$$

where it is:

$c_{(v}$ .... volumetric heat capacity of air at 0 °C,
$c_v = 1300$ J.m^{-3}.K^{-1}

$V_{(v}$.......... volumetric ventilation air flow (m^3.s^{-1})

The volume flow rate of the ventilation air of the space V_v must be based on hygienic or technological requirements. These requirements are given by the required air exchange rate n_h (h^{-1}) in the room. The larger of the ventilation air volume flow rates is then substituted after V_v in the equation for calculating the ventilation heat loss. This is either the case for forced ventilation, where we calculate according to Eq:

$$V_{vH} = \frac{n_h}{3600} \cdot V_m\ (m^3 \cdot s^{-1}) \qquad (13.6)$$

$V_{(m}$ .... internal volume of the space (room) (m^3)

or in the case of natural ventilation by infiltration through window and door joints:

$$V_{vP} = \sum (i_{LV} \cdot L) \cdot B \cdot M \; (m^3 \cdot s^{-1}) \qquad (13.7)$$

In equation (1.19):

$\Sigma(i_{LV}.L)$ ... the sum of the air permeability of the windows and external doors of the room ($m^3.s^{-1}.Pa^{-0,67}$)

i_{LV} .... coefficient of joint aeration ($m^3.s^{-1}/m.Pa^{0,67}$)

L .... length of joints of opening parts of windows and external doors (m)

B............ building characteristic number ($Pa^{0,67}$)

M .... characteristic room number (-)

The values of the coefficient of air permeability i_{LV} of windows and external doors are given in ČSN 73 0540-3. The total joint length L is calculated from the nominal dimensions of windows and doors. This takes into account the joints between each sash and the frame (including centre mullions) and the joints between two adjacent sashes. The building characteristic number B expresses the effect of wind on the infiltration rate. It depends on the location of the building in the landscape (sheltered, unprotected or very unfavourable position) and on the type of building (terraced and detached buildings).

According to the prevailing wind speeds, a distinction is made between normal and high winds (see EN 06 0210). The characteristic number of a room M depends on the ratio between the air permeability of the windows and the internal doors. The following possible cases are distinguished:

- rooms where the ventilation rate of the inner door is less than the ventilation rate of the window (M = 0,4)
- rooms where the ventilation of the inner door is greater than the air permeability of the windows (M = 0,7)
- rooms without internal walls, e.g. large offices, halls, etc. (M = 1,0)
- rooms where the internal door air permeability is approximately the same as the window air permeability (M = 0.5)

As can be seen, the calculation of heat loss of buildings according to ČSN 06 0210 is quite complex. For a preliminary estimation of heat losses, when deciding on the heating method, we are satisfied with the approximate determination of heat losses according to the table on the following page. Table (2.4) gives the heat loss per 1 m^3 of heated space. The total heat loss of the building is then equal to the sum of the heat losses of the individual rooms.

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

Table 13.4 Approximate determination of heat losses

13.2 Calculation of heating input

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

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

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

13.2.1 Direct electric heating

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

$$P_k = Q_c \cdot K \cdot 10^{-3} \; (kW) \tag{13.8}$$

where it is:

$Q_{(c}$ .... total heat loss of the building (W)

K .... coefficient of the heating process, the value is selected:

.... 1.0 - for uninterrupted operation,

.... 1,1 - for heating break up to 4 hours

.... 1,2 - for breaks longer than 4 hours

.... 1.4 - for occasional use

13.2.2 Accumulation electric heating

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

The input power of the storage heat source can be determined from the total daily heat demand Qd, the size of which depends on the total hourly heat loss Qc, the required heating time to full temperature Tv and the damped heating time Tt. The heating time Tv includes the ramp-up time to the desired temperature. The electrical input sizing is the same for continuous and staggered charging times Tn = 8 hours

The operating modes of heating for the calculation of the input power of the heat source are determined from the full heating time Tv to ti = 20 °C. Storage heating is designed for the operating mode given by the time Tv (h):

- kitchens 10 h
- kitchen with dining room 12 h
- living rooms 14 h
- children's rooms 14 h
- other rooms 12 h

The sizing of storage heaters is carried out according to the following relation:

$$P_a = Q_d \cdot k_v \cdot 10^{-3} \; (kW) \tag{13.9}$$

where it is:

P_a .... power input of the storage heater (stove) (kW)

$k_{(v}$ .... coefficient of operation (h^{-1})

Daily heat demand:

$$Q_d = Q_c \cdot T_v \; (W \cdot h) \tag{13.10}$$

Electric central storage heating is proposed for full heating for 12 hours. The remaining daytime operation is either dimmed or intermittent. The total daily heat demand Q_d for hot water systems is determined by the following formula:

$$Q_d = Q_{dd} + Q_{dn} \; (W \cdot h) \tag{13.11}$$

$$Q_{dd} = \frac{Q_c}{\eta} \cdot (T_{vd} + T_{td} \cdot f)\,(W \cdot h) \qquad (13.12)$$

$$Q_{dn} = \frac{Q_c}{\eta} \cdot (T_{vn} + T_{tn} \cdot f)\,(W \cdot h) \qquad (13.13)$$

In equations (2.11), (2.12), (2.13), is:

- Q(dd........heat demand during the day (W.h)
- Q(dn........night time heat demand (W.h)
- T(vd.........required heating time to full temperature in day time (h)
- T(vn.........required heating time to full temperature during night time (h)
- T(td ....required time of damped heating in day time (h)
- T(tn ....required time of damped heating during night time (h)
- f ....coefficient of influence of the building structure, considered equal to 0.3 for heavy, 0.4 for medium and 0.5 for light construction
- η ....heating efficiency,η = 0.95

The required input power is then determined from the formula:

$$P_a = \frac{Q_d}{T_n} \cdot 10^{-3}\,(kW) \qquad (13.14)$$

13.2.3 Mixed (hybrid) electric heating

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

Mixed heating allows more electric heating equipment to be connected to the existing grid, as the consumption rate is lower than for pure storage heating. It is also important to reduce the size of the equipment and thus the acquisition costs. The design of the electric hybrid heater is carried out separately for the storage part and the direct heating part.

$$P_h = 0{,}6 \cdot P_a\,(kW) \qquad (13.15)$$

Where:

- P(h..........hybrid heater power input (kW)
- P(a..........power input of the storage heater calculated according to the relation for storage heaters and for a charging time Tn = 8 hours (kW)

The direct heating part of the hybrid heater is determined according to the relation:

$$P_{ph} = 0{,}4 \cdot P_a\,(kW) \qquad (13.16)$$

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

higher than the heat loss of the room and shall be equal to about half of the input power of a pure storage source with an eight-hour charging period.

14. ELECTRIC HEATING SYSTEMS

The irregularity of daily consumption, resulting from the normal rhythm of human life, has led to efforts to use the available power plant capacity during off-peak periods. This made possible the introduction of storage appliances for heating or hot water, which were switched on only at night.

However, further developments have shown that with only storage heat the possibilities of the electricity system would soon be exhausted, and therefore today the electricity industry also offers direct heating and hybrid systems. Everywhere in the world, the use of electricity for heating is one of the most economically challenging options. However, this cost is completely offset by the characteristics of electric systems:

- high reliability of the heating system,
- perfect controllability (automatic regulation allows precise compliance with the heat regime according to the set program)
- virtually l00% efficiency
- unambiguous measurability of the energy consumed by the customer
- minimal space and maintenance requirements
- the possibility to design the heating system exactly according to the heating needs of the interior thanks to the variability of electric heating systems
- completely noiseless operation (electric boilers can be placed directly in the heated interior without any problems)
- completely clean, environmentally friendly operation (taking into account the environmental pollution only at the point where the electric heating system is directly located)
- high cleanliness of operation (does not require laborious and dirty handling, such as with coal heating)
- an important economic aspect is the relatively low cost of 1 kWh of heat produced

The advantages of electric heating over other possible methods are clearly visible from the above overview. Electric heating is considered to be the cleanest and most comfortable form of creating thermal comfort in enclosed spaces, including residential spaces.

None of the other forms of energy offers such a flexible and controllable heat flow into the room, exactly matching its heat loss and the desired internal temperature. In some locations in the Czech Republic, heating with electricity is the only way to solve the heating problem. These are mainly localities and buildings where it is not possible to count on heat supply by district distribution from heating plants and heating towers, where there is no natural gas distribution yet and where it will be necessary to replace the existing heating with solid and liquid fuels. Depending on the location of the heat source, electric heating systems can be divided into:

- **LOCAL (local)**, where the electric heating appliance is located directly in the respective heated space

- **CENTRAL (central)**, where the heat source is located outside or in one of the heated spaces and supplies heat to several other spaces or buildings

The following systems or appliances are distinguished according to the timing of electricity consumption from the grid and its conversion into heat:

- **ACCUMULATIVE**, in which electrical energy is converted into heat, which is stored in a suitable storage material. The heat is then released spontaneously or in a controlled manner, mainly in the period following charging.
- **PRIMARY**, in which the electrical energy is converted into heat immediately emitted into the heated room
- **MIXED**, in which the conversion of electricity into thermal energy is partly by means of accumulation and partly by means of direct heating

14.1 Accumulation electric heating

This method of heating uses electricity consumption at selected, usually night-time hours (charging from 10 pm to 6 am) and, in justified cases, at selected times of the day (charging after 2 hours or more). The electricity is converted into heat in resistance heating cells or cables that are stored in a storage material. This is in the form of a heater, boiler or is a concrete part of a building structure, usually a floor.

Heating requires a reliable knowledge of the heating time T_v to the calculated internal temperature t_i, which includes the so called ramp-up time to full temperature and the damped heating time T_t. There are several possible ways to use the el. accumulation heating. Magnesite and fireclay are generally used as accumulation materials. Three types of storage heaters are distinguished according to their design and the way in which the heat is shared in the heating of the rooms (discharge of the heater), as shown in Figure 14.1.

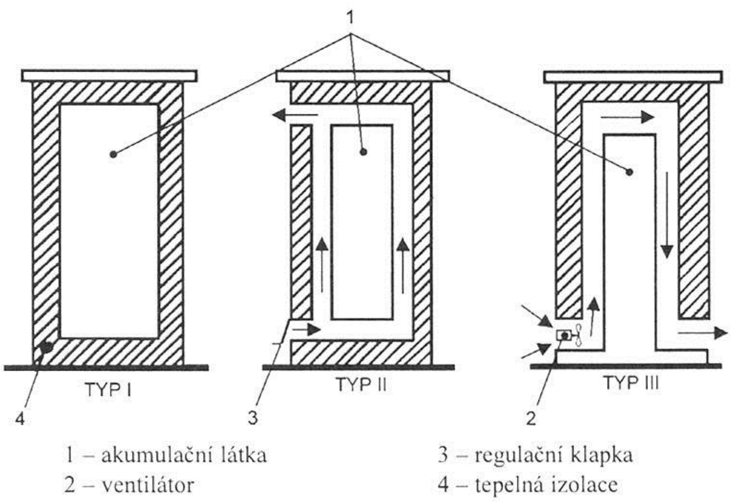


Fig. 14.1 Basic types of storage heaters

14.1.1 Version I

The first type of heater is characterized by heat sharing only from the top of the heater shell. The discharge of the heater is natural or static, and the heat release cannot be controlled once the charging is complete. Heat is shared exclusively by radiation from the surface of the heater and natural convection from the surface. An example is the **Ideal** storage heater**.** The accumulation core is composed of fireclay blocks in which the heating blocks are embedded. The accumulation core is covered with a cladding of glazed tiles. The heat is released immediately when charging through the shell in proportion to the core temperature. These heaters therefore give off the most heat after charging, i.e. in the morning, and the least in the evening**.** They are therefore not recommended for heating living rooms, although satisfactory results are obtained in special cases.

14.1.2 Version II

The heater transfers heat to the rooms mainly through the surface of the shell, radiation and convection. In addition, part of the heat is emitted by controlled heating of the air that flows through the heat channels in the accumulation core. The heat release after charging is therefore partly controlled by the closing or opening of the vent by the space thermostat.

An example is the **Ideal FVS** heater. It differs in design from a heater with static discharge by air channels in the core and partial discharge control. The cool air is fed through a damper into the fireclay core and flows upwards through two channels. The common duct leads downwards.

At the lowest point, the heated air enters a steel outlet from which it exits into the mixing space at the top of the stove. It mixes with the cool air supplied through the openings under the stove along the front wall. The heater is suitable for living rooms with small accumulation properties (all day).

14.1.3 Version III

Heaters where the heat output is controlled automatically according to the internal temperature of the room after charging is complete. The storage core is perfectly insulated. The shell is usually sheet metal, with very low surface temperatures. The heat is primarily discharged (dynamically) by driving air through the fan channels in the core. About 75% of the heat is released in this way. The operation of the fan, usually two-speed, is controlled by a room thermostat. Two types of these heaters are produced here under the name **Fikoterm** and the stove marked **AD (R B).**

Dynamic storage heaters are preferably used for heating apartments and family houses because of their flexible controllable heat output and the fast heat input caused by hot air heating. These features allow very economical heating while maximising internal and external heat gains.

The Fikoterm E consists of an accumulation core, heating resistance rods, fan, insulation, jacket and electrical and control equipment. The accumulation block consists of magnesite blocks with vents for the passage of air driven by the fan during discharge and for the insertion of the heating rods. The construction of the heater is modular. The stove is equipped with a bimetallic controller for the regulation of the outlet air temperature, a two-speed controller controlled by a room thermostat according to the set internal temperature. They allow the connection of an automatic charging device and bulk remote control.

The accumulation core is protected against overheating by a thermal fuse. Unless an automatic charging control is fitted, the heater charging is controlled by a thermostat within the range of the heat capacity of the stove from 35 to 100 %.

14.2 Convection electric heating

CONVECTORS are electric heaters that convert all the electricity supplied into heat. Cold air enters the convector from the lower part, heated air leaves the upper part, and the heated air heats the whole room by natural circulation (Fig. 3.1).

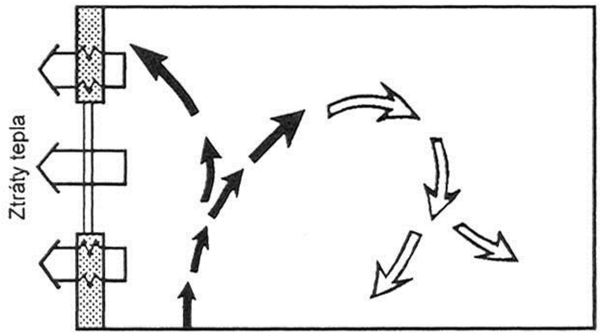


Fig. 14.1 The principle of convection electric heating

Natural convection heaters are mobile, portable or designed for fixed installation on the wall. They are either radiators with a heated cartridge, usually oil, or convector heaters with heating resistance. These are usually tubular stainless steel heating elements with pressed aluminium fins, adapted for quiet operation. The ambient air is heated by natural convection around the heating element.

Modern convectors are equipped with a quality control system with the possibility of central control of their operation. Forced convection heaters are portable or wall-mounted direct-heating appliances in which air is blown past the heating resistances with the help of a fan. The advantages of heating with electric convector heaters include:

- fast room heating with respect to heat gains (glare, large number of people, etc.)
- maximum use of electrical energy for heating the room
- precise compliance with the required room temperature
- simplicity
- automatic operation with the possibility of time programming

14.3 Underfloor heating with heating cables

Large-scale floor systems made by pouring special electric heating cables into the concrete floor are shown in Fig. 14.2.

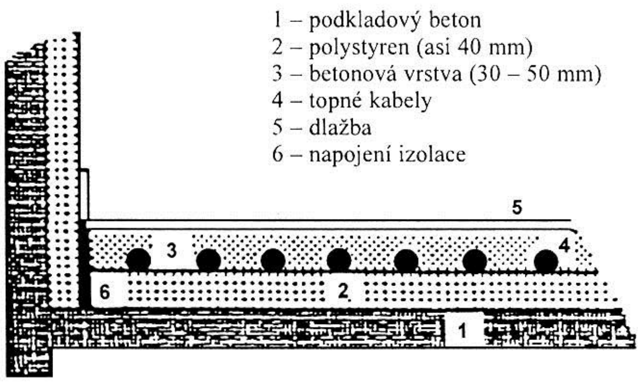


Fig. 14.2 Large-scale floor systems

They are popular mainly because of their high efficiency, even heat distribution over the whole area, excellent use of the heated space, relatively easy implementation and creation of thermal comfort at lower air temperature than e.g. with convectors.

But it must be taken into account that:
- Concrete heating floor has a high inertia and consequently less controllability and a longer rise time to the desired room temperature
- the temperature of the floor surface in the living area may not exceed the values specified in EN 06 5210, which means that the mean surface temperature should not exceed 26 to 28 °C
- the temperature limitation of the floor surface limits the heating capacity, therefore in buildings with higher heat losses or in rooms with a small usable floor area (e.g. in bathrooms) it is necessary to supplement the heating floor with an additional heat source

Heating floors are thermally insulated from the subfloor and side walls, the surface temperature is monitored by an electronic controller.

14.4 Radiant electric heating

While in convection heating the body is heated mainly by air, which transfers heat as it flows over the surface of the heated object, in radiant heating the heat is transferred mainly by radiation (Figure 3.3)

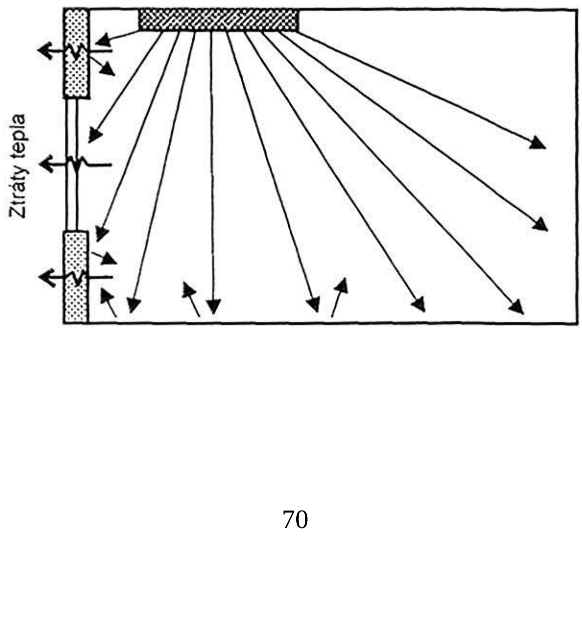


Fig. 14.3 Radiant heating

Every body radiates electromagnetic energy into its surroundings. Of the wide range of wavelengths, we are interested only in those that can be absorbed by objects and converted into thermal energy. Radiant heaters can be infrared emitters whose heating element has a surface temperature greater than 250 °C and whose radiation is directed by a reflector in a specified direction.

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

However, there are hygiene limitations caused by the ability of humans to tolerate only a certain degree of radiation. Experiments have found that the absorption of the human body is 99%, that is, high utilization of radiated heat from objects. The most favourable wavelengths for humans are between 7.5 and 10 m.μ

The radiant flux is partially reflected (about 15%) when it hits the objects, but most of it (85%) is absorbed by the objects it hits. Here, the energy of the radiation is converted into thermal energy and the objects are heated. The air is heated away from the heated objects. The advantages of radiant heating, whether it is heating by radiant panels or heating foils on the ceiling or walls, can be summarised as follows:

- for objects heated by radiant flow to 20 to 22 °C, thermal comfort can be ensured at air temperatures of 18 to 19 °C
- very even temperature distribution in the vertical profile can be achieved (1 to 2 °C difference between floor and ceiling)
- very good control and program control
- energy savings compared to convection heating range from 18 to 24%.

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

14.5 Electrode heaters (electrode boilers)

Many different designs of electrode boilers are used. They are constructed not only for 230 and 400 V, but also for high voltages up to 35 kV. The electrodes can be plate or bar, fixed or convertible tubular. In Sweden and Norway, for example, electrode boilers are being built for up to 100 MW for a three-phase 35 kV system.

Well-made electrode water heaters are very economical in every respect. They are small, simple in design, trouble-free and inexpensive. Boilers of larger outputs above 300 kW in the "classic" resistance version can hardly compete with electrode boilers, both in technological and economic terms. The output of an electrode system at a given voltage, e.g. 400 V, can be controlled in the following ways:

- by adjusting the water conductivity
- electrode flatness (covering with insulating sleeves, shortening, lengthening)
- by zooming in and out of the electrodes
- by inserting insulating baffles between the electrodes

- by dividing the electrodes into groups that are switched and reconnected in different ways
- mechanical immersion and surfacing of electrodes
- by changing the water level in the boiler using a pump with fixed electrodes suspended from above

Electrodes used in low power electrode devices can be made of graphite. The electrodes used in high power devices, which include electrode boilers for heating rooms and buildings, are made of metallic materials, especially hardened steels. These are therefore relatively very cheap materials produced domestically. The advantages of electrode boilers used for heating apartments and rooms, compared to conventional resistance boilers, include:
Simplicity, cheapness, durability and reliability.

Heating elements made of expensive imported heating materials with limited service life are completely eliminated. Electrodes are cheap, easy to make and replace. The lifetime of well-made electrodes approaches that of all other heating equipment. Electrode lifetimes of 20 years or more are known

The electromagnetic field inside the electrode chamber is of sufficient intensity to induce a magnetic treatment effect on the circulating water, so that crystalline deposits cannot form on the inner walls. On the contrary, the deposits formed by the previous operation dissolve in a short time. This improves not only the flow rate in the pipework, but above all the thermal efficiency of the heating elements.

14.5.1 Maximum possible energy efficiency of the boiler

Electricity is converted into heat directly in the heated water. At the highest surface temperature of the electrode boiler jacket of 30 °C, the radiation loss through the boiler insulation is approximately 25 W for a 25 kW boiler.

15. ISSUES OF AUTOMATIC HEATING CONTROL

The purpose of automatic control is to maintain a physical variable subject to change at a desired value without human intervention. In room heating, this variable is usually the internal temperature of the room. Maintaining the variable at the desired value can be achieved as follows:
- By measuring the actual value of the regulated variable (in this case temperature)
- By comparing the measured actual value with the desired (set) value
- Acting on the controlled variable (temperature or water flow) to reduce the difference detected

For the design of the control device it is necessary to know:
- User requirements
- Basic characteristics of the building structure and heating system
- Applicable regulations

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

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

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

Selected response times of the heating system:

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

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

15.1 Control circuits

The control device consists of the following parts:

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

There are several basic types of control circuits:

15.1.1 Closed control circuit

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

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

15.1.2 *Closed feedback control circuit*

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

15.1.3 *Open control circuit*

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

The whole control process is carried out according to the determined dependencies set in the controller and the accuracy and stability of the control depends on how accurately the dependencies have been determined and set.

EXAMPLES

Example 1

Determine the heat loss of a heated room with wall area S = 100 m^2. The heat loss through the ceiling and floor is zero (the room above and below is heated to the same temperature). Indoor temperature t_i = 21 ^{o}C and outdoor temperature t_e = -15 ^{o}C.

- a) Brick wall made of solid bricks 450 mm thick with lime plasters with thermal resistance of the structure R_1 = 0,520 m^{2}K/W.
- b) After thermal insulation on the outside of the wall - polystyrene 40 mm + perlite plaster 10 mm with thermal resistance R_2 = 1,2 m^{2}K/W.

Solution:

a)
Determine the heat transfer coefficient:

$$k_a = \frac{1}{0{,}168 + R} \qquad (1{,}453\ \mathrm{W.K/m^{(2)}})$$

The heat loss through the wall is:

$$Q = k \cdot S \cdot \Delta t \qquad (5230,8\ \text{W})$$

b)
Determine the heat transfer coefficient after additional thermal insulation:

$$k_a = \frac{1}{0{,}168 + R} \qquad (0.53\ \text{W.K/m}^{(2)})$$

The heat loss through the wall after thermal insulation is:

$$Q = k \cdot S \cdot \Delta t \qquad (1908\ \text{W})$$

The heat loss will be reduced by more than 60% after the additional thermal insulation.

Example 2

For Example 1, after additional thermal insulation, design the power input of the direct electric heating system. Choose the heating process.

Solution:

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

$$P_k = Q_{(c)} \,.\, K \,.\, 10^{-3} \qquad (\text{kW})$$

Where: Q_c total heat loss of the building [W]
K coefficient of the heating process, the value is selected:
- 1,0 uninterrupted operation
- 1,1 heating break up to 4 hours
- 1,2 break longer than 4 hours
- 1,4 with occasional use

We choose a heating mode with a break longer than 4 hours, i.e. coefficient K = 1.2.

$$P_k = Q_{(c)} \,.\, K \,.\, 10^{-3} \qquad (2.29\ \text{kW})$$

The actual installed input power of the heater may be higher than the calculated total input power by a maximum of 20% (according to ČSN).

? THEORETICAL CONTROL QUESTIONS

1. (2 points) Explain the term "thermal comfort"
2. (3 pts) What is the ideal temperature distribution in a living room? What does the vertical temperature distribution look like for different types of heating?

3. (4 pts) State the procedure for calculating heat loss.
4. (4 pts) Characterize the basic types of electric heating.
5. (2 pts) What are the advantages of electric storage heating?
6. (5 pts) Describe the basic methods of controlling electric heating.

SUMMARY

New findings:

- thermal comfort and what affects it
- basic types of electric heating
- electrode water heating
- calculation of heat losses
- heating regulation

New concepts:

thermal comfort, heat loss, heating, heating control.

KEY TO THEORETICAL QUESTIONS

1. Chapter 1.1
2. Chapter 1.1.2, Fig. 1.1
3. Chapter 2.1
4. Chapters 2.2.1 - 2.2.3
5. Chapter 3.1
6. Chapter 4

AUTOCONTROL

If you have scored at least 10 points in the theory questions, you can continue your studies. Otherwise, repeat the chapter in a shorter time.

LEARNING OBJECTIVES

After studying:

- You will understand the issue of reducing the energy consumption of your home.
- You will get acquainted with the possibilities of house insulation.
- You will understand the relationship between heating and ventilation.
- You will be able to decide under what conditions it is worth renovating your house, which heat source is the most advantageous under the given conditions and how to save money.
- You will understand the economics - ecology relationship in heating.

ENERGY SAVINGS, ECONOMY AND

KEYWORDS

heat loss, insulation, infiltration, heat pump, solar systems, regulation, emissions.

TIME NEEDED TO STUDY

240 minutes

Text to read

16. ENERGY SAVINGS IN THE HOUSE

Energy savings are quite often associated with home renovation, so they can also bring an increase in comfort or living standards. Almost invariably, the environmental burden is also reduced. However, because energy is never free, we expect energy savings to come with financial savings. It is important to be clear about what energy savings entail and entail.

Much, if not most, of the energy we use in our lifetime is related to housing. Because we think of the money for this energy more as the price of living, we may not be as aware of it as we are of the money for petrol for a car.

We use the energy we consume in our homes for the following three main purposes:
- for heating,
- water heating and
- operation of household appliances.

The last category includes mainly lighting, cooking, washing, cooling, ironing and running electronics.

Each house has a different energy consumption for heating, which is mainly determined by its construction. It depends on the insulating capacity of the envelope as well as the shape and size of the building. This can be clearly seen in a block of flats, where most flats lose heat through only one external wall, while the other walls are adjacent to other flats or corridors. In contrast, a detached house loses heat through all the walls, floor and roof. Another example is a very well insulated low-energy house, where less than half the energy escapes through the envelope compared to an older house of the same size (Figure 1.1).

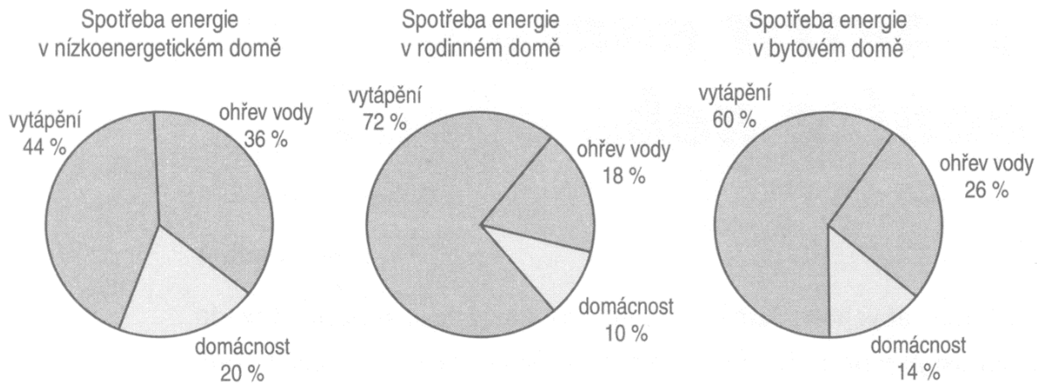


Fig. 16.1 Approximate consumption patterns in different houses

The energy consumption for the operation of household appliances is mainly influenced by their technical maturity and efficiency of design.

The breakdown of energy consumption by purpose is important mainly because each part of the consumption can be covered by a different energy, with a different price and a different environmental impact. We mainly need electricity to run our households, although we can use gas or wood for cooking, for example. We can either heat water with electricity (night-time electricity is popularly used, as it is more cost-effective) or with the same fuel used for heating. In practice, this can be a so-called natural gas (or propane) combination boiler, which works all year round as a karma and also provides extra heating during the winter. If we want to heat with coal or wood, we can use a so-called combination boiler, which is heated with water from the central heating during the heating season and with electricity (or solar) in the summer.

16.1 Energy price

Determining the true cost of energy, which would include the environmental impact, the impact on the health of the population, the reduction of fuel supplies for future generations or the cost of disposal of spent nuclear fuel, is very difficult. Experts all over the world are working on this and their results are not always comparable. It is clear, however, that if these so-called externalities were taken into account, the price of energy would be several times higher. For the sake of simplicity, we will therefore stick to the current fuel prices on the Czech market, even though they may not reflect the correct energy price. Currently, we can choose from many fuels of different quality and price. There are, of course, some limitations: in some places there is no natural gas, in others there is no sufficiently strong electricity connection (Table 16.1).

Fuel type	*Calorific value*	Price of fuel		*Permanent payme (CZK month)*	*Price of heat in fuel*		*Average Efficiency Use of fuel*	*Final heat price*	
					CZK/G	*CZK/kW*		CZK/G	*CZK/kW*
lignite	18,0 MJ/kg	1,49 CZK/kg			82,8	0,30	*55*	151	0,54
black coal	23,1 MJ/kg	2,19 CZK/kg			94,8	0,34	*55*	172	0,62
coke	27,5 MJ/kg	4,09 CZK/kg			148,7	0,54	62	240	0,86
firewood	14,6 MJ/kg	0,93 CZK/kg			63,7	0,23	75	85	0,31
wood briquettes	17,5 MJ/kg	3,50 CZK/kg			200,0	0,72	75	267	0,96
wood pellets	18,5 MJ/kg	3,60 CZK/kg			194,6	0,70	85	229	0,82
chipped	12,5 MJ/kg	2,80 CZK/kg			224,0	0,81	80	280	1,01
natural gas	34,1 MJ/m3	0,675 CZK/kWh		245	199,6	0,72	89	263	0,95
propane	46,6 MJ/kg	21,00 CZK/kg			450,6	1,62	89	506	1,82
TOEL light heating oil	42,0 MJ/kg	13,80 CZK/kg			328,6	1,18	89	369	1,33
		Low tariff	High tariff						
electricity accumulation	3,6 MJ/kWh	0,79	3,13	756	219,4	0,79	93	357	1,28
electricity straight heater	3.6 MJ/kWh	1.08	3.92	1 229	300.0	1.08	95	416	1.50
thermal pump vD55	3,6 MJ/kWh	0,98	3,92	504	272,2	0,98	300*)	123	0,44

Table 16.1 Fuel and heat prices (indicative)

Note: Actual prices, including acquisition costs, are listed in the Appendix.

16.2 How to save on heating

Before deciding where to start saving, it is therefore necessary to understand not only the flow of energy but also the flow of money. The graph in Figure 1.2 gives an example of a family house with different fuel mixes. But we do not build houses to heat them. However, we need heat inside. It is constantly escaping outside - unfortunately, this follows from the laws of physics. So we can either heat and heat, or we can slow down the heat leakage and heat less.

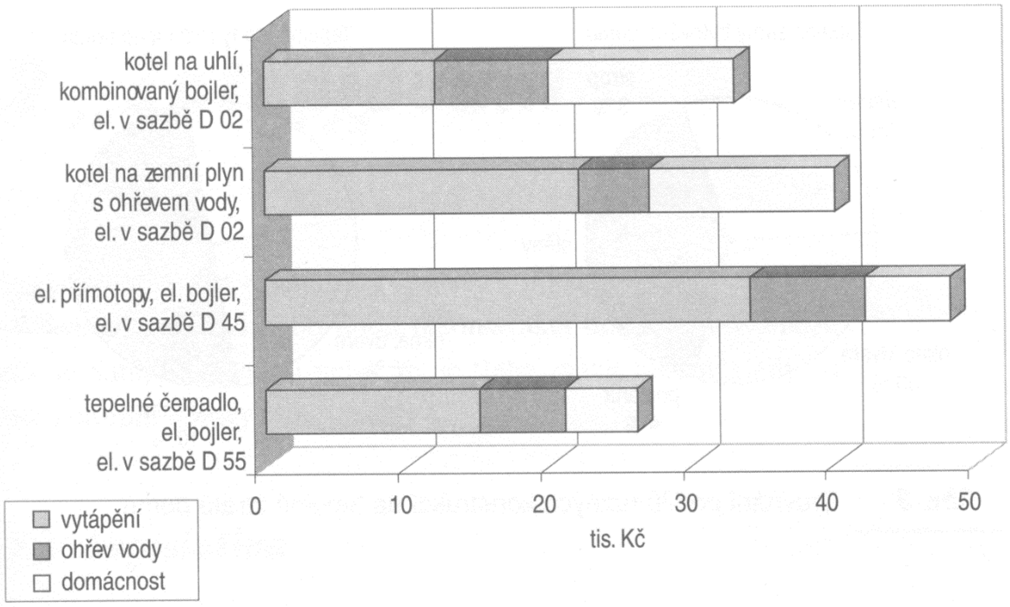


Fig. 16.2 Comparison of energy costs in a family house

Each of the losses shown in the graphs in Fig. 1.3 can be reduced in various ways. It is clear that the envelope is where the most heat escapes. At the same time, it is clear that the best wall insulation will not halve our heat bill. It is therefore advisable to carry out insulation in a comprehensive manner, taking into account not only the effect of insulation on the various structures, but also its cost.

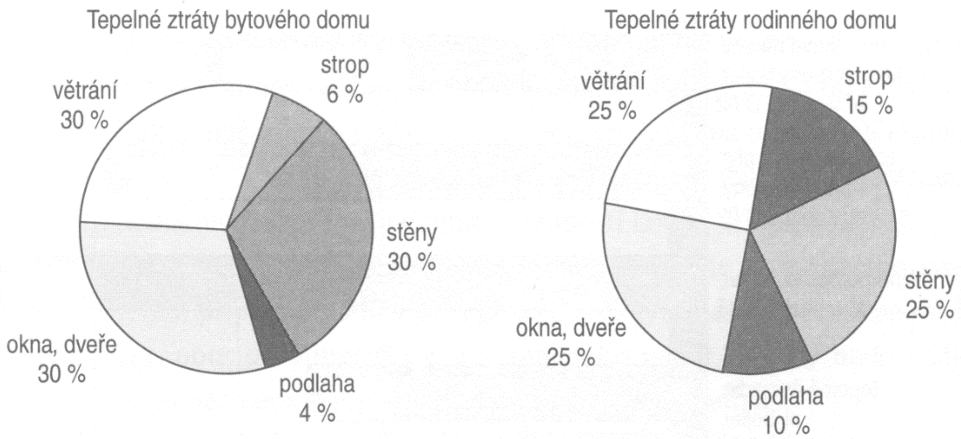


Fig. 16.3 Contribution of different structures to the heat loss of the house

It is tempting to look for savings in reducing heat loss through ventilation. Window sealing is cheap, but comes with big risks. When infiltration is reduced below a certain level, internal humidity can rise so much that it can lead to damage to the building. Restricting ventilation can also affect the health of the occupants of a house or flat *(see Chapter 4).* After any reduction in heat loss, the heating system, the performance of the heating elements and, above all, the controls need to be adjusted. Another option is to use a cheaper fuel, e.g. wood. The cost of replacing the boiler and modifying the heating system is an order of magnitude lower than the cost of insulation and window replacement.

We can combine the two options so that the energy and cost savings match our expectations.

17. INSULATION

Additional insulation of the house is usually associated with a new facade, roof, attic or other reconstruction of the house. When considering whether insulation is worthwhile or not, the cost of these building modifications should also be considered.

In addition to many other reasons, current regulations force us to insulate. The current Decree No. 291/2001 Coll. sets the maximum specific consumption that must not be exceeded by buildings and reconstructions financed from public funds. This applies in particular to buildings built by a municipality, town, regional authority or the state, but also to private houses if they are subsidised. Furthermore, the requirements of the ordinance also apply to completely private buildings and reconstructions. Additional insulation of a house is usually associated with a new façade, roof, attic or other renovation of the house. When considering whether or not insulation is worthwhile, the cost of these building modifications must also be considered.

In addition to many other reasons, current regulations force us to insulate. The current Decree No. 291/2001 Coll. sets the maximum specific consumption that must not be exceeded by buildings and reconstructions financed from public funds. These requirements also apply to private houses if they are subsidised. In addition, the requirements of the Decree also apply to entirely private construction and renovation of larger buildings with a consumption of more than 700 GJ per year, which mainly concerns prefabricated houses. Single-family houses and other private buildings consuming less than 700 GJ per year are not covered by the Decree. However, its requirements can be seen as a standard. Anyone planning to build or renovate a family house should require the designer to comply with the requirements of the decree. A simple guide can be the building's energy label (Fig. 17.1).

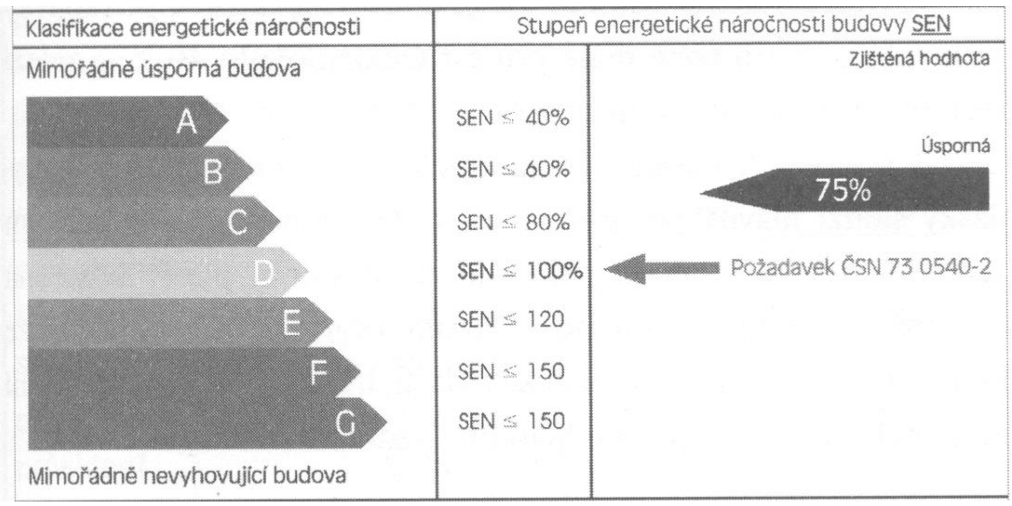


Fig. 2.1 Building energy label

Reconstruction of an older house that complies with the requirements of the standard should in itself bring savings of around 40%. However, it is good to remember that the consumption of houses determined according to the decree is mainly used to compare a particular house with a certain standard, and even then only in terms of the envelope. The actual consumption may differ very significantly from that determined in this way, if only because the house will be located in a warmer climate area, will have efficient heating or will use waste air heat.

17.1 Humidity in the house

Proper ventilation is the easiest and most effective way to get rid of the moisture that is inevitably created by people being inside. Moisture, like heat, always escapes from where there is more of it to where there is less of it - from the inside to the outside in winter. Cold winter air contains less moisture than warm indoor air. How moisture will penetrate the walls depends on what materials were used in the construction. Some materials such as glass, metals, most plastics and others do not let moisture through at all (they have a very high diffusion resistance). Porous materials such as bricks, wood, concrete, etc. are more easily permeable to moisture. These materials can also absorb a certain amount of moisture without problems and later release it back into the interior. This balances the climate in the room and contributes to the well-being of the occupants. However, if water vapour penetrates the structure in large quantities, condensation can occur inside. Excessive moisture in a house structure is always a potential source of problems. When it freezes, it cracks masonry, accelerates corrosion of steel elements, promotes rot in timber structures and mould on internal plaster. It generally reduces the durability of the house.

In older brick houses, moisture builds up in the walls during the winter and evaporates back into the interior and exterior during the summer. The thicker the wall, the more moisture it can easily hold. Insulation can be a barrier to this 'breathing'. Therefore, it is always necessary for the insulation project to assess the risk of condensation, the possibility of water evaporating from the structure and to design a solution where moisture is not dangerous. The simplest principle (although not the only possible one) is to design the composition of the structure so that the diffusion resistance of the materials decreases from the inside out. This means that it will be difficult for moisture to enter the structure from the interior, but if any does penetrate, it will then easily escape to the exterior.

17.2 Reduction of wall losses

There are two basic types of insulation:

- contact and
- insulation with a ventilated gap.

Each of these methods can be implemented as **internal and external** insulation. The structure must always be treated so that thermal bridges are not created: walls must be insulated not only where the space is heated, but also below floor level and above ceiling level, as must window sills, lining and lintels.

17.3 External insulation

For most buildings it is preferable to use external insulation. Especially for prefabricated buildings, it is also an effective way to extend their lifetime. Insulation protects against frost in winter and against the sun's heat in summer, so that the stress on the expansion joints is reduced. Steel fasteners are more protected from the weather and therefore from corrosion. Thermal bridges in the joints between panels and, if properly designed, at window openings are also addressed by insulation.

Advantages and disadvantages:
+ the masonry is "warm" and not as stressed by temperature fluctuations and weathering;
+ increase the storage capacity of the house;
+ thermal bridges in the structure (window lintels, wings, ceilings, etc.) are more easily eliminated;
+ the risk of moisture condensation in the structure is minimal;
+ the building gets a new facade, which leads to savings in maintenance costs;
+ the installation does not disturb too much the stay of people inside;

- the need for scaffolding and space around the house;
- insulation must be carried out in the entire wall area at once;
- the outer contour of the house will be extended (overlapping onto other people's land may occur);
- higher costs

17.4 Internal insulation

In some cases (e.g. if the façade of the house is historically valuable), internal insulation can be considered. For external insulation, it is common to use insulation with a thickness of 15 to 20 cm. Obviously, internal insulation will always be a compromise between the requirement to save heat and the size of the living space. However, because we cannot also insulate horizontal structures, large thermal bridges are created. The original external wall is separated from the warm internal environment by a layer of insulation and is therefore much cooler after insulation. Where it connects to partitions, ceilings and floors, it cools these adjacent structures so intensely that mould can appear at the points of contact. It also creates a cold zone between the original wall and the insulation, where condensed water is likely to appear inside the structure. As a result, not only the perimeter wall but also the load-bearing elements of the ceilings and floors may be compromised.

Advantages and disadvantages:
+ possibility to insulate only one room;
+ easy access, no scaffolding;
+ can be installed regardless of the weather;
+ easier to perform self-help;

- the risk of condensation in the walls of the house;
- risk of freezing of the external masonry;
- risk of mould growth, especially in the area of thermal bridges;
- reduction of the storage capacity of masonry;

- reduction of room area.

17.5 Contact insulation

This is the most common and well-tested method of insulation, where the insulation is glued to the substrate and anchored with dowels (both because of gravity and because of the wind that could tear it away). A gravel plaster is then applied over the insulator with a reinforcing mesh. Polystyrene is most commonly used as an insulator, sometimes rigid mineral fibre boards (especially on the higher floors of buildings, for fire safety). Cork boards are also used abroad as a natural material.

The biggest advantage is a relatively low price and a wide choice of supplier companies. Another advantage is that there are no thermal bridges in the insulation. Smaller shaped elements (trusses, pilasters, cornices, etc.) made of polystyrene, polyurethane or gypsum can also be glued to the insulation. This allows the house to have the same appearance after renovation as before.

The disadvantage is that the system requires a solid and load-bearing substrate. We will hardly be able to use it on old, falling plaster. Never use contact insulation on damp masonry! Some technological operations can only be carried out in good weather, which can prolong construction.

17.6 Economics of insulation

A well-made insulation should have a lifetime of 40 years or more. The walls need to be repainted after a few years, just like an uninsulated house. Insulation of the roof, ceilings and floors will usually last until the building gets a new owner with different ideas about its appearance and use.

When deciding on the right thickness of insulation, we must remember that costs do not usually increase proportionally with the thickness of the insulation. For example, with contact insulation, we have to pay for the design, scaffolding, adhesive and plastering materials and finishes regardless of whether we use 5 or 25 cm of insulation. Only the cost of the insulator and anchoring elements increases with the thickness of the insulation, the cost of the work may increase slightly. In specific cases, the cost of cladding sills and the like may increase significantly.

The price of the insulator is a small part of the total price of the insulation, but on the other hand, in terms of savings, the insulator is the only functional element of the composition. For this reason alone, it is not worth saving on the amount of insulation. Due to the development of energy prices, layers of insulation with a thickness of 15, 20 or more cm are commonly used nowadays. The approach of "always put 5 cm and that's enough" is not the best way to value for money.

	Price of 5 cm polystyrene insulation (CZK/m^2)	*Price of insulation with 10 cm of polystyrene (CZK/m^2)*	*Price of insulation with 20 cm of polystyrene (CZK/m^2)*
preparation (cleaning) of the substrate	60	60	60
scaffolding	350	350	350
Insulant, dowels and mouldings	180	280	510
adhesive and plastering materials	80	80	80
assembly	330	330	350

Total	1000	1100	1350
heat transfer coefficient insulation effect	0,85 W/(m^2.K) 100 %	0,43 W/(m^2.K) 200 %	0,21 W/(m^2.K) 400 %

Table 17.1 Comparison of costs for insulation with double thickness of insulation

18. REDUCING LOSSES THROUGH WINDOWS AND GLAZING

Windows are a major source of heat loss. Heat escapes both by penetration and radiation through the glass and frame and by infiltration with air in the joints between the sash and frame. Infiltration contributes to the necessary ventilation. Developments in window design have made great strides, so that new modern windows are twice as good as those we are used to in older buildings.

18.1 Replacement of windows

Replacing old windows with new ones is always so costly that it is almost never worth it purely in terms of energy savings. However, if we decide to replace the windows (perhaps because of the poor condition of the original ones), we should not skimp on the glazing. Windows are offered with different types of double glazing, with the difference between the cheapest and most expensive type being 10 to 20% of the price of the window. On the other hand, the difference in insulation capacity is up to twice as much.

Quality double glazing is characterised by the fact that the gap between the glass is filled with argon or other gas, which insulates better than ordinary air. So-called vacuum double glazing, where the air between the panes was diluted (i.e. it was a very dense "vacuum") has been surpassed. Another attribute is the microscopic layer of metal (or metal oxides) on the outside of the inner glass. This layer lets daylight in but not heat out. We can think of it as a sieve through which shortwave radiation - light - can easily pass, but through which longwave radiation - heat - cannot (Fig. 3.1).

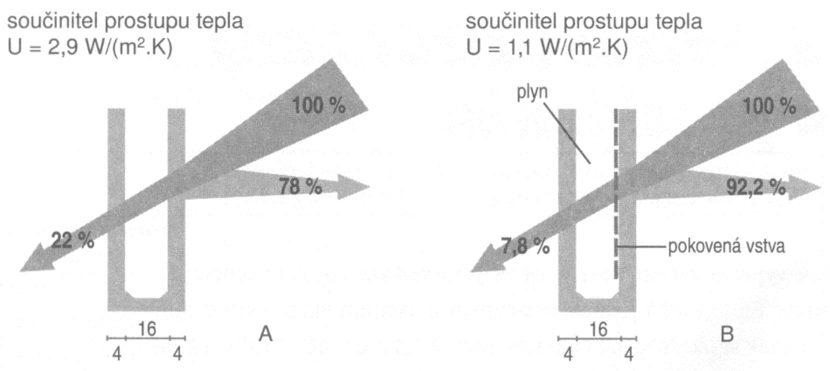


Fig. 18.1 Difference between ordinary (A) and quality (B) double glazing

Even better insulation parameters are achieved by glazing with three panes (triple glazing). A few years ago, the installation of triple glazed windows was one of the popular energy saving measures. Over time, however, triple glazing began to be abandoned, both because of its high cost and because of the high weight of the windows, which placed greater demands on the fixing of the window fittings. In addition, double-glazed windows using reflective layers and inert gas filling began to appear on the market, which were close to triple-glazed windows in terms of their parameters and were significantly cheaper. Nowadays, when solutions are sought to achieve much more demanding values of the thermal transmittance coefficient, there is again a renaissance of windows with multiple glazing. In addition, other solutions are emerging, such as replacing the middle glass with a clear film with a coating. The weight is the same as double glazing and the problems of the different expansion of the three panes of glass are eliminated.

18.2 Window repairs

If the existing windows are in good condition, it is possible to consider refurbishing them. This consists of replacing the inner glass with hard-coated glass. The coating works similarly, but not as effectively, as double glazing (see previous chapter). This is because the coating is permanently in contact with air and must withstand washing. Replacement of the inner glass should be combined with painting, repairs to the fittings, and checking that the fittings are working properly. However, these costs are not related to energy savings.

Replacing one of the panes in existing windows with double glazing is only possible if the frames and fittings can withstand the considerable load of the third pane of glass. The frame will usually only allow the use of thin double glazing. The small distance between the panes is the reason for the poorer insulating power of the window. However, these disadvantages are offset by the cost, which is about a quarter of that of replacement windows.

19. VENTILATION

Ventilation a significant source of heat loss. However, it cannot be reduced easily. Lack of fresh air leads to fatigue and discomfort for the occupants and, in extreme cases, health problems. Ventilation is not only a supply of oxygen, but also the removal of odours and pollutants (smoke, dust, formaldehyde, possibly radon, etc.) that are released in the room. The house itself also benefits from ventilation, as it reduces the humidity caused by the occupants' stay and activities. Adequate ventilation also prevents mould growth.

Reducing unnecessary ventilation can save about 10 to 15% of heating energy. However, as mentioned above, this must not be overdone!

19.1 Air exchange intensity

The standards recommend an air change rate of 0.3 to 0.6 h^{-1} in a room with occupants.The most common value is 0.5 h^{-1}. This means that half the volume of air in the room is exchanged per hour. Obviously, starting from the room volume is not ideal. If there are one or two people in the room, the air demand must be different than if there are twenty guests for a party. So it seems better to base the air volume per person on 15 to 25 m3/h. If there are no people in the room, it is recommended to ventilate at least at an intensity of 0.1 h^{-1} to remove moisture and pollutants. If there is radon in the house, ventilation should be very intensive. In this case, it is advisable to use mechanical ventilation, preferably with heat recovery. Restricting ventilation in this case could have tragic consequences.

19.2 Natural ventilation

The vast majority of houses are ventilated through windows. This is one of their essential functions. People in the house should make sure that they air out thoroughly from time to time, at least once every two hours (especially if they have tight windows). Ventilation should be gusty, i.e. with windows open wide to allow air to flow quickly. It is sufficient to open the windows for 3 to 5 minutes in winter and 10 to 15 minutes in spring and autumn. If we can afford a draft, ventilation will be really intensive and the time can be reduced. Short ventilation times are important so that the walls and floor do not cool unnecessarily.

Ventilation through a permanently open window is highly inappropriate. A lot of heat escapes uselessly straight out. The more secluded corners of the room are not ventilated enough.

19.3 Infiltration

Part of the natural ventilation also works regardless of the user. Cold air enters through leaks between the frame and the sash. Warm air escapes through the joints at the top of the windows when there is no wind, and leaves through the windows on the leeward side when there is wind. The amount of ventilation air depends on the tightness of the windows, the temperature difference between inside and outside and the wind speed. The consequence is that infiltration ventilation is never as much as we need. If the room is not occupied, infiltration is usually unnecessarily high, which increases heat consumption. If the room is occupied, the infiltration is usually insufficient, so it is necessary to ventilate with an open window from time to time anyway. Infiltration rates are higher in winter and in windy conditions, and too low in spring and autumn.

The solution is to seal the windows or use new sealed windows. Modern windows are up to ten times tighter than ordinary older wooden windows. Additional sealing of older windows will increase their tightness several times. However, the occupants then have to take care of ventilation themselves more, i.e. open the windows. If they neglect to do so, they risk the problems mentioned above. Mould in corners and thermal bridges is sometimes an indicator. In older houses with damp walls, sealing the windows would make the dampness problem much worse; the right thing to do is to remove the causes of dampness first. The savings by sealing windows depends on how leaky the original windows were, usually up to 10%. However, this saving must not be achieved at the expense of the home's environment!

19.4 Forced ventilation

Ventilation by means of fans is nowadays commonly used only in kitchen hoods and in bathrooms where more moisture needs to be removed. This is assumed to be only a gust operation, which does not have a lasting effect on the environment in the house.

However, systematic ventilation is no longer the prerogative of industrial and office buildings. If we ventilate the house with fans, we ventilate only when and as much as we need, which has a big impact on energy consumption. However, even greater savings can be made by recovering heat from the exhaust air. If the house is already equipped with air conditioning, this option presents itself. Another advantage can be the ability to cool the house during the summer. While this will not save energy, it can significantly increase comfort. However, the installation of an air handling unit for heat recovery to achieve savings must be carefully considered because the effectiveness of this measure depends on the price of the heat we use for heating, the efficiency of the equipment and the amount and cost of the driving energy consumed by the heat recovery equipment.

19.5 Central ventilation systems

Ventilation air is supplied to the rooms through ducts in the ceiling soffits or in the floor or walls. If it were routed directly through the interior, it would be quite intrusive. The air extraction can either be located in each room or centrally, e.g. in a corridor. The doors of the rooms must then not be tight. The heart of the system is usually a compact unit with exhaust and supply fans, filters, heat recovery heat exchanger and air heater (or even a cooler). The heater can be electric or hot water, which is connected to a boiler or other heat source (possibly via a storage tank). In fact, a central ventilation system can be well combined with the heating of the house. The cost saved on the heating system then offsets the cost of installing the ventilation. Due to the scale of the construction work, it is suitable for new buildings or major renovations. If we want to have a fireplace or other heater in the house with a chimney, we need to design the ventilation as slightly positive pressure, because with a negative pressure system the air would be drawn in through the chimney. This means bringing in slightly more air than is exhausted. If the air is only supplied and the exhaust air escapes through the windows, it is obviously not possible to use heat recovery. It is generally better to use negative pressure systems to reduce the flow of moisture from the interior into the structures. It is usually difficult to provide different ventilation rates in different rooms. The solution is to circulate some of the air in the house, so that the house is one large room in terms of ventilation, with fresh air being brought in according to the number of people. The ventilation system must be able to vary the volume of ventilation air as required, most often by continuously or stepwise changes in fan speed. Central ventilation allows very efficient use of solar gains from sunlit rooms, which are distributed throughout the house so that rooms do not overheat.

Thanks to mechanical ventilation and heat recovery, up to 80% of the ventilation energy can be saved, i.e. about a quarter of the total consumption of the house. The great benefit is increased living comfort and plenty of fresh air.

20. HEATING

Only the best insulated and specially designed houses (so-called passive houses) can do without a heating system. They use the heat emitted by the people inside (an adult person at rest is about as warm as a 100W light bulb) and the appliances (fridge, lighting, etc.) for heating. Of course, they also use the energy of the sunlight that comes in through the windows and glazing. While every house uses this heat, it is usually a very small proportion of the total consumption. The question is therefore how to heat the house with the least possible energy consumption or at the lowest possible cost. To achieve this, we need to choose a heating system, an appropriate heat source and a control system.

20.1 Regulation

The control ensures that the heat is only where we want it and not too much or too little. Modern buildings are sometimes so packed with regulation (not just heating) that they are called smart buildings. The output of the boiler and heating system is sized so that the house is 20°C even if it is -15 "C outside, the sun is not shining and the wind is blowing. These conditions only exist for a few days a year. The basic function of the control is therefore to limit the heating output to the minimum necessary to avoid overheating. The better it works, the less fuel we will consume with the same or even better living comfort. Savings achieved by good regulation range from 5 to 15%. Heating system regulation works on several levels.

Boiler regulation

The most basic control is at the source (boiler) level. The boiler output is changed, e.g. by the amount of fuel (frequency of refuelling). Older gas boilers used to switch the burner on or off, in extreme cases the switching interval was several minutes. This degrades efficiency, emissions and boiler life. Modern boilers can vary the fuel supply and thus adjust the output continuously between 30 and 100%. This also applies to coal or wood boilers. The power control of older coal-fired boilers by 'shrinking' (i.e. limiting the combustion air supply) is the cause of their poor efficiency and emission performance.

Heating system regulation according to time

If the heater is to work efficiently, it must only supply heat at times when it is needed (e.g. at night or in the morning to heat to lower temperatures). This can be solved by a time and temperature switch that switches the heating on according to a pre-set programme, usually for the whole house at once. "Smarter" systems can then control the temperatures in different rooms independently. At night, for example, all rooms are set to a setback temperature, the temperature in the kitchen and bathroom rises in the morning, the setback occurs again in the morning, the temperature rises in the afternoon, first in the children's room and living room, then in the kitchen and finally in the bedroom, and then the whole apartment switches to a lower temperature again. At weekends, when the whole family is at home, the apartment is heated as a whole.

For economical and even heating, it is advisable to maintain a constant flow of heating water through the heating system. If we keep changing the flow rate, some rooms will be overheated and others underheated. But what to do if the outside temperature changes? This question is solved by the draft or equitherm control system, which is now an essential part of a modern heating system. Equithermal control works with so-called heating curves, according to which it mixes the heating water so that it is at the optimum temperature at all times. When the outside temperature is lower, hotter water is driven into the circulation; when it is warmer outside, the heating water temperature drops. In this way, the output of the heating system changes continuously depending on the outside temperature.

You can also adjust the heating water temperature manually, but then you will use about 10% more fuel.

Utilisation of heat gains

The heat needed to maintain the room temperature does not have to come from the heating system alone. If the sun is shining in the windows or the occupants are "heating" with an iron, for example, the heating in the room can be stopped. However, the heating system must be adapted for this purpose, otherwise it will not be able to "recognise" and use the heat gain. The most common device used to take advantage of heat gains are thermoregulating valves (TRVs), which shut off the heating water supply to the heater if the temperature in the room exceeds a set value. Their advantage is the possibility of regulating each unit independently and thus using both solar and local internal heat gains. The disadvantage is the possibility of unprofessional intervention and, in the case of public areas, the possibility of theft.

In large buildings, therefore, a so-called zone control is used, which reacts to the building's glare by closing the heating water supply to all rooms on the glare side. Although this control does not allow the use of local internal heat gains, it is cheaper and resistant to inexpert handling.

If the heat recovery device is retrofitted, further modifications to the heating system are also necessary. In today's forced circulation heating water systems, it is not possible to close all the heating elements or risers at once and throttle the water flow. The circulator is always trying to push water into the system, which results in scary noises (knocking, rattling, etc.), especially in prefabricated houses. The resulting pressure differences can also cause damage to parts of the system. Therefore, when installing a TRV or zone control, it is necessary to install at the same time a pressure differential control device to eliminate the problems.

Balancing the heating system

If the heater is well designed and adjusted, when all the units are open in each room the required temperature is reached and there is the same temperature difference between the supply and return of each unit. If this is not the case, the size of the heating surfaces or the flow rates of the heating water through each part of the heating system must be changed. This is a task for the heating company. This is called balancing the heating system. If the system is poorly balanced, some rooms are overheated, others are underheated and the excess heat is at best captured by the TRV, which in turn leads to a throttling of the heating water flow. Balancing the heating system is a basic prerequisite for its proper functioning.

21. HEAT SOURCES

21.1 Wood, biomass

Wood is still one of the cheapest fuels in our country. For larger sources (e.g. block boiler rooms of apartment buildings) wood chips, straw or other combustible biomass are also used, but their price is individual.

Wood should be burned in special boilers; heating with wood in coal-fired boilers is not very efficient. Because wood burns with a long flame (as opposed to coal, which has a short flame), much of the energy goes up the chimney unused.

It is also necessary to heat only with dry wood, i.e. at least two years stored in a covered border. Raw wood significantly reduces the life of the boiler, and of course much larger quantities are needed. Raw wood has half the calorific value of dry wood, because much of the heat is used to evaporate the water. The need for storage space is (along with the work of preparing it) one of the great disadvantages of wood. If an uninsulated family home consumes 15-25 space meters of wood (prm) per year, then the need for space around the house is really large. Different types of wood have approximately the same calorific value (Fig. 6.1). However, hardwood is 'denser' than softwood, there are more kilograms and therefore more energy in the same size log.

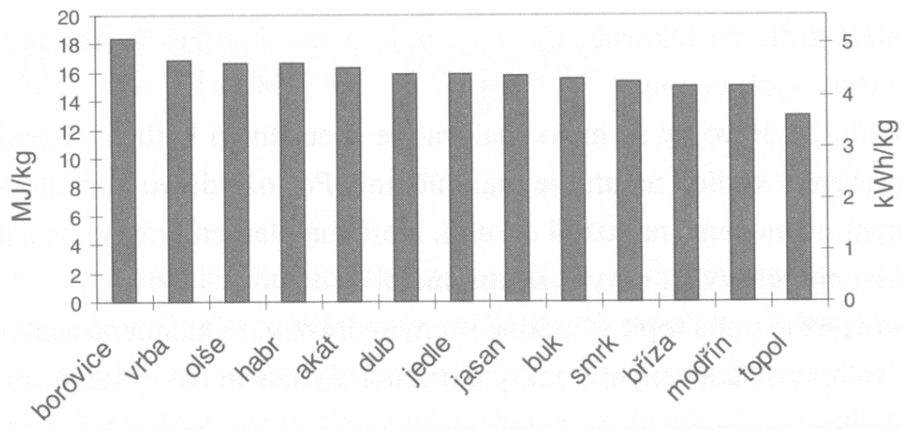


Fig. 21.1 Heating value of wood at 20% moisture content

21.2 Natural gas

It is a very comfortable and relatively environmentally friendly fuel (sulphur oxide and dust emissions are practically zero), which can be used with high efficiency. The boilers are very easy to control. The gas supply is reliable and no storage space is needed in the house.

Recently, natural gas is billed in kWh, not in m^3 as before. However, gas meters still measure in m^3 (there is no other way), so the gas supplier converts the volume to kilowatt hours based on the average heat of combustion over the billing period. The heat of combustion is higher than the calorific value (1.11 x) - see. Both quantities indicate how much energy is hidden in the gas (or any other fuel).

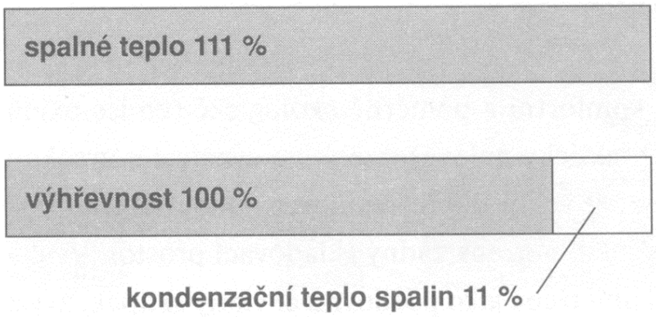


Fig. 21.2 Energy content of natural gas

If the gas is burned, CO_2, water vapour and a small amount of other gases (nitrogen oxides, etc.) are produced. This heat is the difference between the calorific value (which does not consider it) and the combustion heat (which does). Condensation of the flue gas is usually undesirable because it causes so-called low-temperature corrosion of steel boilers. That is why it has never been much considered; the definition of boiler efficiency is just based on calorific value. This is defined as the ratio between the energy in the fuel (i.e. the calorific value) and the energy that is extracted from the boiler (the difference being the losses). The consequence is that modern condensing boilers (which are not compromised by low temperature corrosion) can have efficiencies of over 100%. Another consequence is that the energy delivery figure on the gas invoice must first be converted to calorific value if it is to be used for engineering calculations.

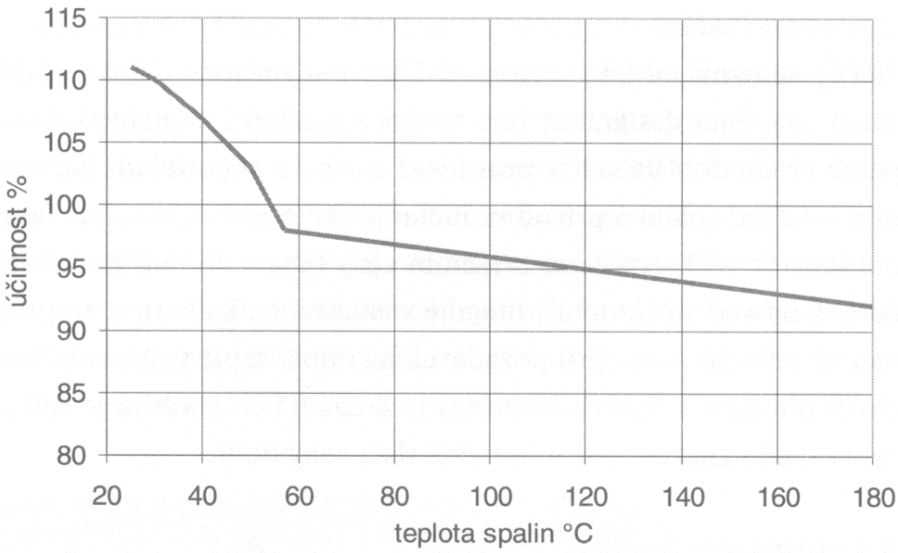


Fig. 21.3 Maximum boiler efficiency depending on flue gas cooling

21.3 Solar systems

They are used as a supplementary source, especially at the beginning and end of the heating season. This is because there is little sunshine in winter, when heat consumption is highest. Hot water collectors can (apart from hot water production, which is usually primary) transfer heat to underfloor heating or low temperature radiators. A storage tank is essential because the house primarily uses passive gains through windows and glazing during sunlight hours.

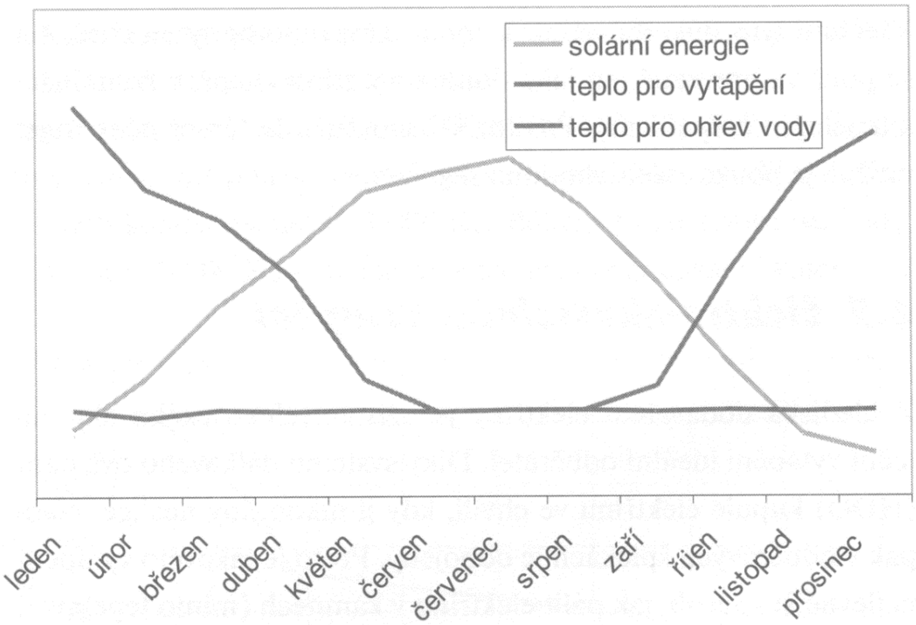


Fig. 21.4 Energy consumption and amount of solar energy during the year

21.4 Heat pumps

A heat pump (HP) is actually a refrigerator. The kitchen fridge takes heat from the food and continuously heats the kitchen through the black grille on its back. A heat pump cools, for example, the air or soil around the house or the water in a stream. It supplies heat to the central heating system.

Just like a refrigerator, a DHW pump needs electricity to operate (however, there are also natural gas powered pumps). The greatest charm of a CH is that it delivers several times more heat than it uses electricity. The ratio between the input power and the output power is called the heating factor and ranges from 2 to 4. The greater the temperature difference the CHP has to overcome (e.g. the ground temperature around the house is 8 °C, the heating water temperature in the central heating is 55 °C), the lower the heating factor - the electricity consumption to drive the CHP increases.

Pump type (cooling/heating)	Possibilities of use
air/water	universal type, for central heating
air/air	supplementary heat source, hot air heating, air conditioning
water/water	waste heat recovery, geothermal energy, central heating
antifreeze/water	universal type for central heating, the heat source is usually a borehole or a ground collector
water/air	hot air heating systems

Table 21.1 Types of heat pumps

Heat sources for CHP:

Air around the house *(Fig. 21.5)* - air is blown by a fan through a cooling unit located on or near the house. The advantage is the lower cost compared to other types. The disadvantages are the lower and variable heating factor (i.e. higher electricity consumption) and the noise of the fan of the outdoor part of the CH.

Soil around the house *(Fig. 21.6)* - heat is extracted through a pipe in which antifreeze flows. The pipe (i.e. the soil collector) is buried in the ground at a depth of about 1.2 m. The advantage is the higher heating factor, the disadvantage is the higher earthwork costs and the limited use of the soil.

Heat of the bedrock *(Fig. 21.7) - the* principle is similar to the previous case, but the pipe is placed in boreholes up to 150 m deep. The advantage is the highest heating factor, the disadvantage is the higher cost of the boreholes. The boreholes need to be sufficiently sized to prevent freezing. There are also proposals to cool the water in a stream, river or pond. In addition to the suitable location of the house, often complex property and water rights have to be resolved. Similarly, the intention to cool water pumped from underground often runs into the fact that the borehole is not sufficiently rich (for a family house, a borehole yield of about 0.3 to 0.5 l/s is required).

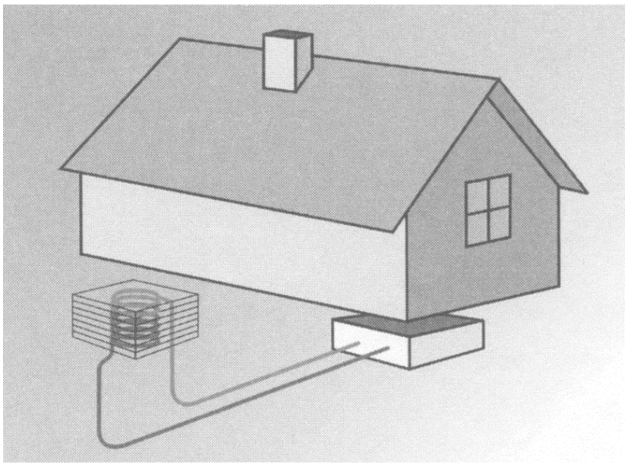


Fig. 21.5 Air-cooling CHP

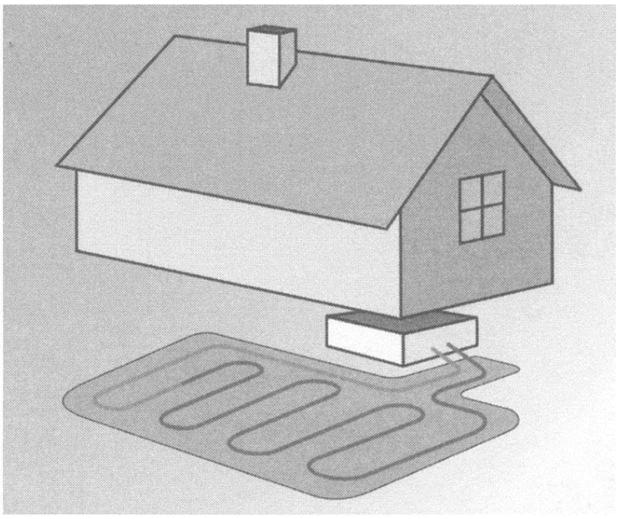


Fig. 21.6 Soil-cooling CHP

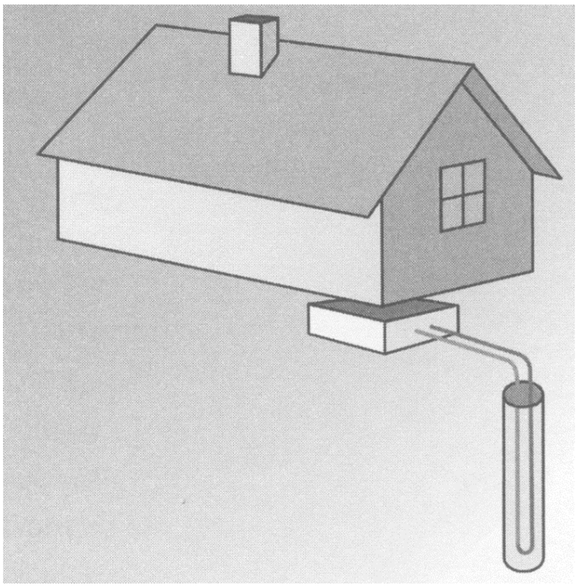


Fig. 21.7 Soil-cooling CHP

22. SAVINGS IN THE HOME

Household consumption is the smallest part of total energy consumption. However, in monetary terms it can account for up to a third of total energy expenditure - see. Figure 1.2.

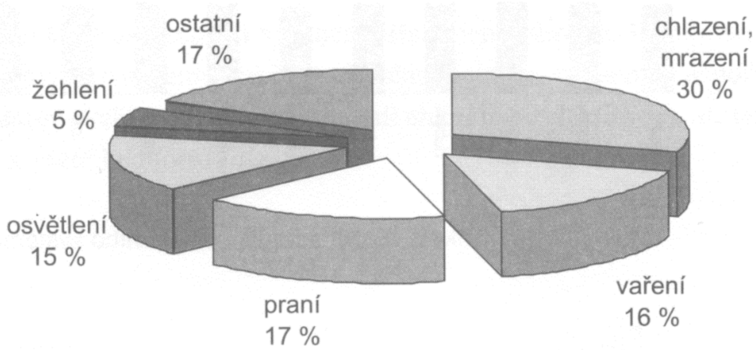


Fig. 22.1 Structure of household electricity consumption

22.1 Rate for electricity consumption

First of all, we need to choose the best possible rate for electricity consumption (we must meet the supplier's conditions, e.g. have a storage appliance installed). The trend in recent years has been to increase the so-called fixed payments (which are paid regardless of the amount consumed). These payments also depend on the size of the connected circuit breaker, which can sometimes be oversized. The cost of replacing a circuit breaker is between 500 and 1000 CZK; this money is usually paid back within a year. For storage, direct heating and heat pump tariffs, the whole house uses electricity for several hours a day at a low tariff (the so-called 'night-time current'). It is worth knowing this time and turning on the washing machine, for example (if you have a heat pump tariff, you have a 'night-time current' of 22 hours a day). If the low tariff time is changed by the supplier operatively, we can get a low tariff indicator that will alert us when it is convenient to switch on the appliance. The specific electricity price for each tariff is shown in the Annex.

At first glance, it seems clear which rate is the cheapest, but the cheaper the price per kWh, the higher the fixed payments (depending on the size of the circuit breaker and the chosen tariff), which can amount to several thousand crowns per month. The cheap price for the energy consumed is only worthwhile for those who consume such a large amount of energy that the cost of the fixed payment is not so significant. From 2006 we will be able to choose our supplier. Each of the eight distributors offers slightly different prices per kWh and fixed payments, but the range of tariffs is the same.

22.2 Replacement of electric heating

A major appliance in the home is the washing machine, which uses most of the electricity to heat the washing water. If we have cheaply heated TV (e.g. a boiler heated by a wood boiler), we should choose a washing machine with a hot and cold water supply. This will reduce the consumption of the washing machine by up to 60%. If we even have an excess of TV (e.g. from a solar system), we can also run lukewarm water into the washing machine for soaking, which will be more efficient. For older washing machines there is a device that runs hot or cold water according to the program set , many new washing machines have a hot and cold water inlet built in. A similar approach can be used for dishwashers.

22.3 Energy labels

Many appliances in the shop today are required to carry an energy label, which indicates how energy efficient the product is compared to others. The letters F and G indicate "power guzzlers". The letter A indicates energy-saving appliances. For refrigerators, the A+ category is already being expanded to A++ as appliances are able to use energy more efficiently. A small fridge or small dishwasher uses less energy than a large one. That is why the consumption of a particular type is always quantified on the label. We have to take into account that the consumption was determined in the laboratory under certain conditions (which were comparable for all appliances). What the consumption really is depends on how we use the appliance - it may be more or less than the declared consumption. There are other important details on the label. For fridges and freezers, for example, this is the quality of the insulation. This is particularly important if there is a power cut. The better the insulation, the longer the food will last undamaged.

The energy label must be compulsorily marked:

- refrigerators and freezers and their combinations;
- washing machines (or washing machines with dryers);
- clothes dryers;
- dishwasher;
- light sources (light bulbs, fluorescent lamps, etc.);
- electric storage water heaters (boilers);
- electric ovens.

	Old refrigerator with freezer, volume 200/80 l	**New refrigerator with freezer, class A, volume 200/80 l**
electricity consumption	800 kWh/year	350 kWh/year
electricity costs	2700 CZK/year	1200 CZK/year
the cost of a new refrigerator		15000Kč
return		10 years

Table 22.1 Return on purchase of a new refrigerator

23. ECONOMICS

We expect an investment to give us value for the money invested, with some return and some risk. We can also look at insulation as an expense. As with a garden pool, insulation is an expenditure that should increase the use and market value of the house. The decision here therefore depends entirely on personal preference. If the house really needs a new facade (roof, attic, heating, etc.), we are faced with a so-called forced investment. Just as we consider whether to make the façade "ordinary" with lower costs, or whether it would be better to make the façade insulated and pay less for heat year after year than before. Insulation is then relatively cheaper (and the return on investment higher), because we would have to incur some costs in any case.

23.1 Returns

When insulating a building, we can use both quick payback and irreversible measures. For a basic economic evaluation of the payback, we need to know three parameters:

7. Cost of energy saving measures - unit prices (e.g. price per m^2 of insulation). For most buildings they are approximately the same.
8. The amount of potential energy savings - the worse the original building is, the more we heat it today, the easier it is to achieve savings (insulation on thin brick walls will yield higher savings than on walls made of insulating blocks).
9. The price of heat - depends not only on the price of fuel, but also on the efficiency of the boiler or other equipment. Sometimes other costs must be included in the fuel price - e.g. for ash disposal, for building a gas connection, etc. Particularly for electric heating, fixed payments are required regardless of the amount consumed. The less electricity we use, the more expensive the kilowatt-hour is. The output of a simple economic evaluation is a simple return on investment. If it is longer than the lifetime of the measure, we will never recover the money invested, so from a purely economic point of view it is better to do nothing at all.

The following tables show the payback periods for different types of reconstruction. The baseline is shown in Table 23.1

	Share of heat consumption	*Heating costs (CZK)*		
		lignite	*natural gas*	*propane*

perimeter walls	29%	7000	12000	24500
windows and doors	12%	3000	5100	10400
floor	9%	2000	3600	7400
Roof	32%	5000	8400	17200
ventilation	18%	4000	7400	15 100
Total	100 %	22 100	36500	74600

Table 23.1 Heating costs of an uninsulated house

Attic insulation	*Lignite*	*Natural gas*	*Propane*
annual heating costs original	36 CZK/m(^{2})	60 CZK/m(^{2})	123 CZK/m(^{2})
annual heating costs after insulation	6 Kč/m(^{2})	10 CZK/m(^{2})	20 CZK/m(^{2})
insulation costs	320 CZK/m(^{2})		
return	10 years	6 years	3 years

Table 23.2 Returns on soil insulation

Replacement of windows	*Lignite*	*Natural gas*	*Propane*
annual heating costs original	103 CZK/m(^{2})	169 CZK/m(^{2})	346 CZK/m(^{2})
annual heating costs after replacement	48 Kč/m(^{2})	78 CZK/m(^{2})	160 CZK/m(^{2})
replacement costs	6000 CZK/m(^{2})		
return	109 years	66 years old	32 years old

Table 23.3 Return on window replacement

Wall insulation	Annual heating costs original	*Lignite* 66 CZK/m(^{2})	*Natural gas* 109 CZK/m(^{2})	*Propane* 223 CZK/m(^{2})
insulation with 5cm layer of polystyrene	annual costs after insulation	21 CZK/m(^{2})	35 CZK/m(^{2})	71 CZK/m(^{2})
	insulation costs	1100 CZK/m(^{2})		
	return	24 years old	15 years	7 years
insulation with 10cm layer of polystyrene	annual costs after insulation	12 CZK/m(^{2})	20 CZK/m(^{2})	42 CZK/m(^{2})
	insulation costs	1200 CZK/m(^{2})		
	return	22 years old	14 years	7 years
insulation with 20cm layer of polystyrene	annual costs after insulation	7 Kč/m(^{2})	11 CZK/m(^{2})	22 CZK/m(^{2})
	insulation costs	1450 CZK/m(^{2})		
	return	24 years old	15 years	7 years

Table 23.4 Return on insulation

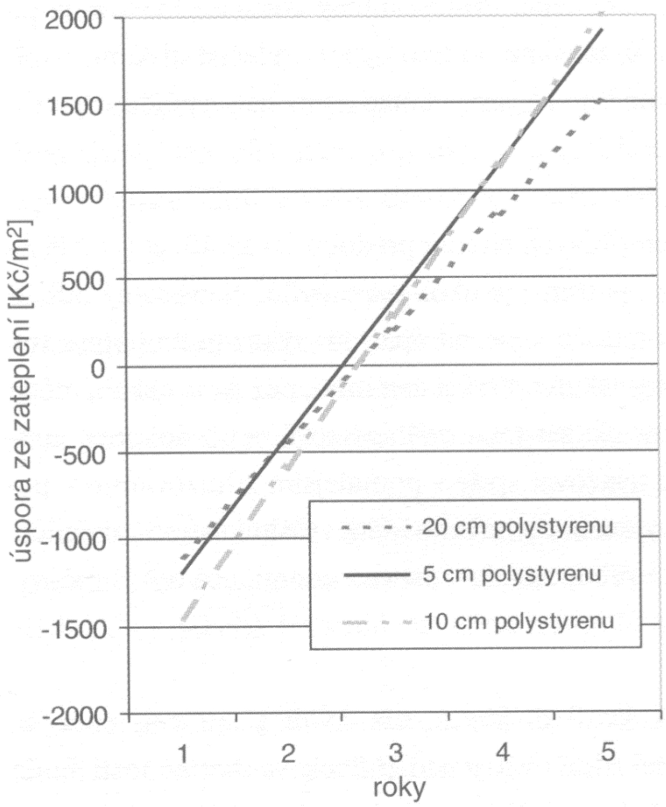


Fig. 23.1 Return on insulation of a 0.5 m thick brick wall with natural gas heating

In addition, the following should be included in the overall assessment:
- the price of money (discount)
- rising energy prices
- inflation
- method of financing

24. ECOLOGY

Saving energy always means reducing environmental impacts. These impacts vary depending on the fuel used and where and how the fuel is burned. For example, a poorly tuned boiler in a family home can have emissions comparable to a waste incinerator in some respects! Having a properly tuned boiler is good not only for the environment, but also to ensure that it is as efficient as possible and does not unnecessarily shorten its life. This applies to all boilers, not just solid fuel boilers.

However, another aspect that we cannot yet quantify sufficiently is the difference between a renewable resource (such as biomass or solar) and a fossil fuel, which is in limited supply. Part of the comparison can be made with the emissions of the greenhouse gas CO_2, which renewables produce little or no emissions (for example, a pump powered by fossil electricity is needed to run a solar system). However, the severity of the greenhouse effect has led many countries to consider a carbon tax that would put fossil fuels at a disadvantage. Similarly, it is difficult to quantify the landscape impacts associated with energy generation and transmission. Surface mining of lignite (and limestone for desulphurisation) means the destruction not only of native nature but also of human habitats. Appropriate reclamation can partially eliminate the former, but only after many years. In the case of electricity pylons, we regard the so-called optical pollution of the landscape, which is blamed on wind farms, as an evil so necessary that we no longer even notice it. Harvesting energy from forests may be looting in one case, but in another it is responsible and sustainable management. On the one hand, the use of uranium to generate electricity means saving fossil fuels and reducing the problems associated with this, but on the other hand it brings with it problems that are still little known - in particular, the question of disposal of spent fuel and the power stations themselves. At the moment, emissions seem to be the only relatively reliably quantifiable indicator. From an environmental point of view, they are very serious. Table 9.1 shows the emission values for different heat sources.

Pollutant	*Black coal*	*Lignite*	*Wood*	*Natural gas*	*Electricity*	*Heat pump*
Efficiency	62%	62%	75%	89%	95%	300 %
emissions	(kg/year)	(kg/year)	(kg/year)	(kg/year)	(kg/year)	(kg/year)
solids	29,23	37,18	38,53	0,024	4,01	1,25
$S0_2$	28,15	63,11	3,08	0,000	20,04	6,24
NO_X	3,77	9,68	9,25	1,899	16,99	5,29
CO	113,00	145.13	3,08	0,380	4,28	1,33
C_xH_y	22,35	28,70	2,74	0,076	1,1	0,30
CO_2	4975	5436	3 165	2352	9612	2991

Table 24.1 Emissions by fuel type at a consumption of 10 000 kWh

Note
This section uses verbatim quotations, tables and figures from the literature:
Srdečný, K., Macholda, F.: Energy savings in the house. GRADA, Prague 2004, ISBN 80-247-0523-0.

? THEORETICAL CONTROL QUESTIONS

1. (2 pts) What is the difference in the energy consumption pattern of a low-energy house and a standard house?
2. (3 pts) Which energy source is currently the most cost-effective in terms of acquisition and operating costs?
3. (5 pts) List the main pros and cons of each method of insulation.
4. (4 points) What should be taken into account when replacing or renovating windows? How does this relate to ventilation?
5. (2 pts) How do you explain the boiler efficiency of over 100%?
6. (6 pts) Characterize the main sources of heat, their advantages and disadvantages.
7. (2 pts) What are the basic principles of heat pumps?
8. (3 points) Where are the possible energy savings?
9. (3 pts) What all needs to be taken into account when evaluating an investment in energy savings as it relates to its payback?

SUMMARY

New findings:
- household energy performance
- house insulation options
- heating - ventilation relationship
- energy saving opportunities
- the relationship between economics and ecology in heating

New concepts:

heat loss, insulation, heat gain, heat pump, ventilation, control, return on investment.

KEY TO THEORETICAL QUESTIONS

1. Figure 1.1
2. Chapter 1.2, Annexes
3. Chapters 2.4, 2.5
4. Chapters 3, 4
5. Fig. 6.2
6. Chapter 6
7. Chapter 6.4
8. Chapter 7
9. Chapter 8

AUTOCONTROL

If you have scored at least 15 points in the theory questions, you can continue your studies. Otherwise, repeat the chapter.