1.9 Heat transfer

Any temperature difference within a body, or between two surfaces, is followed by heat transfer until a temperature equilibrium is reached. This transfer of heat can take place in three different ways:

- □ conduction
- □ convection
- □ radiation

Generally all these take place simultaneously.

1.9.1 Heat content

The amount of heat stored in a body, gas or liquid is:

$$q = c \cdot m \cdot \Delta T$$

where q is the amount of heat
c is the specific heat-capacity in J/(kg·K)
m is the mass of the body in kg
ΔT is the temperature difference in K, measured above a given reference level.

Table 1:19 Some typical specific heat-capacity values

Medium	*c*
air (atm. pressure)	1 004
aluminium	920
copper	390
oil	1 670 – 2 140
steel	460
water	4 185
zinc	385

1.9.2 Conduction

Conduction takes place within solid bodies, or within thin layers of liquid or gas, as rapidly-vibrating molecules give off part of their kinetic energy to neighbouring, more slowly-moving, molecules. The amount of heat transferred is:

$$q=-\lambda \cdot A \cdot t \cdot \Delta T/\Delta x$$

where q is the amount of heat transferred in J
λ is the thermal conductivity in W/(m · K)
A is the area perpendicular to the flow in m^2
t is the time in s
ΔT is the temperature difference in K
Δx is the distance in m.

Table 1:20 Some typical thermal conductivity values

Medium	λ
air (atm. pressure)	0.025
aluminium	140–220
copper	145–395
oil	0.17
steel	29–58
water	0.58
zinc	113

1.9.3 Convection

Convection is the transfer of heat from one point to another within a fluid, gas or liquid, by the mixing of one portion of the fluid with another. There are two types of convection, free and forced. **Free convection** is obtained by the difference in density caused by temperature differences in the medium. **Forced convection** is obtained by using a fan or a pump. The rate increases with the velocity. This type of heat transfer follows the equation:

$$q=\alpha \cdot A \cdot (T_m - T_s) \cdot t$$

where q is the amount of heat transferred in J
α is the surface coefficient of heat transfer in W/(m^2 · K)
A is the area in m^2
T_m is the temperature of the medium in K
T_s is the temperature of the surface in K
t is the time in s.

Although the above equation seems simple, the difficulty lies in determining the proper value of α in a given application. α is a function of the geometry, the thermal properties of the surface and of the gas or liquid, and of the velocity of flow.

Table 1:21 Order of magnitude of the surface coefficient of heat transfer

Medium	α
free air convection	5–30
forced air convection	30–300
forced water convection	300–11 000

1.9.4 Radiation

A hot body gives off heat in the form of radiant energy, which is emitted in all directions. When this energy strikes another body, part may be reflected and part may be transmitted unchanged through the body. The remainder is absorbed and quantitatively transformed into heat. If two bodies, one hotter than the other, are placed within an enclosure, there is a continuous interchange of energy between them. The hotter body radiates more energy than it absorbs; the colder body absorbs more than it radiates. Even after equilibrium of temperature is established, the process continues, each body radiating and absorbing energy.
The heat transferred by radiation is given by:

$$q=\epsilon \cdot \sigma \cdot A \cdot T^4 \cdot t$$

where q is the amount of heat transferred in J
ϵ is the emissivity factor (dimensionless)
σ is the Stefan-Boltzmann constant in W/(m^2 · K^4)
A is the area in m^2
T is the temperature in K
t is the time in s.

$$\sigma=5.67 \cdot 10^{-8} \quad W/(m^2 \cdot K^4)$$

The amount of heat transferred by radiation between two bodies of temperatures T_1 and T_2 is determined by:

$$q=\epsilon \cdot \sigma \cdot A \cdot (T_1^4 - T_2^4) \cdot t$$

Table 1:22 Emissivity factors

Surface	ϵ
absolutely black body	1.00
aluminium, polished	0.05
steel plate, rolled	0.66
steel plate, rusty	0.68
steel plate, shiny	0.24
brass, polished	0.04
glass	0.93

1.9.5 Heat transmission

Since in most cases any actual transfer of heat is accomplished by more than one of the three modes, it is preferable to use the terms **transfer** or **transmission** to describe the process, reserving the use of the terms **radiation, convection,** and **conduction** for that fraction of the heat transmission accomplished by the mechanism designated. The amount of heat transmitted is determined by:

$$q = k \cdot a \cdot \Delta T \cdot t$$

where k is the total heat transfer coefficient in $W/(m^2 \cdot K)$.

Very often heat transmission takes place between two media separated by a wall.
The total coefficient depends on the heat transfer coefficients on both sides as well as on the heat resistance of the wall.
The total heat transfer coefficient is determined from:

$$1/k = 1/\alpha_1 + d/\lambda + 1/\alpha_2$$

where α_1 and α_2 are the surface coefficients of heat transfer in $W/(m^2 \cdot K)$
d is the thickness of wall in m
λ is the thermal conductivity of the wall in $W/(m \cdot K)$ (1:20).

The above equation is valid for a clean, plane wall. In a heat exchanger pipes are normally used. Furthermore these pipes are often fouled. The equation is then modified to:

$$1/k = 1/\alpha_1 + f_1 + 2.303 \cdot d/\lambda \cdot \log [d/(d-2t)] + (f_2 + 1/\alpha_2) \cdot [d/(d-2t)]^2$$

where k is the total heat transfer coefficient in $W/(m^2 \cdot K)$
α_1 is the surface coefficient of heat transfer on the outside in $W/(m^2 \cdot K)$
α_2 is the surface coefficient of heat transfer on the inside in $W/(m^2 \cdot K)$
f_1 is the fouling factor on the outside in $m^2 \cdot K/W$
f_2 is the fouling factor on the inside in $m^2 \cdot K/W$
d is the outside pipe diameter in m
t is the wall thickness in m
λ is the thermal conductivity of the wall in $W/(m \cdot K)$.

Typical fouling factors are given in table 1:23.

Table 1:23 Typical fouling factors

Medium	f
sea water	0.000 10
brackish water	0.000 35
cooling tower, treated	0.000 20
cooling tower, untreated	0.000 55
city or well water	0.000 20
lubricating oil	0.000 20
compressed air	0.000 35

1.9.6 Heat exchangers

The rate of heat transfer between the hot and the cold substances in any heat exchanger, e g an intercooler, is determined by

$$q/t = k \cdot A \cdot \tau_m \quad W$$

where q/t is the rate of heat transfer in W
k is the total heat transfer coefficient in $W/(m^2 \cdot K)$
A is the effective area in m^2
τ_m is the logarithmic mean temperature difference in K.

The logarithmic mean temperature difference is defined as:

$$\tau_m = [(t_{1g} - t_{2w}) - (t_{2g} - t_{1w})] / \ln [(t_{1g} - t_{2w})/(t_{2g} - t_{1w})]$$

However, the logarithmic mean temperature difference applies only for counterflow heat exchangers. For other types of flow the proper mean temperature difference is the product of the logarithmic mean temperature difference and a correction factor.

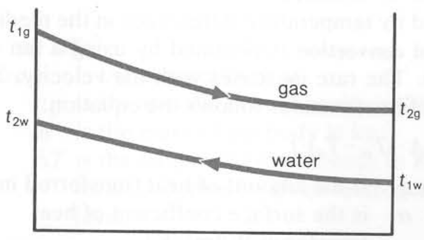

Diagram 1:24 Heat exchanger temperatures

Example: A counterflow-type intercooler has to cool 261 l/s of air from +145° to +20°C. The cooling-water flow is 0.472 kg/s and its temperature is +10°C. The total heat transfer coefficient $k = 117$ $W/(m^2 \cdot K)$. What is the required heat transfer area A (neglecting any moisture condensation)?

Density of the free air:
$\rho = 10^5/(287.1 \cdot 293.2) = 1.188\ kg/m^3$
Mass flow of air:
$m/t = 1.188 \cdot 261 \cdot 10^{-3} = 0.310\ kg/s$

The specific heat-capacity of air is
1 004 J/(kg·K) (1:19)
The specific heat-capacity of water is
4 185 J/(kg·K) (1:19)
Heat load of the intercooler:
$0.310 \cdot 1\,004 \cdot (145-20) = 38\,900$ W

For equilibrium this must be equal to the heat taken up by the water.
$38\,900 = 0.472 \cdot 4\,185 \cdot (t_{2w}-10)$
$t_{2w} = 29.7°C$
$t_{1g}-t_{2w} = 145.0-29.7 = 115.3$
$t_{2g}-t_{1w} = 20-10 = 10$
$\tau_m = 40$ (1:25)

Thus:
$38\,900 = 117 \cdot A \cdot 40$
Answer: $A = 8.3\ m^2$

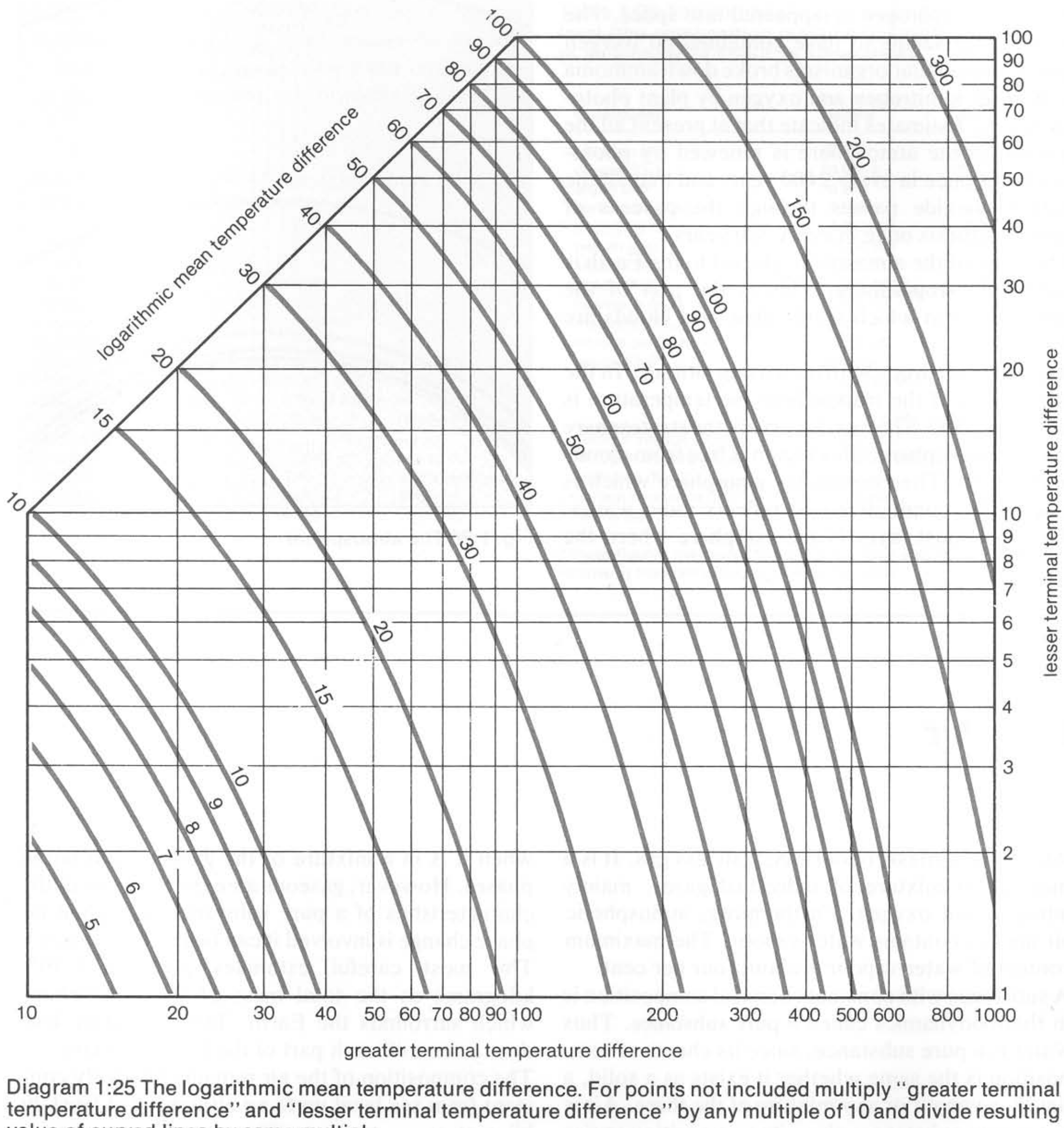

Diagram 1:25 The logarithmic mean temperature difference. For points not included multiply "greater terminal temperature difference" and "lesser terminal temperature difference" by any multiple of 10 and divide resulting value of curved lines by same multiple