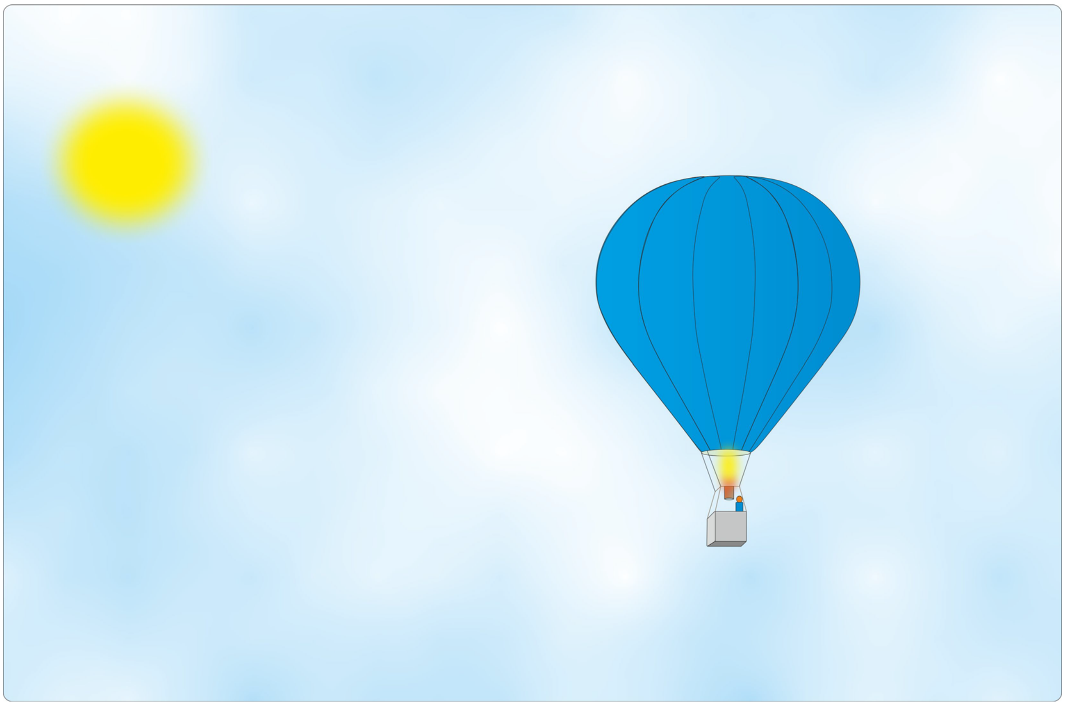
Basic Knowledge

WL	Fundamental Principles of Heat Transfer



Basic Knowledge

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Version 1.0

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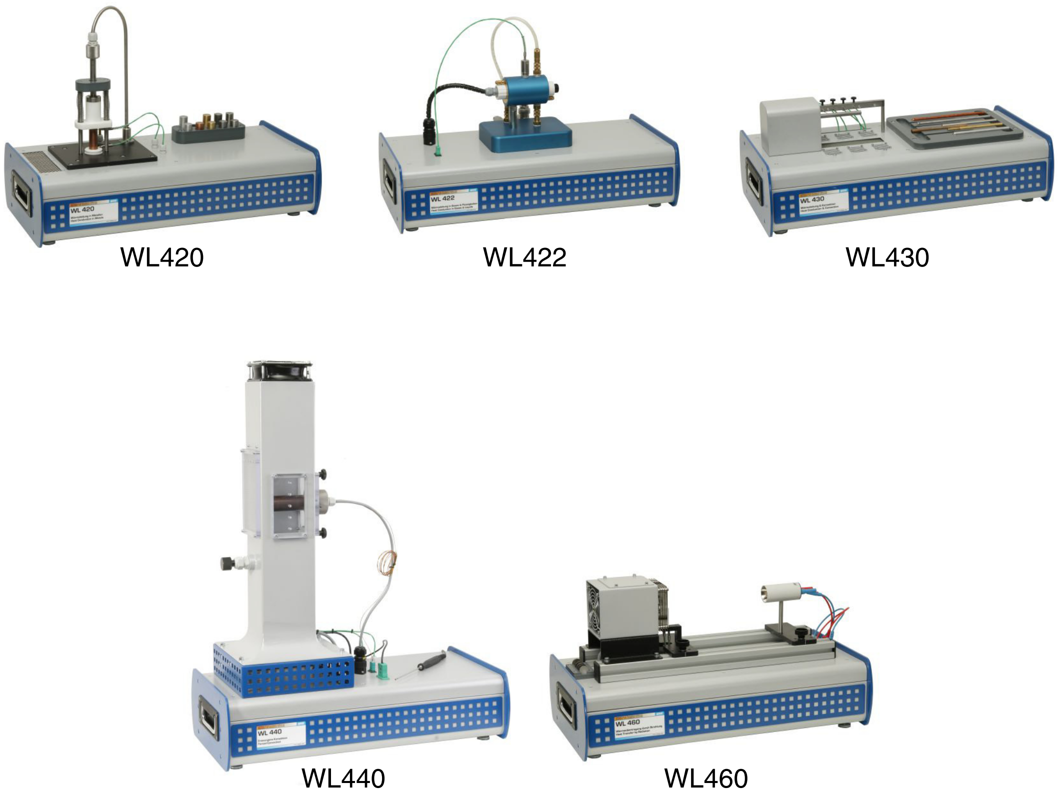
1 Introduction

The WL400 Thermoline device series consists of 5 devices and provides fundamental heat transfer experiments:


WL420 WL422 WL430

WL440 WL460

Fig. 1.1 WL400 Thermoline device series

The exhaustive range of experiments of this device family introduces students experimentally into the fundamentals of heat transfer.

It is didactically necessary that the student already knows the fundamentals before starting to run and evaluate the experiments.

An introduction into the technical language of this field, together with the development of the elementary relations and variables, is presupposed.

Any suitable technical book and any lecture in thermodynamics communicates these fundamentals.

This introduction to fundamentals from GUNT helps you to repeat the necessary knowledge modules, or to attain them. It is presented more illustratively, and less mathematically. The content is selective, based on the experimental areas listed above.

In addition to a hardcopy, these fundamentals are also available as a PDF and as a digital tutorial, integrated into the measurement data acquisition software of the WL400 device series.

1.1 General information on heat transfer

Heat transfer is an effect that you encounter in various situations of everyday life. Almost every change in the temperature of a body is caused by heat transfer processes. This starts with the naturally occurring day-night cycle and can be traced right up to the usage of technical products.

Heat transfer is of essential significance for many technical devices and systems in which heat either accrues during technical processes and must be dissipated to ensure safe operation, or is required to maintain a process.

Two examples:

- In the internal combustion engine, heat is a by-product that accrues during operation. To protect materials from overheating, the heat must be dissipated to the environment, see Fig. 1.2.
- A given temperature must be reached when distilling substances (e.g. crude oil). This is achieved by transferring heat to the substances to be distilled, see Fig. 1.3.

An insight into the fundamentals of the various heat transfer mechanisms is provided in the following. The single effects are first considered. The last chapter provides a consideration of combined effects. These are the normal case.

Each sub-chapter contains a summary with practical examples.

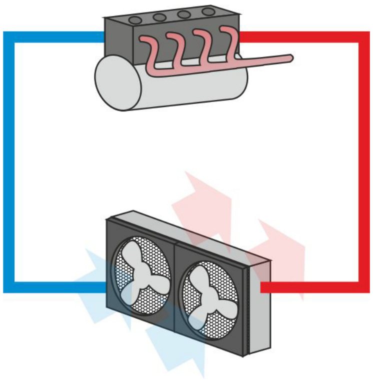


Fig. 1.2 Cooling circuit of an internal combustion engine

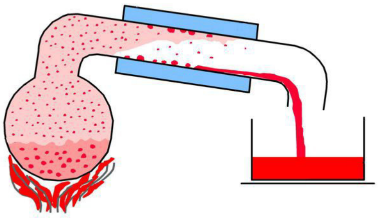


Fig. 1.3 Heat input during distillation

1.2 Heat as a form of energy

Heat is a form of energy that is transferred from one system to another due to a temperature difference. If two bodies with different temperatures are brought into thermal contact, you can see that after a certain time their temperatures balance. This is referred to as thermal equilibrium. Thermal energy has flowed from the body with the higher temperature to the body with the lower temperature. Both bodies now have the same final temperature.

There is no thermal change of state in which heat from a body with low temperature is transferred to a body with a higher temperature.

The terms temperature and heat must be differentiated for a correct understanding of heat transfer. Each body has heat in the form of energy. Part of this thermal energy flows during the equalisation effort involved in balancing a temperature.

1.3 Stationary heat transfer

A consideration of stationary heat transfer suffices for most applications. This applies when the temperatures no longer change over time.

The following statements can be made when there is a stationary state:

- The temperatures remain constant.
- In the system under consideration, the incoming and outgoing energies are identical, $Q_{in} = Q_{out}$.
- No heat storage or heat dissipation occurs in the system.

This is the final state after a heating-up or cooling-down process.

The fundamentals described here relate to stationary heat transfer.

1.3.1 Amount of heat *Q*

The thermal energy of a body is proportional to its mass m, the material property "heat capacity" c and its temperature T:

$$Q = m \cdot c \cdot T \tag{1.1}$$

Q = amount of heat
m = mass of a body
c = specific heat capacity
T = temperature

Heat is a form of energy. Energy is the ability to perform work. Heat, energy and work have the same unit.

During heat transfer, thermal energy flows due to the equalisation effort. The heat is thereby bound to a substance and is therefore present in a given quantity. The heat that is transferred can be calculated by determining the difference in the temperature:

$$\Delta Q = m \cdot c \cdot \Delta T \tag{1.2}$$

ΔQ = difference of heat quantity before - after
ΔT = temperature difference

1.3.2 Temperature *T*

Temperature is a quantity-dependent variable. It describes the energetic state of a body. The temperature is proportional to the average value of the kinetic energy of atoms and molecules. These oscillate. High temperatures are movements with large swings, low temperatures have lower swings.

1.3.3 Specific thermal capacity *c*

A substance stores heat via the movement of atoms or molecules. Less or more heat can be stored, depending on the atomic configuration of a substance. Heat capacity is therefore a substance-dependent value.

The term “specific” indicates that the value refers to the mass.

The specific heat capacity is a measure for the thermal energy ΔQ required to heat 1 *kg* of a substance by 1 *K*.

The specific heat capacity *c* of various substances:

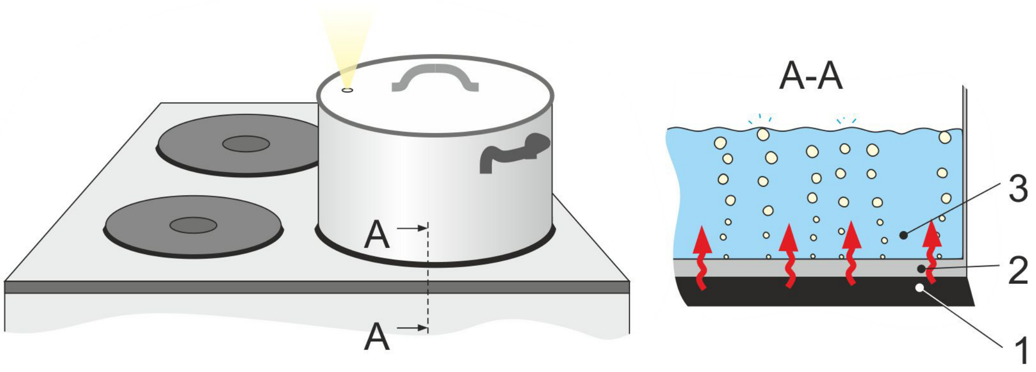
Water	4,182 kJ/KgK
Aluminium	0,896 kJ/KgK
Iron	0,452 kJ/KgK
Lead	0,129 kJ/KgK
Air	1,005 kJ/KgK

1.4 Heat transfer

The driving force in heat transfer is the temperature difference. If there is a temperature difference then a quantity of heat is transferred. This can happen in several ways.

1.4.1 Heat conduction

Heat conduction occurs whenever there is material contact and temperature differences between substances (atoms and molecules) This is the case in solid, liquid and gaseous substances. It also applies when there is a bodily contact between two surfaces, such as a pot on a stove. Convective heat transfers from solid surfaces to fluids (liquids and gases) also occur due to heat conduction.



1 Hotplate
2 Pot
3 Water

Fig. 1.4 Heat conduction based on the example of a pot

The picture shows a pot that transfers heat from the hotplate to the water.

The thermal conductivity of solids is quite high, but it is quite low for liquids and gases. A thin gas layer is therefore used by double-glazed windows as thermal insulation. Cooling fins use the good thermal conductivity of metals to distribute the heat over the entire length.

1.4.2 Convection

A fluid can transmit the heat in flow processes. The transmitted quantity of heat increases in comparison to pure heat conduction, which would only be possible by the unmoved fluid.

Due to the increase in the transmitted quantity of heat, the surface temperature drops and the temperature difference to the fluid reduces. The convective heat transfer improves due to the heat transport with the fluid.

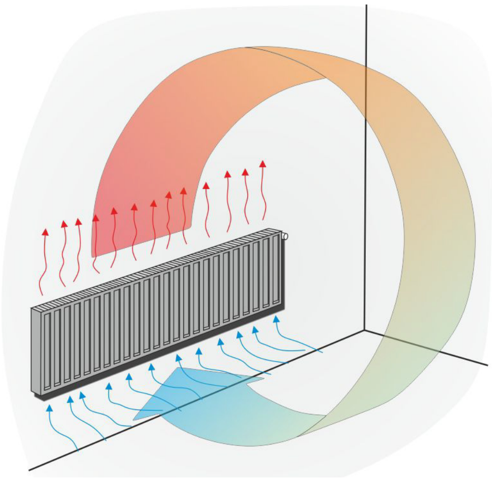


Fig. 1.5 The heater releases heat by convection

Fig. 1.5 shows a heater that dissipates heat to the air. The air circulates in the room and skims over the warm surface. The heat is transferred by convection at the boundary surface.

1.4.3 Electromagnetic radiation

Energy is emitted (transmitted) and absorbed (collected) as electromagnetic radiation at every surface The quantity of heat of a body thereby increases or decreases. The environmental conditions are significantly involved in this process.

Gases can also collect and absorb radiation. However, this only occurs within very narrow bandwidths (absorption band). The surrounding air in the earth's atmosphere can therefore be assumed to be permeable to radiation.

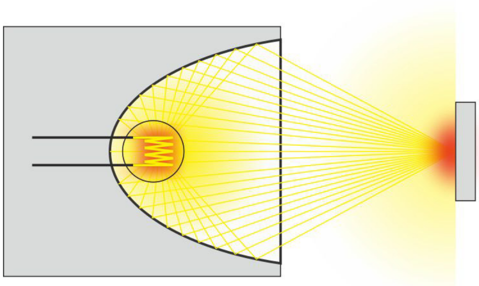


Fig. 1.6 Spotlight for heating specimens

1.5 Heat flux

If a constant heat quantity is emitted over a given time, then Formula (1.1), Page 5 is as follows:

$$\dot{Q} = \frac{Q}{t} = \frac{m \cdot c \cdot T}{t} \qquad (1.3)$$

$\dot{Q}$ = heat flux
Q = heat quantity
m = mass, the quantity of a substance
c = specific heat capacity
T = temperature
t = time

Consideration of two processes:

- The heating of a mass with a temperature increase $\Delta T/\Delta t$
  This temperature change occurs when the system under consideration is not yet in a stationary state.
- The constant temperature increase of the mass flow rate $\Delta m/\Delta t$
  Here, a mass flow rate is heated continuously by a temperature difference, for instance an even air flow during convection.

1.6 Thermal resistance

Heat is transferred when there is a temperature difference. The thermal resistance indicates whether the heat can flow relatively freely or if it is held back. Thermal resistance is generally defined as:

$$R = \frac{\Delta T}{\dot{Q}} \tag{1.4}$$

$\dot{Q}$ = heat flux
R = thermal resistance
ΔT= temperature difference

The thermal resistance can be calculated using Formula (1.4).

2 Heat conduction

Heat conduction is mostly spatial. To simplify matters, reference is made here to only one-dimensional heat conduction (e.g. in a thin rod). The procedure describes the heat flux through a solid body or a still liquid.

The energetic state of a body can be described by its temperature. The temperature is proportional to the vibration state of the material. An active vibration state transfers itself to the surrounding material. Equalisation takes place.

The following substances can be differentiated in the configuration of the materials:

- Heterogeneous materials,
  with variable expansion characteristics. Examples:
  - Wood
  - Reinforced concrete
  - Fibre-reinforced composites
- Homogeneous materials,
  with the same expansion characteristics. Examples:
  - Gases
  - Liquids
  - Metals
  - Non-metals

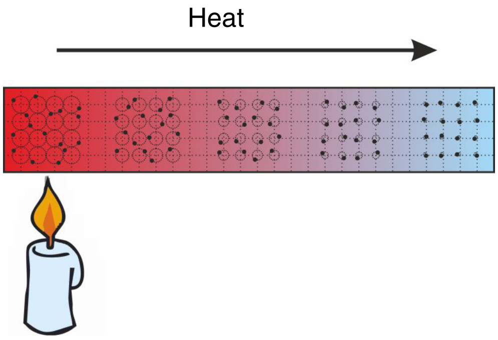


Fig. 2.1 Heat conduction in a metal rod

2.1 Head conduction - Explained by configuration of the material

The arrangement and the cohesion in the configuration of the material is fundamental for heat conduction.

2.1.1 Heterogeneous materials

These materials have variable characteristics. This is due to the different composition within the material itself. This can have effects on the physical characteristics (heat conduction) with regard to spatial expansion.

Related to heat conduction, the preferred direction of reinforced concrete is that in which the steel reinforcements run, because steel is a better heat conductor than concrete.

2.1.2 Homogeneous materials

The characteristics of these materials do not change over the expansion - they are the same. There are no differences in the configuration of the material. This means that there is no preferred direction for the effects of heat conduction. The heat is conducted in all directions evenly.

2.1.2.1 Gases

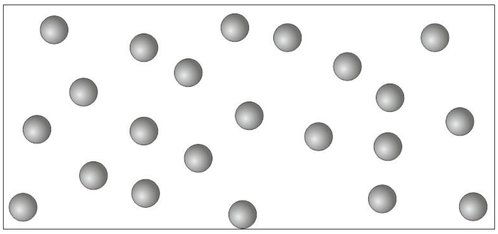


Fig. 2.2 Model of gas

Pure gases and gas mixtures are always homogeneous materials (substances). The single gas particles (atoms and/or molecules) have long distances to the next particle, relative to their own size. Thermal energy can only be transferred by collisions. Therefore, heat conduction of gases is at its lowest compared to solid bodies and fluids. When a gas heats up, the average velocity of the particles increases. This results in an increase in pressure and/or volumes.

2.1.2.2 Liquids

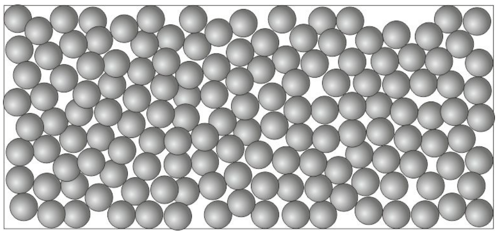


Fig. 2.3 Model of liquids

In contrast to gases, the single liquid particles are connected to each other by bondings. This means that the particles are much closer to each other. In addition to collision, thermal energy can also be transferred by mechanical coupling. Liquids thereby have better thermal conductivity than gases.

2.1.2.3 Metals

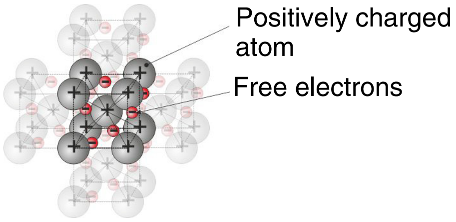


Fig. 2.4 Metal model within the crystal-line structure

Regarding thermal conductivity, metals are classified as homogeneous materials. At room temperature, almost all metals have an ordered, crystal-lattice atomic configuration. The atoms share common electrons within this crystal lattice. These electrons are also called free electrons. They can move freely and are what causes the conductive characteristic of the metals.

Because heat is the movement at the atomic level, the electrons can have heat within them.

The specified configuration of the metals results in them not just being good electrical conductors, but also good heat conductors.

Typical metals are: Aluminium, copper, iron, etc.

Alloys also have these characteristics, whereby the thermal and electrical conductive characteristics of pure metals are always higher.

Typical alloys are: Brass, bronze, steel, etc.

2.1.2.4 Non-metals

In contrast to metals, non-metals have a configuration that does not permit any free electrons. They are therefore considered as non-conductors. Their heat conduction is worse than that of metals.

Typical non-metals are: Ceramics, stone, plastics, etc.

2.2 Level wall

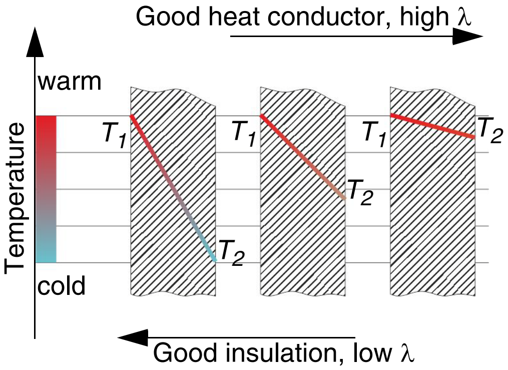


Fig. 2.5 Temperature course in various materials at the same temperature *T1*

Only linear heat conduction is dealt with in the following. This means that there are no heat fluxes transverse to the direction viewed. Heat conduction through an even wall can then be reduced. Thermal conductivity λ is the characteristic variable of the material for good or poor heat conduction.

The higher the thermal conductivity of a material, the lower is the temperature difference at the same heat flux.

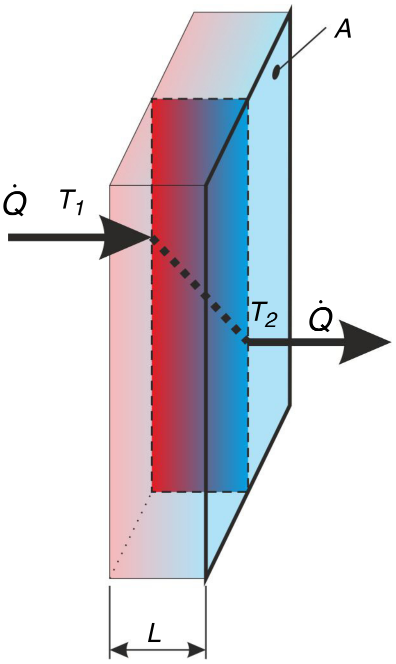


Fig. 2.6 Illustration for the calculation

The heat flux can be calculated using the following formula:

$$\dot{Q} = \lambda \cdot \frac{A}{L} \cdot (T_1 - T_2) \quad (2.1)$$

$\dot{Q}$ = heat flux
λ = thermal conductivity
L = length
A = cross-sectional area
T = temperatures

Thermal conductivity of various materials:

Substance	Thermal conductivity in W/m K
Copper	400
Aluminium	237
Steel	45...55
Stainless steel	15
Concrete	2,1
Teflon	0,23
PVC	0,15
Water (0°C)	0,56
Air	0,026

Tab. 2.1 Thermal conductivity of selected materials:

2.3 Summary/practical significance

High heat conduction (in this case, aluminium) is exploited by the cooler Fig. 2.7 to distribute the heat along the cooling fin. The temperature drop over the length is therefore rather small. This ensures an even level of temperature difference to the air with a good convective heat transfer to the air, compare Chapter 3.

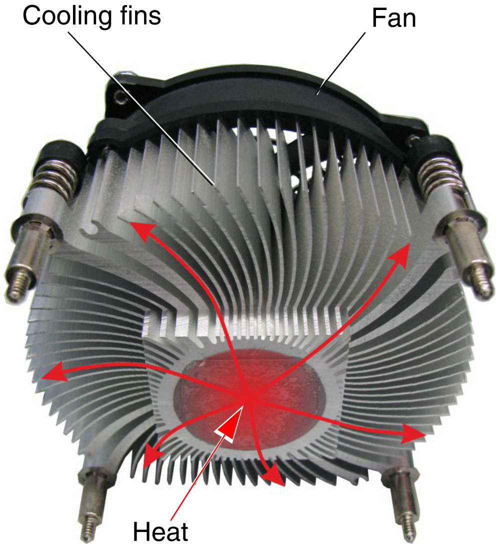


Fig. 2.7 Heat conduction at CPU cooler

Accordingly, a poor heat-conducting material, e.g. foam is used for insulation Fig. 2.8 in order to hinder heat transfer.

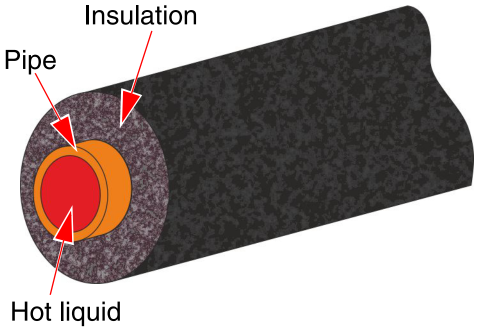


Fig. 2.8 Pipe insulation

Furthermore, the pipe has the smallest ratio of heat-conducting surface to the cross-section of the flow. The conductive cross-section increases in proportion to the circumference. Fig. 2.8 shows a comparison.

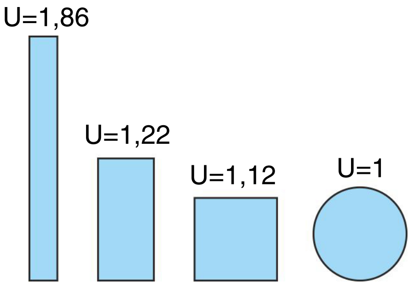


Fig. 2.9 Comparison of circumference to area

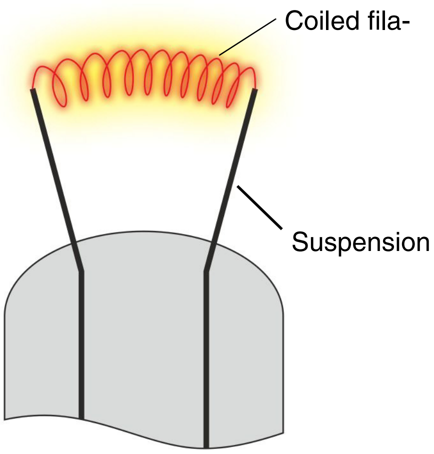


Fig. 2.10 Suspension of a coiled filament in a bulb

Another insulation method is shown in Fig. 2.10. In case of the bulb, an attempt is made to convert the used energy into light as efficiently as possible. Therefore, the coiled filament should not lose any heat through heat conduction.
Because conductors (metals) are required for the suspension, bad heat conductors cannot be used. In return, the suspension is designed relatively long and thin, which also ensures bad heat transfer by conduction.

In this example you can clearly see that the heat flux has been minimised by the design of the cross-sectional area to length *A/L*:

$$\dot{Q} = \lambda \cdot \frac{A}{L} \cdot (T_1 - T_2)$$

$\dot{Q}$ = heat flux
λ = thermal conductivity
L = length
A = cross-sectional area
T = temperatures

3 Convection

Convection is the heat transfer between a surface and a fluid (gas or liquid). To demarcate this from conduction, it is decisive that this fluid transports the heat through motion.

In the following, it is tacitly assumed that we are dealing with the heating of the fluid. The fundamentals are identical when cooling, except for the algebraic sign.

3.1 Definition of free convection

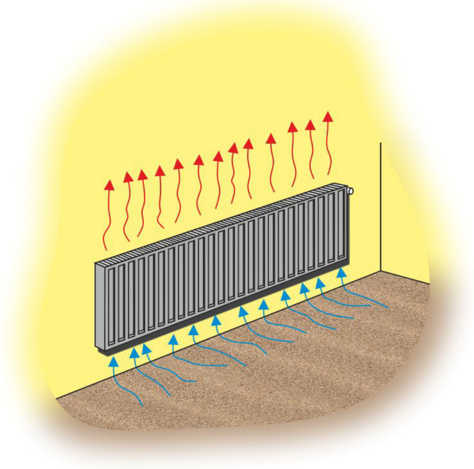


Fig. 3.1 Free convection at a heater

Convective heat transfer is the transfer of heat through fluid particles in motion. In free convection, the motion of the fluid is caused by the density differences resulting from warming. The heated fluid develops a free, vertical and upward-pointing flow. New, cool fluid from the surroundings flows in. An equilibrium occurs. The inward flow and the outward flow must be unimpeded for free convection.

A large temperature difference arises due to the increased transport of heat vis-a-vis conduction. The equalisation effort increases, and the convective heat transfer increases.

3.2 Definition of forced convection

In forced convection, there is an incident flow of the heat transferring surface. This can be facilitated by an external technical device, such as a fan. But it can also be exploited, for instance, by the head wind of vehicles. This results in an increased speed compared to free convection. The quicker transport of the hot fluid causes a higher temperature gradient from the warm surface to the fluid, and thus a better heat transfer.

Fig. 3.2 Forced convection at blown cooling fins

3.3 General procedure

There are similarities in convection, irrespective of the exact procedure.

The hot surface transfers heat to the fluid. This occurs directly at the boundary layer by conduction into the adjacent fluid.

The heat now flows in two directions:

Vertical to the surface into the fluid.

Parallel to the surface with the motion of the fluid.

If convective heat transfer is to be influenced, then these two heat fluxes must be influenced. This cannot be done separately.

Flow formation is directly linked to this topic.

3.3.1 Heat transport - laminar flow

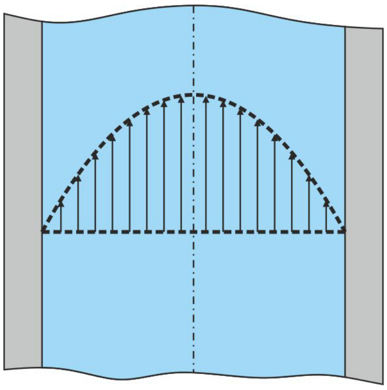


Fig. 3.3 Laminar pipe flow

The flow at a surface can form differently. When the speed of the fluid is relatively low, the movement is in layers parallel to the surface. The layer that covers the surface does not move. This effect is know as the no-slip condition. Adhesion prevents motion.

Fig. 3.3 shows the flow within a pipe. The speed is zero directly at the edge. The speed increases with increased wall clearance, with the maximum in the middle.

In this type of flow, the fluid layers flow off from each other. The flow is ordered, the velocity vector is always aligned in the axial direction. Heat penetrates into the more removed layers due to conduction.

3.3.2 Heat transport - turbulent flow

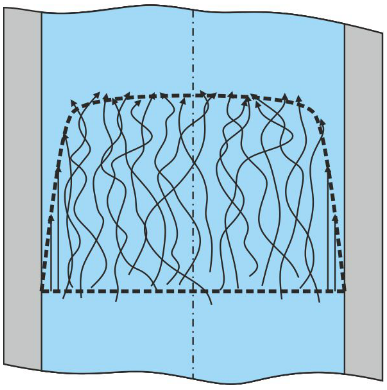


Fig. 3.4 Turbulent pipe flow

If the speed increases, a different velocity profile becomes apparent after a certain point.

The first fluid layer once more adheres to the surface at speed zero (no-slip condition). This is followed by a very narrow area in which the layers show laminar slip; this is the laminar sublayer.

The most significant difference for convection begins behind this. The flow is turbulent. This means that there is indeed a main flow direction, but this is covered by random velocity elements in other directions. For the pipe flow shown in Fig. 3.4, the median is indicated by the dotted velocity profile. Due to the random flow elements, there is also motion transverse to the surface. Turbulence over the thin laminar sublayer causes the layers to mix with each other.

Heat is transported away from the surface by the motion of the fluid particles. In comparison to laminar flow, therefore, there is an improved heat transfer from the wall to the fluid.

3.4 Processes during free convection

Due to conduction of the fluid, the temperature of the fluid drops the further away it is from the surface. The following illustration shows a vertical plate that transfers heat to the surrounding fluid. The temperature is shown by the colour gradient:

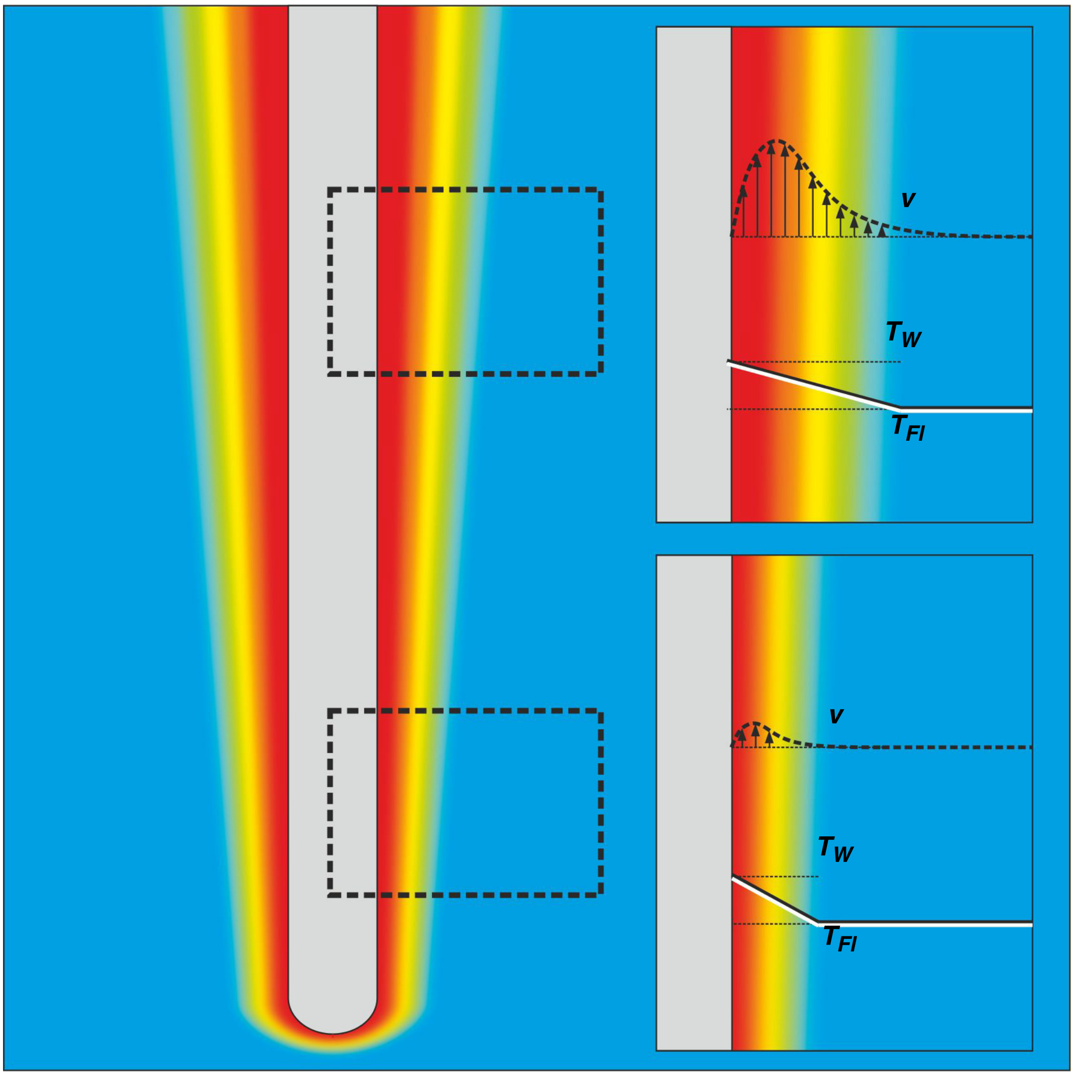


Fig. 3.5 Speed and temperature during free convection

A layer is formed in which the heat penetrates into the fluid. This is called the temperature boundary layer.

There is also an additional velocity boundary layer caused by buoyancy forces. The buoyancy forces only affect the heated fluid layers. Due to the no-slip condition, the hottest fluid layer on the surface is stationary. In the adjacent fluid layers, the velocity increases up to a maximum and then decreases. This viscosity of the fluid influences the thickness of the velocity boundary layer. It ranges up to the undisturbed fluid.

Only fluid layers that rise due to heating can transport the heat. Temperature and velocity boundary layers have a significant influence.

Influence of free convection:

The increase in the **temperature differences** between the surface and the fluid ensures two things:

- The heat penetrates deeper into the fluid.
- The increased heat increases the lift, and therefore the velocity.

The increase in **size** also has two effects:

- The effective area of the heat transfer is increased.
- The larger the swept length, the more heat is absorbed and the greater is the flow velocity.

In practice, one seldom has the opportunity of selecting the **fluid** . If this is possible, then you can influence the heat and flow values. These influences are illustrated based on a comparison of air and water.

- Relation of temperature to velocity boundary layer
  For air, the boundary layer thicknesses are of the same order. For water, the temperature boundary layer is thinner than the velocity boundary layer. This results in a higher temperature gradient. The relatively thick velocity boundary layer moves a greater mass flow, which transports the heat better.
- The effective buoyancy force is influenced by the change in density during warming. Air expands more than water when heated. The air is therefore lifted more when heated to the same extent.

Due to the increase in volume, the buoyancy force counteracts **gravity**. The vertical alignment of cooling fins is often based on this.

3.5 Processes in forced convection

The flow velocity of the fluid over the exothermic wall is induced by technical means. The heated fluid is therefore moved faster over the exothermic surface. The heat-dissipating mass flow is thereby higher than in free convection. The temperature difference to the surroundings drops due to improved heat dissipation.

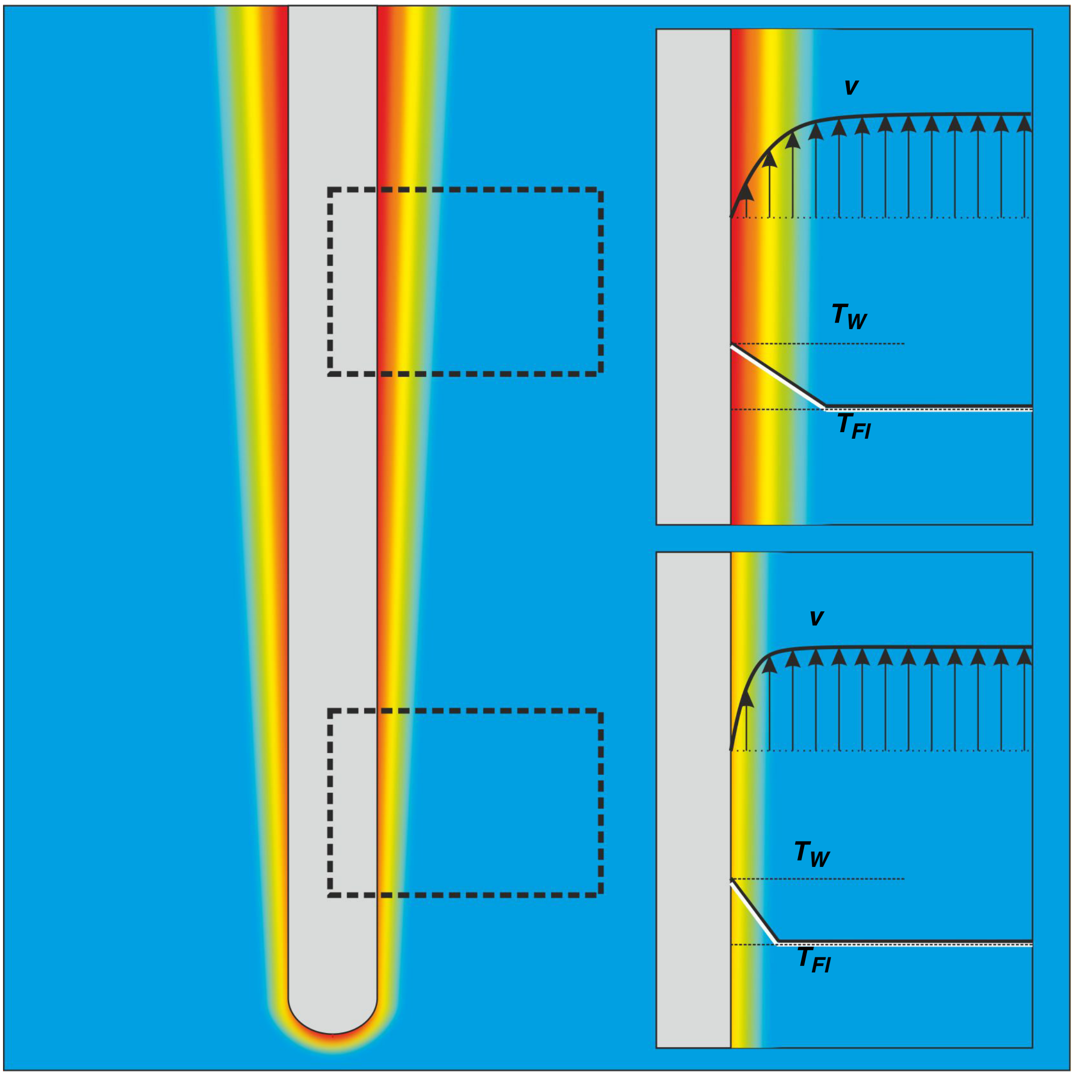


Fig. 3.6 Speed and temperature during forced convection

The temperature drop vertical to the surface is nevertheless greater than in free convection. This results in a higher equalisation effort, and convective heat transfer improves.

Influence of forced convection:

The **flow velocity** determines the volume of heat-absorbing fluid.

The heat transferring area swept by the fluid can be changed by altering the **size**.

The selection of the **fluid** influences the formation of the temperature and velocity boundary layer, although in practice it often can't be selected.

The **geometry** of the control of the flow can **agitate** or **calm** the flow. Configuration of the parameters mentioned allow the **flow formation** to be influenced (**laminar / turbulent**).

3.6 Calculation of convection

The heat flux of convection is calculated from:

$$\dot{Q} = A \cdot \alpha \cdot (T_S - T_{amb}) \qquad (3.1)$$

$\dot{Q}$ = heat flux
A = exothermic surface
α = heat transfer coefficient
T_{amb} = ambient temperature of fluid
T_S = surface temperature

The heat transfer coefficient can be taken from tables for some cases. These values often suffice for an initial estimate.

3.7 Theory of similarity

The theory of similarity is used in many fields of physics and is a particularly important foundation in heat transfer. Physical similarity means that the model is similar to its original in a certain property.

Example of a map:
A map describes a given area as a two-dimensional model. Its special feature is that it shows the position and distances between buildings, roads, streams, mountains, etc. In this example, the scale is the key indicator by which it is possible to transfer the conditions on the map to reality.

The processes during convection can be expressed using the Nusselt number.

Fig. 3.7 Section of a city map

3.8 Nusselt number

The Nusselt number is the improvement of heat transfer in convection compared to the heat transfer, which 'only' takes place by the heat conduction of the fluid.

It is calculated from:

$$Nu = \frac{\alpha \cdot L}{\lambda} \tag{3.2}$$

L = characteristic length
Nu = Nusselt number
α = heat transfer coefficient
λ = thermal conductivity

The length swept by the fluid is called the characteristic length. Fig. 3.8 shows two examples.

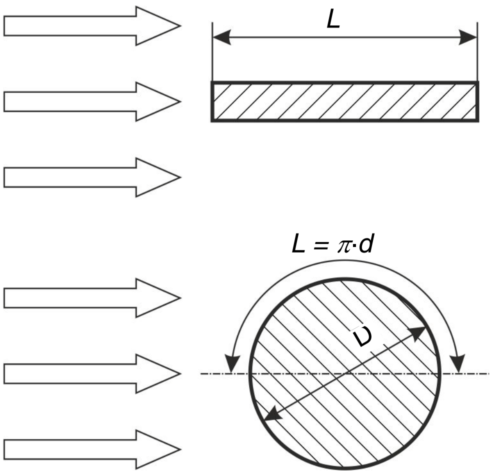


Fig. 3.8 Characteristic length

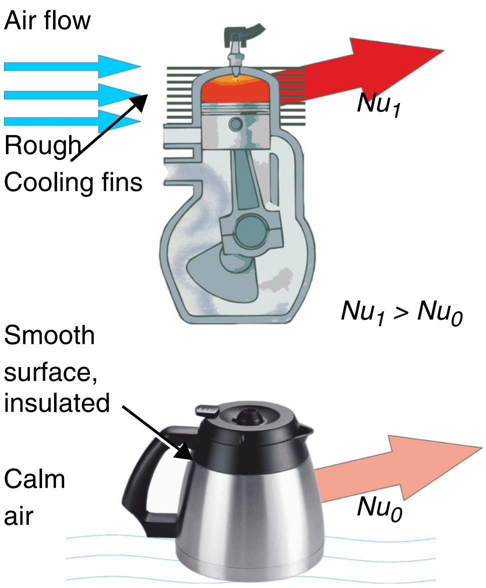


Fig. 3.9 Comparison of extreme Nusselt cases

The higher the Nusselt number, the better is the heat transferred by convection to the surrounding fluid.

The lowest Nusselt number is when air is at rest. The convective heat transfer is then of the same order as the conduction. This hardly ever happens due to density differences caused by heating, or due to naturally occurring air movement.

The Nusselt number changes along the surface flowed over. This is due to the change in the boundary layers, as can be seen in Fig. 3.5, Page 25 and Fig. 3.6, Page 29. The median Nusselt number, indexed as ‘m’, suffices for many applications: Nu_m.

For some geometries (e.g. plate, cylinder), the Nusselt number can be calculated from additional key indicators. Nusselt numbers can only be compared between identical geometries.

This allows a rough theoretical estimate to be made. Free and forced convection as well as laminar and turbulent flow must be differentiated in the calculation.

The heat transfer coefficient α can be determined using the Nusselt number.

Example:

For a flat plate (e.g. cooling fin), the Nusselt number is Nu=80. The fluid is air. The thermal conductivity thereby is λ=0,026 W/m K. The characteristic length is L=0,1 m.

The heat transfer coefficient is:

$$\alpha = \frac{Nu \cdot \lambda}{L} = \frac{48 \cdot 0{,}026 \frac{\mathrm{W}}{\mathrm{m} \cdot \mathrm{K}}}{0{,}1\,\mathrm{m}} = 20{,}8 \frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}} \tag{3.3}$$

3.9 Summary/practical significance

Our understanding of the processes during convection can be used to directly influence the heat flux.

When a body is to be heated or cooled in a targeted manner, a high exchange of energy is desired.

The contrast to this is the insulation of a body, in which there should be no heat exchange, when possible.

3.9.1 Insulating against convection

All convection presupposes a liquid or gaseous medium. One method of transferring less heat to the surrounding fluid is to minimize the motion of the fluid.

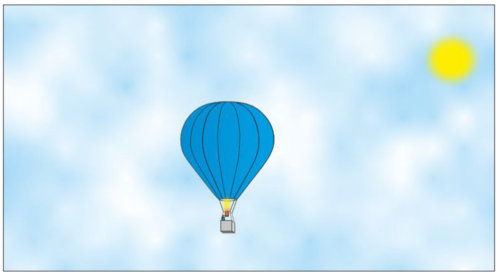


Fig. 3.10 Hot air balloon

The heat transferring surface is also often minimized. A ball is the optimum in terms of surface to volume. The best example for these two effects is the hot air balloon, see Fig. 3.10.

The shape of a hot air balloon approximates that of a ball. At a given volume, it has the smallest possible surface.

The balloon drifts with the air, preventing relative motion between the balloon and the surrounding air.

Fig. 3.11 Houses in cold surroundings must be well insulated.

In the application, the task is to influence the amount of energy transferred to the fluid. If a given flow cannot be influenced, then the surface can be reduced by the size, and the temperature difference between the surroundings and the surface can be reduced by lowering the surface temperatures with insulation. Prime examples of this are in thermally insulated buildings in a cold environment, or insulated pipes in plant manufacturing.

3.9.2 Promoting convection

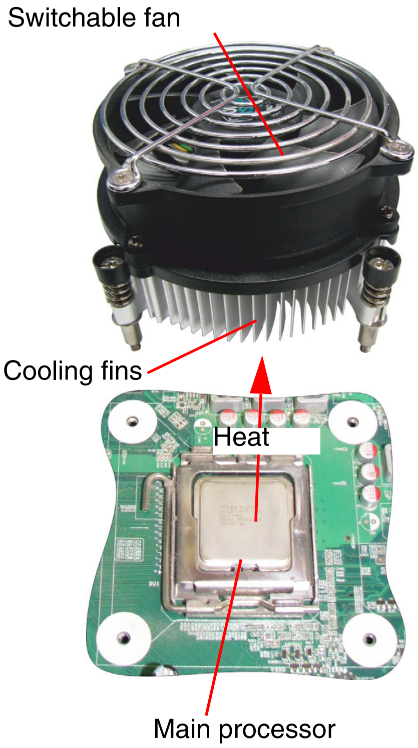


Fig. 3.12 CPU cooler on top of the main processor

Increasing the exothermic surface, and a good approach, promote convection.

Good conduction of the fin material is necessary (copper or aluminium) to efficiently dissipate the heat to the surroundings by convection. Fig. 3.12 shows the CPU cooler from the chapter on conduction. The heat from the main processor is transferred to the cooling fins. If there is insufficient free convection, the fan can additionally ensure forced convection.

Cooling fins are always aligned to the flow. To ensure unimpeded flow-off of the heated fluid, the cooling fins are vertical in free convection. In forced convection, the alignment is determined by the configuration of the flow control.

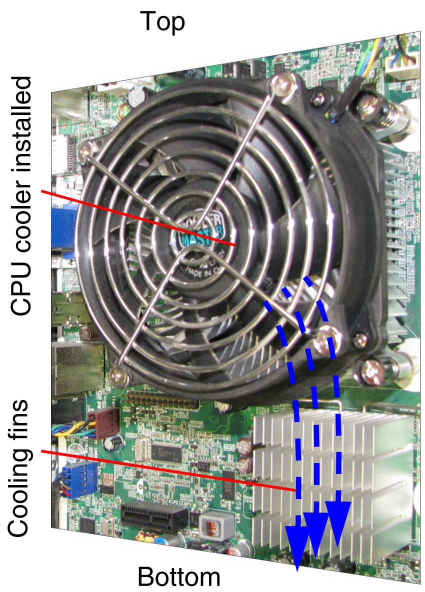


Fig. 3.13 Fan from Fig. 3.12 with additional cooling fins

The CPU cooler is shown in Fig. 3.13. Additional cooling fins are under this, indicating waste heat from an additional processor. These cooling fins are installed vertically to allow the air to flow through freely during free convection.

If the CPU cooler fan also activates, these cooling fins are cooled by the exhaust air. This air flow is indicated by the blue dotted line. This is then also forced convection.

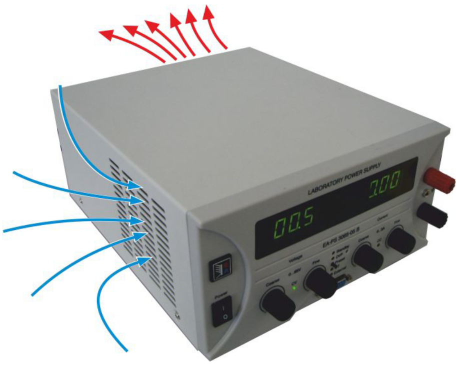


Fig. 3.14 Power supply with fan

In many applications, the provision of the flow means that you do not need to rely on the heated fluid escaping upwards. This is found, e.g. in many electronic devices that are fitted with a fan to ensure air exchange within their enclosure.

Often, it is impossible to easily dissipate the heat that arises at a location. With the help of the cooling circuit, the heat can be transported from its place of origin and can then be dissipated at another location by a separate cooler and enlarged surface.

An example of this or the CPU fan is shown in Fig. 3.12. The heat is transferred from a relatively small processor to the large surface of the cooling fins.

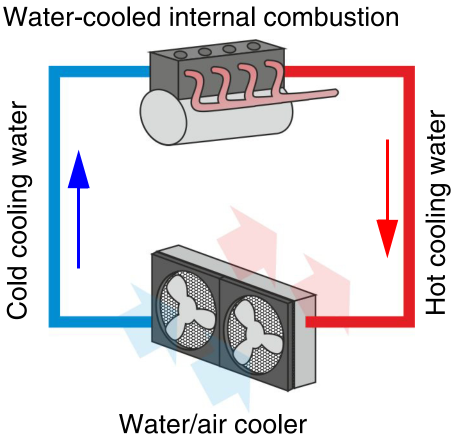


Fig. 3.15 Schematic of car engine with cooling circuit

A better-known example is the car. The heat arising from the internal combustion engine must be dissipated to the surroundings. The heat of the internal combustion engine is first transferred to the water of the cooling circuit, then from the cooling circuit to the ambient air.

In contrast to air, water heats much less at the same rate of thermal absorption. This makes the cooling of the internal combustion engine more efficient.

In contrast to this however, a much larger surface must be provided to cool the water so that the absorbed heat can be dissipated at a relatively lower temperature difference to the ambient air.

This is possible without any problem by heat transport with water. Typically, the cooler is directly at the front of the vehicle, where it can dissipate its heat to the head wind flowing into it.

4 Heat radiation

Energy can be exchanged between two bodies in the form of radiation. The radiation must be able to move from the one body to the other.

This is almost always the case when there is a ‘line of sight’ between the bodies.

4.1 The Stefan-Boltzmann equation

The Stefan-Boltzmann equation states that every body with a temperature over the absolute zero point emits radiation. The radiation corresponds to a heat flux. The principle is:

$$\dot{Q} \sim \sigma \cdot A \cdot T^4 \tag{4.1}$$

σ = Stefan-Boltzmann constant $5{,}67 \cdot 10^{-8}$ [$W/m^2 K^4$]
A = emitting surface
$\dot{Q}$ = heat flux
T = temperature

The emitted radiation increases to the fourth power of the temperature. The temperature is the absolute temperature in Kelvin.

However, energy is not only emitted - it is also absorbed through radiation from the surroundings. This is the only way to achieve equilibrium. This also occurs according to the formula shown.

4.1.1 Emission spectrum

Electromagnetic radiation can be characterised and classified by its wavelength. The wavelength range between 380 to 780 nanometres is known as visible light.

The thermal or infra-red radiation range is at wavelengths from 780 nm - 1 mm. The terms thermal or infra-red radiation are *generally* used synonymously.

NOTICE

Each type of electromagnetic radiation contains energy and can therefore contribute to the increase or decrease in the energy of a body.

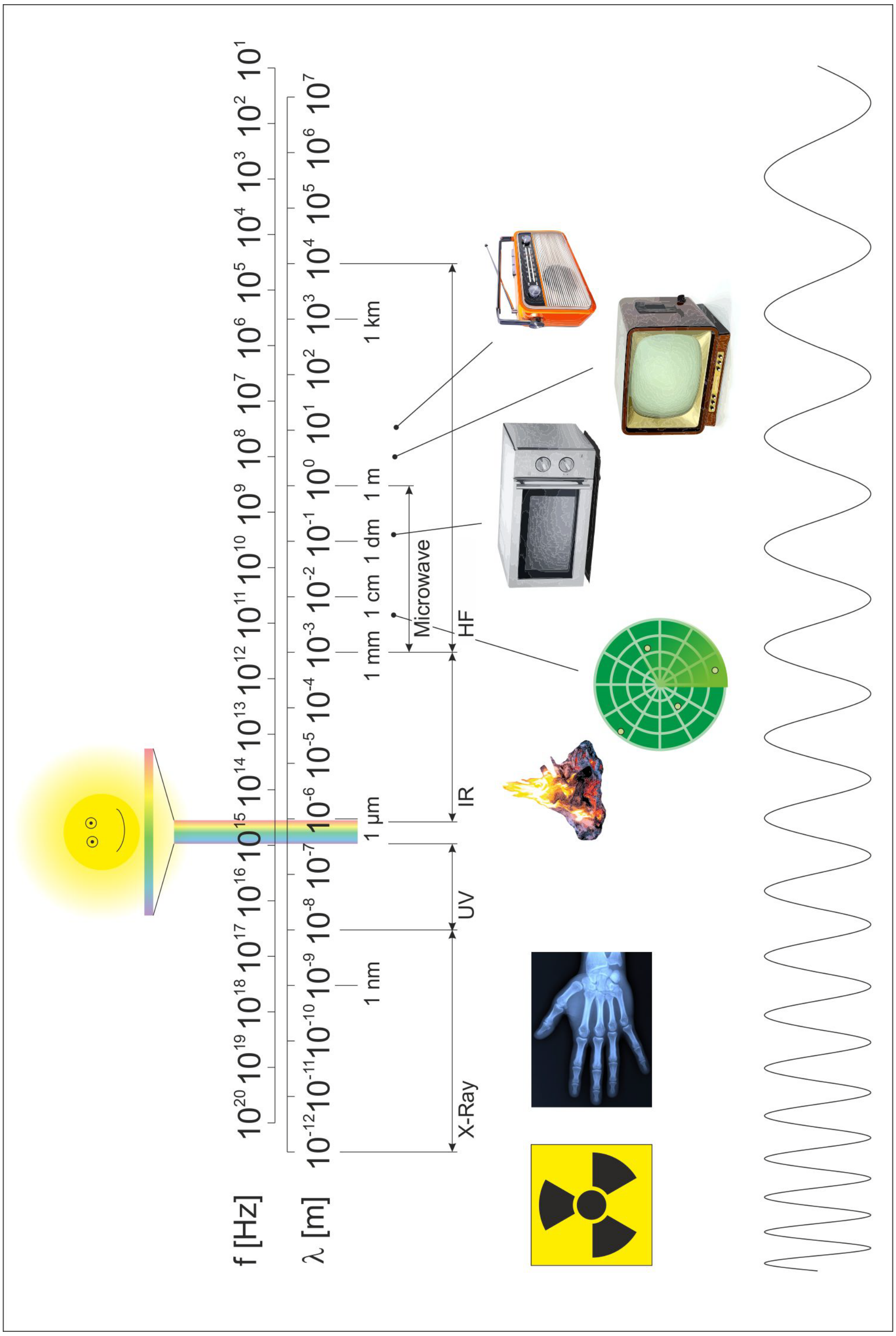


Fig. 4.1 Classification of electromagnetic radiation

Radiation due to temperature always occurs. The requirement for this is a temperature above the absolute zero point.

The radiation is emitted as the temperature increases. The following picture shows the spectrum that is emitted by bodies with certain temperatures:

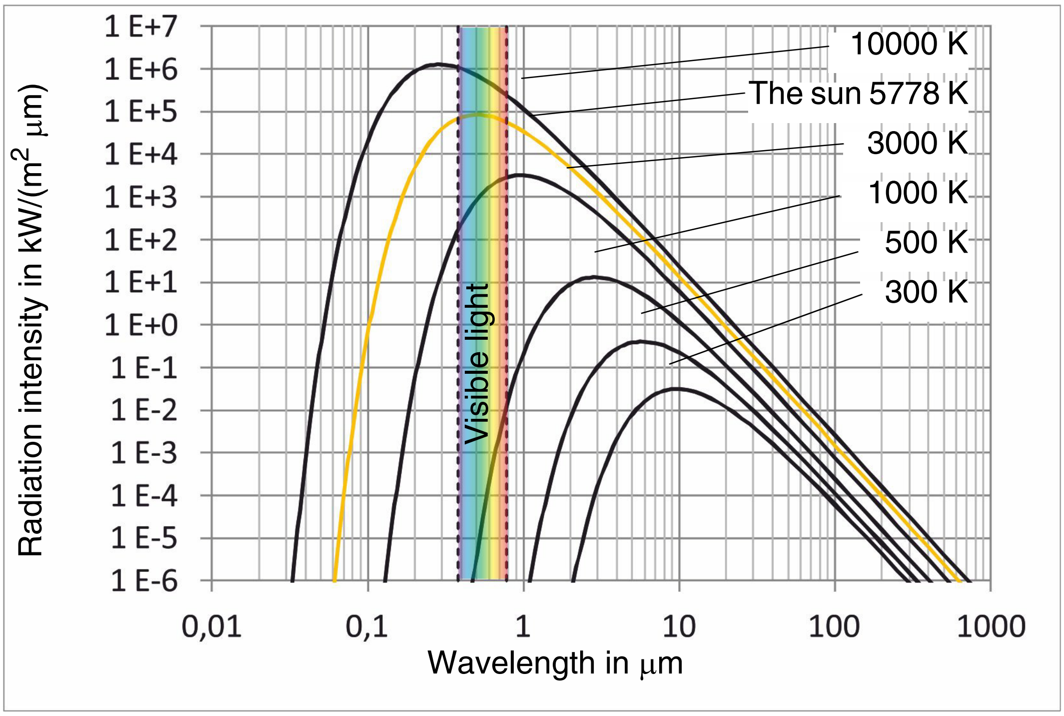


Fig. 4.2 Radiation intensity of a black body, depending on the temperature.

These are referred to as thermal radiators. One of their characteristics is to emit electromagnetic waves in a very wide spectrum according to their temperature.

Fig. 4.2 shows that the spectrum is temperature-dependent. The wavelength determines the characteristic of the radiation. Short-wave radiation is energy-rich.

With increasing temperature, the maximum of intensity shifts to smaller wavelengths.

On the other hand, lasers or LEDs are _not_ thermal radiators, because their electromagnetic radiation is not based on temperature effects. The emitted spectrum cannot be compared for this reason.

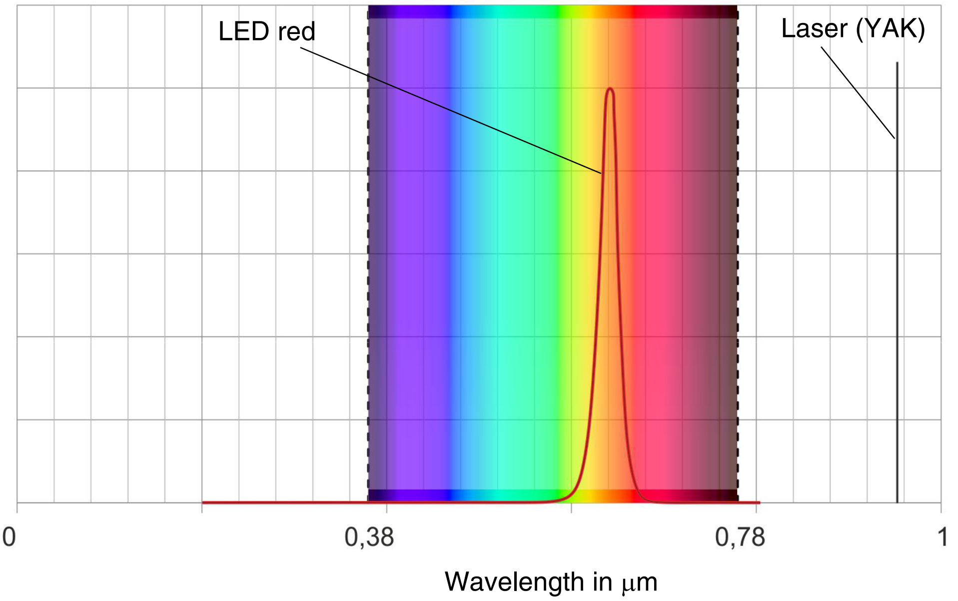


Fig. 4.3 Spectrum of LED and Laser

Fig. 4.3 shows the spectrum of non-thermal radiators such as LEDs and lasers. Visible light has been highlighted in colours The radiated wavelengths are dependent on the temperature for these, and have a much lower bandwidth. The laser (outside of the visible light range) only has a wavelength, whilst the LED also has a low bandwidth.

4.1.2 ...of ‘black’, ‘white’ and ‘grey’ bodies

Physics distinguishes between 2 extreme bodies in regard to radiation:

The **white body** is not in relation to its surroundings. It does not emit any radiation and does not absorb it either.

The **black body** absorbs all and every radiation completely. It also emits the maximum possible radiation.

The **grey body** is between the white and the black body with regard to its radiation behaviour. Formula (4.1) with emission coefficient ε can be expanded for the calculation:

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \tag{4.2}$$

σ = Stefan-Boltzmann constant

$5{,}67 \cdot 10^{-8}\ \mathrm{W/m^2\,K^4}$

ε = emission coefficient
A = emitting surface
$\dot{Q}$ = heat flux
T = absolute temperature

To calculate radiation within endless space, the formula then becomes (due to heat exchange):

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot (T_W^{\,4} - T_{Amb}^{\,4}) \tag{4.3}$$

T_{Amb} = absolute temperature of the surroundings
T_W = absolute temperature of the body

In many cases, this formula suffices for calculations of the energetic consideration of the radiation.

The emission coefficient ε thereby stands for the proportion of the radiation that is absorbed (collected), or emitted (transmitted).

In line with the emission coefficient ε, there are other components of radiation that do not have an effect on the body. These are either reflected or they penetrate the body. It follows:

$$1 = \varepsilon + \tau + \rho \tag{4.4}$$

ε = emissions coefficient
τ = transmission coefficient
ρ = reflection coefficient

These characteristics are material-dependent. The above-mentioned bodies can thereby be defined in more detail.

Ideal white body: $\varepsilon = 0$ $(\rho + \tau = 1)$
Ideal black body: $\varepsilon = 1$ $(\rho + \tau = 0)$
Grey body: $0 < \varepsilon < 1$

Material	Emission coefficient ε
Aluminium, polished	0,05
Aluminium, anodized, bluff	0,7
Aluminium, oxidized	0,2...0.3
Stainless steel, polished	0,14
Stainless steel, rolled	0,45
Stainless steel, sand-blasted	0,7
Stainless steel, oxidized	0,85

Tab. 4.1 Values from the literature for ε for aluminium and stainless steel

Tab. 4.1 provides some values from literature for emission coefficients. The values are often accompanied by a description of the surface, as here. Significant differences are noticeable when comparing the literature, indicating that the values are ultimately only rough guideline values.

4.1.3 'Coloured' body

The spectrum of electromagnetic radiation due to temperature ranges over a wide wavelength range. The characteristics of the radiation differ with the wavelength. Areas with similar characteristics are divided into categories, as shown in Fig. 4.1, Page 41. Thus, we can perceive light in various colours, can feel heat in the vicinity of a hot object, and ultraviolet radiation can cause sunburn without us seeing it.

There are also differences of various wavelengths in the emission coefficient. Black clothes, for instance, absorb the energy of visible light; this hardly occurs with white clothes. Black clothes therefore heat up more than white clothes in intensive sunlight.

A coloured body is referred to when the emission coefficient depends on the wavelengths.

The best-known coloured body is glass (Fig. 4.4):

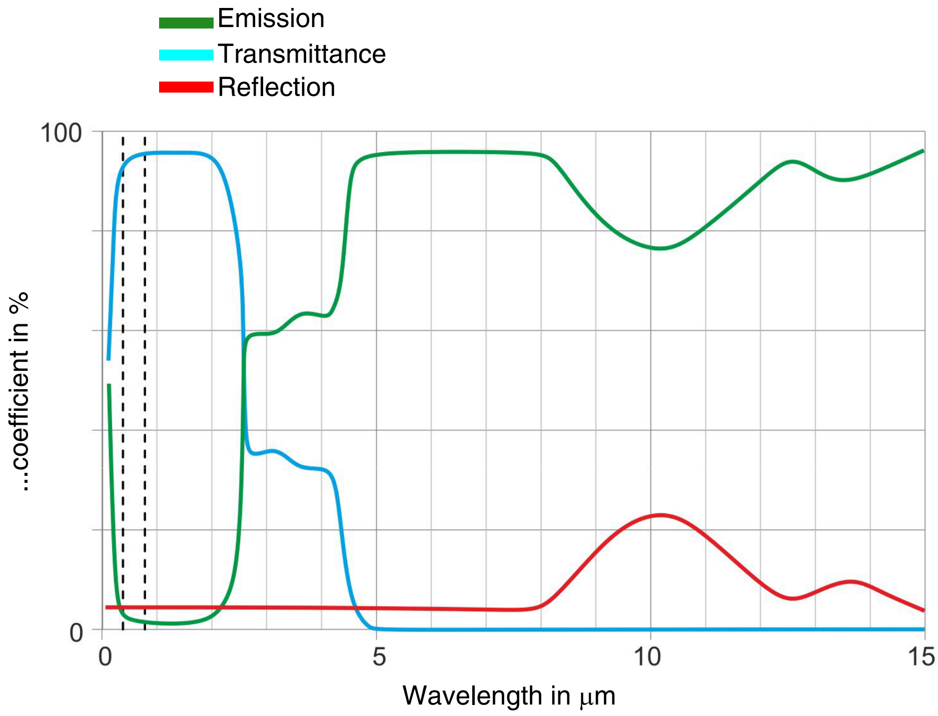


Fig. 4.4 Emission coefficient of window glass, schematic

As we all know, the glass used in windows is mostly translucent in the visible light range, whereby a small amount of the radiation is reflected. There is no longer any transmittance from 5µm. Radiation that is perceived from a glass surface from this wavelength is comprised of emitted and reflected radiation.

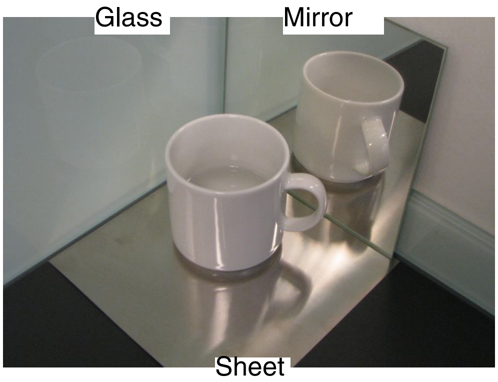


Fig. 4.5 Reflections of a coffee cup filled with hot water, photo

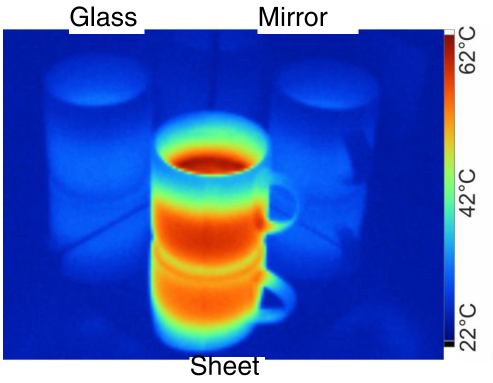


Fig. 4.6 Reflections of a coffee cup filled with hot water, colour photo with thermal radiation

The picture in Fig. 4.6 shows a coffee cup with hot water. A dim reflection can be seen by the naked eye in the glass pane to the left.

The mirror almost completely reflects the visible radiation. This is achieved by a glass pane that is metallised at the back by aluminium. Due to the good transmission characteristics of the glass in the visible area, the light reaches the aluminium layer and is reflected there to the observer.

The cup is on a blank stainless steel sheet. A distorted glare from the cup can be seen in this sheet. This is due to the slightly uneven surface. The stainless steel sheet also reflects a significant amount of the visible light.

In comparison, Fig. 4.6 shows the thermal image of a coffee cup. The infra-red camera calculates a temperature from the intensity of the radiation between 8 and 14 µm. The temperatures are assigned to a colour scale.

Very many surfaces (stonework, wood, paints) have emission coefficients within a narrow range. The picture makes it clear that lack of knowledge may result in misinterpretation. The camera uses a uniform emission coefficient for the complete image section (ε=0,95).

It is evident that no difference can be seen between the mirror and the glass in the colour picture. This is because the glass is not transparent for radiation within this wavelength range and therefore neither the mirror nor the glass have reflecting characteristics, but only emitting and somewhat reflective characteristics. The reflecting, metallised aluminium layer of the mirror is thereby ineffective.

Reflected radiation is received by the blank stainless steel sheet. Its intensity can be compared to the direct picture of the coffee cup. This shows that the blank sheet has very high reflection characteristics in the evaluated band of radiation.

4.2 Heat transfer coefficient of the radiation

The heat flux of the radiation can be calculated just as the convection using the following formula:

$$\dot{Q} = A \cdot \alpha \cdot (T_W - T_{W,Amb}) \qquad (4.5)$$

$\dot{Q}$ = heat flux
A = exothermic surface
α = heat transfer coefficient
$T_{W,\,Amb}$ = surface temperature of surrounding walls
T_W = surface temperature

With the heat transfer coefficient α_{Rad}:

$$\alpha_{Rad} = \varepsilon \cdot \sigma \cdot \frac{T_w^{\,4} - T_{W,Amb}^{\,4}}{T_w - T_{W,Amb}} \qquad (4.6)$$

ε = emission coefficient
σ = Stefan-Boltzmann constant

If convection and thermal radiation occur together, then the total heat transfer coefficient can be calculated:

$$\alpha_{tot} = \alpha_{Conv} + \alpha_{Rad} \tag{4.7}$$

α_{tot} = total heat transfer coefficient
α_{Conv}= heat transfer coefficient, convection
α_{Rad} = heat transfer coefficient, radiation

4.3 Summary/practical significance

Thermal radiation is only interesting at higher temperatures. At temperatures within the range of the ambient temperature, absorbed and emitted radiation are comparable in size.

The increase in emitted heat flux due to increased temperature is limited by the maximum process temperatures and by the materials used.

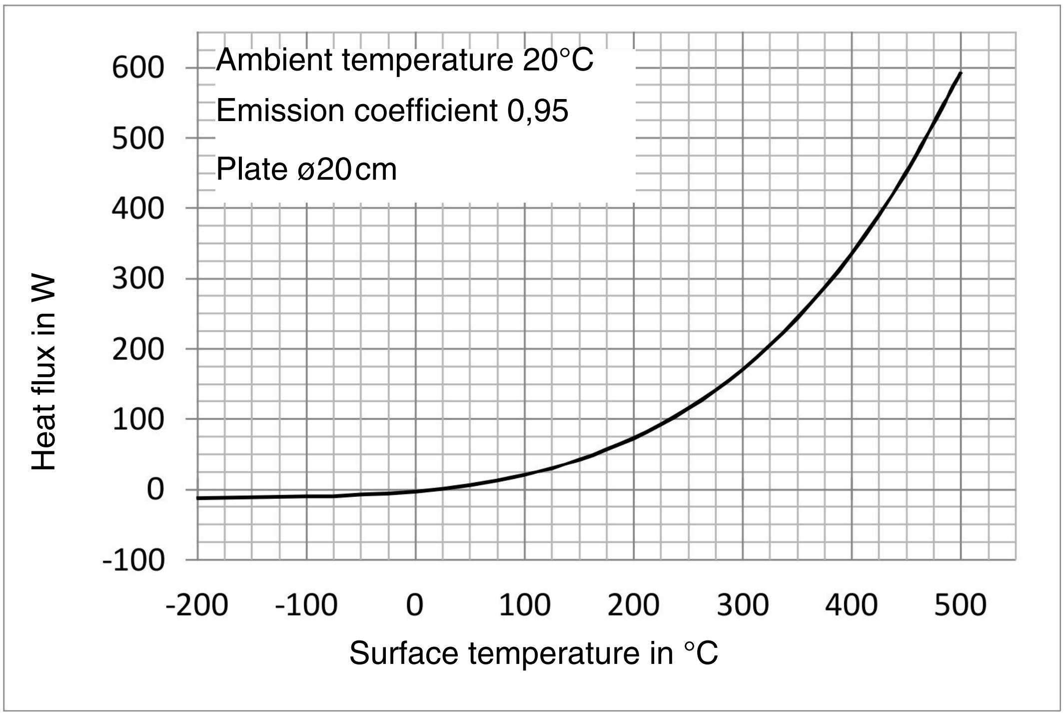


Fig. 4.7 Emitted heat flux over temperature

The picture shows the emitted heat flux of a surface 20cm in diameter at an emission coefficient of 0,95 (e.g. hotplate). The ambient temperature is 20°C.

It can be clearly seen that radiation energy is absorbed at a temperature below 20°C. The emitted radiation increases multiply as the temperature increases. The fourth power of the temperature is noticeable here.

The two extremes - deaden or cool / heat shall be considered in more detail based on examples. The possibilities shown refer to examples in which the radiation characteristics are wilfully manipulated. In almost all cases, influences of convection and conduction are still apparent.

4.3.1 Impeding the radiation exchange

Surface size and emission coefficient provide two different methods of influencing the emission or the absorption of radiation. When influence is exerted wilfully on the radiation, both methods are exploited.

The temperature difference is of no significance here, because there is almost always a given temperature level. Just as with convection, the surface size plays a significant role here. If the thermal radiation of a body is to be reduced, then small bodies with a low surface-to-volume ratio are ideal. The thermos flask in Fig. 4.8 has such a ratio.

Fig. 4.8 Thermos flask

Fig. 4.9 Pipe insulation

Additionally, the blank metal surface shown has a low emission coefficient, which also minimizes the emission of radiation.

The reduction of the emission coefficient is often the easiest way to prevent radiation for a given geometry. Typical applications here are rescue blankets metallized with aluminium, or even metallic bright insulation of pipelines in plant manufacturing.

Such insulation can be seen on vapour-conductive pipes in Fig. 4.9. There is mineral wool between the visible, outer blank pipe and the inner, vapour-transmitting pipe to lower the surface temperature of the outer pipe and to further reduce radiation (and convection).

4.3.2 Promoting radiation exchange

If radiation exchange is to be promoted, an attempt is made to design the surface as large as possible.

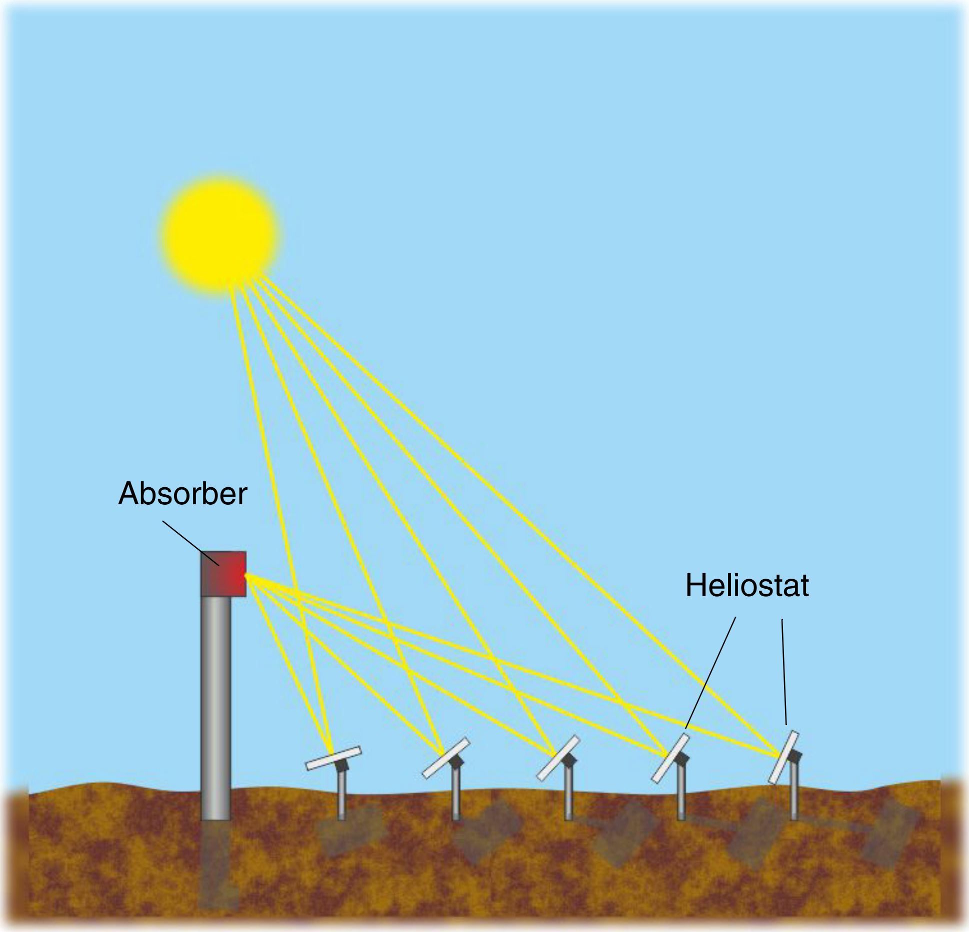


Fig. 4.10 Solar power plant

Solar power plants absorb the sun’s energy and convert it into thermal energy. Fig. 4.10 shows the collimation of the sun’s rays onto a small spot to evaporate water and to drive turbines.

The heliostats reflect the entire spectrum of the solar radiation onto the surface of the solar absorber. The solar absorber thereby heats up and transfers the heat to the power plant process.

The area is decisive in the configuration of this application. In an ideal case, the heliostats reflect the entire radiation ($\varepsilon = 0$; $\rho_{Ideal} = 1$). The absorber absorbs all of the radiation ($\varepsilon_{Ideal} = 1$; $\rho = 0$).

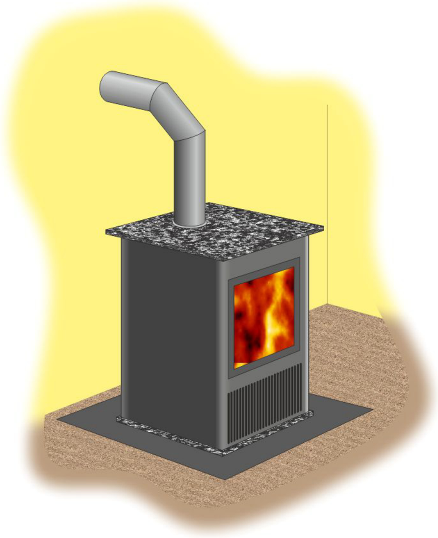


Fig. 4.11 An oven emitting radiant heat

An oven, such as shown in Fig. 4.11, attempts to transfer as much heat from burning as possible into the room. Next to convection, this also occurs by the emission of radiation. The surface is limited here by the firing capacity of the oven, and this determines the heat flux.

The heat is emitted in the form of radiation into the room by surfaces with high emission coefficients (e.g. matt-black).

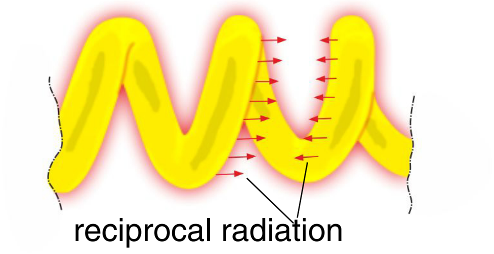


Fig. 4.12 Coiled filament, on the right and showing the self-irradiation

When surfaces that emit radiation are opposite each other, the total area does not emit. Self-irradiation occurs. To calculate this, the *view factor* must be used - the effective surface is reduced.

For coiled filaments such as those shown in Fig. 4.12, the effect is purposefully used to achieve higher filament temperatures with the same use of energy. Light efficiency therefore increases due to the self-irradiation.

Exploiting the temperature difference

The temperature difference plays a much more dominant role in radiation when compared to that of conduction and convection. Due to the fourth power of the temperature, a doubling of the temperature results in the emission of a heat flux that is 16 times higher.

A body emits radiation above the absolute zero point. The difference between the emitted and the absorbed radiation must be formed. This is done based on the absolute temperature scale (Kelvin).

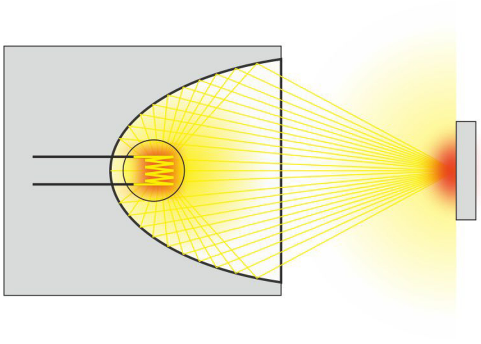


Fig. 4.13 Halogen spotlight for heating a body using radiation energy.

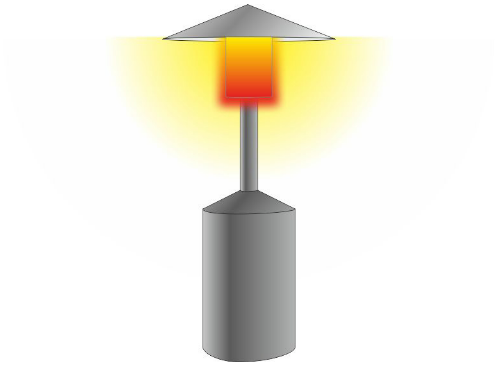


Fig. 4.14 Heating mantle

The temperature differences are often specified by process temperatures, so there is little room for play here.

The halogen lamp in Fig. 4.13 is controlled by the electrical power. The temperature of the coiled filament can therefore be influenced. The shape of the mirror focusses the entire radiation onto one point. The body is heated by the radiation of the coiled filament. The entire emitted radiation spectrum is used for heating.

Due to the high temperature of the coiled filament, enough radiation energy is emitted to allow the workpiece to be heated up to high temperatures.

A typical application using this method is the relatively new procedure of light soldering. The principle of the method is shown in Fig. 4.13. The focussed heat is used to melt solder. However, all radiation heating functions according to this fundamental principle including, for instance, the heating mantle in Fig. 4.14. The rigidity of the material used is a limiting factor here.

5 Combined heat fluxes

There are analogies between heat fluxes in thermodynamics and electrical currents in electrical engineering. Using thermal resistances, rules of electrical engineering can be applied to problems of thermodynamics.

It is therefore possible to compile a calculable thermal model from many different thermal resistances.

5.1 Thermal resistance

The thermal resistance indicates how well the heat is dissipating. This is practically unimpeded when there is a very low thermal resistance The temperature difference over the thermal resistance is very low.

If there is a high thermal resistance, heat dissipation is impeded. The temperature difference over the thermal resistance is high. In this case, even a low heat flux will result in a high temperature difference.

The general calculation is done using the formula:

$$R = \frac{\Delta T}{\dot{Q}} \tag{5.1}$$

$\dot{Q}$ = heat flux
R = thermal resistance
ΔT = temperature difference

The thermal resistance can be determined for the single transmission types.

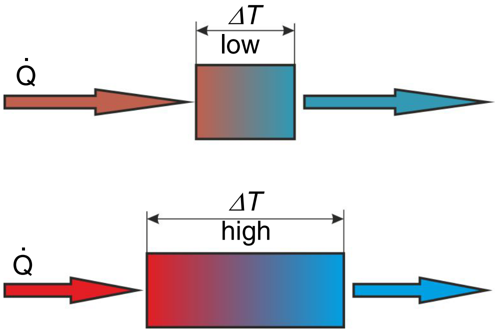


Fig. 5.1 Illustration of thermal resistances

Heat conduction:

$$\dot{Q}_{cond} = \lambda \cdot \frac{A_c}{L} \cdot (T_1 - T_2) \tag{5.2}$$

$\dot{Q}_{cond}$ = heat flux, heat conduction (conductive)
λ = thermal conductivity
L = length
A_c = cross-section area
T_1 = warm temperature
T_2 = cold temperature

Convection:

$$\dot{Q}_{conv} = A_s \cdot \alpha \cdot (T_W - T_{Fl}) \tag{5.3}$$

$\dot{Q}_{conv}$ = heat flux, convection (convective)
A_s = exothermic surface
T_{Fl} = ambient temperature of fluid
T_W = surface temperature

Radiation (with inserted heat transfer coefficient α_{rad}):

$$\dot{Q}_{rad} = A \cdot \varepsilon \cdot \sigma \cdot (T_w{}^4 - T_{W,Amb}{}^4) \tag{5.4}$$

$\dot{Q}_{rad}$ = heat flux, convection (radiative)
$T_{W,Amb}$ = surface temperature of surrounding walls
T_W = surface temperature
ε = emission coefficient
σ = Stefan Boltzmann constant $5{,}67 \cdot 10^{-8}\,\mathrm{W/m^2K^4}$

The thermal resistance is calculated by adjusting the formula. This is shown using an example of heat conduction:

Heat conduction:

$$R_{cond} = \frac{\Delta T}{\dot{Q}} = \frac{T_1 - T_2}{\dot{Q}_{cond}} = \frac{(T_1 - T_2) \cdot \mathrm{L}}{\lambda \cdot A_c \cdot (T_1 - T_2)} \tag{5.5}$$

$$R_{cond} = \frac{L}{\lambda \cdot A} \tag{5.6}$$

Convection:

$$R_{conv} = \frac{1}{\alpha \cdot A} \tag{5.7}$$

Heat radiation:

$$R_{rad} = \frac{T_2 - T_1}{\sigma \cdot \varepsilon \cdot (T_2^{\,4} - T_1^{\,4}) \cdot A} \tag{5.8}$$

R_{cond} = heat conduction resistance
R_{conv} = convective thermal resistance
R_{rad} = radiation resistance

5.2 Electrical analogy

Just as an electrical resistance limits the electrical current, the thermal resistance limits the heat flux. It is calculated analogously.

	Electrical engineering	**Thermodynamics**
Driving potential	Voltage ΔU	Temperature ΔT
Current	Electrical current I	Heat flux $\dot{Q}$
Resistance	Electrical resistance R	Thermal resistance R

Tab. 5.1 Analogy between electrical engineering and thermodynamics

If there are several thermal resistances, they can be combined into a total resistance. Particularly when calculating complex systems, it can be useful to transfer the events into a model comprised of thermal resistances.

5.2.1 Thermal resistances in series

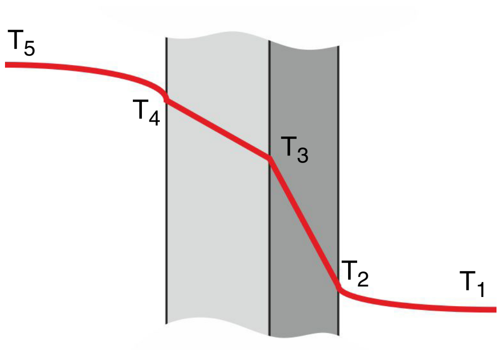


Fig. 5.2 Overall heat transfer through a two-layered, level wall

Thermal resistances are arranged in series when aheat flux crosses various materials or even transfer mechanisms in series.

Example: Wall of a heated residential building

When there is a temperature difference between the interior of a house and the outdoor temperature, a heat flux occurs through the walls.

In the illustration, for instance, this occurs by convection inside - heat conduction (e.g. stonework) - heat conduction (e.g. insulation) - convection outside.

The connection can be drawn as per the single resistances:

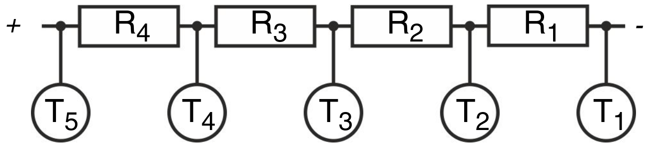


Fig. 5.3 Serial connection of thermal resistances

The total resistance is calculated by adding the single resistances:

$$R_{total} = R_1 + R_2 + R_3 + \ldots + R_n \tag{5.9}$$

R = thermal resistance

Formula (2.1), Page 17 can be expanded to:

$$\dot{Q} = (R_1 + R_2 + R_3 + \ldots + R_n) \cdot (T_1 - T_n) \tag{5.10}$$

$\dot{Q}$ = heat flux
T = temperature

The heat flux is the same though all layers:

$$\dot{Q} = \dot{Q}_1 = \dot{Q}_2 = \dot{Q}_3 = \ldots = \dot{Q}_n \qquad (5.11)$$

$\dot{Q}$ = heat flux

Example calculation at the two-layered, even wall:

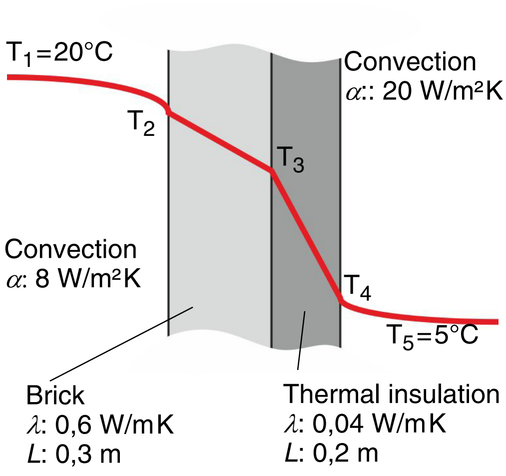


Fig. 5.4 Overall heat transfer through a two-layered, level wall

As an example, the values for Fig. 5.4 are assumed and the single resistances are then calculated. A size of 1 m^2 is assumed for the area.

For the single resistances, we get:

$$R_1 = \frac{1}{\alpha \cdot A} = \frac{1}{8\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}} \cdot 1\,\mathrm{m}^2} = 0{,}125\frac{\mathrm{K}}{\mathrm{W}}$$

$$R_2 = \frac{L}{\lambda \cdot A} = \frac{0{,}3\mathrm{m}}{0{,}6\frac{\mathrm{W}}{\mathrm{m} \cdot \mathrm{K}} \cdot 1\,\mathrm{m}^2} = 0{,}5\frac{\mathrm{K}}{\mathrm{W}}$$

$$R_3 = \frac{L}{\lambda \cdot A} = \frac{0{,}2\mathrm{m}}{0{,}04\frac{\mathrm{W}}{\mathrm{m} \cdot \mathrm{K}} \cdot 1\,\mathrm{m}^2} = 5\frac{\mathrm{K}}{\mathrm{W}}$$

$$R_4 = \frac{1}{\alpha \cdot A} = \frac{1}{20\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}} \cdot 1\,\mathrm{m}^2} = 0{,}05\frac{\mathrm{K}}{\mathrm{W}}$$

The total resistance:

$$R_{tot} = R_1 + R_2 + R_3 + R_4 = (0{,}125 + 0{,}5 + 5 + 0{,}05)\frac{\mathrm{K}}{\mathrm{W}} = 5{,}675\frac{\mathrm{K}}{\mathrm{W}}$$

When considering the relations, it is clear that the thermal insulation R_3 makes the most significant contribution to insulation.

Therefore, to achieve a temperature difference of 5,675 K with the square metres assumed, 1 W is required. Thus, for the example we get:

$$\dot{Q} = \frac{T_1 - T_5}{R_{tot}} = \frac{((273+20)-(273+5))\mathrm{K}}{5,675\frac{\mathrm{K}}{\mathrm{W}}} = 2{,}64\,\mathrm{W}\ \text{per}\ 1\,\mathrm{m}^2$$

This calculation method does not require any surface temperatures or intermediate temperatures.

5.2.2 Parallel heat resistances

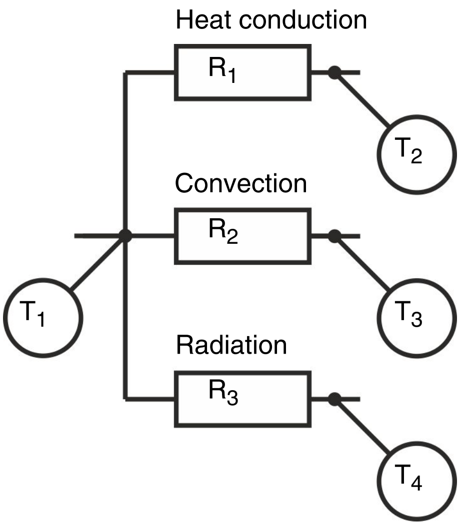


Fig. 5.5 Parallel heat fluxes

Parallel heat fluxes occur wherever a temperature difference is balanced out by more than one heat transport mechanism. In this case, even all three heat transfer mechanisms can be involved. This is shown in Fig. 5.5.

Because transfer is by means of various mechanisms, the temperature differences are not necessarily the same.

The total flux is the sum of all partial heat fluxes:

$$\dot{Q}_{tot} = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_n \tag{5.12}$$

$\dot{Q}$ = heat flux

A total resistance can be formed when there is the same temperature difference over the various resistances:

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}} \tag{5.13}$$

R = thermal resistance

Example calculation for a heater:

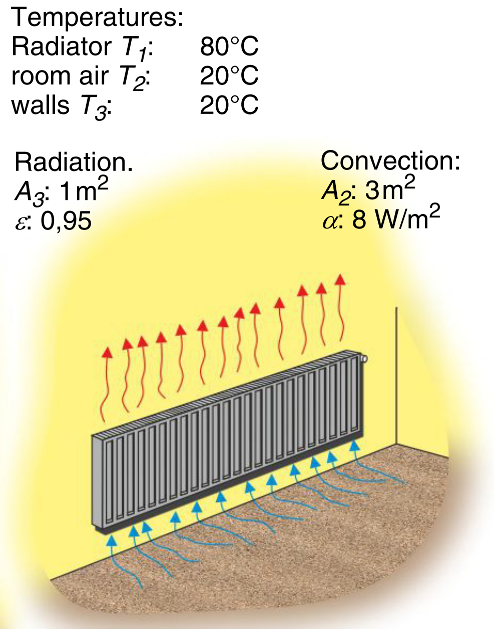


Fig. 5.6 Radiator

A heater is used as an example. There is convection and radiation. The most important details for the calculation are shown in Fig. 5.6.

There are differences here in the heat transferring surface area. When heat is transferred by radiation, only the outer surface of the radiator counts. In convection, a larger surface contributes to heat transfer, because air flows through the heater.

The temperature differences are the same in the example. This is a simplification that is made to be able to calculate the size of the transferred heat more easily.

The thermal resistances are calculated as follows.

Convection:

$$R_{Conv} = \frac{1}{\alpha \cdot A_2} = \frac{1}{8\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}} \cdot 3\mathrm{m}^2} = 0{,}042\frac{\mathrm{K}}{\mathrm{W}}$$

Heat radiation:

$$R_{Rad} = \frac{T_2 - T_1}{\sigma \cdot \varepsilon \cdot (T_2^4 - T_1^4) \cdot A_3}$$

$$R_{Rad} = \frac{((273+80)-(273+20))\mathrm{K}}{5{,}67 \cdot 10^{-8}\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}^4} \cdot 0{,}95 \cdot ((273\mathrm{K}+80\mathrm{K})^4-(273\mathrm{K}+20\mathrm{K})^4) \cdot 1\mathrm{m}^2}$$

$$R_{Rad} = 0{,}137\frac{\mathrm{K}}{\mathrm{W}}$$

From the relation of the heat resistances to each other it can be seen that the radiation component is not to be underestimated.

Due to $T_2 = T_3$, the total resistance can be determined from the parallel connection formula:

$$R_{Tot} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{1}{0{,}042\frac{K}{W}} + \frac{1}{0{,}137\frac{K}{W}}} = 0{,}0321\frac{K}{W}$$

It is therefore smaller than the smallest resistance, because each additional parallel heat flux favours the outflow of additional heat.

For the heat flux, this results in:

$$\dot{Q} = \frac{T_1 - T_2}{R_{Tot}} = \frac{80\text{K} - 20\text{K}}{0{,}0321\frac{K}{W}} = 1869\text{W}$$

This value only applies to the operating point considered, because the resistance of the radiation component changes with the temperature. Above all at high temperatures, a small change in temperature results in a relatively large difference in the thermal resistance.

5.3 Summary/practical significance

At almost all temperature differences, heat transfer occurs over several mechanisms. The division of heat fluxes can be estimated using the thermal resistances.

This provides you with information on the thermal system, and you can take more targeted action to influence an increase or decrease in heat flux, depending on the requirements.

However, knowledge of all transfer mechanisms is presupposed in order to do this, because the single heat fluxes can *never* be considered in isolation from each other.

6 Appendix

6.1 List of formula symbols and units

Formula symbols	Mathematical/physical variable	Value/unit
A	Area	m^2
c	Specific heat capacity at constant pressure	J/kg K
L	Length	m
m	Mass	kg
Nu	Nusselt number	-
Q	Amount of heat	J
$\dot{Q}$	Heat flux	W
R	Thermal resistance	K/W
T	Temperature	K
α	Heat transfer coefficient	W/m^2 K
Δ	Difference	-
ε	Emission coefficient	-
λ	Thermal conductivity	W/m K
ρ	Reflection coefficient	-
σ	Stefan-Boltzmann constant	$5{,}67 \times 10^{-8}$ W/m^2 K^4
τ	Transmission coefficient	-

Indices

Abbreviation	Meaning
Amb	Ambient
c	Cross-section
Cond	Conduction
Conv	Convection
Fl	Fluid
Ideal	Ideal state
in	Incoming
s	Surface
Rad	Radiative
out	Outgoing
tot	Total

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