Practical Electrotechnology

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Cambridge Scholars Publishing

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This book first published 2023

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-2658-5
ISBN (13): 978-1-5275-2658-7

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PREFACE

Electrotechnology is a science that deals with the theory and practice of conversion of electric energy to thermal, mechanical, chemical, and other forms of energy and their combination with technological processes.

In the process of conversion, electric energy causes the thermal, chemical, mechanical, and optical effects, and their combination.

According to the electric energy action, electrical equipment can be divided into electrothermal, electrochemical, and electrophysical. This equipment is classified as technological installations, for example, heating devices, electric pulse devices, air ionizers, etc.

The methods of converting electric energy in technological processes serve as the basis to classify electrotechnological installations.

Historically, it has happened so that the lighting technology is concerned with the use of electromagnetic radiation of optical (10 nm–1 mm) wavelengths, while the electric drive – with the use of electric energy that puts machines and mechanisms into motion.

The subject matter of electrotechnology is the theory and methods of electric energy conversion, the arrangement and operation principles of converters, their calculation, choice, and operation. These are considered from the standpoint of power engineering and electrotechnology. Emphasis is made on the study of electrical equipment used in agriculture.

The offered book can be useful for students, engineers, and researchers specializing in the use of electric energy for producing and processing agricultural products.

The authors are very grateful to Elvira Zharkova who translated the book and gave many pieces of advice on improving it.

CHAPTER 1

GENERAL PROBLEMS OF ELECTROTECHNOLOGY

1.1 Electromagnetic field action

Electromagnetic field energy is converted to other-form energy when it is absorbed by a medium. The medium is conductors, semi-conductors, and dielectrics.

The strength of electric E and magnetic H fields and the frequency f are the main electric characteristics of the electromagnetic field. The medium is characterized by specific electric conductivity γ, dielectric ε_a and magnetic μ_a permeability.

The ability of the medium to absorb electromagnetic field energy and, accordingly, the ability of the field to penetrate into the medium are assessed by the electromagnetic radiation attenuation coefficient, m^{-1}:

$$K = \omega \sqrt{\frac{\varepsilon_a \mu_a}{2}\left[\sqrt{1+\left(\frac{\gamma}{\omega\varepsilon_a}\right)^2}-1\right]}$$

where $\omega = 2\pi f$ is the circular frequency, s^{-1}; f is the electromagnetic field frequency, s^{-1}.

In perfect dielectrics, for which $\gamma = 0$, $\gamma / \omega\varepsilon_a = 0$ and, hence, $K = 0$, electromagnetic waves do not attenuate, the medium does not absorb energy, but passes it through itself.

In semi-conductors and perfect dielectrics, for which $\gamma > 0$, $0 < \gamma / \omega\varepsilon_a << 1$ and, hence, $K > 0$, the medium absorbs energy, attenuating a radiation flux, as it deeply penetrates into the semi-conductor.

In metal conductors, for which $\gamma >> \omega\varepsilon_a$, the attenuation coefficient takes the form:

$$K = \sqrt{\omega\mu_a\gamma / 2}\ .$$

From here, it follows that due to high conduction of metals and high magnetic permeability of ferromagnets, electromagnetic radiation attenuates quickly in them, i.e., it penetrates into the medium at a small depth and is almost completely reflected at super-high frequencies.

In practice, by choosing a required frequency value, we regulate the electromagnetic field impact on the medium. By varying the strength of electric and magnetic fields, we change the input energy and the time impact.

According to the energy conservation law, no electric energy is used and consumed. It is converted from one-form energy to other-form energy, having this or that impact on the medium. The energy form impacts depend on the parameter ratio of the main field characteristics and the medium.

The main electromagnetic field actions on media are: thermal, chemical, kinetic, mechanical, optical, and physiological. Sometimes, the kinetic and mechanical impacts stand for the 'physical action of the electromagnetic field'.

The thermal impact manifests itself in varying the temperature of the medium that absorbs electromagnetic energy.

The chemical impact consists in generating and changing chemical reactions.

The kinetic impact imparts the directed motion to the charged particles in the electric or magnetic field.

The mechanical impact is that the electric and magnetic fields act upon the charged particles, micro and macro bodies and change their shape, volume, position.

The optical impact is based on the photoelectrical and photochemical effects, the pressure due to optical wavelength electromagnetic radiation.

The physiological impact manifests itself in the changes of the rate of various physiological processes in living organisms (animals, microorganisms, plants) when acted upon by the electromagnetic field. It can be assumed that these changes are taking place under the above-mentioned actions, since the mechanism of the electromagnetic field impact directly on physiological processes has not yet been described.

The process based on the above electromagnetic field impacts on media is referred to as electrotechnological.

The device, in which at a time, electric energy is converted to other-form energy and the technological process is in progress, is called electrotechnological.

The science that studies the theoretical and technological fundamentals of conversion of electric energy to other-form energy and their use in the production is called electrotechnology.

1.2 Classification of electrotechnological equipment

Electrotechnological equipment is classified by type of the electromagnetic field action on media, current type, strength, and by some other less significant features.

According to the electromagnetic field action on media, installations are electrothermal, electrochemical, electrokinetic, and electromechanical.

Electrothermal installations are in turn divided into devices of direct and indirect conversion of electric energy to thermal one.

Among the direct energy conversion installations are the devices, whose operation is based on the Joule–Lenz law (element, electric-contact, electric-arc, induction, and capacitor heating). Among the indirect energy conversion installations are the thermoelectric heating and cooling devices.

Electrochemical installations include electrolysis devices, electrochemical metal and water treatment devices, electrocoagulators and electroflotators, as well as chemical current sources such as storage batteries.

Electrokinetic installations are based on the electric field strength action upon charged particles: electric gas filters, seed separators, aerosol plants, desalters, etc.

Electromechanical plants incorporate electric pulse, ultrasonic devices, as well as magnetic material treatment installations. These plants are based on the mechanical electromagnetic field action, although they also include the devices of predominant thermal action – electroerosion and pulse raw material processing. In this case, they have been united through the electric energy pulse shape and the common pulse principle.

The individual group consists of air ionizers and ozonizers that are not affected by the electromagnetic field, but nevertheless they have a significant influence of air ions and, first, of oxygen ions on the physiological processes in living organisms.

By current type, the installations can be DC, AC, and pulse current. In this case, the frequency can be from industrial to optical, for example, infrared radiators.

By strength used in electrotechnological processes, practically no limitations are available: from several volts – in electric contact heating installations to several tens of thousands of volts – in electric filters and separators of mixtures.

CHAPTER 2

ELECTROTHERMAL EQUIPMENT

2.1 Conversion of electric energy to heat

2.1.1. Electric heating methods. Classification of heating devices. A heating element is a primary and most important part of electrothermal installations. It is a device, in which electric energy is converted to heat and is transferred from it to heated material by conduction, convection, radiation or their combination.

An electric heater is a device comprising a heating element equipped with facilities to supply voltage and to protect against unauthorized access of people and environmental impacts. It is meant for transferring heat from a heating element to a heated material.

The electric heating installation is a device comprising a heater and facilities to place and move a heated material, to control and regulate a temperature, as well as to protect from inadmissible electric and heat engineering operating conditions of the installation. It is meant for carrying out a certain technological process, for example, water heating, material drying, and metal hardening.

The heating method is the main classification feature of electric heating installations. However, the heating methods are not classified according to any criterion. As such a criterion, we can take the installation embodiment, in which electric energy is converted to heat. In this case, the following electric heating methods can be distinguished.

Element heating is the case in which electric energy is converted to heat in the heating element representing a conductor shaped as a wire, a spiral, a tape, a thin-layered plate or as some other shape. This method is most widespread and serves as the basis for designing tubular heaters, heating wires, cables, etc.

Electrode heating is the case in which electric energy is converted to heat in the conductive liquid between current-carrying electrodes. This method is used for heating ionic conductive materials.

Electric contact heating is the case in which electric energy is converted to heat in the metal between current-carrying contacts. This method is used for heating metal bodies, welding thin-sheet metals, as well as for overlaying one metal on top of the other.

Electric arc heating is the case in which electric energy is converted to heat in the arc burning between current-carrying electrodes in the air or in other gas. This method finds use in electric arc welding, melting, and metal cutting.

Induction heating is the case in which electric energy is converted to heat in the metal acted upon by the alternating magnetic field of the inductor. This method is used for heating ferromagnetic materials.

Capacitor heating is the case in which electric energy is converted to heat in the dielectric when acted upon by the alternating electric field of the capacitor. This method is used for heating non-conductive materials. Very often, this method is called microwave heating.

Thermoelectric heating is the case in which electric energy transports electric charges from one conductor (semi-conductor) to another. Charges are different in *n*- and *p*-conduction. In the conductor contact zone, heat is released or absorbed depending on the current direction. This method is used in thermoelectric batteries and modules.

The next sections are concerned with physics and conversion of electric energy to heat when the above-mentioned heating methods are used. In addition to the above electric heating methods, another practice is also known: laser, electron-beam, plasma, ion, and infrared. But it is not the subject of our study.

Electric heating installations are classified according to the above methods. By heating type, these are direct and indirect heating installations. With direct heating, electric energy is converted to heat directly in a heated material. This occurs at electrode, electric contact, induction, and capacitor heating. With indirect heating, electric energy is converted to heat in a heating element. It is transferred from it to a heated body when one of the heat transfer methods or their combination is adopted.

Other classification features are:

– technological use (water heaters, air heaters, steam generators);

– operating regime (continuous, periodic);

– current type (DC, AC) and frequency (industrial, medium, high, super-high);

– supply voltage (low and high volt), etc.

In addition to the heating methods, we distinguish the ways how to convert electric energy to heat: direct and indirect. With direct conversion, electric energy is converted directly to heat. This finds use in the heating element, electrode, and other heating methods with the exception of the thermoelectric one. With indirect conversion, electric energy serves as intermediate, additional energy; for example, it transfers different-kinetic energy charges from one medium to another as at thermoelectric heating. In this case, the share of electric energy being converted to heat is negligible in comparison to that of the charges transported from one conductor (semi-conductor) to another.

To gain a better understanding of the conversion mechanism of electric energy to heat, we should remember the definition: the temperature is a physical quantity responsible for the kinetic energy of elementary particles of a macroscopic system. To raise the temperature, the kinetic energy of the elementary particles of a body must be increased.

2.1.2. Physical laws of conversion of electric energy to heat. In 1842, Russian Academician E. K. Lenz in his article 'On the Laws of Heat Release by Galvanic Current' made a conclusion: galvanic current heating of a wire is proportional to a wire resistance and to a squared electric current. Although the English scientist Joule was the first who in 1841 carried out experiments to measure the thermal effect of electric current, his results became law after Lenz's convincing experiments. Therefore, it is perfectly true that the established law is named after the first researchers: Joule and Lenz. Later on, the effect of electric current heating of a conductor was explained on the basis of the theory of electronic conduction of metals.

A free charge e in the conductor, to which the electric field of strength E is applied, experiences force:

$$\bar{F}_i = e\bar{E} \tag{2.1.1}$$

and gains acceleration

$$\bar{a}_i = \bar{F}_i / m \tag{2.1.2}$$

where m is the charge mass. During the free path time τ_i, the charge with an initial velocity ϑ_{ii} gains an additional velocity:

$$\vartheta_{ia} = \vartheta_{ii} - a_i\tau_i = \bar{\vartheta}_{ii} - e\bar{E}\tau_i / m\,. \tag{2.1.3}$$

The kinetic energy of the charge increases

$$0.5m\left(\bar{\vartheta}_{ii}{}^2 - \bar{\vartheta}_{ii}{}^2\right) = -e\bar{E}\bar{\vartheta}_{ii}{}^2\tau_i + 0.5e^2E^2\tau_i^2 / m\,. \tag{2.1.4}$$

Considering that the charge velocities in the directions in the absence of the electric field are distributed randomly, it may be assumed:

$$-e\overline{E}\Sigma\overline{\vartheta}_{ii}\tau_i = 0. \qquad (2.1.5)$$

The increase in the kinetic energy of *n* of particles per unit volume of the conductor is:

$$W = \int_0^\infty \frac{e^2E^2\tau_i^2 n}{2m}\frac{n}{\tau}e\frac{-r^1}{r}d\tau = \frac{ne^2}{m}E^2\tau^2 \qquad (2.1.6)$$

where τ is the mean time of the charge free path. Taking into account that the specific electric conductivity of conductor materials is:

$$\gamma = ne^2\tau / m\,, \qquad (2.1.7)$$

the electric power conversion to heat per unit volume of this conductor, W/m^3, is equal to

$$p = \gamma E^2\,. \qquad (2.1.8)$$

In the conductor element of volume *dV*:

$$dp = \gamma E^2 dV \text{ or } dp = \rho j^2 dV \qquad (2.1.9)$$

where ρ is the resistivity of conductor materials; *j* is the current density in the conductor. To determine the power releasing in the conductor, we need integration:

$$p = \iiint \rho j^2 dv \text{ or } p = \iiint j^2\overline{E}dv. \qquad (2.1.10)$$

We will consider a thin current tube of cross-section *S* and length *l* from point A to point B. The power in this tube is

$$\int_A^B j\overline{E}d\overline{S}d\overline{l}\,. \qquad (2.1.11)$$

As the current density over the tube cross-section is the same $jd\overline{S} = j_1 d\overline{S}_1$, integral (2.1.11) becomes $j_i d\overline{S}_1\int_A^B \overline{E}d\overline{l} = j_1 d\overline{S}_1(U_A - U_B)$ when applied to the sum of the current tubes

$$P = \iint_{S_1}(U_A - U_B)j_1 d\overline{S}_1 = (U_A - U_B)I$$

and finally, since $U_A - U_B = IR$:

$$P = I^2R \text{ or } P = U^2 / R\,. \qquad (2.1.12)$$

The Joule–Lenz law in differential (2.1.8) and integral (2.1.12) form shows that the electric energy converted to heat, when the current flows in the conductor, is directly proportional to the squared voltage and inversely proportional to the conductor resistance. The electric field energy increases the velocity of free charges. Interacting with other elementary particles, these charges increase their oscillation velocity and, hence, the temperature of the conductor as a whole.

The above-said can be applied to all electric heating methods, with the exception of the thermoelectric one. A mathematical description of conversion of electric energy to heat is somewhat different depending on the type of '*heating*' current – conduction current or bias current.

2.1.3. Heat flux between bodies. The power or the heat flux transferred between the bodies with different temperature, W, is

$$P_T = \varphi_T A \tag{2.1.13}$$

where φ_T is the surface density of the heat flux, W/m^2; A is the heat transfer surface area, m^2.

The heat flux density is:

$$\varphi_T = (t_{hs} - t_m) / R_T \tag{2.1.14}$$

where t_{hs}, t_m is the temperature of the heater surface and the medium between, which heat is transferred, respectively, °C; R_T is the thermal resistance of the unit area of the heat transfer surface respectively, m^2·°C/W.

The main calculation difficulty lies in determining the thermal resistance R_T that depends on the used heat transfer method, the heat transfer conditions, the heating installation embodiment, etc.

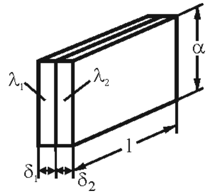
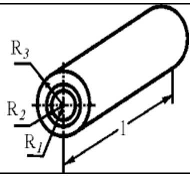
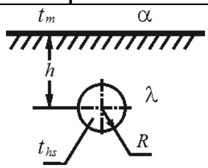
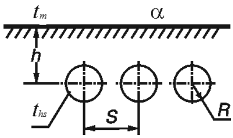
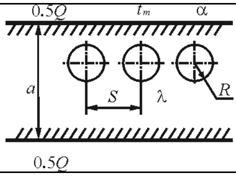
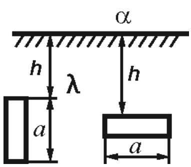
Table 2.1.1 contains the thermal resistance results for some bodies at heat transfer by conduction.

In the simplest case, the power transferred by heat conduction through a one-layer wall is

$$P_{T1} = \frac{\delta}{\lambda}(t_2 - t_1)A \tag{2.1.15}$$

where λ is the thermal conductivity of the wall material, W/m·°C; δ is the wall thickness, m; t_1, t_2 is the temperature of the cold and hot wall sides respectively, °C.

Table 2.1.1 Thermal resistance of bodies

Body shape and location, application	Calculation scheme	Thermal resistance, m²·°C/W
1. Long flat multi-layer wall (walls of water heaters, ovens, various fences)		$R_T=\sum_{i=1}^{i=n}\frac{\delta_i}{\lambda_i}$
2. Cylindrical multi-layer wall (walls of water heaters, inductor tubes, tubular heaters)		$R_T=\sum_{i=1}^{i=n}\frac{R_{im}}{\lambda_i}\ln\frac{R_{i+1}}{R_i}$ where $R_{im}\frac{R_{i+1}+R_i}{2}$
3. Single tube in the semi-bounded space (pipeline in the ground)		$R_T=\frac{R}{\lambda}\ln\left(\frac{h}{R}+\sqrt{\left(\frac{h}{R}\right)^2}-1\right)$ $\frac{h}{R}>4:\ R_T=\frac{R}{\lambda}\ln\frac{2h}{R}$
4. Number of identical tubes with the same temperature in a semi-bounded space (electrically heated floors)		For one of the tubes $R_T=\frac{R}{\lambda}\ln\left[\frac{S}{\pi R}\mathrm{sh}\left(\frac{2\pi h}{S}\right)\right]$
5. Number of identical tubes with the same temperature in the space bounded by two planes (electrically heated panels, mats)		For one of the tubes $R_T=\frac{R}{\lambda}\ln\left[\frac{S}{\pi R}\mathrm{sh}\left(\frac{\pi a}{2S}\right)\right]$
6. Long thin plate in the semi-bounded space (tape heater in liquid media)		$0.5<\frac{h}{a}<12$ Vertical plate $R_T=\frac{0.42a}{\lambda}(h/a)^{0.24}$ Horizontal plate $R_T=\frac{0.34}{\lambda}(h/a)^{0.32}$

The thermal resistance of the bodies at convective heat transfer is:

$$R_T = 1/\alpha \tag{2.1.16}$$

where α is the heat transfer coefficient, W/(m^2·°C).

In the general case, the heat transfer coefficient is equal to:

$$\alpha = \mathrm{Nu}\frac{\lambda}{l_0}, \ \mathrm{Nu} = C_1 \pi^A \,\mathrm{Pr}^B \left(\frac{l_1}{l_2}\right)^{C_2} \tag{2.1.17}$$

where Nu is the Nusselt number; λ is the thermal conductivity of the heated liquid or the gas, W/(m·°C); l_0 is the characteristic length of the body, m; l_1, l_2 are the geometric sizes of the body, e.g., l_1 is the transverse size, l_2 is the longitudinal size. The Prandtl number $\mathrm{Pr} = \nu/a$ where ν is the kinematic viscosity, m^2/s, and a is the thermal diffusivity, m^2/s.

Other parameters in formula (2.1.17) are the criteria that depend on heat transfer conditions (Table 2.1.2). The Reynolds number is: $\mathrm{Re} = Vd/v$ where V is the liquid or gas velocity, m/s; d is the heater diameter, m; μ is the dynamic viscosity, Pa·s. The hydrodynamic similarity number is $V_S = \beta\Delta t$ or $y_S = \left((\mu/\rho)^2/g\right)^{1/3}$ where β is the temperature volume-expansion coefficient, 1/°C; Δt is the temperature difference between the wall and the liquid, °C; ρ is the density, kg/m^3; g is the gravitational acceleration, m/s^2.

In Table 2.1.2 μ and μ_w are the dynamic viscosity in the medium and near the wall respectively.

For differently shaped bodies and heat transfer conditions, relations (2.1.17) realize and yield the heat transfer coefficient α and the thermal resistance R_T. For example, the free-convection heat transfer coefficient from:

the flat surface to the air is

$$\alpha = 2.56 \cdot \sqrt[4]{t_{hs} - t_m} \tag{2.1.18}$$

the open spiral blown by the air is

$$\alpha = 2.5 V^{0.446} / d^{0.534} \tag{2.1.19}$$

the bundle of staggered finned tubular heaters is

$$\alpha = 0.213 \frac{\lambda}{S_p^{\;0.35}} \mathrm{Pr}^{0.35} \left(\frac{d}{S_p}\right)^{-0.54} \left(\frac{h_p}{S_p}\right)^{-0.14} \left(\frac{V}{\nu}\right)^{0.65} \tag{2.1.20}$$

where S_p, h_p are the fin pitch and height respectively, m; d is the tube outer diameter, m; λ is the medium thermal conductivity, W/(m·°C); V is the velocity, m/s.

The power transferred by convection, W, is:

$$P_\alpha = \alpha(t_{hs} - t_m)A. \tag{2.1.21}$$

Table 2.1.2 Constants and parameters responsible for the Nusselt number

Heat transfer conditions	C_1	A	B	C_2
Forced flow, turbulent: $\pi = \text{Re}$, $l_1 = d$, $l_2 = L$ 1.1. Parallel to the tube 1.2. Transverse to the single tube 1.3. Transverse to the in-line, staggered tube bundle	 0.23 0.26 0.26 0.33	 0.8 0.6 0.6 0.6	 0.40 0.30 0.33 0.33	 0 0 0 0
2. Forced flow laminar: $\pi = \text{Re}$, $l_1 = d$, $l_2 = L$ 2.1. For liquids $\text{RePr}\frac{l_1}{l_2} < 13$ 2.2. For liquids $\text{RePr}\frac{l_1}{l_2} > 13$	 $1.86(\mu/\mu_w)^{0.14}$ 0.5	 1/3 1	 1/3 1	 1/3 1
3. Free flow over the wall, turbulent: $\pi = \text{Re}$, $l_1 = y_S$, $l_2 = h$ 3.1. Vertical wall, vertical tube, horizontal tube wall	0.01	1/3	1/3	0
4. Free flow over the wall, laminar: $\pi = \text{Re}$, $l_1 = y_S$, $l_2 = h$ 4.1 Vertical wall	0.67	1/9	0	0
5. Free flow, natural convection $\pi = V$, $l_1 = y_S$, $l_2 = h$ 5.1. Vertical wall $10^3 < \text{Pr}\ V_S(l_1/l_2)^{-3} < 10^9$ $\text{Pr}\ V_S(l_1/l_2)^{-3} > 10^9$ 5.2. Horizontal tube $10^3 < Pr\ V_S(l_1/l_2)^{-3} < 10^9$	 0.59 0.13 0.53	 1/4 1/3 1/4	 1/4 1/3 1/4	 1/4 1/3 1/4

Table 2.1.3 Values of α for heat transfer at free convection from the flat metal or brick surface to the air at t_m = 20 °C

Body surface	Surface temperature t_{hs},°C							
	40	60	80	100	125	150	200	300
Horizontal, upwards	8.6	9.9	10.8	11.9	13.2	14.4	17.0	23.3
Horizontal, downwards	12.0	14.5	15.2	16.7	18.5	19.9	23.0	29.8
Vertical	10.6	12.2	13.4	14.6	16.3	17.6	20.3	27.2

The thermal resistance at radiant heat transfer, (m^2·K)/W, is:

$$R_{TR} = \frac{1}{4C_{hsm}\sigma_0 T_{hsm}^3} \qquad (2.1.22)$$

where C_{hsm} is the reduced emissivity of bodies; $\sigma_0 = 5.67\cdot10^{-8}$W/ (m^2·K^4) is the Boltzmann constant; $T_{hsm} = T_{hs} + T_m$ is the mean temperature of heat transfer surfaces, K.

Radiant heat transfer becomes significant at a heater temperature of more than 500 °C.

The reduced emissivity of the heater and the heated body is:

$$C_{hsm} = \left[1 + \varphi_{12}\left(\frac{1}{\varepsilon_1} - 1\right) + \varphi_{21}\left(\frac{1}{\varepsilon_2} - 1\right)\right]^{-1} \qquad (2.1.23)$$

where φ_{12}, φ_{21} are the angular coefficients of radiant heat transfer allowing for the system configuration (Table 2.1.4); ε_1, ε_2 are the relative radiation coefficients of the heater and heated body material.

In the case of simplified calculations, we have:

$$C_{hsm} = \frac{1}{1/\varepsilon_1 + A_2/A_1\left(1/\varepsilon_2 - 1\right)} \qquad (2.1.24)$$

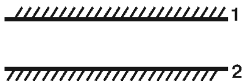
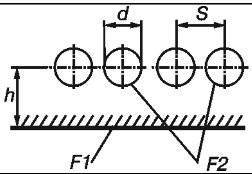
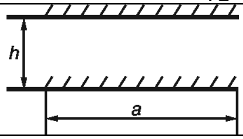
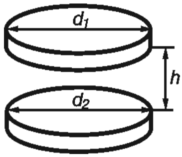
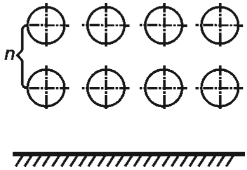
where A_1, A_2 is the surface area of the heater and the heated body respectively, m^2.

In the case of simplified calculations, the heat flux transferred by radiation between the bodies, W/m^2, is:

$$\varphi_{TR} = \varphi_T \alpha_{eff} \qquad (2.1.25)$$

where φ_T is the heat flux calculated by (2.1.14), the temperature is given in K; α_{eff} is the efficiency coefficient of the heater. It depends on the shape of the heater and its location relative to the heated body (Table 2.1.5).

Table 2.1.4 Some formulas for angular radiation coefficients

Shape and mutual location of a radiant heat transfer surface	Calculation scheme	Angular radiation coefficient
1. Two parallel plates, whose sizes are much larger than the distance between them		$\varphi_{12}=\varphi_{21}=1$
2. Indefinite plate and a number of tubes in the parallel plane (h is dimensionless)		$\varphi_{12}=1-\sqrt{1-\left(\frac{d}{S}\right)^2}+ + \mathrm{arctg}\sqrt{\left(\frac{S}{d}\right)^2-1}$
3. Two parallel strips, h is the distance between the strips. The strip width is $a_1=a_2=a$		$\varphi_{12}=\varphi_{21}=\sqrt{1+\left(\frac{h}{a}\right)^2}-\frac{h}{a}$
4. Two discs $d_1=d_2=d$ at a distance h		$\varphi_{12}=\varphi_{21}=1+2\left(\frac{h}{d}\right)^2- -2\frac{h}{d}\sqrt{1+\left(\frac{h}{a}\right)^2}$
5. Multi-row system of tubes and the parallel plane		$\varphi_{12}=1-(1-\varphi_{12})$

In this case, the mutual radiant heat transfer surface (in formula (2.1.24)) is calculated as:

$$A=\varphi_{12}A_1=\varphi_{21}A_2$$

where A_1, A_2 is the geometric surface of the radiator and the receiver respectively, m^2.

Table 2.1.5 Efficiency coefficients of open heaters

Heater configuration	Values of α_{eff}
Tape, zigzag-shaped, freely suspended	0.46
Wire, zigzag-shaped, freely suspended	0.62
Wire, spirally wound on the tube	0.46
Wire, spirally wound on the edge	0.39
Wire, spiral groove	0.31

In the case of mixed heat transfer

$$R_T = \sum_{i=1}^{i=n} R_{Ti} \qquad (2.1.26)$$

where R_T is the thermal resistance to heat transfer by conduction, convection, and radiation.

The total thermal resistance is:

$$R_{TT} = \sum_{i=1}^{i=n} \frac{R_{Ti}}{A_i} \,. \qquad (2.1.27)$$

The reciprocal of thermal resistance is called the heat transfer coefficient.

2.1.4. Heating kinetics. The temperature of a heated body is a ‘burden’ that balances the energy supplied to a body, the energy spent for heating a body, and the energy lost to the environment. Violating the equality of these energies increases or decreases the body temperature and, finally, can disrupt a technological process or destroy a heating element.

The body temperature variation at heating is called heating kinetics of a body.

We will consider the simplest case of heating a homogeneous and isotropic body. We assume that only the body temperature varies with heating, and its other physical parameters, environmental temperature, and heat transfer conditions remain unchanged. We also assume that heat conduction of the body material is infinite and, hence, body temperature is uniform.

The heat balance equation is of the form:

$$dQ_1 = dQ_2 + dQ_3, \qquad (2.1.28)$$

where dQ_1, dQ_2, dQ_3 is the heat amount supplied to the body during the time $d\tau$ that is spent for body temperature variations and is lost to the environment respectively.

The heat balance components are:

$$dQ_1 = Pd\tau;\ dQ_2 = mcdt;$$

$$dQ_3 = k\,(t - t_0)\,Ad\tau$$

where P is the power supplied to the body, W; m is the body mass, kg; c is the specific heat capacity of the body at heating, J/(kg·°C); dt is the body temperature variation during $d\tau$, °C; k is the coefficient of heat transfer from the heated body to the environment, W/,m^2·°C; t_0 is the environmental temperature, °C; A is the heat transfer surface area, m^2.

Equation (2.1.28) can be presented in the form:

$$Pd\tau = mcdt + k(t - t_0)\,Ad\tau, \tag{2.1.29}$$

or

$$mcdt\,/\,(kAd\tau) + t - [t_0 + P/(kA)] = 0. \tag{2.1.30}$$

The heating time constant, *c,* is denoted by:

$$T = \frac{mc}{kA}, \tag{2.1.31}$$

and the steady-state temperature of the body (at $dt/d\tau = 0$) by

$$t_S = t_0 + P/(kA). \tag{2.1.32}$$

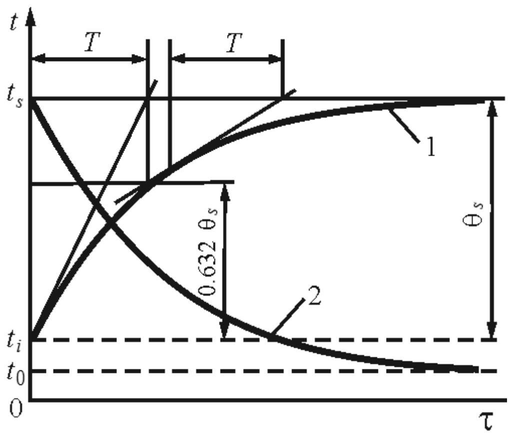


Fig. 2.1.1. Temperature variation with body heating (1) or cooling (2)

Differential equation (2.1.30) can then be written as

$$T\frac{dt}{d\tau}+t-t_s=0\,.$$

In the heating case, its solution has the form

$$t = t_i e^{-\tau/T} + t_s(1 - e^{-\tau/T}) \tag{2.1.33}$$

where t_i is the body temperature at the initial time instant (at $\tau = 0$).

Relation (2.1.33) is the heating equation for a homogeneous body. Graphically, it represents the exponent (Fig. 2.1.1) that starts with the temperature $t = t_i$ at $\tau = 0$. Asymptotically, it approaches the steady value of t_s when $\tau \to\infty$. Practically, already at $\tau = (3–4)T$ the steady-state regime is coming and $t = (0.95–0.98)\ t_s$.

Equation (2.1.33) can yield an expression for definition of the heating time of the body at any temperature t in the range from t_i to t_s

$$\tau = T\cdot\ln[(t_s - t_i) / (t_s - t)]. \tag{2.1.34}$$

We designate the current and steady excess of the temperature of the body over its initial temperature as $\theta = (t - t_i)$ and $\theta_s = t_s - t_i$. Equation (2.1.33) can then be given in the form:

$$\theta = \theta_s\,(1 - e^{-\tau/T}). \tag{2.1.35}$$

The heating time constant T is an important parameter of the heated body. Numerically, it is the ratio of the heat capacity of the body to its heat-release ability and is the time, during which the body would achieve a steady-state temperature, when heat is not transferred to the environment. At such conditions, the body temperature would vary in time linearly. It is easy to verify by substituting $k = 0$ into expression (2.1.29). This is the basis of the graphical definition of the time constant T (Fig. 2.1.1). Expression (2.1.35) shows that at $\tau = T$, $\theta = 0.632\theta_s$.

As seen from formula (2.1.31), the time constant does not depend on the power supplied to the body, but it depends only on the conditions between its heat transfer and the environment.

Similarly, we can derive the equation for cooling if according to formula (2.1.29), $P = 0$:

$$t = t_s\, e^{-\tau/T} + t_0\,(1 - e^{-\tau/T}) \tag{2.1.36}$$

or

$$\theta = \theta_s\, e^{-\tau/T} \tag{2.1.37}$$

where $\theta_s = t_s - t_0$ is the steady excess of the body temperature over the environmental temperature; T is the cooling time constant. In the general case, it is not equal to the heating time constant.

Heating processes of complex real objects are described by higher-order (second, third) differential equations that cannot always be solved in a simple manner. The heating curves for real objects differ from those in Fig. 2.1.1 in virtue of those simplifications that were made in deriving equation (2.1.33). However, the general variations of the temperature and its parameters remain unchanged.

The important characteristic of the thermal process is the heating rate. It can be obtained by differentiating equation (2.1.33) with respect to τ:

$$\frac{dt}{d\tau} = \frac{t_s - t_i}{T} e^{-\tau/T} = \frac{t - t_i}{T} \cdot \frac{e^{-\tau/T}}{1 - e^{-\tau/T}} . \qquad (2.1.38)$$

The heating rate is limited by the technological requirements, for example, by excluding a possible spoilage of heated materials, which is of special significance during heat treatment of agricultural products (grain drying, milk pasteurization, fodder steaming).

2.1.5. Calculating the power of electric heating devices. The heating power of material depends on its thermophysical properties and technological heating parameters. Power can be: useful, calculated, consumed, installed, and nominal. But all starts with energy.

The useful energy for material heating, J, is:

$$Q = mc(t_2 - t_1) \text{ or } Q = m(h_2 - h_1). \qquad (2.1.39)$$

The useful energy is consumed only for increasing the material temperature.

The useful power, W, at material heating is:

$$P = \frac{m}{\tau} c(t_2 - t_1),\ P = \frac{m}{\tau}(h_2 - h_1) . \qquad (2.1.40)$$

With melting and evaporation, it is equal to:

$$P = \frac{m}{\tau}\left[c(t_2 - t_1) + q\right] \qquad (2.1.41)$$

where m is the material mass, kg; c is the specific heat capacity of the material, J/(kg·°C); t_1, t_2 is the initial and final heat temperature, respectively, °C; τ is the heating time, s; q is the phase transition specific heat of the material, J/kg; $m / \tau = m_\tau$ is the device performance, kg/s; h_1, h_2

is the material enthalpy at the beginning and end of heating respectively, J/kg.

The power needed for room heating or the heat flux lost through the room fences, W, is approximately equal to:

$$P_H = q_H V(t_{in} - t_{out}) \tag{2.1.42}$$

where q_H = 0.45–0.95 (W/(m^3 °C)) is the specific heating characteristic of the room; V is the room volume, m^3; t_{in}, t_{out} is the calculated air temperature indoors and outdoors respectively, °C.

If the livestock room volume is unknown, then it can be calculated

$$V = v_0 N \tag{2.1.43}$$

where v_0 is the standardized specific volume of the room. Depending on the animal species, it ranges from 6 to 15 m^3/head; N is the number of animals or poultry in the room, heads.

The air heating power at room ventilation, W, is:

$$P_{vent} = q_{vent} V(t_{in} - t_{out}), \tag{2.1.44}$$

at drying of materials, W, it is:

$$P_{vent} = \rho_a L_{vent} (h_{in} - h_{out}) \tag{2.1.45}$$

where q_{vent} is the specific ventilation characteristic of the livestock room. It ranges from 1.0 to 1.4, W/(m^3·°C); ρ_a is the air density equal to 1.2 kg/ m^3; L_{vent} is the volumetric air supply, m^3/s.

The air supply, m^3/s, is equal to

$$L_{vent} = \frac{m_{moist}}{d_{in} - d_{out}}, \; L_{vent} = l_{vent} N \tag{2.1.46}$$

where m_{moist} is the removed moisture mass, kg/s; d_{in}, d_{out} is the moisture content of the incoming (outdoor) and outgoing air respectively, kg/m^3; l_{vent} is the minimum standardized air exchange, m^3/head. For example, for 300–500 kg cows, air exchange is 51–85 m^3/head.

The removed moisture mass, kg, is

$$m_{moist} = \omega_{an} N; \; m_{moist} = \frac{m_{dr}(W_1 - W_2)}{100 - W_2} \tag{2.1.47}$$

where ω_{an} is the amount of the water vapors released by animals or poultry, kg/head. For example, for pregnant sows, it is 0.39–0.45 kg/head; m_{dr} is the supply of the drying material, kg/s; W_1, W_2 is the initial and final moisture content of the material respectively, %.

The power lost through the fences of forcing beds and greenhouses, W, is:

$$P_{loss} = \varphi_0 A_0 k_0 \tag{2.1.48}$$

where the φ_0's are the heat losses through the fences, W/m^2; A_0 is the inventory area, m^2; k_0 = 1.25–1.50 is the fence coefficient – the fence-to-inventory area ratio.

Heat losses can be determined by the formula:

$$\varphi_0 = k(t_{in} - t_{out})k_{inf} \tag{2.1.49}$$

where k = 3.3–10.0 is the heat transfer coefficient, W/(m^2·°C); t_{in}, t_{out} is the calculated temperature of the incoming and outgoing air respectively, °C; k_{inf} = 1.25–1.4 is the infiltration coefficient in greenhouses and k_{inf} = 1 is the infiltration coefficient in forcing beds.

The calculated power, W, is:

$$P_C = \frac{P}{\eta_T} \tag{2.1.50}$$

where η_T = 0.7–0.95 is the thermal efficiency of the installation.

The power consumed from the electrical network, W, is:

$$P_{el} = \frac{P}{\eta_T \eta_{el}} \tag{2.1.51}$$

where η_{el} = 0.5–0.98 is the electrical efficiency of the installation.

The installed power, W, is:

$$P_{in} = \frac{k_S P}{\eta_T \eta_{el}} \tag{2.1.52}$$

where k_S = 1.05–1.10 is the safety factor. It takes into account the power decrease during the operation of the installation.

The nominal power is the installation power at nominal supply voltage, current frequency, temperature, resistance of heaters, and other parameters indicated in the technical data sheet of the installation.

The main energy characteristics of electric heating installations are: nominal power, thermal and electrical efficiency, and power factor cos φ.

The thermal efficiency takes into account the energy losses spent for heating the installation and the environment. It depends on the mass and thermophysical parameters of the materials used in manufacturing the installation, as well as on the temperature and the surface area, the temperature and velocity of the air surrounding the installation. Thermal insulation and the decrease in the heat transfer surface area, as well as the increase in the heating rate effectively enhance the thermal efficiency, but they lead to other additional costs.

Expression (2.1.50) shows that the thermal efficiency is:

$$h_T = \frac{P}{P_C} = \frac{P}{P + \Delta P_T} \tag{2.1.53}$$

where $\Delta P_T = \Delta P_{in} + \Delta P_{env}$ are the total heat losses spent for heating the installation and the environment, W.

The electrical efficiency allows for electric energy losses in wires, contacts of switching units, signal lamps, etc. Especially large energy losses are available in the devices many times converting the network voltage and the industrial frequency current to the high voltage and to the high-frequency currents in induction and capacitor heating installations.

The power factor of heating installations used in the agricultural production is close or equal to unity. Exceptions are the induction and capacitor heating installations, in which the value of the power factor cos φ increases up to 0.95–0.98 with the use of the generally accepted reactive energy compensation methods.