Climate and Built Environment
Lecture 5

Heat Transfer

Heat flows from areas of higher temperature to areas of lower temperature. Heat is energy or more precisely transfer of thermal energy. As energy, heat is measured in watts whilst temperature is measured in degrees Celsius or Kelvin. Heat is a form of energy and heat transfer refers to the heat being transferred from one object to another. Usually heat transfers from higher temperature to lower temperature. Thermal energy travels from a hot material to cold material. The hot material heats up cold material and the cold material cools down to hot material.

Usually, you would've observed if you have two different materials in contact with each other or close with each other at different temperatures. Eventually after sometime, this will be almost in the same temperature as the air temperature of the surrounding environment or the room in which it is kept in. There is a constant heat transfer that's happening between any two heated objects that have different temperatures to maintain the thermal equilibrium. Heat always moves from a warmer place to a cooler place. If it's a hot object, the heat will automatically begin to transfer to the cold object and in turn heat the cold object. Eventually, the object that was hot and the object that was cold will come to equilibrium. Only then this heat transfer will come to an end. Hot objects in a cooler room will cool to room temperature. You might have observed in our day to day activities that when we leave a hot cup of coffee, it cools down , the temperature decreases compared to the point when you left the cup of hot coffee. This is because of the heat transfer that's happening between the cup of coffee and the surface of the cup and the surrounding air that is present. Cold objects in a warmer room will heat up to the room temperature. If you leave a popsicle or an ice cream inside a room, it will begin melting in a while since you have left it in a temperature that's higher than that of the ice cream. It is because of this difference between the icecream and the surrounding air. There is a heat transfer and this is why the coal temperature begins melting to meet up to the air temperature.

How does heat transfer? Heat transfer happens in three ways; conduction, convection and radiation. Let's take a look at conduction. When you heat a metal strip at one end, the heat travels from one to the other end. As you can see here, the metal strip has been lit on one end and the carbon atoms get activated and begins moving inside the metal strip and from this point the heat is being transferred to the other end of the metal strip through the presence of the carbon atom which transfers the thermal energy from one end of the strip to the other end. As you heat the metal, the particles vibrate, these vibrations make the adjacent particles vibrate and so on. When this gets heated, it starts vibrating and this vibration is transferred throughout the metal strip. The vibrations are passed along the metal and so is the heat. Hence, we call this as a conduction. The thermal which is being induced at one point is transferred through vibration of the carbon atom to the other end of the metal strip, the transfer of heat that happens via this method is called conduction.

We might have observed a different metal behaving a different way. For an example, if you are in a room with two different materials such that one is steel and one is wood, each material will hold different temperatures, why does this happen? This is because the outer electrons of metal atoms drift and are free to move. When the metal is heated, the 'sea of electrons' gain kinetic energy and transfer it throughout the metal. All this depends on the electrons that is present in different materials. Different materials have different carbon compositions. Due to the difference in all this makes each and every material act differently due to thermal changes. Insulators such as wood and plastic do not have this 'sea of electrons' which is why they do not conduct heat as well as metals. Metals or good conductors. By conductors we mean that it can absorb more amount of heat when compared to elements such as wood and plastic which are called insulators. There's a difference in the property of these two materials; wood, plastic when compared to metal and aluminium. This is because of the presence of 'sea of electrons' which is absent in insulators. Insulators or elements which do not transfer thermal energy as much as the conductors.

Why does metal feel colder than wood, if they are both at the same temperature? Inside a room we might have observed one piece of wooden table and one piece of steel table, steel being much more colder when compared to the wood. Even though it is being kept under the same air temperature, same room temperature, the surface temperature of these two elements are different. This is because the metal is the conductor, wood is the insulator. The presence of sea of electrons in the metal, makes it a conductor and the lack of electrons in the wood makes it an insulator. Metal conducts the heat away from your hands. Wood does not conduct the heat away from your hands as much as how metals do. Hence, the wood feels warmer than the metal although they kept under same room temperatures.

Conductivity - the better the conductor, the quicker the blue on the thermometer strip changes from dark blue to yellow. These four strips have been kept inside a tub of hot water in which a thermometer strip has been placed for metals such as aluminium, copper, brass and steel to understand thermal conductors and their properties. For each and every material we have a thermometer strip that has been attached to every metal strip. This keeps changing. The higher the conductivity, the quicker the thermometer changes its colour from blue to yellow. As observed, from the experiment the metal and time taken for the thermometer to change the colour, aluminium took almost 25 seconds, Brass took 70 seconds, Copper took 32 seconds and steel took 110 seconds, which means Aluminium is comparatively higher thermal conductivity when compared to other metals such as brass, copper and steel. Next comes the copper, the brass and then the steel.

Convection - What happens to the particles in a liquid or a gas when you heat them? When you heat a liquid or a gas, this happens - the particles spread out and become less dense. It is much more free and open to move, the particles inside the liquid and gas are more free to travel compared to solid elements. This effect is called fluid moments, what is fluid? A liquid or a gas is called fluid.

The third method of heat transfer - how does heat energy get from the Sun to the Earth? Since we need particles to connect from one point to another to conduct thermal energy i.e transferring thermal energy from one end to the other end. But when you observe the open environment, there is the Sun and the Earth is being located further away from each other. How does the heat radiation from the Sun reach the Earth? There are no particles between the Sun and the Earth, it cannot travel by conduction or by convection. This happens via Radiation.

Different Properties

Moving on to the different properties of a material to hold on to thermal energy, that happens through heat transfer. At first let's have a look at Thermal conductance and resistance. Thermal resistance (R) and thermal conductance (C) of the materials are reciprocals of one another and can be derived from the thermal conductivity (k) and the thickness of the materials. Thermal resistance means the property of the material which resists or blocks the heat from being transferred from one end to the other end or from one object to the other object. This is called thermal resistance whereas thermal conductance means the presence of a sea of electrons which helps or promotes heat transfer or thermal transfer. The K-value is thermal conductivity. Thermal conductivity is the time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area, it is expressed in W/m-k. It is the rate at which the heat starts flowing from one end of the material to the other end. This is called thermal conductivity, it is expressed in k.

Where the thickness of the specimen or the material which is expressed in meters and T is the temperature, measured in K or degree Celsius and q is the heat flow rate, which is the property of the material, expressed in W/m^2. R value is thermal resistance.

Where, thermal resistance is the temperature difference at a steady state between two defined surfaces of a material or construction that induces a unit heat flow rate through a unit area, K - m^2/W. The amount of thermal resistance is how much a material can reduce the heat transfer from one end to another end. It is expressed in km^2/W.

Moving on to thermal conductance.

Since the thermal conductance and the resistance of a material is reciprocal to each other. Thermal conductance, C is equal to reciprocal.

Thermal conductance is the time rate of steady state heat flow through a unit area of a material or construction induced by a unit temperature difference between the body surfaces, in W/m^2-K. It is the same as what we just discussed.

Specific Heat - The amount of heat needed to change the temperature of a body depends on; the material of the body, the mass of the body and the change in temperature. If you need to change the temperature of a material from hot to cold and cold to hot, you need to know the material in which its made, the weight of the body, the weight of the material whose properties need to change and the change in temperature, how much you need to change. IF you need to change from 1 degree celsius, of its 15 degree celsius you need to know how much change in temperature can happen. For a given body we can define a quantity known as the thermal capacity as the heat energy needed to raise its temperature by 1 K. The amount of heat energy that is needed to increase the temperature of a material by 1 degree celsius is what is meant as thermal capacity of a material. If a wood is maintained at 15 degree Celsius and if you want to increase its temperature to 16 degree Celsius, how much heat is required to transform the material's heat from 15 degree Celsius to 16 degree Celsius is called thermal capacity of that material. A rather more useful quantity is the specific heat capacity of a material defined as follows - The specific heat capacity of a material is the heat energy needed to raise the temperature of 1kg of the material by 1 K, which means it is defined by 1 kg of a material to raise to 1 degree Celsius. If its a bulk material, it will require a lot of thermal energy to have a change of 1 degree Celsius. However, since it is 1kg of material, the volume is fixed and we will know the specific heat capacity of that material. The units of thermal capacity are joules per kelvin ($J\ K^{-1}$) and those of specific heat capacity joules per kilogram kelvin ($J\ Kg^{-1}\ K^{-1}$). This is the difference between thermal capacity and specific heat. Thermal capacity doesn't define the volume whereas the specific heat is defined for 1kg of the material.

Therefore, heat energy = mass x specific heat capacity x temperature change.

The values of some specific heat capacities are given in the following table. We need to know how much specific heat capacity each and every material can hold in order to choose the materials that can be used in our designs. In order to know that, there are few materials which have good specific heat capacity that have been listed below. They are; copper, lead, aluminium, sodium, iron, steel, concrete, polypropylene, marble and glass. It has different specific heat capacities depending on which location you are going to use and what kind of climatic condition to which you are choosing, this material can be chosen according to the environmental aspects.

In principle, use of cavities is similar to the use of insulating materials. We might have come across insulating materials which is materials used to protect your interior spaces from exterior climatic condition. Even if you have a small air cavity which is filled with nothing but air can also act like an insulating material due to the presence of a gap between two materials which reduces the heat transfer happening between the two when they were in contact. if the air space is left between two layers making a wall or a roof in any building, the air trapped between two layers being poor conductor of heat acts as a barrier to transfer heat.

Heat is transferred across an air space by a combination of conduction, convection and radiation. Heat transfer by conduction is inversely proportional to the depth of the air space. Convection is mainly dependant on the height of the air space and its depth. This heat transfer in air space happens in all three methods - conduction, convection and radiation. Heat transferred by conduction is inversely proportionate to the depth of air that is being filled in that space whereas the height is the factor that determines the convection heat transfer process. Heat transfer by radiation is relatively independent of both thickness and height but is greatly dependent on the reflectivity of the internal surfaces. When we are considering heat transfer through radiation, it doesn't take into account how much depth has the air cavity occupied or how much height has the air cavity has filled. It takes into account the reflectivity of different materials that have been used in your internal surfaces.

Say if you are using shining materials like steel or giving very finishes to your flooring, it will have high reflective value which will reflect the thermal energy or bounce back but when you are having different textures, it is going to absorb more. This type of surface finish determines the radiation component of heat transfer. All three mechanisms are dependent on the surface temperatures. All this depends on surface temperatures in each material. It has been found that with gaps broader than 50mm, movement of trapped air due to temperature gradient starts which in turn increases the coefficient of heat transfer. If you are going to keep an air cavity between two objects to act as an insulating material, the minimum gap that has to be maintained is 50mm. If it is lesser than 50mm, the air starts conducting in between and it is not effective as keeping it as far as 50mm. This increase in heat transfer takes place due to convective heat transfer taking place in addition to conductive heat transfer. Therefore, cavities broader than 50mm are normally not preferred. However, if more thickness of air cavity is required for getting heavy insulation, by putting partitions in the main broad cavity multiple can be used as an alternative. Keeping 50mm as your limit, if you have buildings that are subject to high or harsh climatic conditions, you might have one layer of material, a 50mm gap and then the next layer and then again a 50mm air gap and once again, the same material can be repeated. This will form a combination of different air cavities which can have much more effective heat transfers or reduction in heat transfers compared to keeping one huge air cavity.

Some typical values of thermal resistance for air cavities are given below - what thickness and what thermal assistance can be achieved is mentioned here. If it is a wall, it is going to be a vertical air cavity, if it is a floor or a roof, it is going to be a vertical air cavity. Depending on the thickness, the thermal resistance changes.

Air to Air Transmittance i.e U Value. Thermal transmittance, commonly known as the U-value, is a measure of the rate of heat loss of building component. The U-value is the sum of the combined thermal resistances of all the elements in a construction, including surfaces, air spaces, and the effects of any thermal bridges, air gaps and fixings.

Thermal resistance is the property of a material to resist the temperature from being transferred from one point to another point. This happens in all your construction elements. There is a typical U-value for your wall, your roof and your floor. For instance, if you are considering the U-value for your wall, you need to construct the interior finishes to the exterior finishes. You cannot eliminate any of the surface treatments, any of the elements that is used under wall sections, you need to take interior plastering, brick walls and then the cement being used for next layer or air cavity or the next block masonry and then the final finishing layer. If the U-value of your wall is 0.2 which means you are adding the thermal resistance of each and every material that goes under the wall section. The U-value is expressed in watts per square metre, per degree kelvin or W/m^2K.

Calculating U-Values - the thermal resistance U -value is; sum{1/R}

Thermal resistivity (R) = material thickness (d) / Thermal conductivity coefficient (k)

There is an online calculator to calculate different U-values for different construction methods typically used in your location.

Time Lag and Decrement Factor - the time delay due to the thermal mass is known as time lag. The thicker and more resistive the material, the longer it will take for heat waves to pass through. The reduction in cyclical temperature on the inside surface compared to the outside surface is known as the decrement. If you are using thermal mass which has high specific capacity, the material doesn't allow the heat or cold to get transferred from outside to the interior easily. This property of a material is called thermal mass and the time it takes for the heat to transfer from outside to the interior space is called time lag. Thus, a material with a decrement value of 0.5 which experiences a 20 degree diurnal variation in external surface temperature would experience only a 10 degree variation in internal surface temperature. If a material has 0.5 decrement value, it means that it is going to experience half of the diurnal variation that has been happening outside. Say if, the morning temperature is 40 degree and at night it is 20 degree, the diurnal variation is 20 degree Celsius but inside what you might experience is, morning to be 35 degree celsius and at night 25 degree Celsius which leads to a difference of only 10 degree celsius, which has been reduced due to the presence of 0.5 decrement value. This is the time lag. This is the day time temperature and this is the interior temperature and the temperature difference between the peak hours is called time lag. This effect is particularly important in the design of buildings in environments with a high diurnal range. In some deserts, for example the daytime temperature can reach well over 40 degrees. The following night, however temperatures can fall below freezing. If you are located in a climatic condition with a good amount of diurnal variation which means your daytime temperature is very high and your night time temperature is very cold, this type of time lag and choosing materials with higher decremental values can be used which can be beneficial.

This is how thermal mass acts. This is your thermal comfort and this is your daily variation and interior spaces are not affected as much as your exterior temperature. This is the presence of good amount of thermal mass.

In climates that are constantly hot or constantly cold, the thermal mass effect can actually be detrimental. This is because both surfaces will tend towards the average daily temperature which when above or below the comfortable range, will result in even more occupant discomfort due to unwanted mean radiant gains or losses. Thus, in warm tropical and equatorial climates, buildings tend to be very open and lightweight. Thermal mass cannot be used for all type of climatic conditions, you need to know if the climate demands for such type of construction. In very cold and subpolar regions, buildings are usually high insulated with very little exposed thermal mass, even if it is used for structural reasons.