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Temperature field

Modeling of multiphysical problems

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- Temperature
- Triple point
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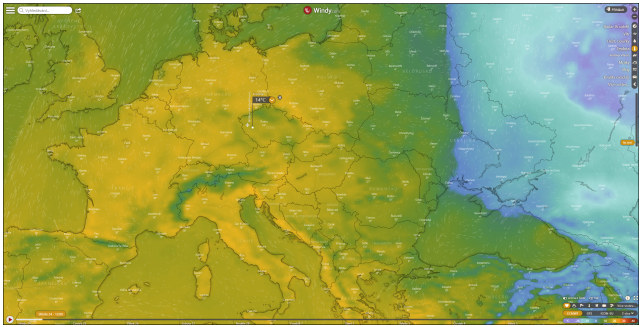


Temperature field

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Temperature is one of the basic physical quantities that can be used to accurately quantify feelings as "cold"or "hot."Low temperature characterizes cold objects while high temperature indicates hot objects. These are macroscopic manifestations of microscopic movement.



We commonly encounter a temperature map.

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- A scalar quantity that is related to the kinetic energy of mass particles.

$$W_{\mathrm{k}} = \sum_{i=1}^{n} \frac{1}{2} m v_i^2,$$

where $\boldsymbol{v}_i$ is the velocity of the individual particles corresponding to their microscopic motion. The body as a whole remains in rest.

- The Latin word "temperatura"can be translated as "pleasant feeling".
- There are various thermometer scales - the most common are Celsius and Kelvin, others such as Fahrenheit or Réaumur

$$K = C + 273.15\,, \quad F = \frac{9C}{5} + 32\,, \quad R = \frac{4}{5}C\,.$$

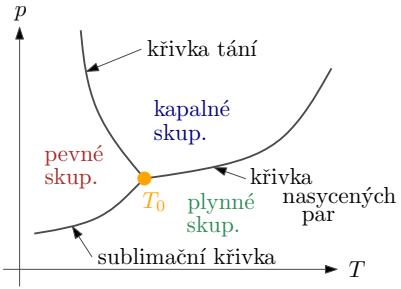


- 1 °C = 1 K (water melting point 0 °C, water boiling point 100 °C).
- Absolute zero is defined as a temperature of 0 K, which corresponds to a temperature of -273 , 15 °C.

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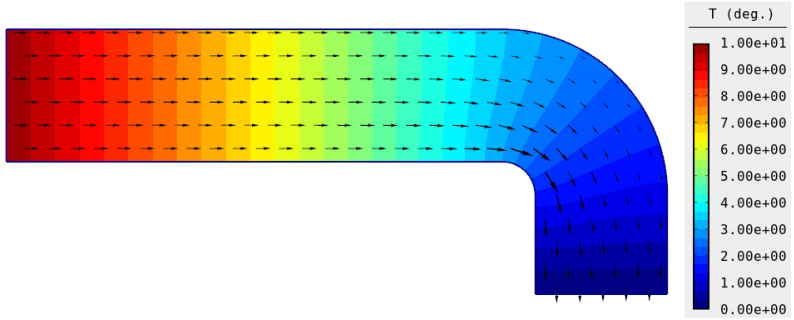
The phase diagram is used to display the dependence of the state variables of a thermodynamic system (temperature and pressure).

- **Melting curve** - passing through the curve leads to melting of the solid phase or solidifying the liquid phase.
- **Sublimation curve** - passing through the curve leads to subliming the solid phase or, conversely, desubliming the gas phase.
- **Saturated vapor curve** - passing through the curve leads to evaporating the liquid or, conversely, condensating the gases.



- The phase changes on the curves. The supplied energy is used to change the state and does not increase the temperature of the body.
- The triple point specifies the state in which all states can exist at the same time. The triple point temperature is the basic temperature for implementing the thermodynamic temperature scale.
- 1 Kelvin is $1/273{,}16$ part of the absolute temperature of the triple point of water.

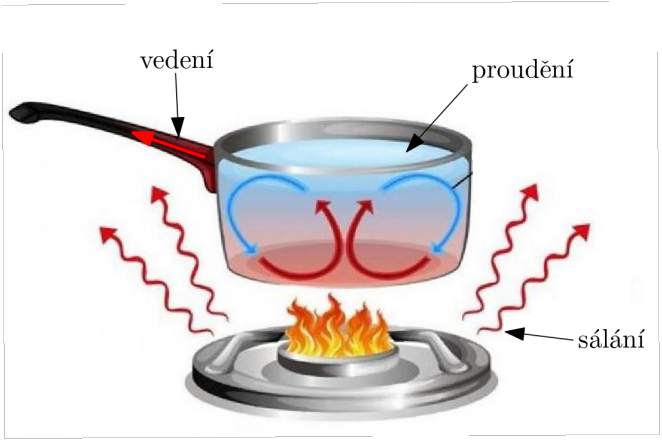
- By heat transfer we mean the transport of energy due to the existence of a temperature gradient. Therefore, if there is a temperature difference in any environment, heat transfer must occur.
- Thermal energy in a system without external sources flows freely from places with higher temperatures to places with low temperatures.



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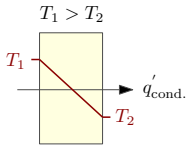
Forms of heat transfer



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Heat transfer by conduction is caused by direct contact of particles in the substance. Energy transfer is mediated by the direct pressure of molecules in fluids, the movement of free electrons in metals, or the vibration of phonons [1]

- Conducted heat transfer is most important in solid materials where the atoms are in a close contact. In liquids or gases, the molecules are sparsely distributed and thus have a lower chance of colliding and transferring thermal energy.
- Metals are the best conductors of thermal energy. This is caused by the metal bond (unlike a covalent or ionic bond), in which the valence electrons of atoms form a so-called electron gas. Electrons are shared by all atoms and can move freely in the lattice. These electrons are able to quickly transfer thermal energy from one place to another.



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[1] A phonon is a quasi-particle that propagates a vibrational quantum in a crystal lattice. Using phonons, we can describe the propagation of sound waves in crystals.

The heat transfer capacity can be quantified by the thermal conductivity $\lambda\,(\mathrm{W m^{-1} K^{-1}})$. This is defined as the amount of heat Q (J) that can be transferred at the unit temperature gradient ΔT (K) per unit time Δt (s) through the wall of unit thickness Δl (m) in the direction of the normal.

The heat flux density through the conduit can be qualitatively expressed as

$$q'_{\mathrm{cond.}} = -\lambda \cdot \mathrm{grad}\, T,$$

where $q'_{\mathrm{cond.}}$ is the conductive heat flux density ($\mathrm{W m^{-2}}$), λ is the thermal conductivity and T is the thermodynamic temperature. Next, we introduce the temperature gradient by the relation

$$\boldsymbol{G} = -\mathrm{grad}\, T.$$

The relationship between the temperature gradient and the heat flux density is

$$\boldsymbol{q} = \lambda \boldsymbol{G}.$$

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The temperature field has generally divergence and is circulation-free. The temperature gradient equation must therefore apply

$$\operatorname{rot} \boldsymbol{G} = 0, \quad \oint_c \boldsymbol{G}\,\mathrm{d}\boldsymbol{l} = 0.$$

and heat flow continuity equation (stationary case)

$$\operatorname{div} \boldsymbol{q} = p, \quad \oint_S \boldsymbol{q}\,\mathrm{d}\boldsymbol{S} = P.$$

	$\lambda\,(\mathrm{W m^{-1} K^{-1}})$
Copper	385
Aluminum	237
Iron	80
Concrete	1.23
Brick	0.418
Glass	0.14

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There is a strong analogy between the temperature and electric fields. It is given by their own principles. The dominant method of conduction is the same for metals for thermal and electrical conductivity (free electrons), so that it is logical that there is a dependence between the two conductivities defined by the textbf Wiedemann-Franz's law

$$LT = \frac{\lambda}{\gamma},$$

where λ is the thermal conductivity, γ is the electrical conductivity and $L = 2.45 \cdot 10^{-8}\,(\mathrm{W\Omega K^{-2}})$ (Lorentz number) is the proportionality constant.

Wiedemann-Franz's law states that the ratio between thermal and electrical conductivity of metals varies proportionally (linearly) with temperature.

The principle can be explained by the fact that free electrons in metals participate in the transfer of heat and electric charge. Thermal conductivity increases with the average velocity / vibration of electrons, as this increases the ability to transfer thermal (disordered) energy. However, the electrical conductivity decreases with increasing velocity of the particles (disordered motion - "thermal"vibrations), because the collisions of electrons with the nuclei of atoms reduce the ability of ordered oriented motion of electrons.

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Similarly as in electric field, the thermal resistance of the material can therefore be defined

$$R = \frac{d}{\lambda \cdot S}\,(\mathrm{KW}^{-1})\,, \quad \left(R_{\mathrm{el}} = \frac{l}{\gamma \cdot S}\,(\Omega)\right)$$

where d is the thickness of the insulating material and S its area.

!!! Do not confuse the thermal resistance and thermal conductivity !!!

Thermal conductivity

$$a = \frac{\lambda}{\rho c_{\mathrm{p}}}\,(\mathrm{m}^2\mathrm{s}^{-1})$$

it includes three physical constants of the material (thermal conductivity λ, density ρ, specific heat capacity c_{p}) and comprehensively characterizes each substance. The higher a, the faster the body heats or cools.

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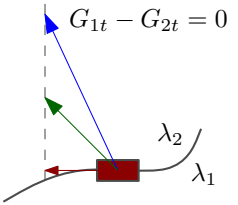
The differential heat conduction equation applies only at regular points in the environment. For example, regular points are not points that separate one environment from another and where the conductivity of λ changes abruptly. The state vectors of the gradient of the temperature field $\boldsymbol{G}$ and the heat flux $\boldsymbol{q}$ change

- Condition for $\boldsymbol{G} = -\mathrm{grad}\, T$

$$G_{1t} - G_{2t} = 0$$

- Condition for $\boldsymbol{q} = -\lambda \cdot \mathrm{grad}\, T$

$$q_{1n} - q_{2n} = \frac{P}{\triangle S} = q^{'}$$

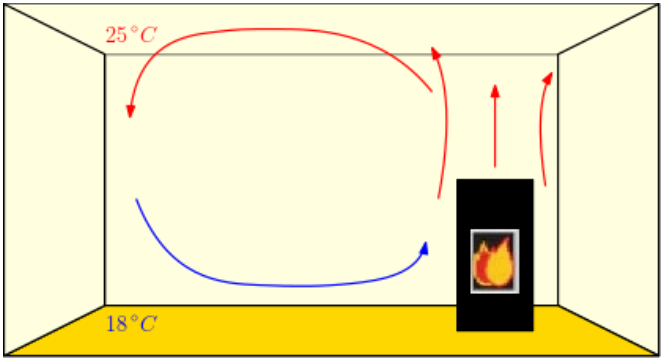


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By flow we mean the transfer of heat from one place to another by means of a liquid or gas. This method of heat transfer is dominant in these states.



An example is the flow of air in a room.

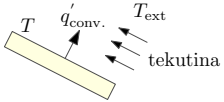
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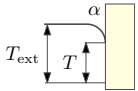
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Convection is the transfer of thermal energy between solids and flowing fluids. As the velocity of the fluid moves, the heat flux caused by convection also increases. Convection can be divided into two basic categories:

- Natural convection is conditioned by the presence of a solid in a fluid and by the difference in temperature of its surface and the surrounding environment. An example is the natural convection of heat flow from a building.
- Forced convection is induced by forced movement of the fluid around the solid body. An example could be cooling the body with a fan or flowing water.





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The convective heat flux density can be written as

$$q'_{\mathrm{conv.}} = \alpha \left(T - T_{\mathrm{ext}} \right),$$

where $q'_{\mathrm{conv.}}$ is the heat flux density, α is the heat transfer coefficient, which generally depends on the density, velocity and temperature of the flowing fluid, T is the thermodynamic temperature and finally T_{ext} is the ambient temperature of the flowing fluid.

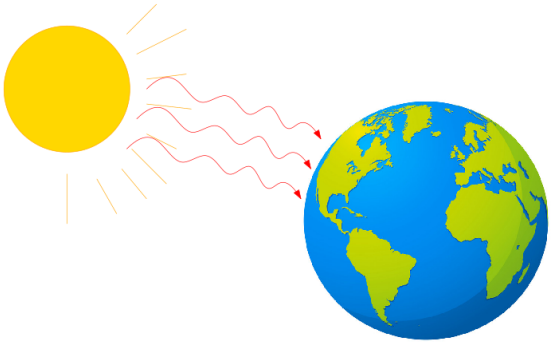
	$\alpha\,(\mathrm{Wm^{-2}K^{-1}})$
air (natural convection)	2 - 25
liquids (natural convection)	50 - 1000
air (forced convection)	25 - 250
liquids (forced convection)	100 - 20000
convection with phase change (boiling or condensation)	2500 - 100000

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By radiation we mean the transfer of heat to the surrounding space by electromagnetic waves. This energy is emitted by every body with a non-zero temperature. Thermal energy from the Sun travels in the form of electromagnetic waves to our planet. Another example can be the heat emitted by home heating - infrared panel.



The most important thing for life is the transfer of heat by radiation from the sun.

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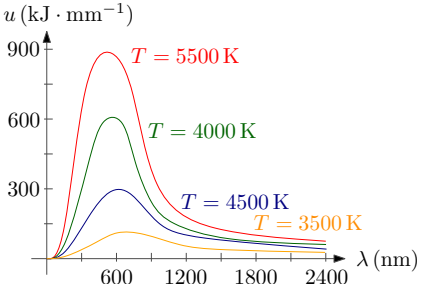
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Wien's law of displacement

The ability of a body to absorb or emit electromagnetic radiation depends on the wavelength. The amount of energy emitted by a body thus varies with frequency, and its amount is described by Wien's displacement law

$$\lambda_{\max} = \frac{2.898 \cdot 10^{-3}}{T}.$$

This relationship means that the higher the temperature T, the more the maximum radiation shifts to the shorter wavelength side. The value $2.898\ \mathrm{mmK}$ is the so-called Wien constant.



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The emissivity of the surface of each body depends on the wavelength of the electromagnetic radiation emitted by the body and thus also on the surface temperature.

The body emits only long-wave, infrared radiation from its surface at low temperatures.

With increasing temperature, the spectral radiance curve increases upwards and at the same time shifts its peak to shorter wavelengths.

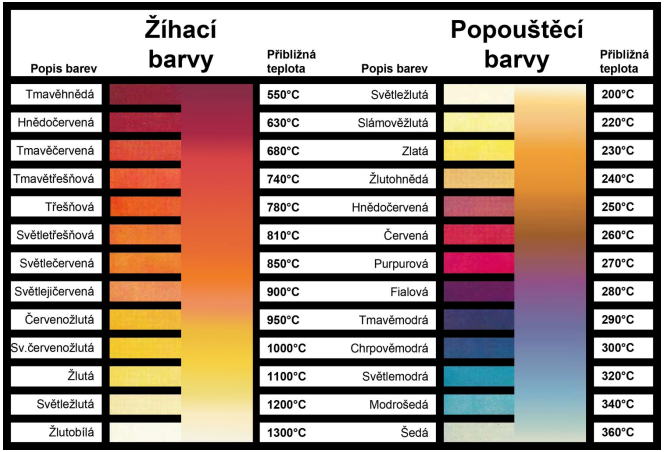
As the temperature of the body rises, we first see its surface as dark red, and gradually the color changes to orange, yellow and finally to white as the part of the emission area, that extends into the visible spectrum, increases.

The table of annealing and tempering colors is then defined on this principle.

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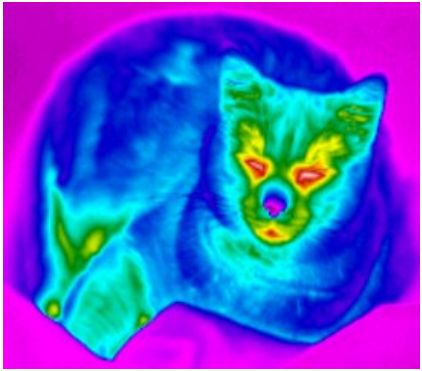
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Every body with a non-zero thermodynamic temperature glows.



Cat in the visible spectrum



Cat in the infra spectrum

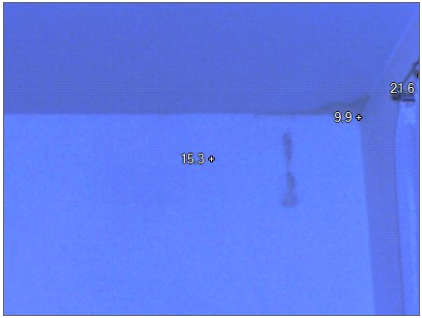
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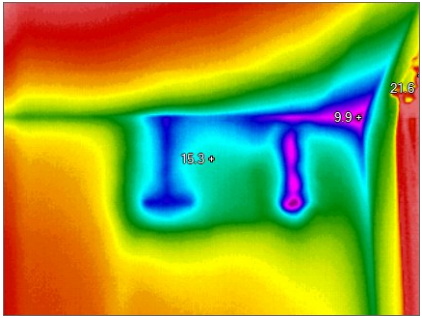
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Temperature field

Heat transfer by radiation



Corner in the apartment in the visible spectrum



Corner in the apartment in the infra spectrum

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Gases absorb and emit energy in characteristic wavelength patterns and can therefore be identified in this way. Visible light is another form of electromagnetic radiation with a lower wavelength (and thus a higher frequency) than the wavelength of infrared light.
The heat flux density emitted by radiation can be expressed by the relation

$$q'_{\mathrm{conv.}} = \epsilon\sigma \left(T^4 - T_{\mathrm{ext}}^4\right),$$

where $\epsilon \in \langle 0, 1 \rangle$ is the emissivity of the surface, $\sigma = 5.670374 \times 10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$ is the Stefan-Boltzmann constant and T_{ext} is the temperature of surrounding objects such as walls.

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The emissivity of a given material depends not only on the color of the surface but also on its purity and roughness. For these reasons, and to make it easier to adjust the emissivity during the measurement, a matt black paint is often used.

	$\epsilon\,(-)$
brick	0.93
concrete	0.88
iron	0.25
copper (oxidized)	0.50
copper (polished)	0.04



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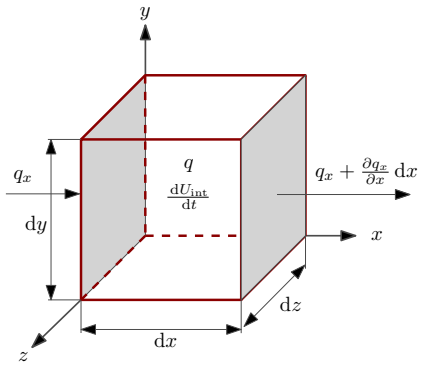
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Consider a homogeneous medium according to the figure. Taking into account the first law of thermodynamics, the overall energy balance of the system can be expressed by the relation

$$P_{\mathrm{in}} - P_{\mathrm{out}} = \frac{\mathrm{d}U_{\mathrm{int}}}{\mathrm{d}t} + P_{\mathrm{g}},$$

where P_{in} and P_{out} represent the incoming and outgoing heat flux, P_{g} expresses the power generated in the volume by an external source (for example Joule losses) and finally the term $\frac{\mathrm{d}U_{\mathrm{int}}}{\mathrm{d}t}$ represents the change in the internal energy of the system.



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The difference between the heat fluxes P_{in} and P_{out} in the direction of the x axis can be written in the form

$$P_{\mathrm{in},x} - P_{\mathrm{out},x} = \int_S \left(q_x - \left(q_x + \frac{\partial q_x}{\partial x}\,\mathrm{d}x \right) \right) \mathrm{d}y\,\mathrm{d}z = \int_V -\frac{\partial q_x}{\partial x}\,\mathrm{d}V = \int_V \frac{\partial}{\partial x}\lambda\frac{\partial T}{\partial x}\,\mathrm{d}V.$$

In a similar way, we obtain the difference in heat fluxes in the directions of the axes y and z, which can be summarized by the relation

$$P_{\mathrm{in}} - P_{\mathrm{out}} = \int_V \mathrm{div}\,\lambda\,\mathrm{grad}\,T\,\mathrm{d}V.$$

Note that the same result would be achieved by integrating the total flow over the surface of the elementary cube and then using the Gauss theorem

$$P_{\mathrm{in}} - P_{\mathrm{out}} = -\oint_S \boldsymbol{q}\,\mathrm{d}\boldsymbol{S} = -\int_V \mathrm{div}\,\boldsymbol{q}\,\mathrm{d}V = \int_V \mathrm{div}\,\lambda\,\mathrm{grad}\,T\,\mathrm{d}V.$$

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MINISTERSTVO ŠKOLSTVÍ MLÁDEŽE A TĚLOVÝCHOVY

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The change of the internal energy of the system accumulated in the volume $\mathrm{d}V$ is given by the relation

$$\frac{\mathrm{d}U_{\mathrm{int}}}{\mathrm{d}t} = \int_V \rho c_{\mathrm{p}} \frac{\mathrm{d}T}{\mathrm{d}t}\,\mathrm{d}V,$$

where ρ is the density of the material and c_{p} is the heat capacity. The complete time derivative can be further decomposed as

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \mathrm{grad}\, T,$$

where the term $\frac{\partial T}{\partial t}$ represents the rate of accumulation of internal energy and the term $\boldsymbol{v} \cdot \mathrm{grad}\, T$ the rate of convective flow due to the motion of a medium (most often a fluid). In most practical cases, a time change will suffice and we will not consider the velocity term. However, this member is strongly used in equipment for mixing or pumping molten metals.

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The term representing the power generated by the external source can be written in the form

$$P_{\mathrm{g}} = \int_V p \,\mathrm{d}V,$$

where p is the specific power supplied by the external source. Substituting all terms into the heat balance we get the following equation

$$\int_V \operatorname{div} \lambda \operatorname{grad} T \,\mathrm{d}V = \int_V \rho c_{\mathrm{p}} \left(\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \operatorname{grad} T \right) \mathrm{d}V + \int_V p \,\mathrm{d}V,$$

By eliminating the elementary volume $\mathrm{d}V$ (the balance must hold for any volume) we obtain a nonstationary Fourier - Kirchhoff partial differential equation of heat conduction in the form

$$-\operatorname{div} \lambda \operatorname{grad} T + \rho c_{\mathrm{p}} \left(\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \operatorname{grad} T \right) = p,$$

where T is the thermodynamic temperature, ρ is the specific gravity of the material, c_{p} is the heat capacity and p is the external heat source.

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In the linear case, the conductivity λ can be put before the divergence operator and we get the equation in the form

$$\operatorname{div}\operatorname{grad} T = -\frac{\rho c_{\mathrm{p}}}{\lambda} \cdot \frac{\partial T}{\partial t} - \frac{p}{\lambda}.$$

In the case of the steady state, the derivative on the right is zero and the equation becomes the Poisson's equation

$$\triangle T = -\frac{p}{\lambda}.$$

The temperature distribution in an environment without internal sources is described by the Laplace equation.

$$\triangle T = 0.$$

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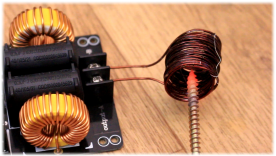
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Induction heating

Induction heating



Induction cooker - https://careershapers.wordpress.com/



Homemade induction cooker - https://electronoobs.com/



Induction crucible in Belgium- https://www.induction-furnaces.com/

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Induction heating

A special area in temperature problems is induction heating. This is a separate chapter with huge potential for practice. Induction heating has largely replaced or is replacing conventional heating methods in a number of industries. In practice, it

can be used from heating food to large melting furnaces with a volume of many tons. The main benefits include:

- efficiency - the charge is heated directly (internal source)
- easy regulation and localizability
- cleanliness of operation, ecology
- can be realized in a protective atmosphere

As for induction heating, it is based on the principle of electromagnetic induction. The harmonic current flowing through the conductor (usually at higher frequencies on the order of kHz) generates a harmonic electromagnetic field and a voltage is induced in the charge due to the principle of electromagnetic induction. If the charge is conductive, eddy currents (Foucault currents) will begin to flow through it, and as a result of the Joule losses, the charge will begin to heat up.

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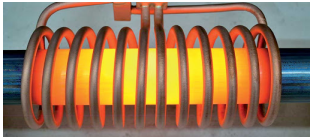
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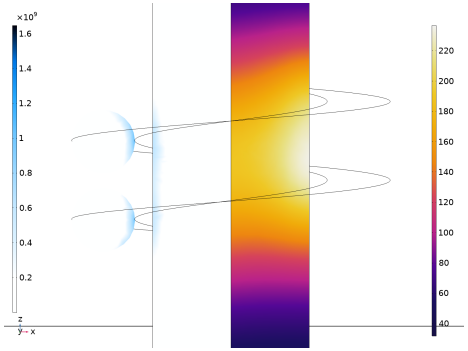
Induction heating

Thanks to physical principles, eddy currents and thus also heating are dominant at the surface of the charge, which is why it is also referred to as surface heating. For practical use, a known relationship for penetration depth is important

$$\delta = \sqrt{\frac{2}{\omega\gamma\mu}}.$$



ceia-power.com



Distribution of losses (left) and temperature (right) in the section

From the viewpoint of modeling, this is a combined task of electromagnetic and temperature fields.

By a combined problem we mean the problem of multiple physical domains described by several different partial differential equations solved with a certain degree of interconnection.

The harmonic electromagnetic field can be described by a previously derived Helmholtz equation in the form for harmonic quantities

$$\Delta \underline{\boldsymbol{A}} - \mathrm{j}\omega\gamma\mu\underline{\boldsymbol{A}} = -\mu\underline{\boldsymbol{J}}_{\mathrm{ext}} \,,$$

where the conversion of the equation into a complex equation, using a complex operator. To do this, it is necessary to consider the parts of the linear environment and the velocity term is neglected.

The term $-\mathrm{j}\omega\gamma\mu\underline{\boldsymbol{A}}$ corresponds to eddy currents or current density of induced currents.

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The temperature field is described by the Fourier-Kirchhoff equation

$$\operatorname{div}\ (\lambda \operatorname{grad} T) = \rho c_{\mathrm{p}} \frac{\partial T}{\partial t} - w\,,$$

where again the moving member is neglected.

The variable w respects the internal heating sources. In the case of a combination of a temperature field with an electromagnetic field, such sources are losses that can be divided into eddy current losses (Joule losses) and hysteresis losses

$$w = w_{\mathrm{J}} + w_{\mathrm{H}}\,.$$

Hysteresis losses have a dominant effect only at lower frequencies, for example as losses in transformers or rotating machines. At frequencies in the order of kHz, hysteresis losses against eddy current losses can be neglected, without any significant error, and it is possible to define the relationship between the electromagnetic field (as a loss generator) and the temperature field (where they represent the source quantity).

$$w = w_{\mathrm{J}} = \frac{|\underline{\boldsymbol{J}}_{\mathrm{ind}}|^2}{2\gamma} = \frac{|-\mathrm{j}\omega\mu\gamma\underline{\boldsymbol{A}}|^2}{2\gamma}\,.$$

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Děkuji za pozornost

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