Thermodynamics
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Lecture 17
Modes of Heat Transfer

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Conduction, convection and radiation are the modes of heat transfer.

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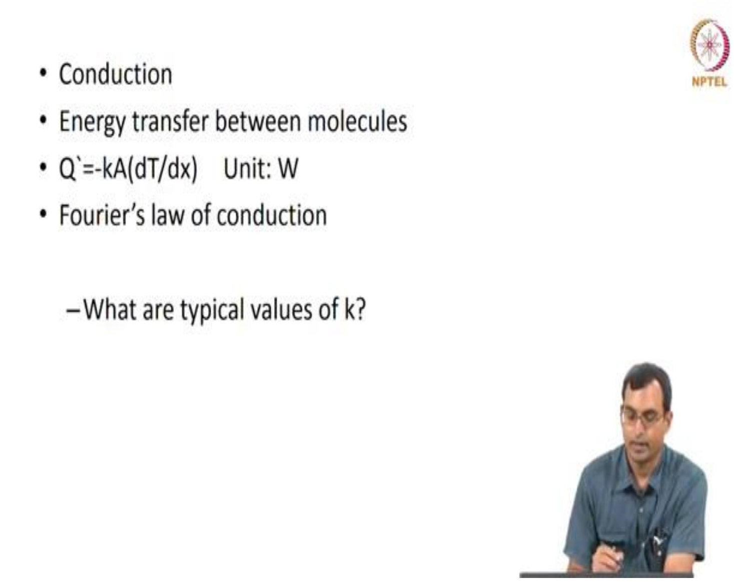

Conduction is the energy transfer (heat transfer) between molecules (or through molecules). In liquids and gases, the molecules or atoms are free to move. Hence, conduction happens because of their movement. In solids, the molecules or atoms are fixed. However, they can vibrate and transfer energy from one to another through those vibrations.

Heat transferred through conduction is expressed using Fourier's law of conduction:

$\dot{Q} = -kA\frac{dT}{dx}$, where $\dot{Q}$ is the rate of heat transfer, k is the thermal conductivity of the material, A is cross-sectional area of the material perpendicular to the direction of heat transfer, and $\frac{dT}{dx}$ is the gradient of temperature. The unit of $\dot{Q}$ is watt.

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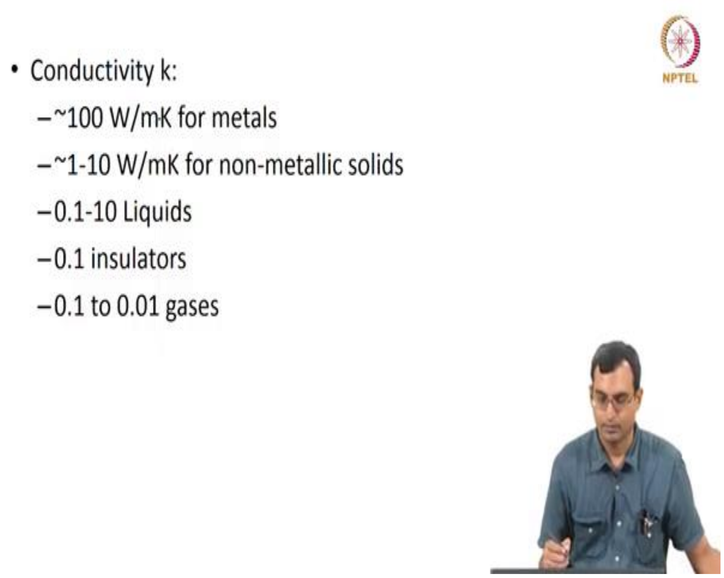

Figure 1.

Figure 1 shows typical values of k for different materials. Metals have the highest values of k, whereas the gases have the least. Hence, for a given temperature difference, conduction is more in the case of metals compared to that for a gas. The unit of k is W/m·K

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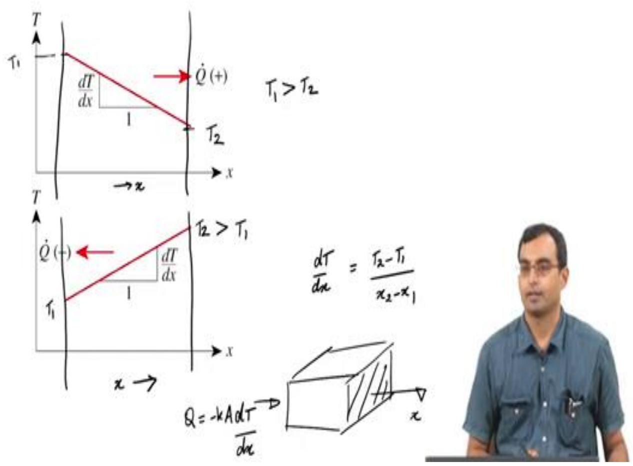

Figure 2.

Consider a block as shown in Fig. 2. T_1 represents the temperature of its left wall and T_2 represents the temperature of its right wall. If $T_1 > T_2$, the slope, which is dT/dx and is also the gradient of temperature, is negative, and the heat transfer is considered positive (heat transfer happens in the positive x direction). If $T_2 > T_1$, the slope is positive, and the heat transfer is considered negative (heat transfer happens in the negative x direction). Hence, we have the negative sign in the expression for the Fourier's law. For solids, conduction is significantly strong.

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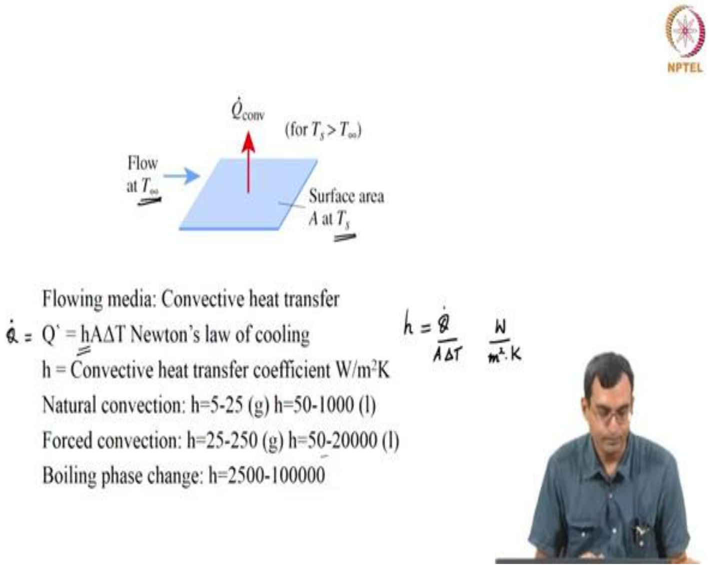

Figure 3.

In the case of flowing media like liquids and gases, we also have convective heat transfer because the substance can flow (conduction is also there). In this case, $\dot{Q} = hA\Delta T$, where h is the convective heat transfer coefficient, A is the area of material which is exposed to the flow (of liquid or gas), ΔT is the temperature difference between the material and the ambient. It is also known as Newton's law of cooling. For a surface (of a material) shown in Fig. 3 where a fluid at temperature T_∞ is flowing over it, ΔT is $T_s - T_\infty$ (if $T_s > T_\infty$). The unit of h is W/m^2K.

Natural convection happens if there is a temperature difference between a substance and the surroundings. This temperature difference creates density gradient in the surrounding gas or liquid setting up the natural convection currents which take away heat from the substance (assuming the temperature of the substance is higher compared to the surroundings'). Typical h values for natural convection in the case of liquid and gas (which could be the surrounding medium around the considered substance) are shown in Fig. 3.

If there is an external agency (such as a fan or blower) to force liquid or gas over the considered item, heat is transferred away through forced convection. Typical h values for such cases for liquids and gases as surrounding medium are shown in Fig. 3. We have even higher h values during phase changes, for example, water boiling in a pan. It is the most efficient way of cooling a hot substance.

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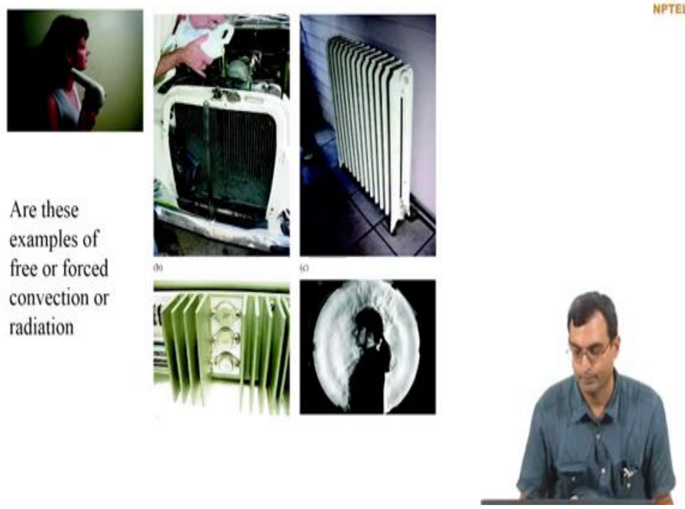

Figure 4.

Identify if it is a forced or natural (free) convection in the images shown in Fig. 4.

(a) hair dryer – forced convection

There is a fan inside a hair dryer which blows out air.

(b) radiator of the car – forced convection

There is forced flow of air around the radiator because of either a fan behind it or velocity difference between the car and the ambient.

(c) room heater - natural convection

If the heat transfer from the heater to the room is considered, it is free convection if the room air is stagnant (there is not much air movement).

(d) Fins on electronic instrument – free convection

Fins are used to increase the surface area in order to facilitate the heat transfer (as $\dot{Q} \propto A$) . Here, there is no fan shown for forcing away the hot air near the fins. Hence, it is a case of free convection.

(e) A person standing in a cold room – natural convection

It shows a schlieren image of a person. As there is temperature gradient between the body and the surroundings, natural convection currents are setup in surroundings taking away the heat from the body. You can see strong currents near the head and open skin (or exposed surfaces of the skin).

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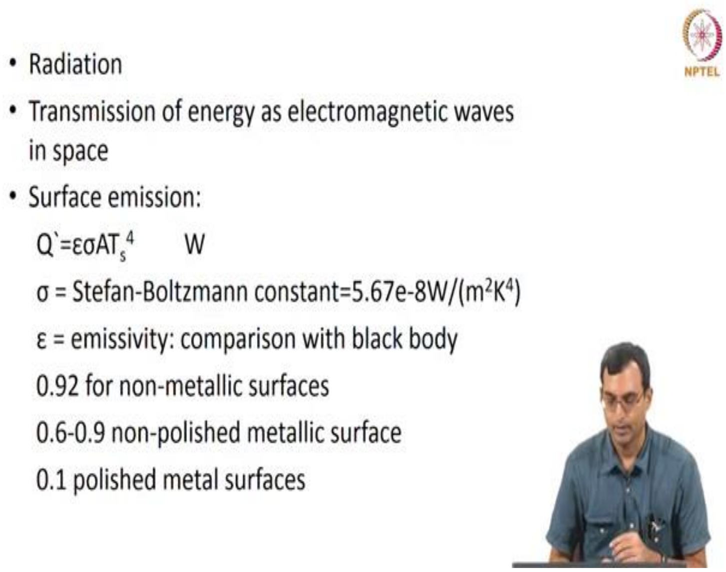

Figure 5.

Radiation is another mode of heat transfer. Here, the energy is transmitted as electromagnetic waves through space. It does not need any medium for heat transfer. The rate of heat transfer from a surface is $\dot{Q} = \varepsilon\sigma A T_s^4$, where ε is the emissivity of the surface, σ is Stefan Boltzmann constant, A is the surface area and T_s is the surface temperature. $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$.

Black body is the best emitter and the best absorber of the energy. Its emissivity is 1. Emissivity value denotes how good or bad emitter a given surface is compared to the black body. Emissivity values for different types of surfaces are shown in Fig. 5.

In space, radiation is the only mode of heat transfer. Hence, for space applications, materials are chosen keeping in mind their emissivity values. However, in our daily lives, the heat transfer happens in a combination of the 3 modes mentioned above.

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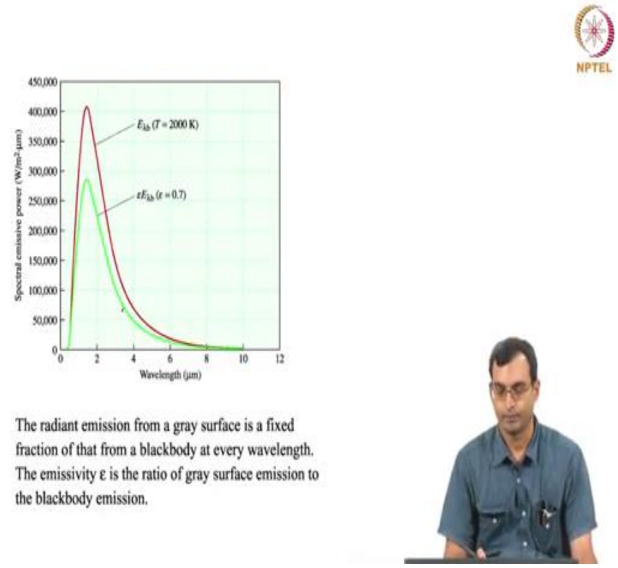

Figure 6.

A gray body surface emits radiation at all the wavelengths as the black body. However, the ratio of the emission from a gray body to black body is fixed at all the wavelengths and it is less than 1. This ratio is called emissivity. Figure 6 shows spectral emission power as a function of wavelength for a gray and a black body.

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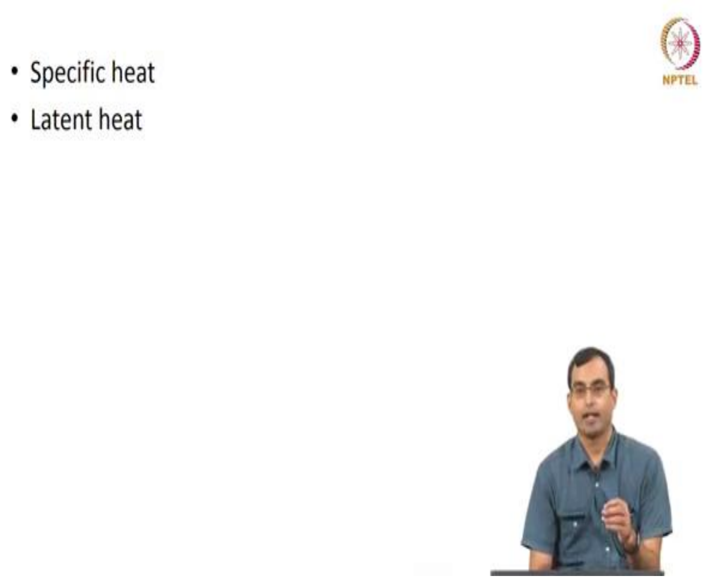

Let's discuss the concepts of the specific heat and the latent heat.

Specific heat is the amount of heat needed to raise the temperature of a unit mass of a substance by unit change in temperature. Its unit is J/kgK. The heat needed depends on the substance whose temperature we want to raise by a unit. The amount of heat needed to raise the temperature of 1 kg of water by 1 K (or 1 °C) is larger than the amount of heat needed to raise the temperature of 1 kg of air by 1 K (1 °C). The specific heat may also depend on the temperature. For example, the amount of heat needed to raise the temperature of 1 kg water from 16 °C to 17 °C is different than raising its temperature from 90°C to 91 °C.

The latent heat is the amount of heat we need to give in order to change the phase of a substance. If I have 1 kg of ice and I want to change it into 1 kg of water at the same temperature, the amount of heat I need to give is the latent heat of melting. It would be the same as the latent heat of freezing (amount of heat which need to be removed) if I had 1 kg of water at 0 °C and I want to convert it to ice at the same temperature. Similarly, we have the latent heat of boiling or latent heat of condensation which is the amount of heat needed to convert the given liquid substance into gaseous phase (or convert given gaseous substance into liquid phase) at the same temperature. This also depends on the substance under consideration.

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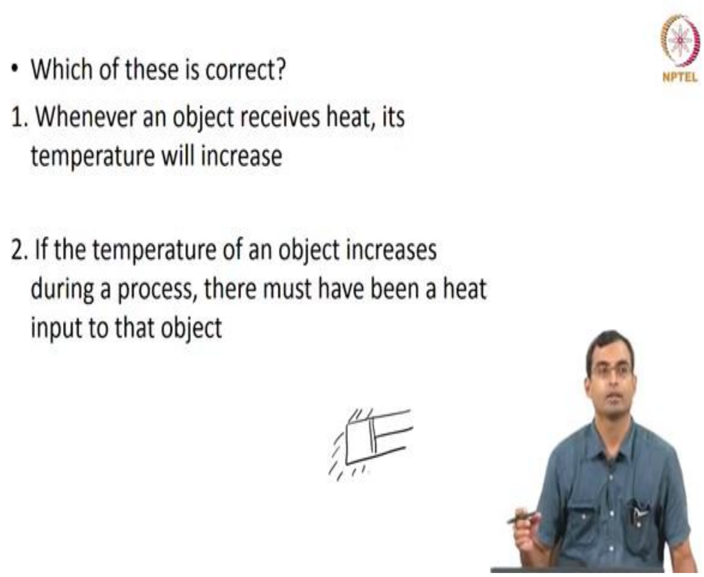

Figure 7.

Answers for the questions in Fig. 7:

1. In phase change processes, the temperature of the substance does not increase even when it receives heat, for example, conversion of ice at 0 ℃ to water at 0 ℃. Hence, the temperature of the object does not always have to increase when heat is given to it.

2. It is not the case always. The temperature of the object can also be increased by doing work on it. The temperature of gas inside an insulated piston-cylinder arrangement would increase if the piston is moved inside (work is done on the gas). Think of other such examples.

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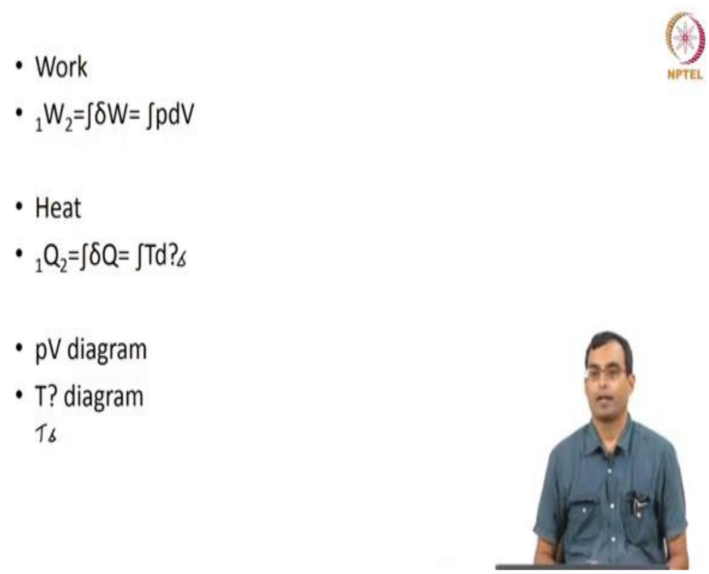

We know that displacement work is given as $\int \delta W = \int pdV$. In a similar way, can we write an expression for δQ? Such expression exists and it is $\int \delta Q = \int TdS$, where S represents entropy, which we will discuss in more detail later on in the course.

The area under a curve on a p-V diagram gives work for a quasi-static process. In a similar way, we will see that for a reversible quasi-static process, the area under a curve on a T-S diagram gives heat transferred.