

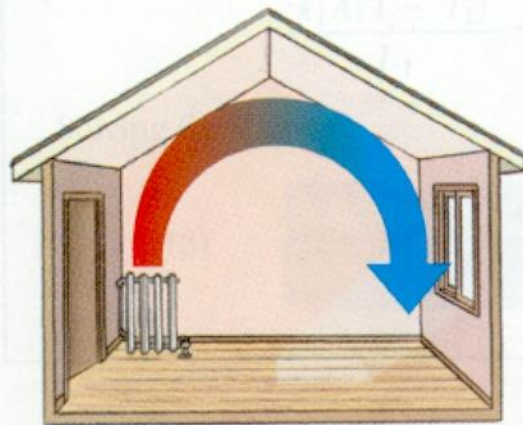
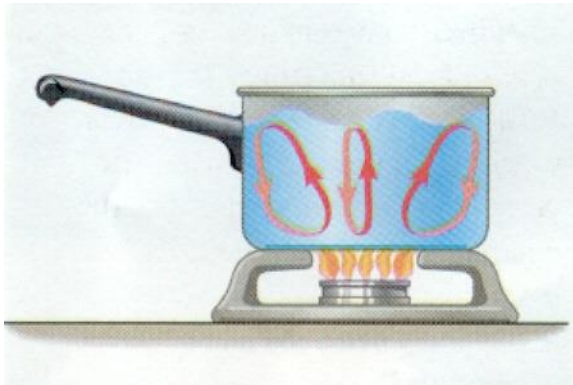
# **FUNDAMENTAL OF CONVECTION**

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# Convection

- Bulk movement of thermal energy in fluids

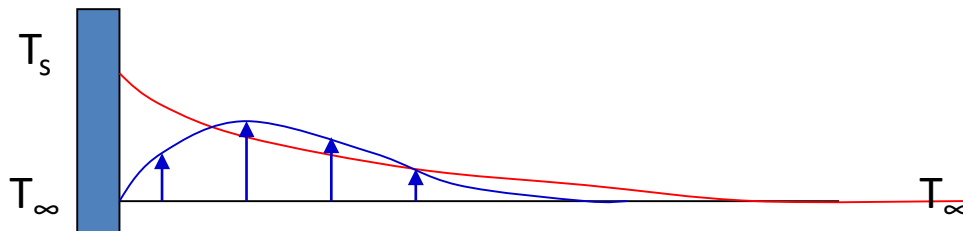


# Physical Mechanism of Convection Heat Transfer

Convection is the mechanism of heat transfer between a solid surface and a pool of fluid in the presence of bulk fluid motion. It can be classified as:

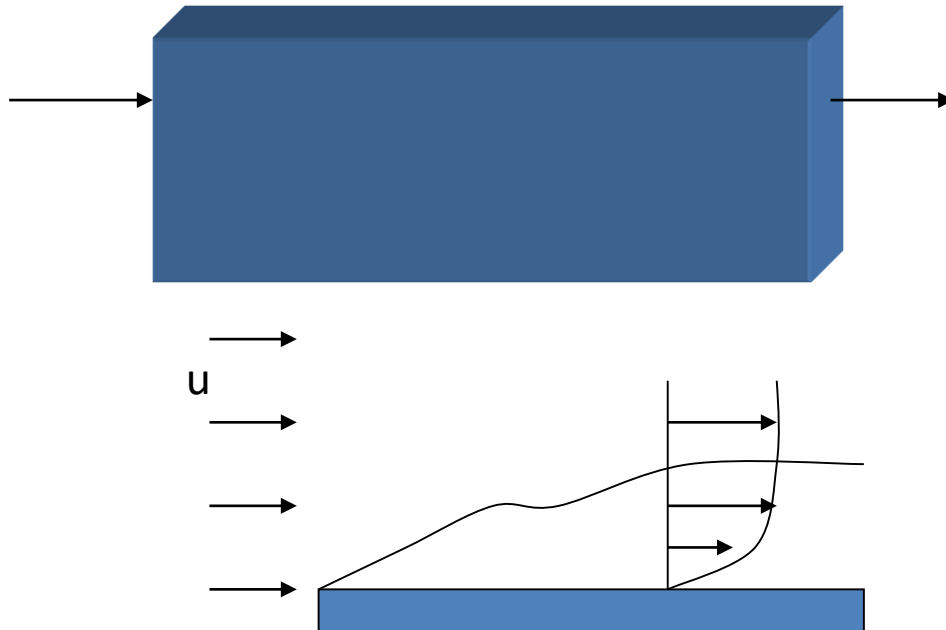
1) **Natural or free convection:**

The bulk fluid motion is due to buoyant force caused by density gradient between the hot and cold fluid regions. The temperature & velocity distributions of free convection along a vertical hot flat surface is shown in figure below.



## 2) **Forced convection** :

The bulk fluid motion is caused by external means, such as a fan, a pump or natural wind, etc.



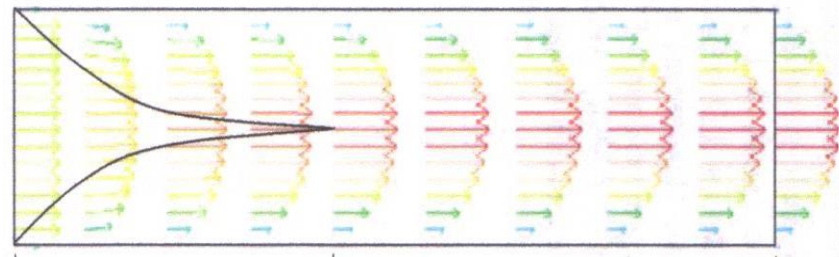
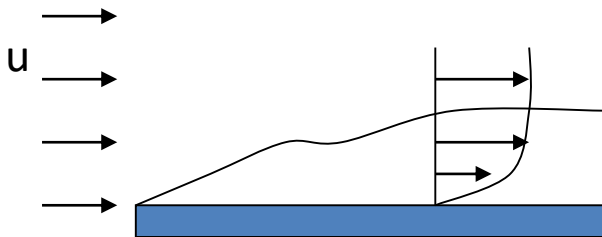
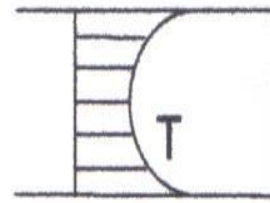
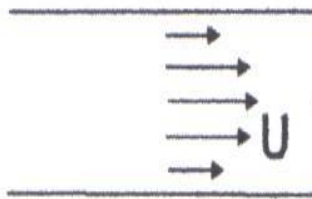
# The properties of the flow fields

- Due to the properties of fluid both velocity and thermal **boundary layers** are formed. Velocity boundary layer is caused by viscosity and thermal boundary layer is caused by both viscosity and thermal conductivity of the fluid.
- Internal versus external flow
  - External flow : the solid surface is surrounded by the pool of moving fluid
  - Internal flow : the moving fluid is inside a solid channel or a tube.

# The properties of the flow fields

- **Laminar flow versus turbulent flow**

- Laminar flow: the stream lines are approximately parallel to each other
- Turbulent flow: the bulk motion of the fluid is superimposed with turbulence



# The governing parameters of convection heat transfer

- **Newton's law of cooling**

$$\dot{Q} = hA(T_s - T_\infty)$$

- The main objective to study convection heat transfer is to determine the proper value of convection heat transfer coefficient for specified conditions. It depends on the following parameters:
  - The Bulk motion velocity,  $u$ , (m/s)
  - The dimension of the body,  $L$ , ( m)
  - The surface temperature,  $T_s$ , °C or K
  - The bulk fluid temperature,  $T_\infty$  , °C or K

# The governing parameters of convection heat transfer (Cont.)

- - The density of the fluid,  $\rho$  ,  $\text{kg/m}^3$
- The thermal conductivity of the fluid,  $k$ , ( $\text{W/m.K}$ )
- The dynamic viscosity of the fluid,  $\mu$  , ( $\text{kg/m.s}$ )
- The specific heat of the fluid,  $C_p$  , ( $\text{J/kg.K}$ )
- The change in specific weight,  $\Delta\rho g$ , ( $\text{kg}/(\text{m}^2\text{s}^2)$  or ( $\text{N}/\text{m}^3$ )
- The shape and orientation of the body,  $S$

- The convection heat transfer coefficient can be written as

$$h = f( u, L, T_s, T_\infty, \rho, k, \mu, C_p, \Delta\rho g, S)$$

- It is impossible to achieve a correlation equation for convection heat transfer in terms of 10 variables. **A better way to reduce the number of variables is required.**

- **Dimensionless analysis**

There are 11 parameters with 4 basic units (length, m), (mass, kg), (temperature, °C or K) , and (time, s).

Applying the method of dimensional analysis, it can be grouped into  $11 - 4 = 7$  dimensionless groups, they are:

$$\frac{hL}{k} = F\left(\frac{\rho u L}{\mu}, \frac{\mu c_p}{k}, \frac{\rho g \Delta \rho L^3}{\mu^2}, \frac{T_s}{T_\infty}, \frac{u^2}{c_p T_\infty}, S\right)$$

1. Nusselt number :  $Nu_L = \frac{hL}{k}$

2. Eckert number :  $E_k = \frac{u^2}{c_p T_\infty}$

3. Reynolds number :  $Re_L = \frac{\rho u L}{\mu}$

4. Temperature ratio :  $\theta_s = \frac{T_s}{T_\infty}$

5. Grashof number :  $Gr_L = \frac{\rho g \Delta \rho L^3}{\mu^2}$

6. S : shape of the surface

7. Prandtl number :  $Pr = \frac{\mu c_p}{k}$

- **To find Reynolds number**

Choosing density ( $\rho$ ), dimension ( $L$ ), surface temperature ( $T_s$ ), and dynamic viscosity ( $\mu$ ) as the 4 basic parameters, and velocity ( $u$ ) as the input parameter. The dimensionless number is obtained by solving the 4 constants,  $a$ ,  $b$ ,  $c$ , &  $d$ .

$$\rho^a L^b T_s^c \mu^d u = 0$$

$$\left(\frac{kg}{L^3}\right)^a (L)^b (^\circ C)^c \left(\frac{kg}{sL}\right)^d \frac{L}{s} = \pi_1$$

$$L \Rightarrow -3a + b - d + 1 = 0$$

$$kg \Rightarrow a + d = 0$$

$$^\circ C \Rightarrow c = 0$$

$$s \Rightarrow -d - 1 = 0$$

$$d = -1, c = 0, a = 1, b = 1$$

$$\frac{\rho L u}{\mu} = \pi = \text{Re}_L$$

- **Simply the dimensionless equations**

Now we have reduced the equation involving 11 variables into a 7 dimensionless group equation. However, 7 dimensionless groups is still too large, we need neglecting the unimportant dimensionless groups. **Eckert number is important for high speed flow.** It can be neglected for our application. **If the average fluid temperature is used for getting the fluid properties, the temperature ratio can also be discarded.** After neglecting the two unimportant dimensionless groups, the general convection equation is

$$Nu_L = F(Re_L, Pr, Gr_L, S)$$

**Forced convection: the density change is very small, the Grashof number is neglected**

$$Nu_L = F(Re_L, Pr, S)$$

- Natural convection: there is no bulk fluid motion induced by external means,  $u = 0$ , Reynolds number is disappeared.

$$Nu_L = F(Gr_L, Pr, S)$$

# The Physical Meaning of The Dimensionless Numbers

- Nusselt number

It is the ratio of convection heat transfer rate to the conduction heat transfer rate.

Consider an internal flow in a channel of height  $L$  and the temperatures at the lower and upper surfaces are  $T_1$  &  $T_2$ , respectively.

The convection heat transfer rate is

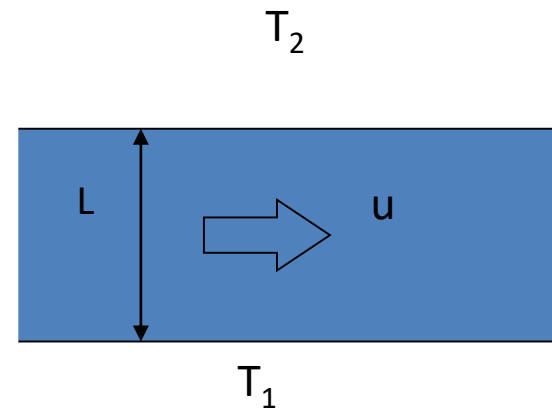
$$\dot{Q}_{\text{cov}} = hA(T_1 - T_2)$$

The conduction heat transfer rate is

$$\dot{Q}_{\text{cond}} = \frac{kA}{L}(T_1 - T_2)$$

The ratio

$$Nu_L = \frac{\dot{Q}_{\text{cov}}}{\dot{Q}_{\text{cond}}} = \frac{hA}{\frac{kA}{L}} = \frac{hL}{k}$$



- **The Reynolds number**

**It is the ratio of inertia force to viscous force of the moving fluid.**

- Inertia force

$$F_i = ma = \rho L^3 \frac{L}{s^2} = \rho L^2 \left(\frac{L}{s}\right)^2 = \rho L^2 u^2$$

- The viscous force

$$F_v = \tau A = \mu \frac{\Delta u}{\Delta y} L^2 = \mu \frac{u}{L} L^2 = \mu u L$$

- The ratio

$$\text{Re}_L = \frac{\rho u L}{\mu} = \frac{u L}{\frac{\mu}{\rho}} = \frac{u L}{\nu}$$

- **The Prandtl number**

**It is the ratio of the momentum diffusivity to the thermal diffusivity.** Thermal diffusivity controls how fast the heat diffuses in a medium. It has the form

$$\alpha = \frac{k}{\rho c_p}$$

The momentum diffusivity is the kinematic viscosity and it controls the rate of diffusion of momentum in a fluid medium. The ratio of the two is called Prandtl number.

$$\text{Pr} = \frac{\nu}{\alpha} = \frac{\frac{\mu}{\rho}}{\frac{k}{\rho c_p}} = \frac{\mu c_p}{k}$$

- **The thermal expansion coefficient**

It is defined as

$$\beta = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p$$

The negative sign results from the fact that, for gases, the change of density with respect to temperature under constant pressure process is always negative. From ideal gas law

$$p = \rho RT \Rightarrow dp = \rho R dT + RT d\rho = 0 \quad \longrightarrow \quad \left( \frac{d\rho}{dT} \right)_p = -\frac{\rho}{T} \quad \longrightarrow \quad \beta = \frac{1}{T}$$

For ideal gas, the thermal expansion coefficient is the inverse of the absolute temperature

- **Grashof number**

The Grashof number represents the ratio of the buoyant force to the viscous force.

$$Gr = \frac{g \Delta \rho L^3}{\nu^2 \rho}$$

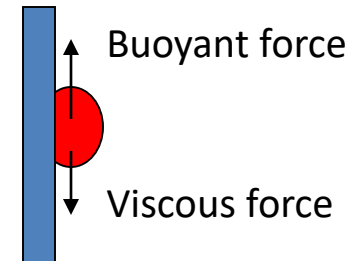
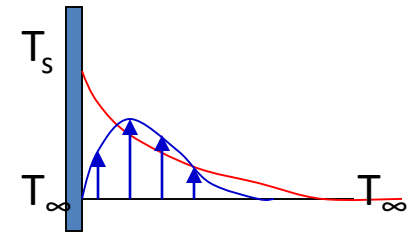
- **Grashof number**

The change of density is

$$\Delta\rho = -\rho\beta\Delta T = \rho_\infty - \rho = -\rho\beta(T_\infty - T) = \rho\beta(T - T_\infty)$$

Substituting into Grashof number

$$Gr_L = \frac{g\Delta\rho L^3}{\nu^2\rho} = \frac{g\rho\beta(T - T_\infty)L^3}{\nu^2\rho} = \frac{g\beta(T - T_\infty)L^3}{\nu^2}$$



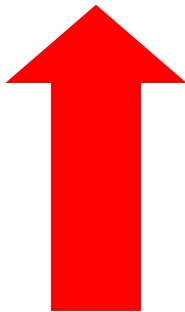
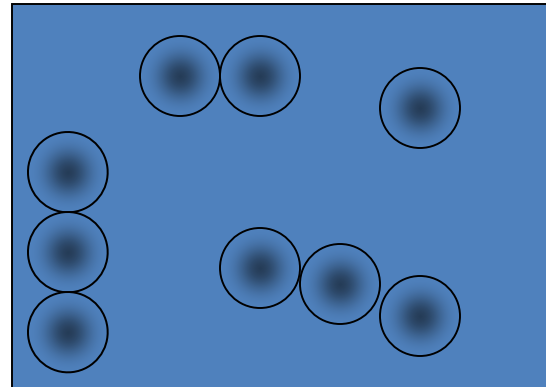
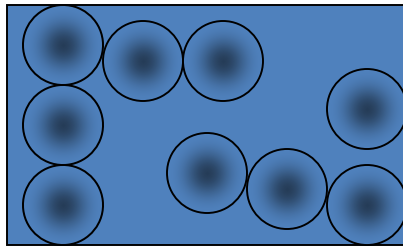
The subscript  $L$  means that the characteristic length of the Grashof number. It may be the length of the surface. For ideal gas,  $Gr_L$  is

$$Gr_L = \frac{g(T - T_\infty)L^3}{\nu^2 T}$$

# Convection

What happens to the particles in a liquid or a gas when you heat them?

The particles spread out and become less dense.



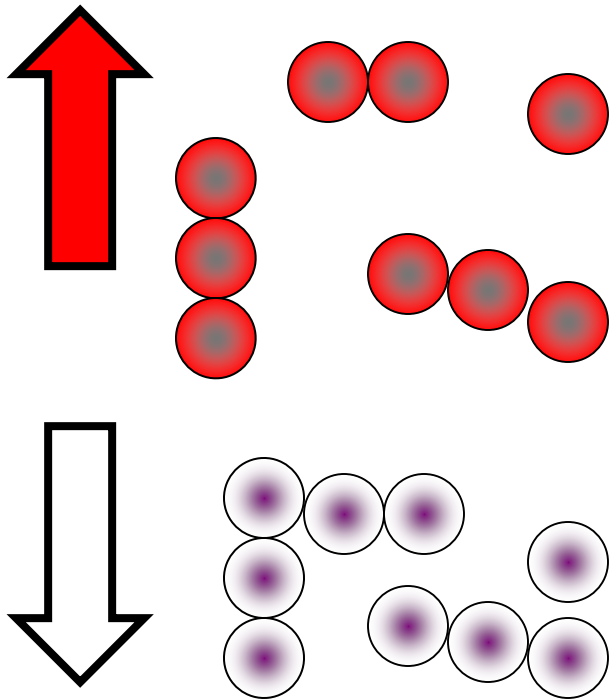
This effects fluid movement.

# Fluid movement

Cooler, more dense, fluids sink through warmer, less dense fluids.

In effect, warmer liquids and gases rise up.

Cooler liquids and gases sink



# Why is it windy at the seaside?



## Why is it windy at the seaside?

The land is warmer than the sea.



This land warms the air above it, and it rises.



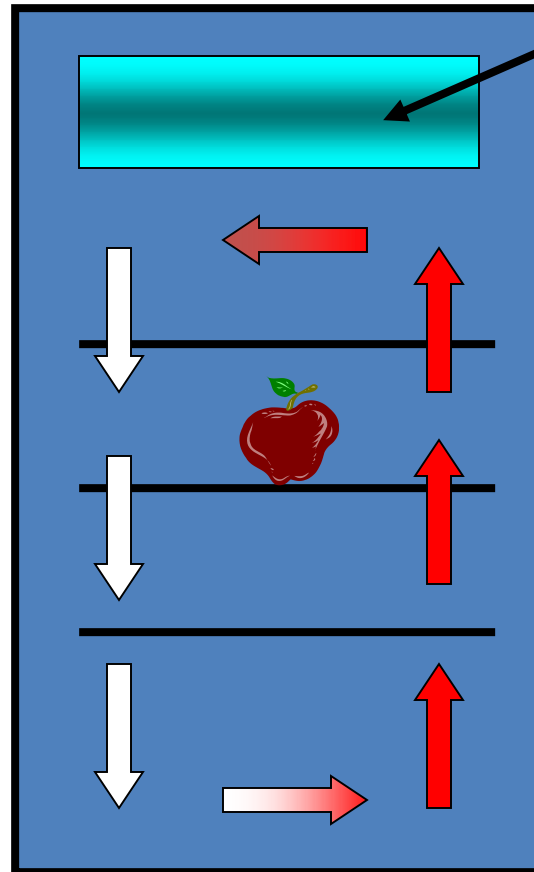
The cold air from above the sea moves in to take the place of warm air that has risen.



# Cold air sinks

Where is the freezer compartment put in a fridge?

It is put at the top, because cool air sinks, so it cools the food on the way down.



Freezer compartment

It is warmer at the bottom, so this warmer air rises and a convection current is set up.

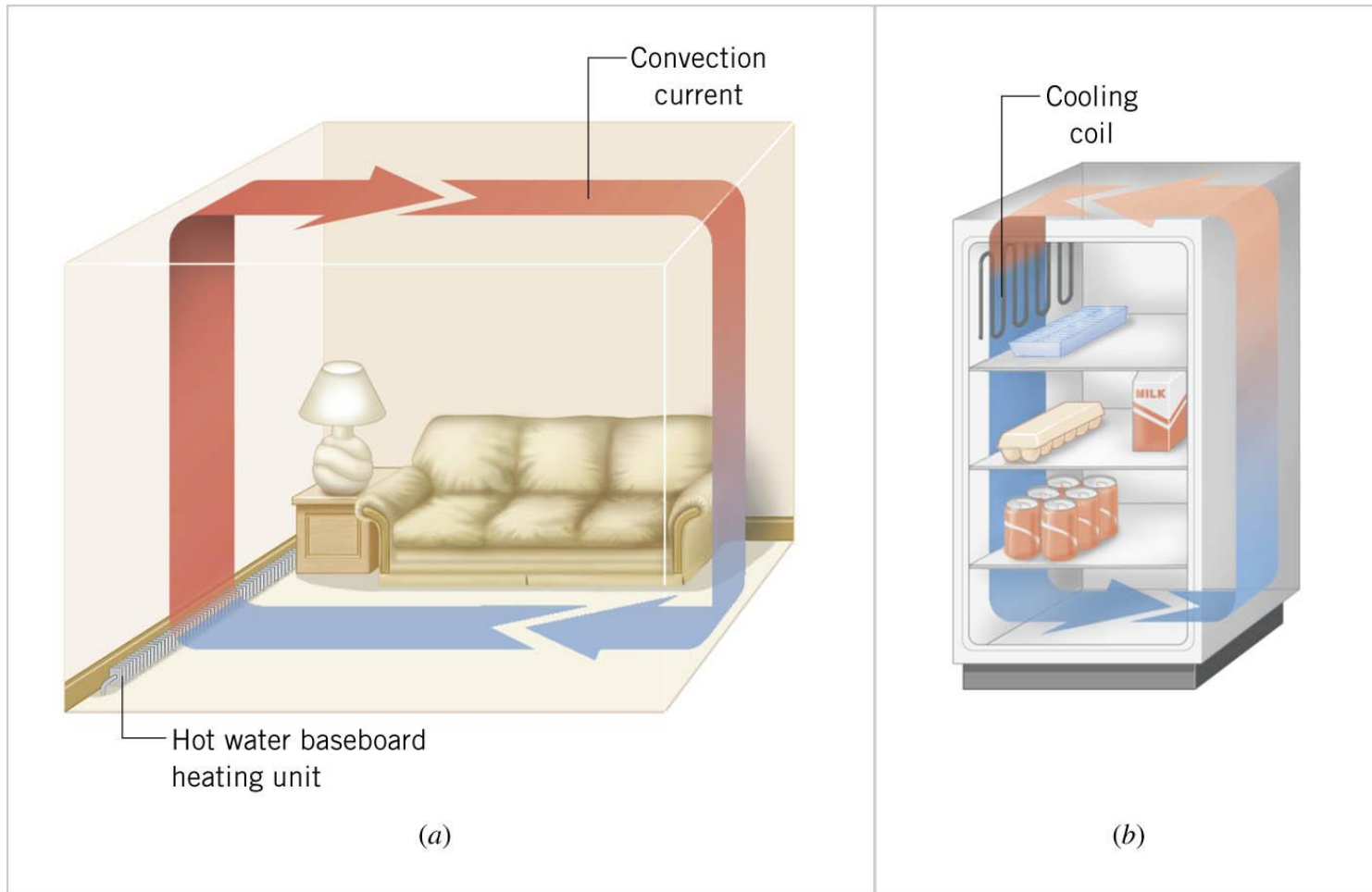
# Convection

**Convection** is the process in which heat is carried from place to place by the bulk movement of a fluid.

**Convection currents** are set up when a pan of water is heated.

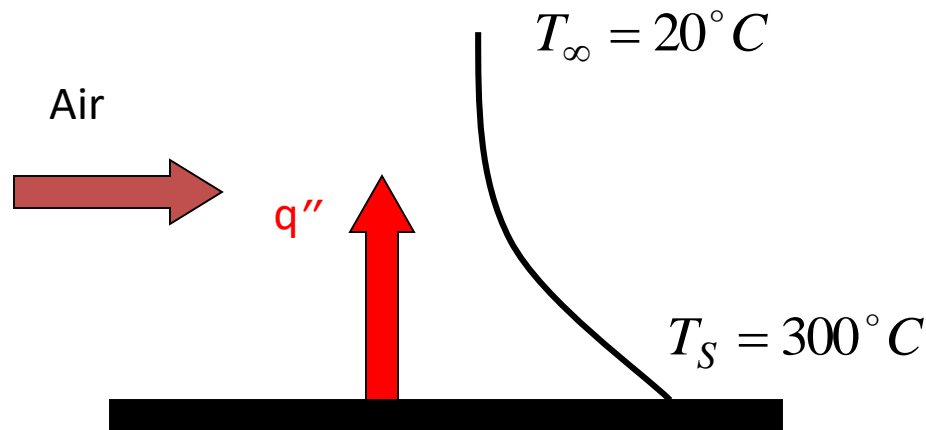


# Hot Water Baseboard Heating and Refrigerators



# Convection

Air at  $20^{\circ}\text{C}$  blows over a hot plate, which is maintained at a temperature  $T_s = 300^{\circ}\text{C}$  and has dimensions  $20 \times 40$  cm.



The convective heat flux is proportional to

$$q_x'' \propto T_s - T_{\infty}$$

- The proportionality constant is the *convection heat transfer coefficient*,  $h$  ( $\text{W}/\text{m}^2\cdot\text{K}$ )

$$q_x'' = h(T_S - T_\infty) \quad \text{Newton's law of Cooling}$$

- For air  $h=25 \text{ W}/\text{m}^2\cdot\text{K}$ , therefore the heat flux is  $q_x'' = 7,000 \text{ W}/\text{m}^2$
- The *heat rate*, is  $q_x = q_x'' \cdot A = q_x'' \cdot (0.2 \times 0.4) = 560 \text{ W}$ .
- In this solution we assumed that heat flux is positive when heat is transferred from the surface to the fluid
- *How would this value change if instead of blowing air we had still air ( $h=5 \text{ W}/\text{m}^2\cdot\text{K}$ ) or flowing water ( $h=50 \text{ W}/\text{m}^2\cdot\text{K}$ )*

**The End**

**Terima kasih**

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