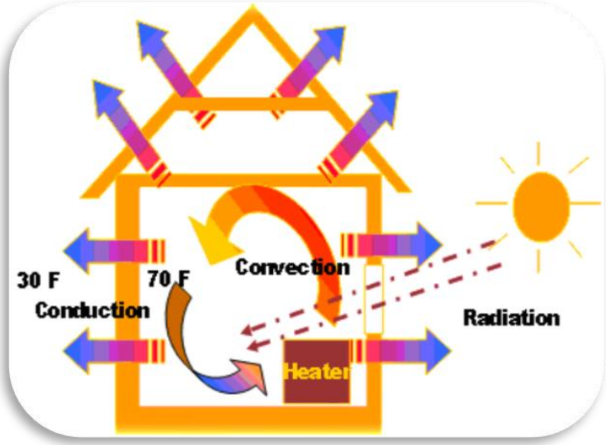
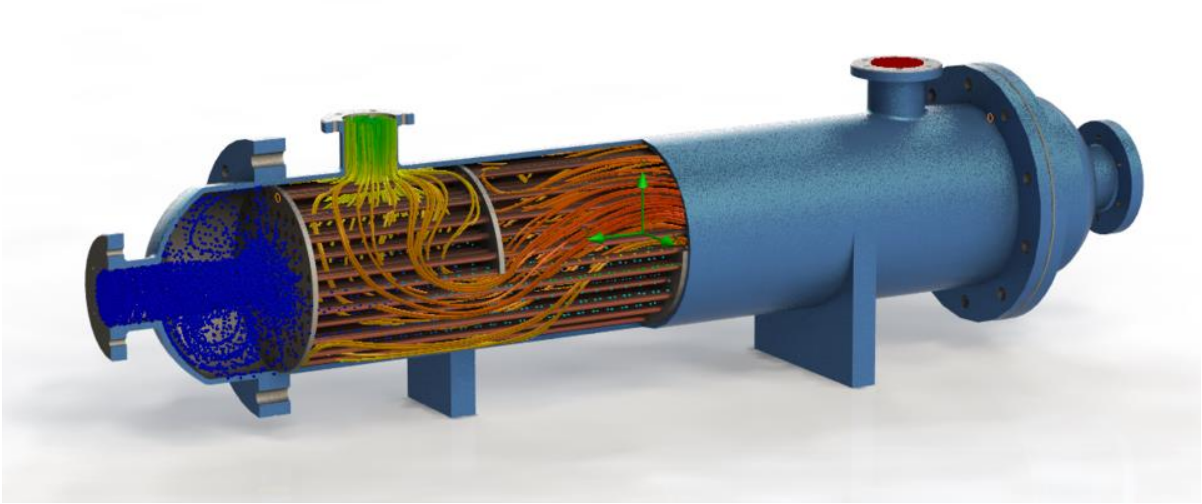
Heat Transfer Operations

Session-11. Heat Convection





Dr. Jogender Singh (JS)

Objectives: Convection (Without Phase Change)

- Energy balance.
- Heat transfer global coefficient.
- Logarithmic mean temperature difference (LMTD).
- Newton's Law of cooling and the local heat transfer coefficient.
- Forced convection in laminar and turbulent regimes inside tubes.
- Forced convection in outside tubes
- Natural convection.
- Tubular heat exchangers.
- Plate heat exchangers
- Extended surfaces (fins)

Convection: (Without Phase Change)

- Heat transfer through a solid is always by conduction, since the molecules of a solid remain at relatively fixed positions.
- Heat transfer through a liquid or gas, however, can be by conduction or convection, depending on the presence of any bulk fluid motion.
- Heat transfer through a fluid is by convection in the presence of bulk fluid motion and by conduction in the absence of it.
- Convection heat transfer is complicated by the fact that it involves fluid motion as well as heat conduction.
- The fluid motion enhances heat transfer, since it brings hotter and cooler chunks of fluid into contact, initiating higher rates of conduction at a greater number of sites in a fluid.

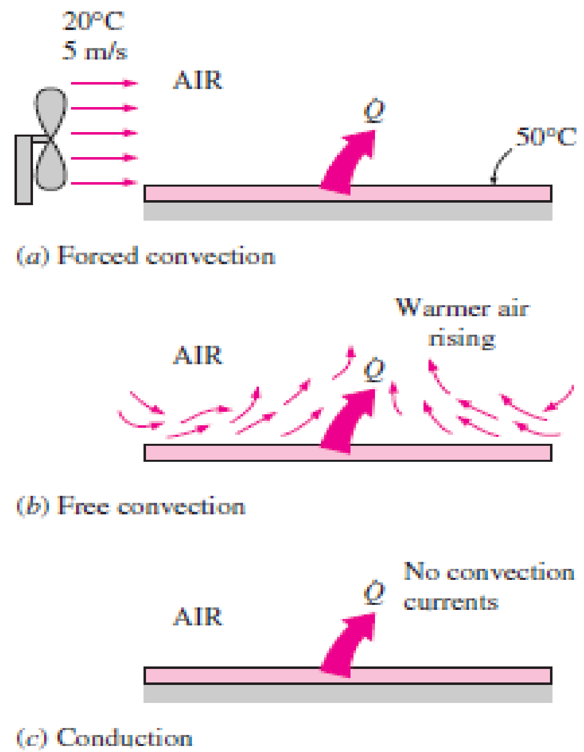


Fig. 6.1 Heat transfer from a hot surface to the surrounding fluid by convection and conduction.

Therefore, the rate of heat transfer through a fluid is much higher by convection than it is by conduction. In fact, the higher the fluid velocity, the higher the rate of heat transfer.

Convection: (Without Phase Change)

- The temperatures of the fluid and the plate will be the same at the points of contact because of the continuity of temperature.
- Assuming no fluid motion, the energy of the hotter fluid molecules near the hot plate will be transferred to the adjacent cooler fluid molecules.
- This energy will then be transferred to the next layer of the cooler fluid molecules. This energy will then be transferred to the next layer of the cooler fluid, and so on, until it is finally transferred to the other plate.
- This is what happens during conduction through a fluid.

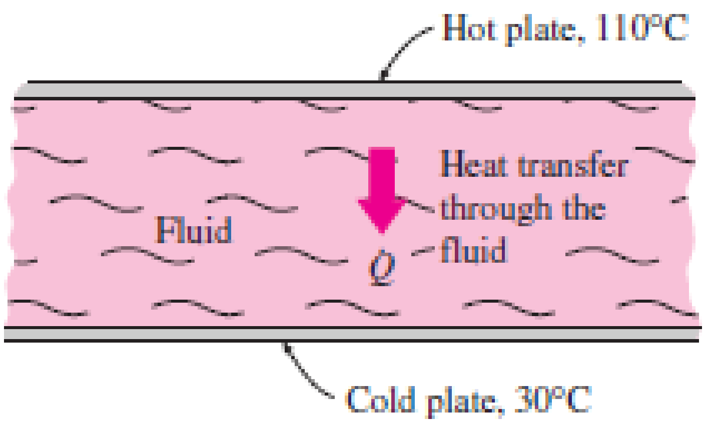


Fig. 6.2 Heat transfer through a fluid sandwiched between two parallel plates.

Now let us use a syringe to draw some fluid near the hot plate and inject it near the cold plate repeatedly. You can imagine that this will speed up the heat transfer process considerably, since some energy is carried to the other side as a result of fluid motion.

Newton’s law of cooling

- We know that heat will be transferred from the hot block to the surrounding cooler air, and the block will eventually cool. We also know that the block will cool faster if the fan is switched to a higher speed. Replacing air by water will enhance the convection heat transfer even more.
- Convection heat transfer strongly depends on the fluid properties dynamic viscosity μ, thermal conductivity k, density ρ , and specific heat Cp, as well as the fluid velocity v. It also depends on the geometry and the roughness of the solid surface, in addition to the type of fluid flow (such as being Laminar or turbulent).
- Despite the complexity of convection, the rate of convection heat transfer is observed to be proportional to the temperature difference and is conveniently expressed by Newton’s law of cooling as

$$\dot{q}'' \propto (T_w - T_\infty) \qquad (6.1)$$

Isaac Newton (1642–1726/1727)

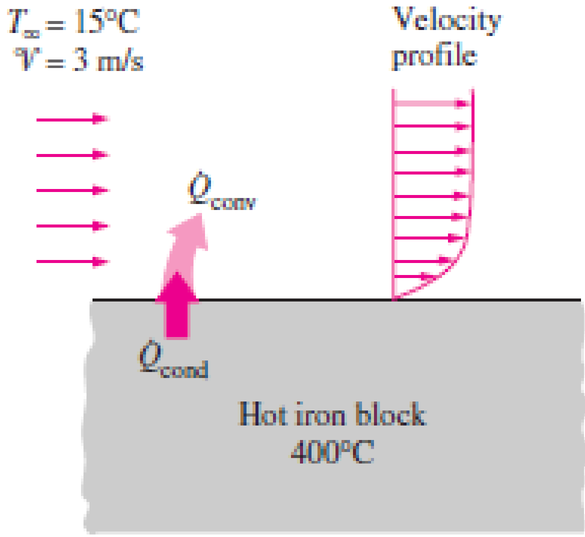


Fig. 6.3 The cooling of a hot block by forced convection.

Newton’s law of cooling

$$\dot{q}'' = h(T_w - T_\infty) \qquad (6.2)$$
$$\dot{q} = hA(T_w - T_\infty) \qquad (6.3)$$

Where,
h convection heat transfer coefficient, $W/m^2\ °C$
A_w heat transfer surface area, m^2
T_w temperature of the surface, °C
T_∞ temperature of the fluid sufficiently far from the surface, °C

The **convection heat transfer coefficient** h can be defined as *the rate of heat transfer between a solid surface and a fluid per unit surface area per unit temperature difference.*

- When a fluid is forced to flow over a solid surface that is nonporous (i.e., impermeable to the fluid), it is observed that the fluid in motion comes to a complete stop at the surface and assumes a zero velocity relative to the surface.
- That is, the fluid layer in direct contact with a solid surface “sticks” to the surface and there is no slip. In fluid flow, this phenomenon is known as the **no-slip condition**, and it is due to the viscosity of the fluid

Isaac Newton (1642–1726/1727)

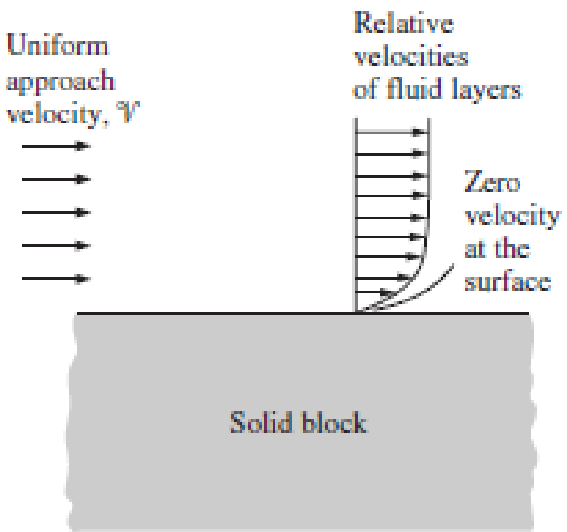


Fig. 6.4 The cooling of a hot block by forced convection.

- The **convection heat transfer coefficient** h can be defined as the rate of heat transfer between a solid surface and a fluid per unit surface area per unit temperature difference.
- If k is the thermal conductivity of the fluid, the rate of heat transfer can be written directly by following the Fourier's law. Therefore, we have,

$$\dot{q} = -kA\boxed{\frac{(T_w - T_\infty)}{\delta}} = \frac{k}{\delta}\mathrm{A}(T_w - T_\infty) \qquad (6.4)$$

Temperature gradient in the thin film where the temperature gradient is linear

$$\boxed{\dot{q} = hA(T_w - T_\infty) \qquad (6.3)}$$

On comparing eq. 3.3 and 3.4, we have,

$$h = \frac{k}{\delta} \qquad (6.5)$$

- The equation 6.5 looks simple but not really easy for the calculation of real problems due to non-linearity of *k* and difficulty in determining δ.
- The heat transfer coefficient is important to visualize the convection heat transfer phenomenon as discussed before.
- In fact, δ is the thickness of a heat transfer resistance as that really exists in the fluid under the given hydrodynamic conditions.
- Thus, we have to assume a film of δ thickness on the surface and the heat transfer coefficient is determined by the properties of the fluid film such as density, viscosity, specific heat, thermal conductivity etc.
- The effects of all these parameters are lumped or clubbed together to define the film thickness. Henceforth, the heat transfer coefficient (*h*) can be found out with a large number of correlations developed over the time by the researchers. These correlations will be discussed in due course of time as we will proceed through the modules.

Typical values of *h* under different situations

Description	Heat Transfer Coefficient ($W/m^2 \cdot {}^{o}C$)
Free convection in air	5-25
Forced convection in air	10-500
Free convection in water	500-1,000
Forced convection in water	1,000-15,000
Boiling water	2,500-25,000
Condensing water	5,000-1,00,000

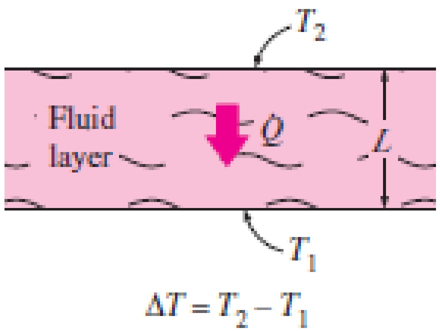
Nusselt Number

Wilhelm Nusselt
German engineer

In convection studies, it is common practice to **nondimensionalize** the governing equations and combine the variables, which group together into *dimensionless numbers* in order to reduce the number of total variables

$$Nu = \frac{hL_C}{k} \ldots\ldots(6.6)$$

To understand the physical significance of the Nusselt number, consider the heat transfer through a fluid layer of thickness L_c and temperature difference T



Heat transfer through the fluid layer will be by *convection* when the fluid involves some motion and by *conduction* when the fluid layer is motionless.

$$\dot{q}''_{conv} = h\Delta T \ldots\ldots\ldots(6.7)$$

$$\dot{q}''_{cond} = h\frac{\Delta T}{L_c} \ldots\ldots\ldots(6.8)$$

Taking their ratio gives

$$\frac{\dot{q}''_{conv}}{\dot{q}''_{cond}} = \frac{h\Delta T}{h\frac{\Delta T}{L_c}} = \frac{hL_C}{k} = Nu \ldots\ldots\ldots(6.9)$$

Individual and overall heat transfer coefficient

- If two fluids are separated by a thermally conductive wall, the heat transfer from one fluid to another fluid is of great importance in chemical engineering process plant.
- For such a case the rate of heat transfer is done by considering an overall heat transfer coefficient.
- However, the overall heat transfer coefficient depends upon so many variables that it is necessary to divide it into individual heat transfer coefficients.

Heat transfer between fluids separated by a flat solid wall

- The average temperatures of the warm bulk fluid and cold bulk fluids are slightly less than the maximum temperature T_h (bulk temperature of hot fluid) and slightly more than the minimum temperature T_c (bulk temperature of cold fluid), respectively.
- The average temperatures are shown by T_1 and T_4, for the hot and cold fluid streams, respectively.

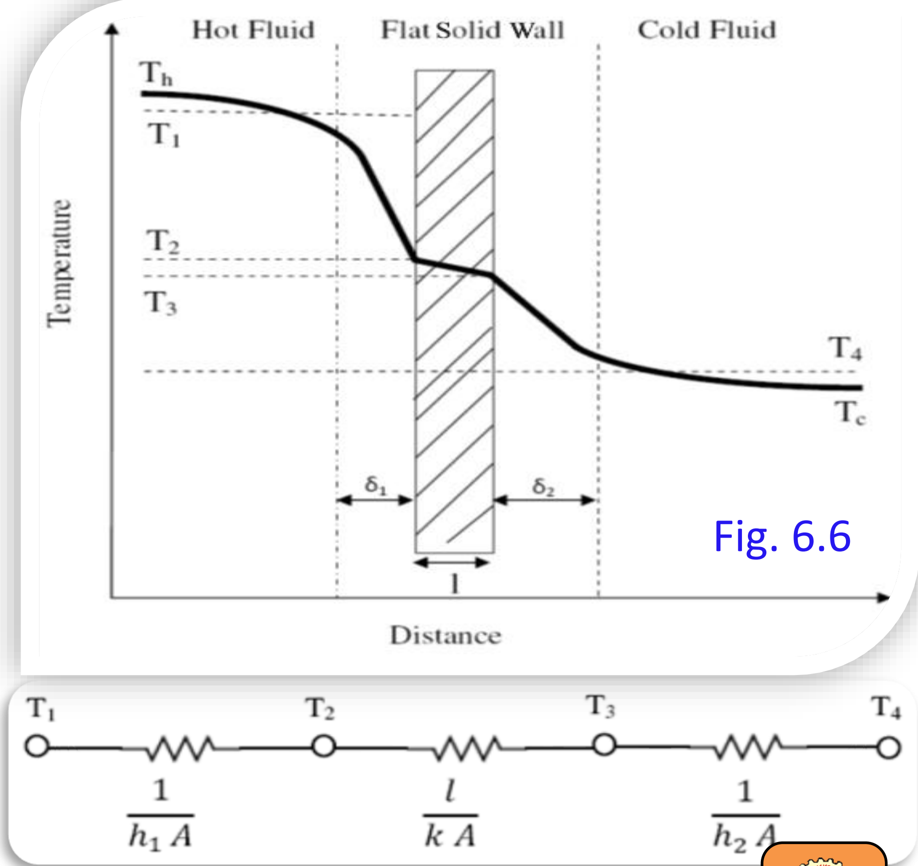


Fig. 6.6

Considering that the heat transfer is taking place at the steady-state through a constant area and the heat loss from other faces are negligible, then the rate of heat transfer on two sides of the wall will be

Rate of heat transfer from the hot fluid to the wall,

$$\dot{q}_1 = h_1 A (T_1 - T_2) \ldots \ldots \ldots (6.10)$$

Rate of heat transfer through the wall,

$$\dot{q}_2 = kA \frac{(T_2 - T_3)}{l} \ldots \ldots \ldots (6.11)$$

Rate of heat transfer from the wall to cold fluid,

$$\dot{q}_3 = h_2 A (T_3 - T_4) \ldots \ldots \ldots (6.12)$$

At steady state, the rate of heat transfers $(\dot{q}_1, \dot{q}_2, \dot{q}_3)$ are same and can be represented by $\dot{q}$. Therefore,

$$T_1 - T_2 = \frac{\dot{q}}{h_1 \; A} \qquad (6.13)$$

$$T_2 - T_3 = \frac{\dot{q}}{A \; k/l} \qquad (6.14)$$

$$T_2 - T_3 = \frac{\dot{q}}{h_2 \; A} \qquad (6.15)$$

On adding equations (6.13 to 6.15) $$T_1 - T_4 = \frac{\dot{q}}{A}\left(\frac{1}{h_1} + \frac{1}{k/l} + \frac{1}{h_2}\right)$$

Or $$T_1 - T_4 = \frac{\dot{q}}{A}\frac{1}{U} \quad \text{.........(6.16)}$$

Where

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{k/l} + \frac{1}{h_2} \quad \text{.........(6.17)}$$

Thus

$$\dot{q} = UA(T_1 - T_4) \quad \text{.........(6.18)}$$

The quantity U is called the overall heat transfer coefficient *(can be calculated if the* h_1*,* h_2*, k and l are known)*.

Q. 3.1. *The steady state temperature distribution in a wall is* $T = 300 - 3050 * x^2$*, where x (in meter) is the position in the wall and T is the temperature (in ◦C). The thickness of the wall is 0.2 m and the thermal conductivity of the wall is 1.2 (W/m·◦C). The wall dissipates the heat to the ambient at 30 ◦C. Calculate the heat transfer coefficient at the surface of the wall at 0.2 m.*

Take away from todays session

- ✓ Energy balance.
- ✓ Heat transfer global coefficient.
- ❑ Logarithmic mean temperature difference (LMTD).
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- ❑ Forced convection in laminar and turbulent regimes inside tubes.
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