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Heat Transfer, An Overview

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Abstract: ***This paper analyzes the growing need of efficient way of heat transfer in present day environment. The present standard of living became possible by the energy available in the form of heat obtained from a variety of sources, for example fuels. The process of this energy conversion falls under the scope of Thermodynamics. Thermodynamics is main subject of mechanical engineering that deals with the end state of processes involving heat or work transfer and provides no information concerning the nature of the interaction or the time rate at which it occurs. In practical or industrial applications, time factor i.e. the rate of energy (called power) transferred plays a very important role. That is why an efficient way of heat transfer is necessary. So the equipments used in heat transfer are designed according to the rate of heat transfer considering practical aspects. There is a long list of various equipments where heat transfer rate influences their operation. Heat is in fact, a low grade energy where work is high grade energy. The driving force which causes the transfer of energy as heat is the temperature difference between the systems. Other parameters which affect the heat transfer are material properties like conductivity, emissivity, flow parameters like velocity of flow and geometry In addition to the temperature difference. Some other transport processes of the heat transfer the transfer of mass, electrical energy and momentum. The amount of energy transferred as heat can be calculated from the "law of conservation of energy" (First law of Thermodynamics)***

Keywords: Energy conversion, heat transfer (HT), heat transfer equipments, low grade energy, high grade energy, momentum, conductivity, emissivity.

1. Introduction

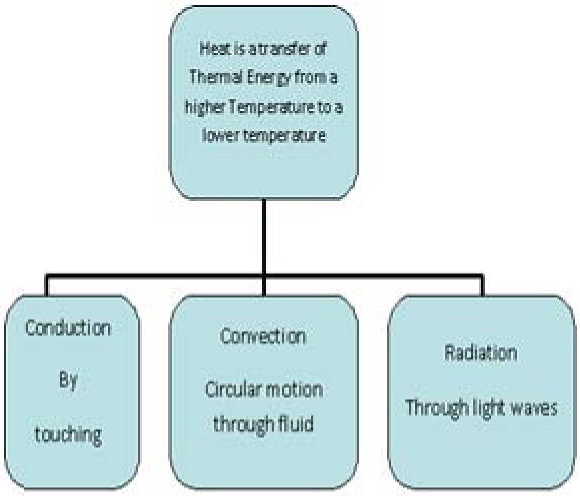

Figure 1: Modes of heat transfer

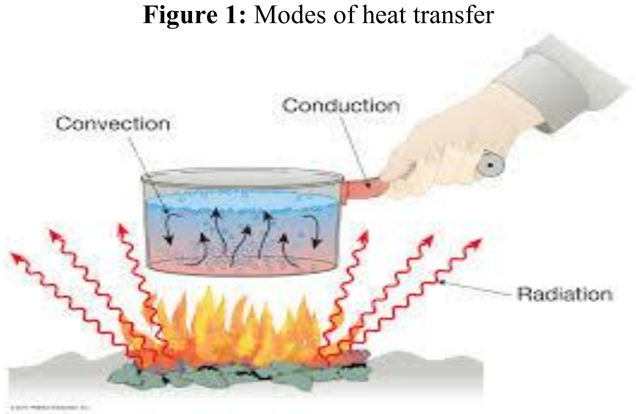

Figure 2: Modes of heat transfer (another figure)

Heat transfer may be defined as the transmission of energy from one place (system) to another as a result of temperature gradient.

Or

Heat transfer is a branch of Thermal Science which deals with the analysis of rate of Heat transfer and temperature distribution taking place in a system as well as the nature of Heat transfer. The design of boilers, condensers, evaporators, heaters, refrigerators and heat exchangers require quite a good knowledge of the amount of heat transferred as well as rate of Heat transfer. Heat transfer deals with:

(i) Amount of heat to be transmitted
(ii) Time taken (duration heating and cooling) and area required for the process
(iii) Possibility of addition or removal of heat at a desired rate.
(iv) Temperature distribution existing within the system

2. Laws of Heat Transfer

Like other branches of Physics, there are some fundamental and some subsidiary laws that are being used while dealing with the Heat transfer.

The fundamental laws are applied in all major area. These are

1. Law of conservation of mass
2. Newton's second law of motion
3. First and second law of Thermodynamics

The subsidiary laws are nothing but experimental results. These are:

1. Fourier's law of heat conduction
2. Newton's law of cooling (or heating)
3. Stefan- Boltzman's law of thermal radiation.
4. Equation of state.

Law of conservation of mass (Equation of continuity): It says that mass of an incompressible fluid system remains constant (in absence of any nuclear reaction). Basically it is nothing but the equation of conservation of mass for steady incompressible fluid flow system and is given by;

$. = \rho A \upsilon$;

Where , A → Area of cross-section of flow (m^2) ,
ρ→ density of fluid (kg/ m^3)

υ → fluid velocity (m/s)

Newton's second law of motion:
It states that the rate of change of momentum in any system is proportional to the external force applied on the system. i.e.
F ∝ d (m υ)/ dt

3. Modes of Heat Transfer

1. Conduction
2. Convection
3. Radiation

Conduction:

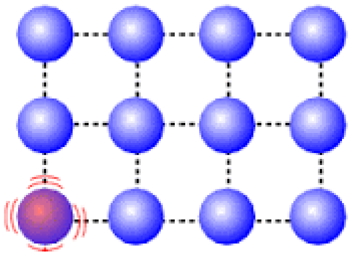

Figure 3: Modes of heat transfer in conduction

Conduction is phenomenon of heat propagation in which heat is transmitted from a region of high temperature to a region of low temperature within a medium (solid, liquid or gas) or between different mediums in direct physical contact. In case of heat transfer taking place through Conduction, there is no actual movement of particles. Higher temperatures are associated with higher molecular energies Heat is supplied at one end of the material and propagates to the other end of the material by the vibration of the atoms as shown in figure 3. Actual movement of electron takes place. Here vibrational energy of the atoms is transferred. For example, let us consider heat propagation through a metal rod, one end of which is placed adjacent to flame. The elementary particles (molecules, atoms & electrons) composing the rod and which are in the immediate vicinity of the flame, get heated. Due to the growth of temperature, their kinetic energy increases and this put them in to violent state of agitation and they start vibrating more vigorously than the earlier about their mean positions. These more active particles (molecules, atoms & electrons) collide with less active particles (in fact there is no collusion) lying near to them. During collision, the less active particles get energy and get excited i.e. thermal energy is imparted to them. There is the net transfer of energy by random molecular motion as a *diffusion* of energy. This gets repeated for layer by layer of molecules until the other of the rod is reached.

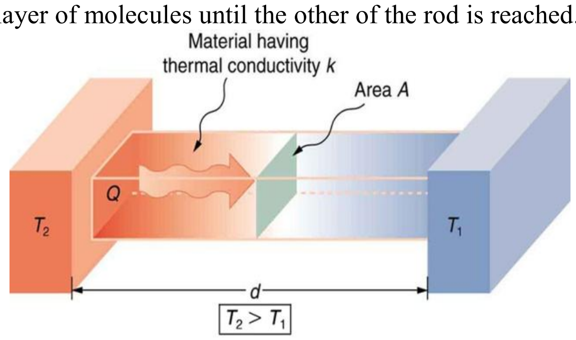

Figure 4: Heat conduction in a rod

The governing equation is Fourier's law.

$$Q = -KA\frac{dT}{dx} \quad \text{.....................(1)}$$

Where; Q → Rate of heat transfer,
K → Thermal conductivity,
A → Area of heat transfer surface
dT→ Temperature difference
dx→ distance
heat conducted per unit time per unit area is denoted by q and is called heat flux. i.e. $q = Q/A = -K\frac{dT}{dx}$

$$= K\frac{T2 - T1}{dx};$$

$T_2 > T_1$

Example: A pot placed on hot burner, touching a spoon which is placed in a pool of boiling water, using a heating blanket to get worm, etc.

Thermal conductivity: Thermal conductivity is the property of the materials and is defined as the ability of the materials to allow heat to pass through it. From equation (1), thermal conductivity can be defined as the rate of heat transfer through a unit thickness of materials per unit area per unit Temperature difference (dx = 1, A = 1, dT = 1, respective units). Thermal conductivity of a material is a direct measure of how fast heat will transmit in that material. If the value of the thermal conductivity is large, it is a good conductor and vice versa. The thermal conductivity of a substance is maximum (highest) in solid state and lowest (minimum) in gaseous state.

Table 1: Typical values Thermal conductivity at 20 °C (in decreasing order)

Material	Thermal conductivity , k(W/m/K)
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminium	237
Iron	73
Carbon steel, 1 % C	43
Non –metallic solids	
Window glass	0.780
Brick	0.720
Asbestos	0.149
Cork	0.045
Glass wool	0.038
Liquids	
Water	0.556
Ethylene glycol	0.249
Ammonia	0.54
Gases	
Helium	0.152
Air	0.024
Steam	0.0206
Carbon dioxide	0.0146

The value of Thermal conductivity also depends on the manner in which the energy has been transferred. The pure metals allow fastest transfer of heat energy by the vibrations of their crystal lattices and hence have highest value of Thermal conductivity (so, good conductors). The thermal conductivity decreases with increasing amount of impurities in the metals. Most non – metals are poor conductor of heat transfer i.e. they have low value of thermal conductivity and hence they are called *thermal insulators*.

In case of gases, thermal conductivity depends on the square root of the absolute Temperature.

If the thermal conductivity of a material does not vary with the change in direction, the material is called the *isotropic material* and if the thermal conductivity of a material varies with the change in direction of heat flow, the material is called the *anisotropic material*.

Convection:
Convection is a phenomenon of heat propagation due to circulation or mixing of a liquid medium (gas, liquid or powdery substance). In this case, unlike conduction, transport of medium particles is there. Convection may be classified in to: (i) Free convection (ii) forced convection

Natural or Free convection: in this case, circulation or mixing of the fluid particles is caused mainly due to buoyancy or gravity effect i.e. due to the difference of the densities of the cold and hot fluids. Some examples are:
→ Chilling effect of a cold wind on a worm body.
→heat exchange on the outside of the cold and worm pipes
→ heating of air in a room by a stove

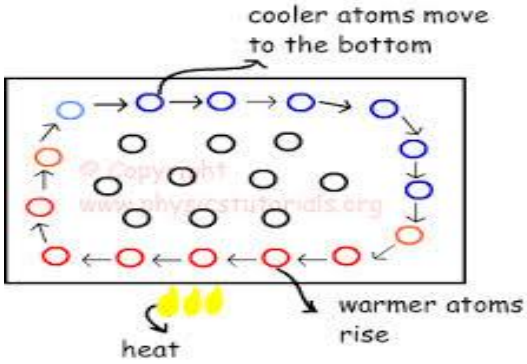

Figure 5: Heat transfer in free convection

Newton was a great scientist who invented many laws. He gave law for cooling or heating fluids.

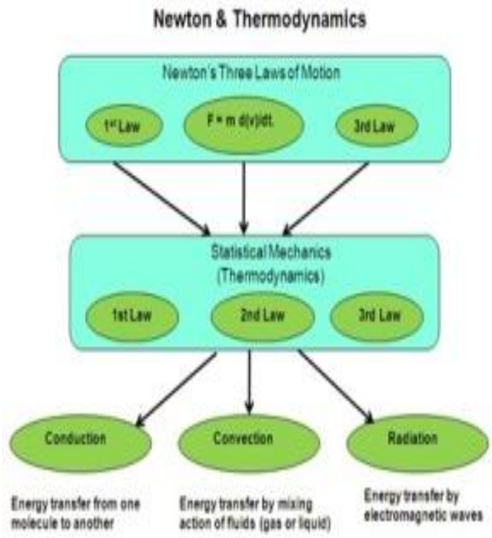

Figure 6: Newton's laws for thermodynamics

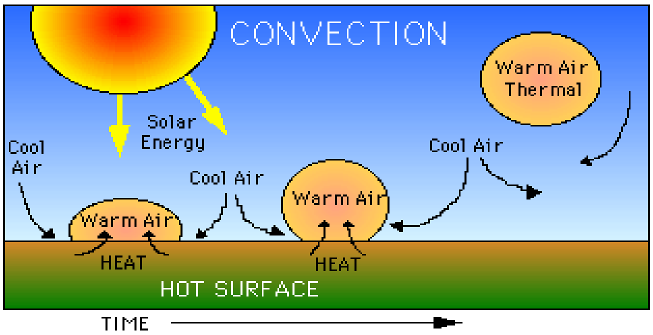

Figure 7: Modes of heat transfer in convection

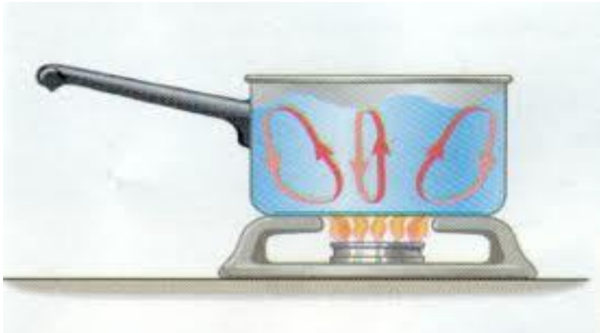

Figure 8: Heat transfer in a free convection

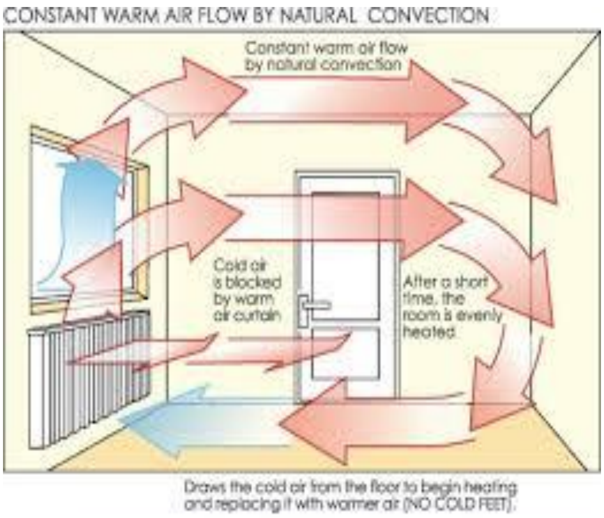

Figure 9: Heat transfer in a free convection

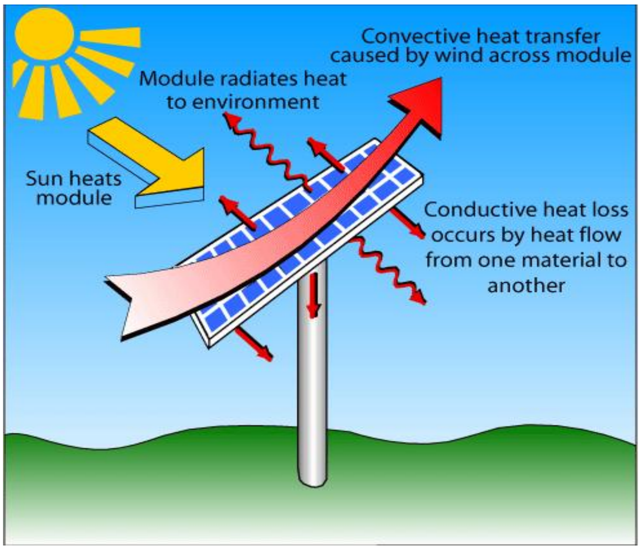

Figure 10: Heat transfer in a free convection

Forced convection: The flow of the particle is caused by a pump, fan or atmospheric winds. These mechanical devices provide a definite path for the particles and set up direction of flow that speeds up the rate of heat transfer.

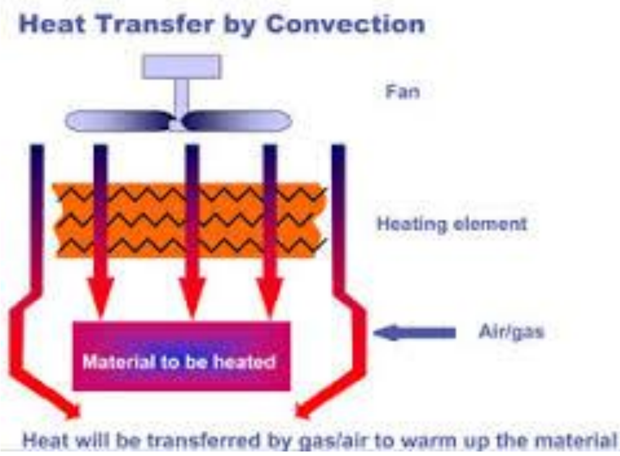

Figure 11: Heat transfer in a forced convection

Figure 12: Heat transfer in a forced convection

Some examples of forced convections are:
→Flow of water in condenser tubes
→Fluid passing through the tubes of Heat Exchanger
→Cooling of I. C. Engine

The governing equation is Newton's law of cooling (or heating).

$Q = h A (T_s - T_f)$

Where; T_s → Surface Temperature,

T_f → Fluid Temperature ,
A→ Surface area exposed to heat transfer
h→ heat transfer coefficient

Area (A) is taken in m^2 and Temperature can be taken in any suitable units as the difference is to considered. The heat transfer coefficient (h) has the unit $W/m^2/K$ and depends density, viscosity, specific heat and thermal conductivity.

In general, the following parameters affect the value of 'h':
→It (h) varies from 10 to 100,000 as per nature of convection (free or forced) and type of fluid i.e. air or water.
→depends on type of fluid (its physical properties) and nature of motion (laminar or turbulent)
→As the value of 'h' is very high, the correct value is essential for designing different heat transfer equipments.

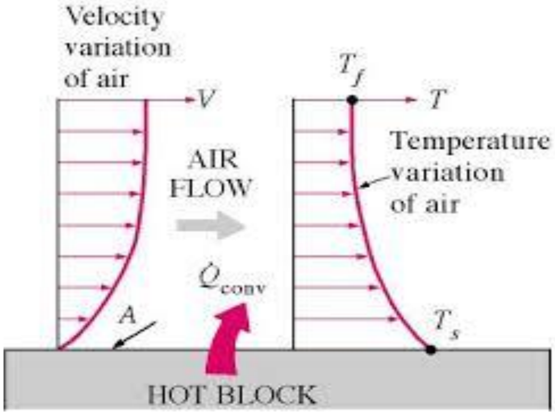

Figure 13: Temperature profile in a forced convection

Table 2: Typical values of heat transfer coefficient (h)

Fluid flow condition	h ($W/m^2/K$)
Air(1 bar, free convection)	6-30
Air(1 bar, forced convection)	10- 200
Water(free convection)	500-1000
Water(forced convection)	600-8000
Vaporization of water	2500- 100,000
Condensation of steam	400- 25000

Radiation: Radiation is a phenomenon of heat propagation in the form of wave motion or radiant energy from one body to another without any intervening medium. Unlike the heat transfer by Conduction and Convection, transport of radiations does not affect the material medium between heat source and the receiver.

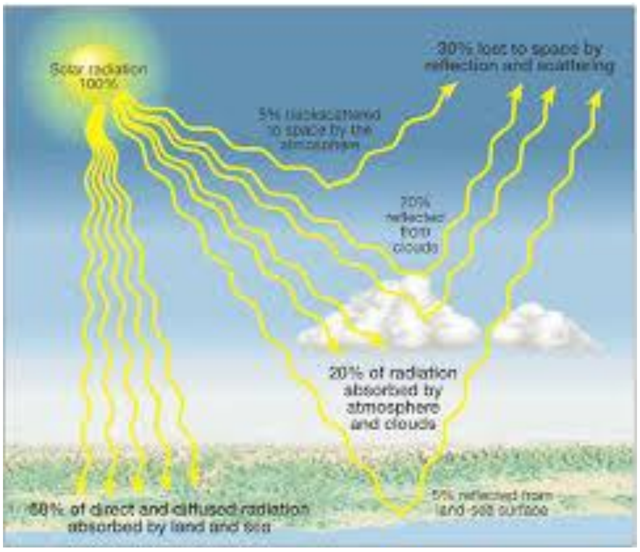

Figure 14: Heat transfer in radiation

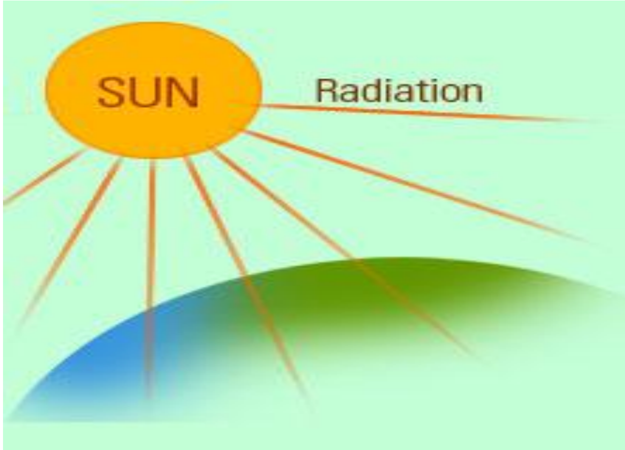

Figure 15: Heat transfer in radiation

Radiation heat exchange occurs mostly in vacuum.

The governing equation is Stefan- Boltzman's law of thermal radiation.
$Q_b = \sigma A T^4$;
Where; Q_b →rate of heat transfer by a black body
T→ absolute surface Temperature (K)
σ → constant of proportionality constant (also called Stefan-Boltzmann constant) = 5.67×10^{-8} W/m^2 /K^4.

In actual practice, the heat flux q (Q/A) is always less than the theoretical one. To accommodate this, an additional term is introduced. So, $\mathbf{Q = \sigma \epsilon A T^4}$;
Where, ϵ → Radiative property of the surface (called emissivity)

The *emissivity* of a surface is nothing but a measure of how it emits radiant energy as compared with black body surface at the same temperature. The emissivity of a material varies with surface temperature and wave length of the radiation.

4. Classification of Radiation:

Radiation can be further classified into:
1. Ultra –Violet Radiation
2. Infra red Radiation
3. Microwave Radiation
4. Radio wave Radiation

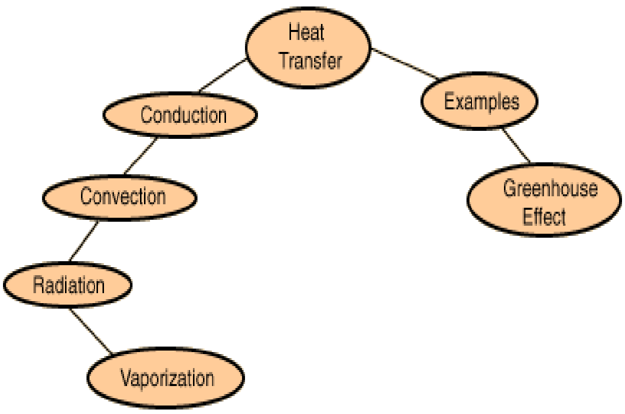

Figure16: Generalised modes of Heat transfer

Figure 17: Types of Radiation

The basic difference between radiation and other two forms of heat transfer is that while in case of conduction and convection is that, that the heat transfer is directly proportional to the first power of Temperature difference where as it is directly proportional to the fourth power of Temperature in case of radiation. One can explain the basic phenomenon like land breeze and sea breeze.

Land and Sea Breeze:

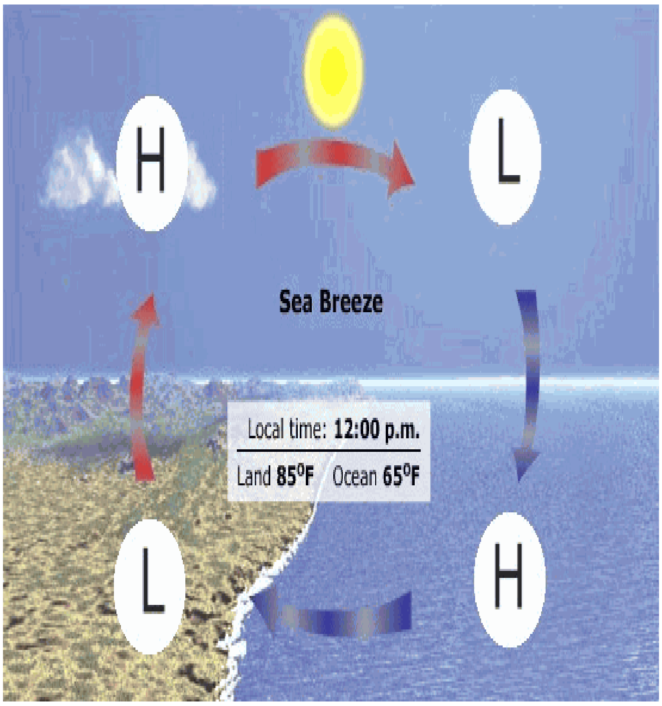

Figure 18: Land and Sea Breeze:

Air pressure at the Earth's surface is different in different places. This is partially due to the different amounts of heat received from the sun. When the Sun heats up the Earth, the air above warms and becomes less dense, expands and rises. The air above is pushed upwards and then spreads out horizontally. Due to this horizontal air movement there is less air above the ground where the heating took place and this leads to an area of low pressure. As the air rises, it cools. As it cools, the air becomes denser and sinks. This sinking means that there is more air above the ground in this area and an area of high pressure is formed. Air starts moving from high pressure areas to low pressure regions to even out the pressure differences, generating winds and atmospheric circulation as a result.

The same behavior occurs on a smaller scale during the formation of sea breezes during the day and land breezes during the night and these are shown in the animation below. During the day, the land heats up faster than the sea, warming the air above. During the night, the sea cools slower than the land so the air is warmer over the sea compared to the land. In both cases, the warm air rises and leaves an area of low pressure (L) below. Air from higher pressure (H) regions moves towards the low pressure regions to even out the pressure differences. At higher altitudes the air is transported back in the opposite direction.

5. Application of Heat Transfer:

(1) In the design of thermal and nuclear power plants (steam generators, condensers etc.)
(2) Internal combustion engines
(3) Heat engines , heat exchangers ,, catalytic converters
(4) Refrigeration and air conditioning units
(5) Heating and cooling load calculations in chemical plants
(6) Furnaces , heat shields for space vehicles
(7) design of cooling systems for electric motors and transformers
(8) Thermal control of space vehicles
(9) Heat treatment of metals
(10) Minimization of building heat losses using improved insulation techniques.

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