

HEAT TRANSFER

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Summary

Heat transfer is a basic transport phenomenon which plays a crucial role in chemical engineering (as well as in other engineering branches). Energy integration is very important for the economic and ecologic performance of chemical plants and requires

large numbers of heat exchangers in nearly all parts of a plant.

In the first part the fundamental concepts of heat transfer, that is, the definitions of terms like *work*, *heat*, *internal energy*, and *enthalpy* are explained, based on their use in the fundamental laws of thermodynamics. The kinetics of heat transfer, that is the relationship between the *heat rate* and the *driving force*, the temperature gradient, or a temperature difference are discussed.

There are only *two basic mechanisms of heat transfer*: heat transfer by *radiation* (electromagnetic waves), and heat transfer by *conduction* (due to the random motion and collisions of atoms and molecules).

Convection, that is the transfer of heat by conduction (and radiation) to moving matter, *is no independent, separate, 'third' mechanism of heat transfer*, as is very often wrongly claimed in the literature even today (in spite of the fact that this has been pointed out already in 1915 by Wilhelm Nusselt, one of the most esteemed pioneers of modern heat transfer knowledge).

To make a reader more easily familiar with the importance of heat transfer in many aspects of our life, a few examples for relevant orders of magnitude of heat fluxes occurring in nature are specified. The orders of magnitude of relevant physical properties, like surface properties important for radiation (*emissivity*), physical properties of matter, such as the *specific heat capacity*, and the *thermal conductivity* are discussed at the end of part one.

The second part deals with the prediction of *heat transfer coefficients*, which are defined as *heat rate per cross-sectional area and driving temperature difference*. These coefficients can be predicted in cases of radiation, steady-state conduction, and transient conduction in stagnant media, for heat transfer to externally and internally flowing fluids, both for forced flow, and density-gradient-driven flows. They are also useful quantities in condensation and evaporation heat transfer.

1. Concepts, Basic Laws, Typical Orders of Magnitude

1.1. Heat, Work, and the First Law of Thermodynamics

The first law of thermodynamics – as initially recognized in 1842 by Robert Julius Mayer and more formally written by later thermodynamics scientists, like Clausius, in the second half of the 19th century – states that the energy, E , of a (closed) system, that is a separated part of the universe, having no material exchange with its surroundings but exchanging energy with it, can be changed, from E to $E + \Delta E$, by adding *heat*, Q , and/or *work*, W :

$$\Delta E = Q + W \quad (1)$$

The total energy, E , of a system can be subdivided into internal energy, U , potential energy, E_{pot} , and kinetic energy, E_{kin} . Internal energy, U , is the part of energy that's

stored inside the system (and is a state function, or a property of the system, while Q , and W are no state functions, or properties of the system). In most applications of heat transfer the change of potential and kinetic energy play no significant role. In these cases $\Delta E \cong \Delta U$. The (thermal) internal energy can also be balanced separately from the mechanical energies if the rates of expansion (or compression) and dissipation are taken into account (which does not mean any loss of generality):

$$\rho c_p \frac{DT}{Dt} = -\nabla(\dot{\mathbf{q}}) + \beta T \frac{Dp}{Dt} + \dot{\Gamma} \quad (2)$$

Equation (2) is written for a differential volume, dV . The divergence of the heat flux (first term on the right side), the (reversible) rate of work done by expansion (or compression) and the (irreversible) rate of work done by dissipation of mechanical or other energies, (the second and third terms on the right side), that is heat and work, change the internal energy, and thus the enthalpy, and the temperature of the fluid element.

The total, or substantial, derivatives D/Dt in Eq. (2) are given by the sum of the local and the convective changes with time in a coordinate system fixed in space:

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + w_i \frac{\partial}{\partial x_i} \quad (i=1,2,3) \quad (3)$$

The thermodynamic relationship between temperature, T , and (mass-) specific enthalpy, h , is

$$\rho dh = \rho c_p dT + (1 - \beta T) dp \quad (4)$$

(for an ideal gas, because of $(1 - \beta T)_{\text{ideal gas}} = 0$, h is independent of pressure).

The (mass-) specific enthalpy, h , is related to the (mass-) specific internal energy, u , by

$$dh = du + d(pV) \quad (5)$$

From Eqs. (4) and (5) one can find that Eq. (2) is nothing else but the first law applied to a volume element, dV , of a fluid for an incremental time dt .

1.2. Kinetics of Heat Transfer

The first law, whether in the form of Eq. (1) or (2), only states that addition of heat and/or work can change the (internal) energy of a system; it does not give any clue about the possible mechanisms of heat or work transfer.

It is often found in the heat transfer literature that heat could be transferred by three mechanisms: radiation, conduction, and convection. This, however, is not true. Wilhelm Nusselt, one of the most well-known pioneers of heat transfer research, has pointed to

this inconsistency already in 1915.

Convection is not a mechanism of heat transfer, because heat (just as work) is not a state function, or a property of matter. That is, convective transport can carry internal energy, enthalpy, and temperature, but never heat or work. The changes in the convective terms of energy are not the causes, but the effects of heat (or work) transfer!

Heat transfer means energy transfer from a system A to a system B , with, $T_A > T_B$, (the two systems are not in thermal equilibrium). This is possible *without material contact* of the two systems by *radiation* (net transfer of energy via electromagnetic waves from system A to system B). The heat rate under these conditions is given by the Stefan-Boltzmann law of radiation

$$\dot{Q} = c_{12}(\varphi_{12}, \varepsilon_1, \varepsilon_2)A_1(T_1^4 - T_2^4) \quad (6)$$

where the subscripts 1 and 2 stand for the surfaces of the systems A and B respectively, and c_{12} is a coefficient that depends on the geometrical configuration of the two surfaces in space (expressed by a view factor φ_{12}), and on the emissivities, $\varepsilon_1, \varepsilon_2$, ($\varepsilon_i \leq 1$) of the two surfaces of the systems A and B . The emissivity is a property of the surface, which is close to zero for well-reflecting, mirror-like surfaces, such as polished metal surfaces, while it is close to one for non-metallic and rough, surfaces.

The kinetics of radiative heat transfer is non-linear in the temperature difference ($T_1 - T_2$), but, nevertheless, can be linearized by

$$\dot{Q} = \alpha_{\text{rad}}A_1(T_1 - T_2) \quad (7)$$

which means that the heat transfer coefficient α_{rad} itself depends upon the temperatures, T_1, T_2 .

$$\alpha_{\text{rad}} = 4c_{12}T_m^3 \left[1 + \left(\frac{T_1 - T_2}{T_1 + T_2} \right)^2 \right] \quad (8)$$

In this equation, which follows from Eqs. (6) and (7), T_m is the arithmetic mean of the two temperatures. The difference of two absolute temperatures is typically much smaller than its sum, so that the factor in square brackets usually is close to 1. If T_2 tends to absolute zero, the term in square brackets tends to its maximum possible value of 2.

If the two systems have direct *contact* over a common surface, A , the mechanism of heat transfer is called *conduction*. In such a case the kinetics of heat transfer follows Fourier's law:

$$\dot{\mathbf{q}} = -\lambda \nabla T \quad \text{or} \quad \dot{Q} = -\lambda_i A \left. \frac{\partial T_i}{\partial n} \right|_{\text{surface}} \quad (9)$$

where i stands for any one of the two systems, and n is the normal vector to the surface A . The property λ denotes the thermal conductivity, a transport property of matter defined by Fourier's law.

With a given contact temperature T_0 at the common surface A , Fourier's law can be integrated over a distance s_i in the direction from the surface to the interior of the system to give:

$$\dot{Q} = \frac{\lambda_i}{s_i} A(\bar{T}_i - T_0) \quad (10)$$

The ratio of thermal conductivity λ to the distance s may be called a heat transfer coefficient α :

$$\alpha_i \equiv \frac{\dot{Q}}{A(\bar{T}_i - T_0)} \Rightarrow \alpha_i = \frac{\lambda_i}{s_i} \Rightarrow s_i = \frac{\bar{T}_i - T_0}{-(\partial T_i / \partial n)_0} \quad (11)$$

where the distance s_i , defined by the last form of Eq. (11), is called the thickness of the thermal boundary layer.

Graphically this boundary layer thickness is represented by the distance of the intersection of the tangent of the local temperature distribution in a T versus x plot (x is the spatial coordinate in the direction of the normal vector n , $x = 0$ at the surface) with $T = \bar{T}_i$.

1.3. Orders of Magnitude of Heat Rates and Heat Fluxes

Heat rates, \dot{Q} , that play an important role in nature and in our human environment, may vary over many orders of magnitude. The heat rate irradiated to the Earth can be easily calculated from the solar constant \dot{E}_0 and the mean radius of Earth $r_E = 6370$ km, from

$$\dot{Q}_{\text{in,Earth}} = \dot{E}_0 \pi r_E^2 \quad (12)$$

to be about

$$\dot{Q}_{\text{in,Earth}} = 1.7 \cdot 10^{17} \text{ W}$$

The solar constant, which according to measurements is $\dot{E}_0 = 1367 \text{ W m}^{-2}$, is the heat flux of solar radiation on a spherical surface $A = 4\pi r^2$, with the mean radius of the Earth's orbit, $r = r_{\text{oE}} = 149.6$ (a Gigameter = $10^9 \text{ m} = 10^6 \text{ km}$) from the centre of the sun. Multiplying \dot{E}_0 with this spherical surface gives the heat rate emitted by the sun:

$$\dot{Q}_{\text{out,Sun}} = \dot{E}_0 4\pi r_{\text{oE}}^2, \quad (13)$$

that turns out to be

$$\dot{Q}_{\text{out,Sun}} = 3.8 \cdot 10^{26} \text{ W}.$$

which is more than 2 milliard-fold the rate irradiated upon Earth. At the Sun's surface with a radius of $r_s = 0.696 \text{ Gm}$, the heat flux is greater by a factor $(r_{\text{oE}} / r_s)^2$, that is 46 200 fold:

$$\dot{q}_{\text{out,Sun}} = 63.2 \cdot 10^6 \text{ W m}^{-2}$$

From this flux, one can calculate the Sun's surface temperature (or vice versa) via the Stefan-Boltzmann laws of radiation. It turns out to be about $T_s = 5777 \text{ K}$, if an emissivity of $\varepsilon = 1$ (blackbody radiation) is assumed.

An energy balance around a "black" planet, orbiting on a radius r_{oP} around its "black" sun with the surface temperature T_s , and a radius r_s , and the Stefan-Boltzmann law allows to find a simple relationship between the average temperature T_p of this planet (in steady state, that is for $dT / dt = 0$) and the surface temperature of the sun:

$$T_p = T_s \sqrt{\frac{r_s}{2r_{\text{oP}}}}. \quad (14)$$

With the above given data for the Earth and its Sun, we can get the average surface temperature of a fictive "black" Earth (without an atmosphere) to be $T_p = 279 \text{ K}$ (or about 6°C). The temperature according to Eq. (14) obviously does not depend on the size of the planet. The real Earth, however, is not at all a "black body", it reflects about 30% of incoming radiation, and because of its atmosphere that contains dust, liquid and gaseous water, CO_2 , and other gases that interact with the solar radiation, the correct balancing of incoming and leaving radiation is much more complicated.

The energy balance of our human body shows that the typical energy input of about 2000 kcal/day (4187 J/kcal, and 86 400 seconds/day) requires an average heat rejection of about

$$\dot{Q}_{\text{out,man at rest}} \approx 100 \text{ W}, \quad (15)$$

This energy rate, depending on the state of the environment, consists of different parts due to radiation, conduction to the surrounding air ('free convection'), and evaporation cooling. The latter contribution (both by breathing and sweating) is the only possible path if the surrounding temperatures are equal or higher than the body temperature.

1.4. Orders of Magnitude of Relevant Physical Properties

The most important physical properties which are needed to calculate heat rates and temperatures from the balance equations and from the equations describing the kinetics of heat transfer are the emissivities ε_i of the surfaces of solids (and liquids), the volumetric heat capacities ρc_p , in Eq. (2), and the thermal conductivities, λ , in Fourier's law (Eq. (9)).

1.4.1. Emissivities

The emissivity ε , which describes the reduction of emitted radiation of a real solid surface compared with the surface of a "blackbody radiator" ($\varepsilon = 1$), is a number in the range of 0 to 1. At room temperature the emissivity of non-metal surfaces (irrespective of their color in the visible range) is typically found to be about

$$\varepsilon_{\text{non-metal}} \cong 0.85 \dots 0.97, \quad (16)$$

These surfaces reflect only 3% to 15% of the incoming radiation and absorb 85% up to 97%.

For metallic surfaces the emissivity is generally lower and strongly depends upon the state of the surface (highly-polished, polished, pre-polished, oxidized, highly oxidized, and so on). For rolled aluminum at 400 K, for example, one can find an emissivity of

$$\varepsilon_{\text{aluminum, 400 K}} = 0.05.$$

In this case the emission of radiation is reduced to 5% of the emission of a "blackbody radiator" at the same temperature. Wrapping an apparatus or a pipeline with aluminum foil can therefore considerably reduce the heat losses by radiation.

1.4.2. Volumetric Heat Capacities

The volumetric heat capacity ρc_p is a state function, and therefore can be calculated proportional to the values of the phases and the volume fractions of multiphase systems. This is not possible for the kinetic (or transport) properties, like viscosity, thermal conductivity, or diffusivity. For preliminary calculations and feasibility studies, it is important to know the orders of magnitude of these properties.

Only the product of density ρ and mass-specific heat capacity c_p is needed in the energy balances for a specified volume, if temperature is used as the relevant variable to describe a certain process of this kind. This product remains the same, when mass in density (mass/volume) and capacity (energy stored/mass) is replaced by amount of substance (mole):

$$\rho c_p = \tilde{\rho} \tilde{c}_p \quad (17)$$

For ideal gases, with $\tilde{\rho} = p/(\tilde{R}T)$ one finds for 2-atomic molecules (N_2 , O_2 , H_2 , etc.)

$$(\rho c_p)_{g,2-A} = 3.5 \frac{p}{T} \quad (18)$$

For monatomic gases the factor is 2.5 in place of 3.5 (for the 2-atomic ones). For gases with more than two atoms per molecule the factor becomes greater and more temperature dependent.

For a temperature of 350 K ($\cong 77^\circ\text{C}$) and a pressure of 10^5 N m^{-2} (1 bar) the typical value of a volumetric heat capacity of a (2-atomic) gas under normal conditions is

$$(\rho c_p)_{g,2-A,N} \approx 1 \text{ kJ m}^{-3} \text{ K}^{-1} \quad (19)$$

For liquids and solids one can find that the volumetric heat capacities vary much less than the densities and the mass-specific heat capacities do.

It is therefore quite useful to remember the range of values that covers nearly all liquids and (compact, that is, non-porous) solids:

$$1 \text{ MJ m}^{-3} \text{ K}^{-1} \leq (\rho c_p)_{l,s} \leq 4 \text{ MJ m}^{-3} \text{ K}^{-1} \quad (20)$$

Water with $4.18 \text{ MJ m}^{-3} \text{ K}^{-1}$ is slightly above the upper limit of the range given in Eq. (19); some metals are in the same range. Organic substances are more in the middle or lower range. If the density and heat capacity of a solid or liquid are not known, $(\rho c_p) \approx 2 \text{ MJ m}^{-3} \text{ K}^{-1}$ seems to be a reasonable estimation. It is important to know that the volumetric capacities of liquids and solids are higher than that of gases (at normal conditions) by a factor of about 2000. For multiphase systems containing gases under normal conditions, the heat capacities of the gas phase can usually be neglected against the heat capacities of the solid or liquid phases. That means that the temperature of the gas phase quasistationarily follows the temperature of the condensed phases.

1.4.3. Thermal Conductivity

Thermal conductivities, defined by Fourier's law, Eq. (9), strongly depend on the chemical nature and the state of the substance. For gases at normal conditions they are found in a range of

$$0.015 \text{ W K}^{-1} \text{ m}^{-1} \leq \lambda_{g,0} \leq 0.15 \text{ W K}^{-1} \text{ m}^{-1} \quad (21)$$

As a typical round value for technically important gases it is useful to keep

$$\lambda_{\text{air},80^\circ\text{C}} = \lambda_{\text{saturated vapour},140^\circ\text{C}} = 0.03 \text{ W K}^{-1} \text{ m}^{-1} \quad (22)$$

in mind. Lower values are found for larger gas molecules, like SO_2 , CO_2 , five- to six-fold higher values are only found for the two lightest gases, hydrogen

(H₂: $\lambda_{25^\circ\text{C}} = 0.18 \text{ W K}^{-1} \text{ m}^{-1}$), and helium (He: $\lambda_{25^\circ\text{C}} = 0.15 \text{ W K}^{-1} \text{ m}^{-1}$)

The thermal conductivities of many liquids (except liquid metals) are in the range

$$0.1 \text{ W K}^{-1} \text{ m}^{-1} \leq \lambda_{l,0} \leq 0.6 \text{ W K}^{-1} \text{ m}^{-1} \quad (23)$$

The upper limit of this range is also the round value for liquid water, which thus conducts heat about 20-fold better than air.

Many organic liquids and solid polymers have conductivities in the range of 0.1 to 0.3 $\text{W K}^{-1} \text{ m}^{-1}$.

For a number of non-metallic solids a typical range is

$$1 \text{ W K}^{-1} \text{ m}^{-1} \leq \lambda_{s,\text{non-metal}} \leq 10 \text{ W K}^{-1} \text{ m}^{-1} \quad (24)$$

Water as a solid, has a conductivity of about $2 \text{ W K}^{-1} \text{ m}^{-1}$ at the ice point.

There are, however, a few notable exceptions from this range: silicon carbide, SiC, may have a heat conductivity in the order of magnitude of about $100 \text{ W K}^{-1} \text{ m}^{-1}$, and pure diamond, C, is reported to have an extremely high heat conductivity: $\lambda_{\text{pure diamond}}(20^\circ\text{C}) \approx 2000 \text{ W K}^{-1} \text{ m}^{-1}$.

For pure metals typical values are higher by one to two orders of magnitude:

metal	$\lambda/[\text{W K}^{-1} \text{ m}^{-1}]$	metal	$\lambda/[\text{W K}^{-1} \text{ m}^{-1}]$
Cu	400	Al	200
Fe	85	Cr	95
Ni	95	Pb	35

Alloys have always lower conductivities than those of their components:

$$\lambda_{\text{steel, 18Cr8Ni}} \approx 15 \text{ to } 20 \text{ W K}^{-1} \text{ m}^{-1}$$

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Biographical Sketch

Holger Martin, Professor of Thermal Process Engineering at the Institut f ur Thermische Verfahrenstechnik Universit t Karlsruhe (TH) (now KIT) since 1980 (retired since 2008). He got a Degrees Dipl.-Ing. (1969), Dr.-Ing. (1973) and Habilitation (1980), Universit t Karlsruhe **Research interests** in Drying, Heat and Mass Transfer and Heat Exchangers

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Scientific Director of the *International Seminar for Research and Teaching in Chemical Engineering and Physical Chemistry* at the Universität Karlsruhe (TH) from 1980 to 2004

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