Basic Principles and Calculations in Chemical Engineering
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Module – 2: Process Variables and Rate
Lecture – 2.3
Rate of Process

Welcome to massive open online course on Basic Principles and Calculations in Chemical Engineering. So, we were discussing about the process variables and rate under module 2. Now under this module 2, in this lecture, we will try to discuss about the rate of processes.

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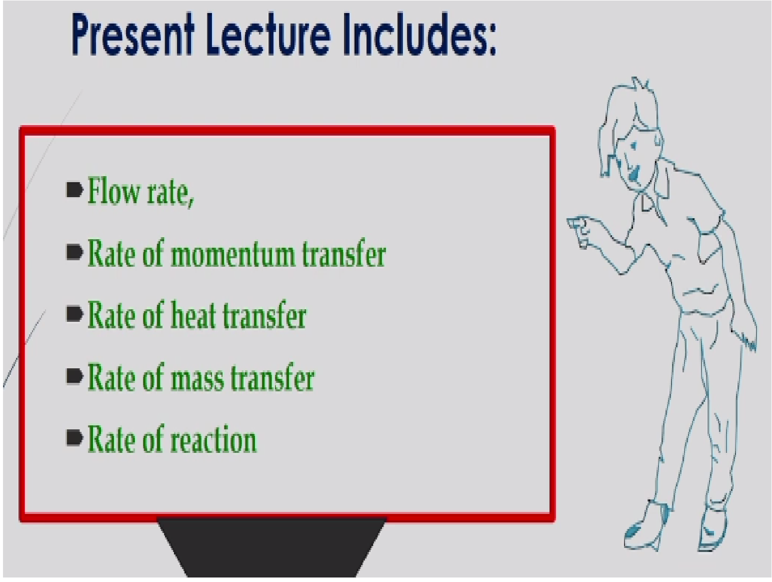

So, this lecture will include the flow rate, rate of momentum transfer, rate of heat transfer, rate of mass transfer, and also a rate of reaction.

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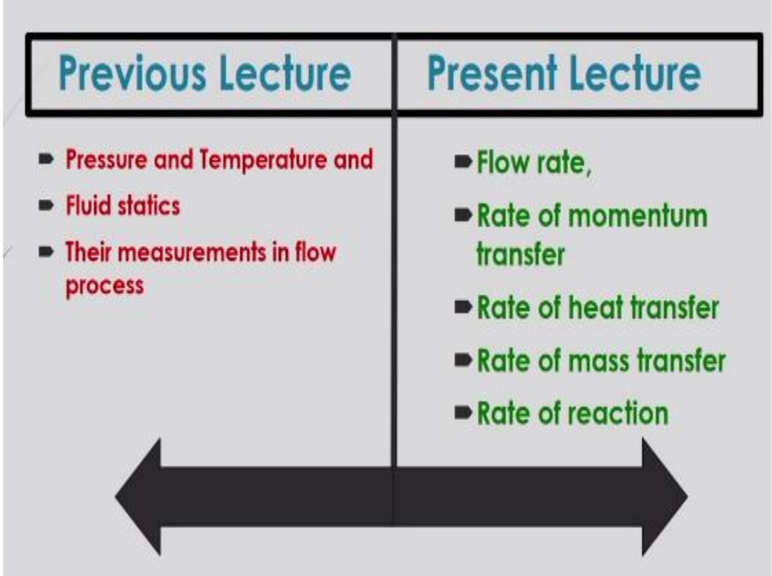

Now, previous lecture we have described the different variables out of which temperature and pressure was discussed and also we have derived the fluid statics equation based on which how the pressure drop between 2 points can be calculated by manometer and also we have discussed that if there are any flow through the pipe, how to measure that flow rates. I think we have described that different flow measuring instruments like that rotameter and also other flow meters are there that we have described and by which you can calculate how to measure that flow rates.

In this lecture we will try to describe that how to estimate that flow rate and also how to calculate the flow rate and also whenever that fluid will be flowing through the process unit, what should be the momentum transfer and also if there are different components present in the fluid system and if you know that flow is in a certain manner like convictive or other flow processes and they are how heat is being actually transferred from one phase to another phase and also from one location to another location within the same system and within the same liquid or within the same you know that materials.

Also we will discuss that what is the mass transfer, how that one components in a particular phases can be transferred to another places that will be regarded as the mass transfer and how that rate can be calculated. Also in most of the cases that in chemical engineer processes, of course reaction will be involved. So, in that case, what should be the rate of that reaction between two components and based on that product components, how the rate of the reaction can be calculated to be described here.

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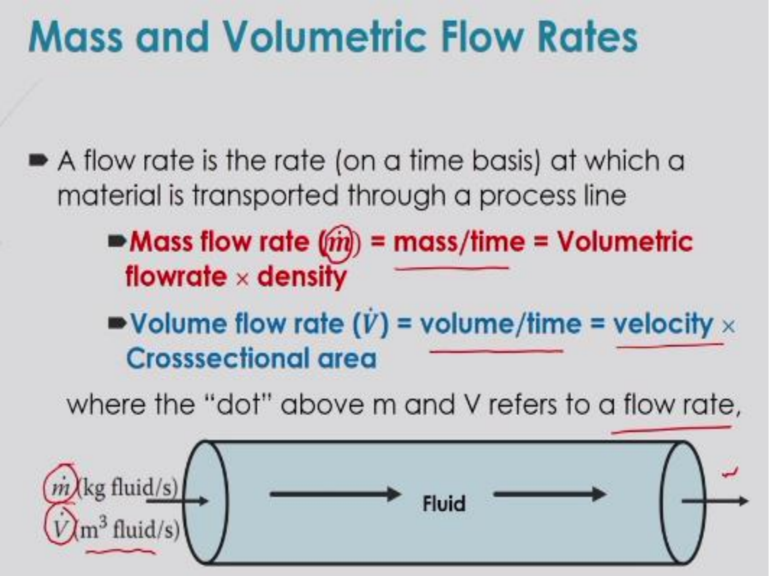

Now, coming to that point of that flow rates, first that mass and volumetric flow rates which is to be important aspects are you are going to analyze any process of that chemical engineering or biochemical engineering in a particular process unit and there you will see some streams will be coming to the process unit at a particular flow rate and also the systems will give you that output and that output will be coming out as a particular stream with certain flow rate.

So, that also to be measured that what should be that flow rate in and also flow rate in outlet position, and of course, based on this flow rate that process performance will be analyzed and also you can say that based on this flow rate, there are several aspects of that design of that process unit depends on and also these flow rates will give you that particular way of that different mechanism of transfer like a mass transfer and heat transport there.

Also this mass flow rate will also govern that how momentum of the phases will be changed inside the process unit and that momentum change will give you that how much energy is required, to process that equipment and also to process that particular system and also to analyze that how this that process can be designed based on this momentum or that energy transfer. So, what is that mass or volumetric products.

So, if flow rate that is expressed for the fluid flowing through the process unit at which a material is transported through the process line and in that case the rate of that fluid will be transferred that will be called as flow rate and the mass flow rate is generally defined as how much amount of that materials or that object will be transferred per unit time or flow of that object or fluid you can say that or gases in that case how it will be flowing at a particular rate.

So, it will be called as flow rate of in terms of mass, then it will be called as mass flow rate and if it is suppose the expression based on that volumetric flow, then it will be regarded as volumetric flow rate. The mass flow rate is denoted by m dot generally. So here dot represent the rate and then it will be defined as mass per unit time and also volumetric flow rate will be defined as volume per unit time, that is volume of materials flowing per unit time. So, it will be called us volumetric flow rate.

Now, you can relate this mass flow rate with this volumetric flow rate just by multiplying the volumetric flow rate by its density of the fluid, then you can get that mass flow rate of that fluid and volumetric flow rate can also be regarded or can also be defined based on the velocity of the fluid through the pipe, where mass flow rate also can be converted into volumetric flow rate and then in terms of velocity you can express.

The volumetric flow rate, it will be actually if you know the velocity of the fluid through the particular process unit and if you know the crosssectional area that particular process unit like when a fluid is flowing through the pipe or in the crosssectional area of the pipe and if you know the velocity of the fluid through the pipe, then you can get the volumetric flow rate in terms of velocity and the crosssectional area. So, volumetric flow rate will be is equal to velocity into crosssectional area.

Also you can get the velocity in terms of volumetric area, volumetric flow rate like what is that, velocity can be then calculated based on that volumetric flow rate and also crosssectional area. So, velocity will be is equal to volumetric flow rate divided by crosssectional area. So, in this way you can calculate what should be the volumetric flow rate, and in this case, you have to remember that whenever you will see that dot above that particular variables like mass flow, even volumetric flow.

So in that case dot will be representing here above m and V as shown here in the slides that will be as a flow rate. Now here see in this figure that mass flow rate of the fluid that is flowing through the pipe as m dot and volumetric flow rate as V dot and its unit will be kg of fluid per second that is kg per second and volumetric flow rate will be meter cube per second that is meter per second there. So, in this way you can calculate the volumetric flow rate of the fluid whenever it will be coming through the process unit.

Then another important aspect of that, it is called rate of momentum, that also actually depending on that mass flow rate of that fluid there and also velocity, so we will be discussing.

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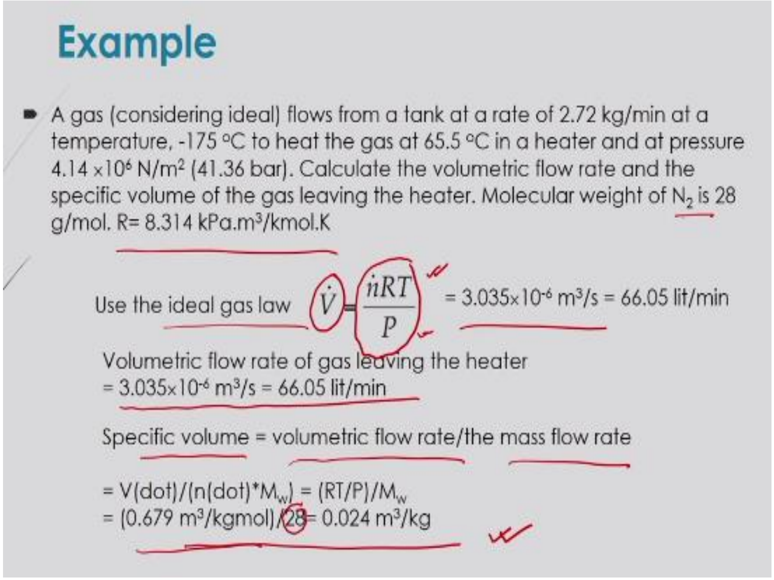

Before going to that, let us have an example of this mass or volumetric flow rate how to calculate. Suppose a gas considering ideal flows from a tank at a rate of 2.72 kg per minute at a temperature of minus 175 degrees Celsius and it has to be heated at 65.5 degrees Celsius in a heater and at pressure of 4.14 into 10 to the power six 6 Newton per meter square around 41.36 bar. So, in this case you have to calculate what should be the volumetric flow rate and the specific volume of the gas that will leave the heater.

Also, it is given that in this case that gas if it is consisting of nitrogen and hydrogen gas, then what would be the molecular weight of nitrogen and also what will be the universal gas constant is given as for that unit of this consistency here to be considered and in this case as per ideal gas law, then volumetric flow rate of the gas can be expressed based on that ideal gas law as V dot is equal to n dot RT by P, and after substitution of this value here, you can get this value of 66.05 liter per minute.

So, volumetric flow rate of the gas leaving the heater, it will be here 66.05 liter per minute, and in this case, what will be the specific volume. Then the specific volume you can calculate volumetric flow rate per mass flow rate of that gas. So, it will give you directly after substitution of this value or from this equation of ideal gas law, you can get it from that like V dot divided by n dot that will be your specific volume. So, it will be simply RT by P.

So, if you substitute that RT by P value, then you can get it in terms of meter cube per mole and then if you convert it to mass, you have to then divide it by or you have to multiply it that moles by its molecular weight, then you can get it in terms of meter cube per kg. So, in this way you can get this volumetric flow rate. So, this is regarding that gaseous system where you have to calculate the volumetric flow rate from its ideal gas law.

Whereas if you have that fluid that is not compressible, that is incompressible like water or other liquid, there we will see that volumetric flow rate to calculate you need to know that mass flow rate and from that mass flow rate you can get it to just by dividing mass flow rate that is dividing by its density, then you can get it volumetric flow rate there.

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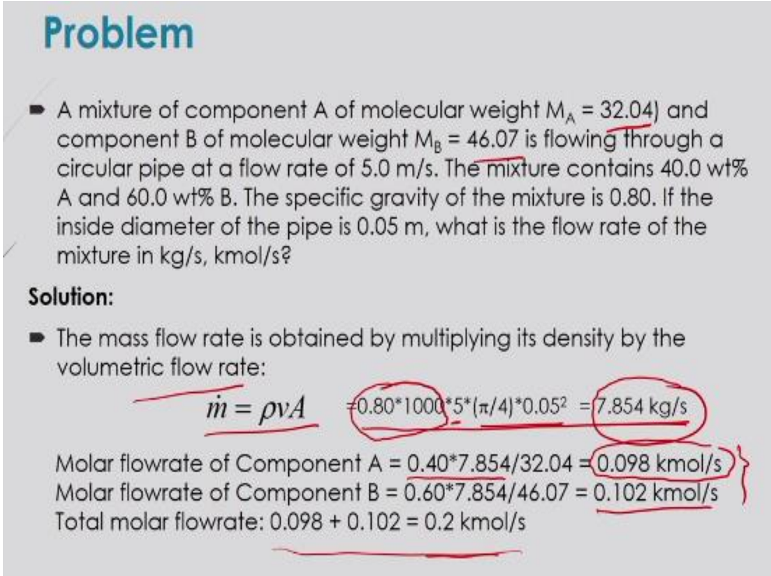

Another example like in this case, suppose a mixture of component A of molecular weight is given as 32.04 and component B of molecular weight of this 46.07 is flowing through a circular pipe at a flow rate of 5 meters per second. Now, the mixer contains 40 weight percent of A and 60 weight % of B. In this case, the specific gravity of the mixture is given to you as 0.80. Now, if the inside diameter of the pipe is 0.05 meter, then what should be the flow rate of the mixture in kg per second or kilomole per second.

So, in this case here interesting is that the mass flow rate is obtained by multiplying its density by the volumetric flow rate. So, here it is given to you that volumetric flow rate whereas from this volumetric flow rate you can get this mass flow rate just by multiplying it by density. So, you can calculate it as like this here from this m dot is equal to rho v A. Rho is given here to you that is 0.80 into 1000, this is your rho, v is given here meter per second, it is given that mixture flow rate is 5 meter per second and crosssectional area is given to you.

From this, you can get to this mass flow rate as 7.854 kg per second. So, molar flow rate of the component A, then can be calculated as what should be the first mass flow rate of component A. Since your component is of 40% for this component A, so you can just multiply this mass flow rate into its composition, that means here mass fraction or you can if it is mole fraction, you have to multiply it by this fraction, then it will come as here 0.40 into 7.854. So, this will be your mass, you can say mass fraction into total mass flow rate, then you will get here total amount of component A per unit time.

So, it will be coming as kg per second of this component A and if you divide it by its molecular weight, then you can get simply what should be the mole per second to be here expressed as kilomole per second. Similarly, molar flow rate of component B, you can get it by the same way after calculation you can get that as 0.102 mole per second. Now, total molar flow rate then you can get here 0.098 + 0.10 as per these two components here. So, it will come as 0.2 kilomole per second.

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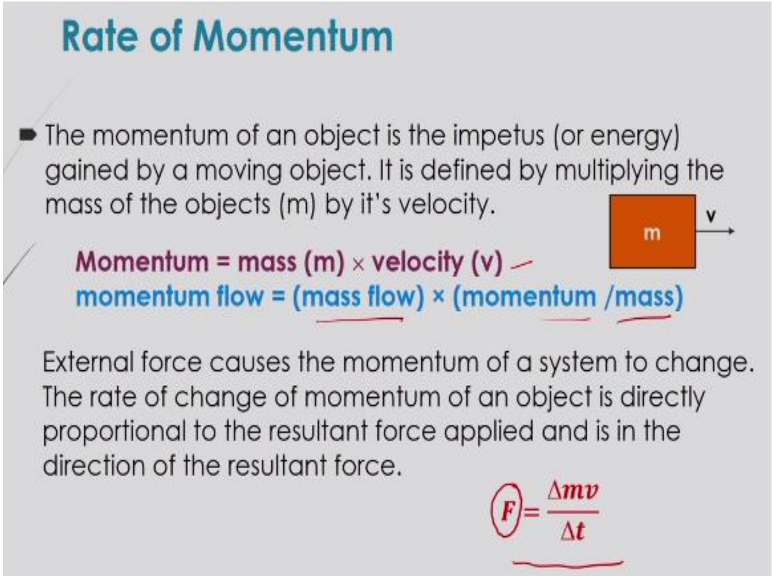

Next, let us consider that momentum rate. The momentum of an object actually is the impetus or you can say the energy that is gained by a moving object. It is defined by multiplying the mass of the objects by its velocity. So, momentum will be defined as mass into velocity and momentum flow would be basically that mass flow into momentum by mass. Now, external force generally causes this momentum of a system to change.

The rate of change of that momentum of an object is directly proportional to the resultant forces that is applied to get its momentum and is in the direction of the resultant force at which it will be applied. So, we can express this force based on which this change of momentum will be there. So, this F will be denoted by here this equation or defined by this equation based on that momentum.

So, F will be is equal to delta mv by delta t, what does it mean? How much momentum will be changed based on this applying force there if per unit time. So, that will be called as momentum change per unit time, which is actually equal to the external force applied to the system

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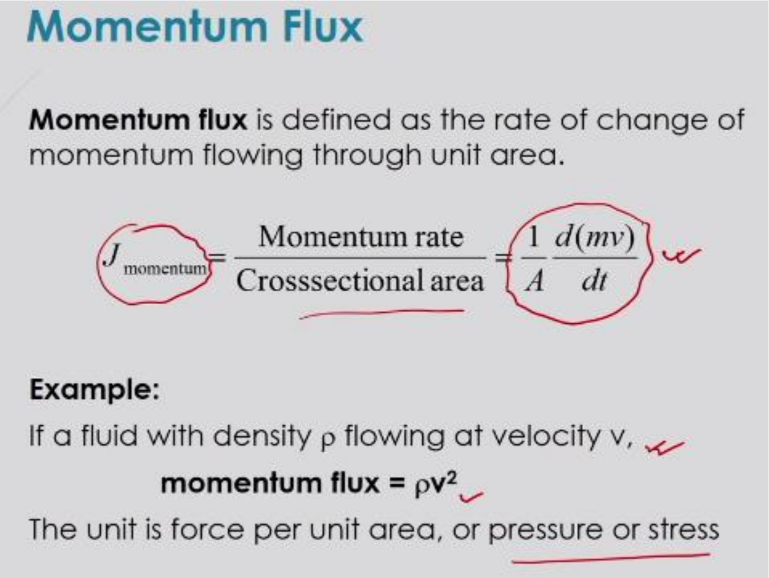

Also another term you will see that there will be during the energy balance equation for a particular process, it is generally expressed by that momentum flux. So, in this case it is defined as the rate of change of momentum flowing through per unit area. So, it will be a denoted by J momentum that will be equals to momentum rate per crosssectional area. So, it can be expressed by this mathematical expression as given here in the slide.

Like if a fluid with density rho that is flowing at a velocity v, then you can express this momentum flux by this rho into v square and the unit will be as the unit of force per unit area or you can express this as part the unit of pressure or stress. This is basically that force, so force per unit area, so force per unit area is the pressure or you can say stress. So, what will be the unit for pressure or stress, that unit will be of the momentum flux.

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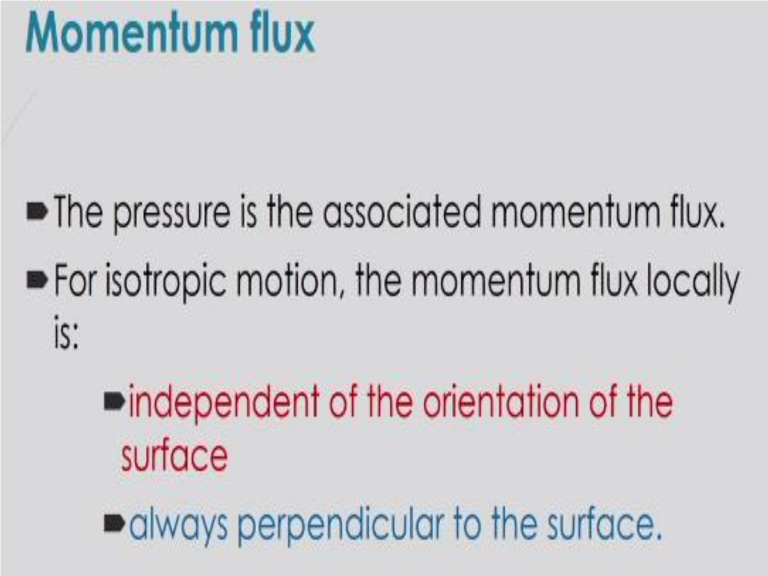

Now, the pressure is the associated momentum flux. For isotropic motion, the momentum flux which is locally is independent of the orientation of the surface and also it will always be perpendicular to the surface.

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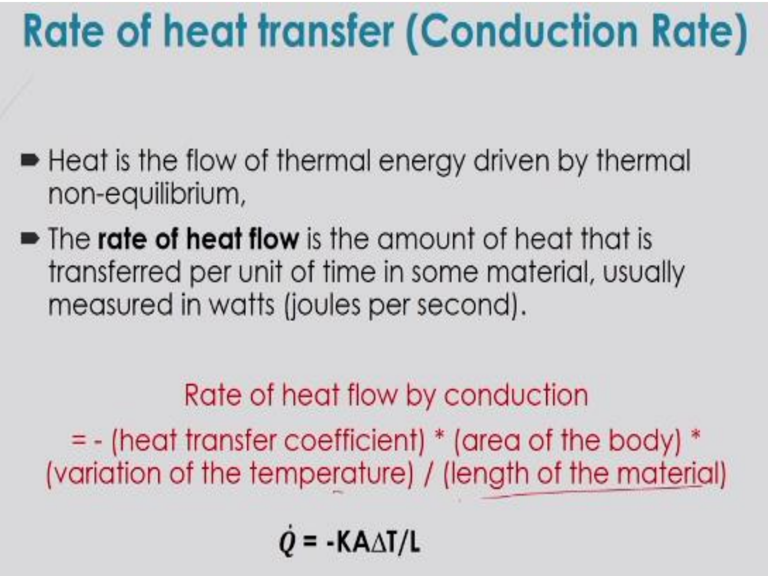

Next we will discuss how rate of heat transfer can be expressed. There are different mechanisms of transferring heat. Of course, you will learn in depth in other chemical engineering subject like heat transfer operation there. So, basically that heat is the flow of thermal energy that is driven by thermal non-equilibrium and the rate of heat flow is the amount of heat that is transferred per unit of time in some material usually measured in watts or you can say joules per second.

There are different mechanism of expressing this heat transfer rate like conduction, convection and radiation. So, whatever mechanism will be there, the heat transport rate will be expressed as per temperature gradient or you can say that the temperature difference of these two points of the object and based on which that a heat will be transferred. So, rate of heat transfer basically will be proportional to the temperature difference. Also, it will depend on the surface area through which the heat will be perpendicularly flows there.

So, if I consider that there is a mechanism like conduction, so the heat transfer rate by conduction that will be represented by that is variation of the temperature per unit length and also it will be depending on the surface area of the object through which heat will be transferred. So, it is generally expressed as rate of heat flow by conduction is equal to minus of heat transfer coefficient into area of the body and variation of the temperature per length of the material.

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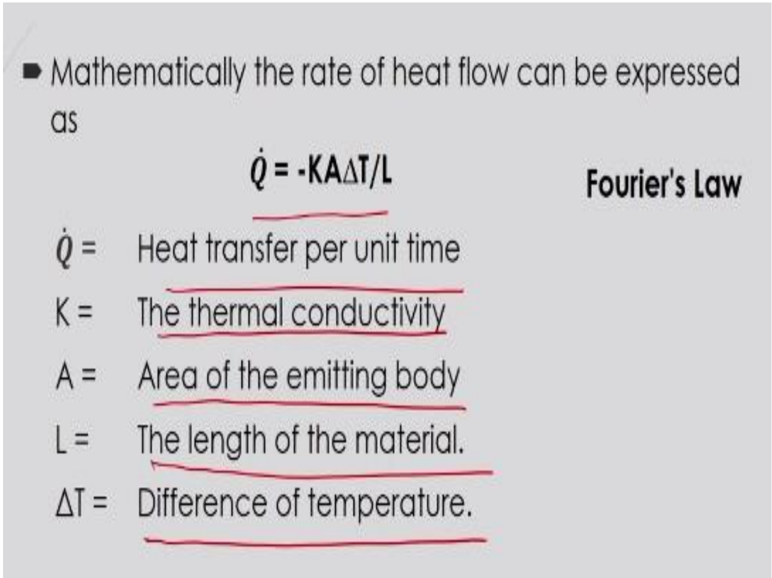

So, this mathematical expression given by Fourier. So, that is why it is called Fourier's law. So, mathematically the rate of heat flow by conduction can be expressed as Q dot will be is equal to minus KA delta T by L where Q dot is heat transfer per unit time, K the thermal conductivity, A is the area of the emitting body from which this heat will be transferred, L the length of the material, and delta T is the temperature difference there between the two points.

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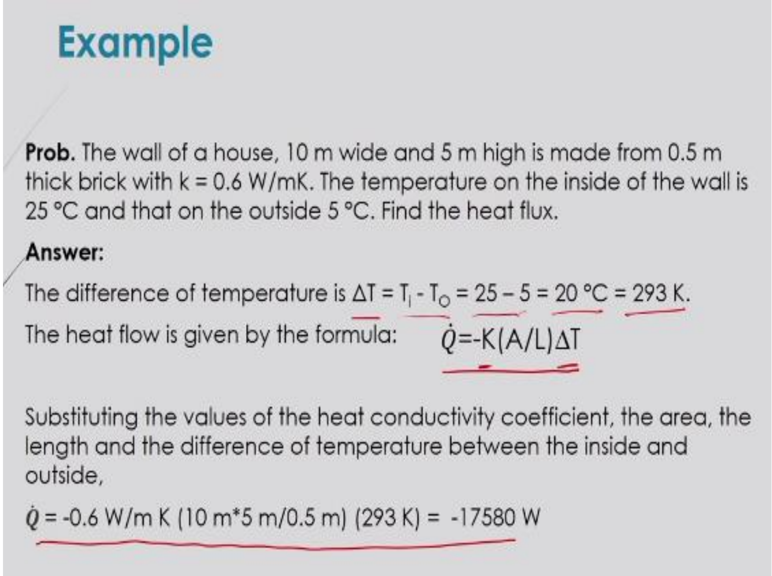

Let us do you an example based on this. Suppose, the wall of a house that is 10 meter wide and 5 meter high that is made from 0.5 meter thick brick with thermal conductivity that is K that will be is equal to 0.6 watt per meter K and the temperature on the inside of the wall is 25 degrees Celsius and that on the outside is 5 degree Celsius. Now in this case, find the heat flux. Now, the difference of the temperature is delta T, so this T of course always will be in terms of unit Kelvin.

So, you have to convert it to Kelvin from the Celsius here and since it is the difference you can say that 25-5, so, it will be 20 degrees Celsius, then it is actually 293 K. Now, the heat flow is given by the formula here as per Fourier's law, that is Q dot equals to minus K into A by L into delta T. Here K is the thermal conductivity of the material, A is the crosssectional area, L is the length of the object or you know that here in this case wall that is your width of the wall here in this case to be considered and delta T is the temperature difference between the sides of the wall.

Now, substituting these values of this heat conductivity coefficient, the area, the length and the difference of the temperature between the inside and outside, you can get this heat flux, that is heat transfer rate per unit area that will be is equal to here minus 17580 watt.

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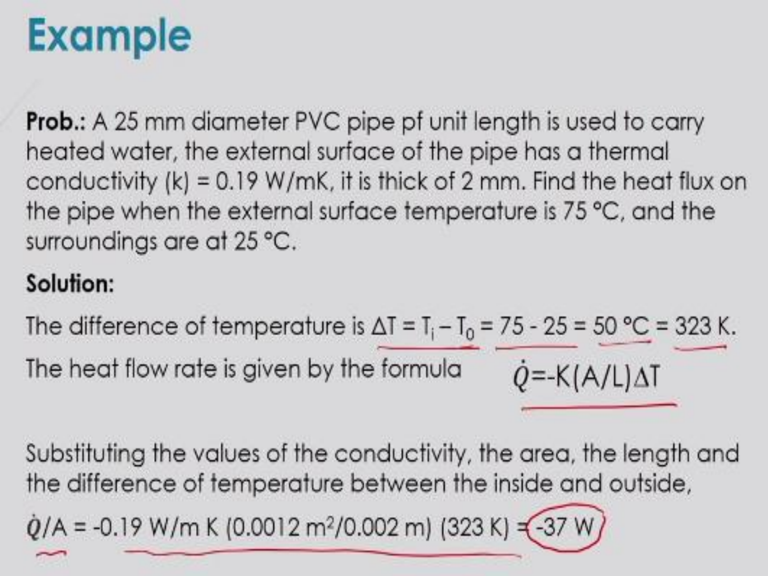

Now, let us do another example, like a 25 millimeter diameter PVC pipe of unit length is used to carry heated water. The external surface of the pipe has a thermal conductivity K that is 0.19 watt per meter K. It is thick of 2 millimeter. In this case, you have to find out the heat flux on the pipe when the external surface temperature will be at 75 degrees Celsius and the surrounding are at 25 degrees Celsius. So in this case, first of all you have to calculate what will be the temperature difference, that will be you know delta T is equal to Ti minus T0.

Ti is basically what is the temperature at external surface and T0 is the temperature at the surrounding that will be difference as 50 degrees Celsius that will be is equal to 323 K. Now, the heat flow rate is given by the formula as per you know Fourier’s law. If you substitute those values, then you can get Q dot A will be is equal to what, after substitution and **you** calculation you will get that it will be minus 37 watt. So, it is your heat transfer flux or heat flux you can say based on this temperature difference.

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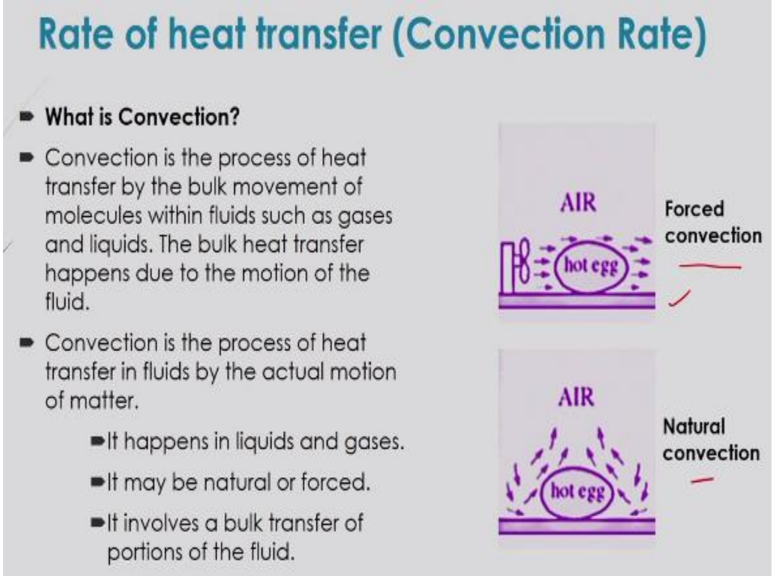

Now, how to calculate that heat transfer rate or unit area based on the convection rate. Before going to that, what is that actually convection? Basically, convection is the process of heat transfer by the bulk movement of molecules within fluids such as gases and liquids and the bulk heat transfer that happens due to the motion of the fluid. The convection is the process of heat transfer in fluids by the actual motion of matter and it happens in liquids and gases. It may be natural or forced.

It involves a bulk transfer of portion of the fluid. Here in this slide, 2 pictures are shown here one is heat is transferring from this plate by forced convection where air will be flowing over the hot surface or you can say that if there is a hot egg and how that heat will be convecting by the cold air convection over the surface of this hot egg, then how heat will be transferring from this hot body of egg to the surrounding of that cold air. So, it will be regarded as forced convection whereas natural convection there will be no flow by any external force.

In that case, you will see necessarily that it will be transferring to the atmosphere that will be regarded as natural convection.

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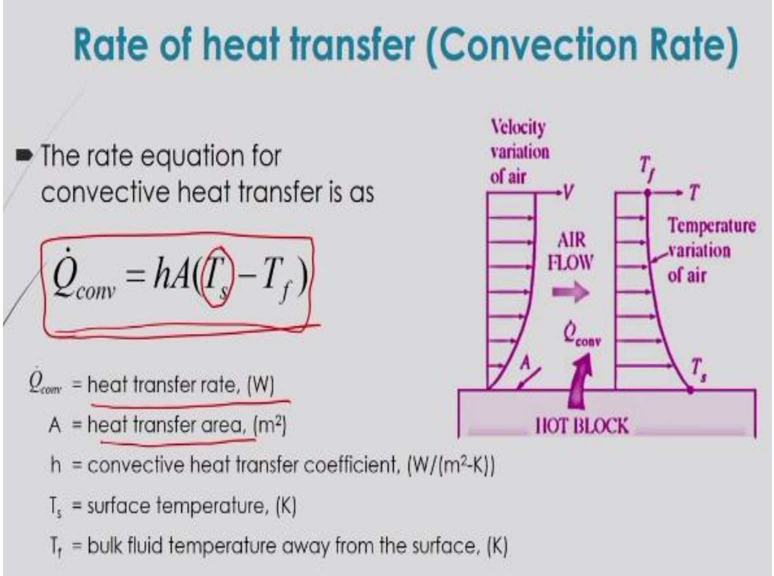

Now, the same way you can say that that rate of convective heat transfer depends on the temperature difference between two locations. Here in this case, one location will be in the hot surface and other will be in the fluid by which that heat will be transferred by convective mode and this law is called the Newton's law of heating or cooling and according to that, the rate of convective heat transfer can be expressed as Q dot convective that will be is equal to hA into Ts minus Tf.

Here Q dot convect is basically heat transfer rate and A is basically heat transfer area through which the heat will be transferred and h here in this case another coefficient, this is called coefficient of heat transfer and this coefficient is called convective heat transfer coefficient and the temporary here Ts it is basically the surface temperature from which heat will be transferred or on which the heat will be gained by that object from the surrounding and Tf is the bulk fluid temperature away from the surface by which the convection of the heat will be there.

So, according to this equation, you can easily calculate what should be the convective heat transfer rate. So, in this case this heat transfer coefficient depends on different parameters like that flow rate of the fluid, even sometimes the conduit through which that fluid will be flowing that diameter of that conduit, even length of the conduit as well as you can say that material properties of the conduit at which that heat will be flowing and also it depends on viscosity of the fluid. So, there are several parameters that effect on the this heat transfer coefficient.

Now, you will get that heat transfer coefficient in more details in the subject heat transfer operations and there you will get different correlations to calculate these heat transfer coefficient. Once you get this heat transfer coefficient and also surface area from which that heat is transferred or through which it is transferred and also if you know the temperature difference, you would be able to calculate what should the convective heat transfer rate as per this Newton's law of cooling or heating.

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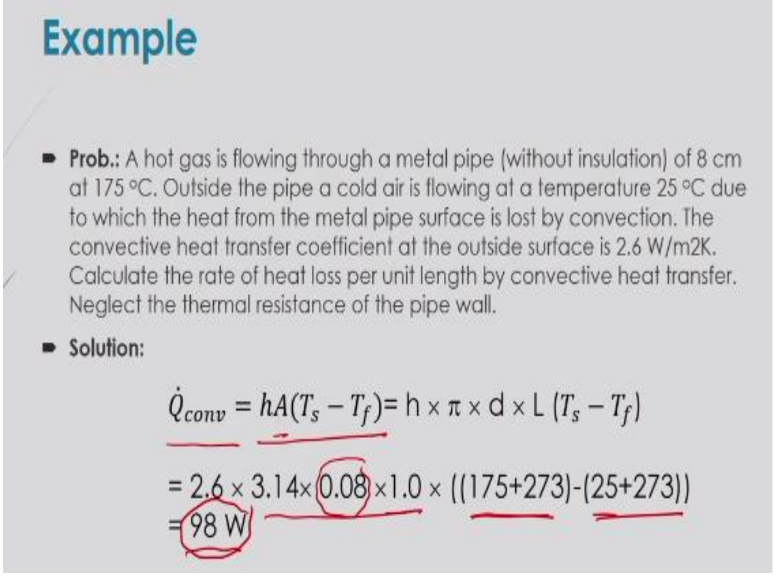

Now, let us do an example for this. Suppose a hot gas is flowing through a metal pipe, that case the metal pipe is not insulated there and its diameter is 8 centimeter and it is kept at 175 degrees Celsius, at which that this hot gas at that particular temperature is flowing through the pipe. Now, outside the pipe, a cold air is flowing at a temperature of 25 degrees Celsius due to which the heat from the metal pipe surface is lost by convection. Now, the convective heat transfer coefficient at the outlet surface or outside surface of the pipe is 2.5 watt per meter square K, it is given to you.

Now, at this condition you have to calculate what should be the rate of heat transport per unit length by convective heat transfer and in this case you can neglect the thermal resistance of the pipe walls. So, as per Newton's law of heating or cooling, the rate of heat transfer by this convective mode can be defined as this hA into Ts minus Tf. Here h is given to you it is a 2.6 here and A means surface area through which actually heat is transpiring, in this case the surface area of the pipe will be pi d into L.

So, it will be a 3.14 into you know d is 0.08 meters and length is 1 meter it is given to you and Ts is here that inside hot gas temperature is 175 degrees Celsius, we are assuming that the surface of the pipe will have that same temperature of 175 degrees Celsius and in this case, then in Kelvin unit it will be 175 + 273. Similarly, what would be the outside temperature of this pipe, it will be 25 degrees Celsius as per your problem. So, again you have to convert it to Kelvin unit.

So, finally if you substitute this value and after calculation, you will see that value will be coming as ninety eight watt. So, this is your convective heat transfer rate based on this temperature difference of 175 to the outside temperature of 25 degree Celsius and also the surface area as per this diameter of this pipe, how it is to be calculated.

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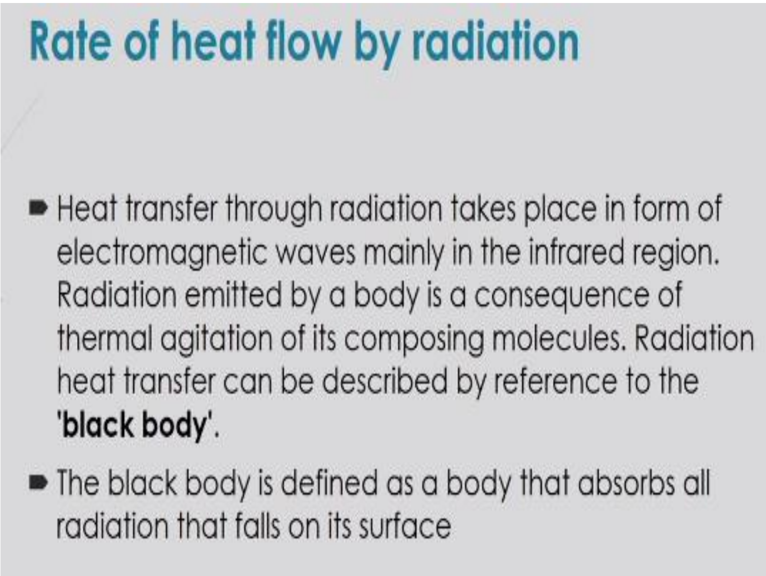

Also we can calculate the rate of heat transfer by radiation. There also it is important sometimes that if you keep the metals in open atmosphere you will see that heat will be transferred not only by conduction, not only by convection, there will be a transfer of heat based on radiation also. Now, in this case the heat transfer through radiation takes place in the form of actually electromagnetic waves, mainly in the infrared region and radiation emitted by a body is actually the result of thermal agitation of its composing molecules there.

Radiation heat transfer can be described by reference to the black body. The black body is basically defined as a body that absorbs all radiation that falls on the surface. If the body is absorbing all the radiation, then the body will be regarded as black body. So, whenever you are going to calculate the rate of the radiation that you have to refer this black body because the radiation is basically that reference rate from this black body rate.

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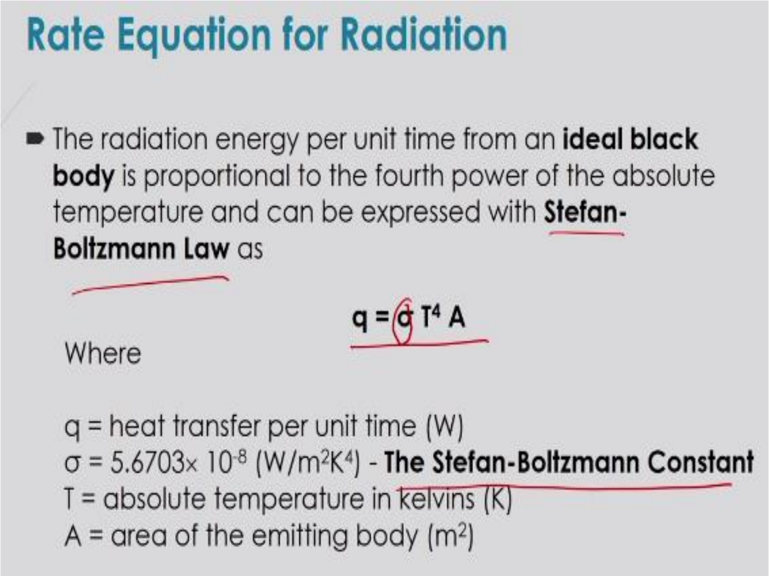

So, in this case the radiation energy per unit time from an ideal black body is proportional to the fourth power of the absolute temperature and can be expressed as per Stefan-Boltzmann law as like q will be is equal to sigma into T to the power four 4 into A. Here also, this heat transfer rate depends on the surface area through which this heat will be transferred and also this radiation depends on the temperature of the surface there. In this case, you will see that the proportionality constant is coming as sigma here.

This sigma is called the Stefan-Boltzmann constant and its value is 5.6703 into 10 to the minus 8 watt per meter squared Kelvin to the power 4, T is the absolute temperature, of course should be absolute temperature you cannot use here only that in degrees Celsius or Fahrenheit unit, you have to consider it as absolute temperature here in Kelvin, and A is the area of the emitting body through which that heat is transferred.

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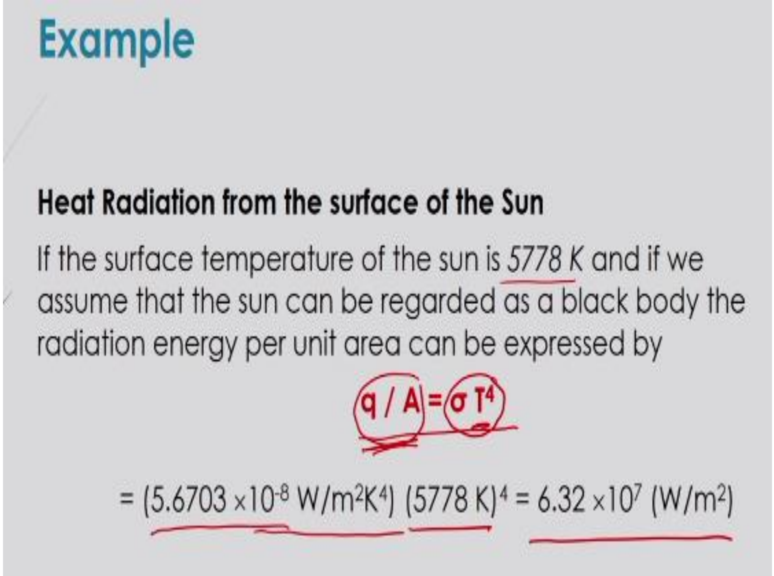

Now, let us see an example here, heat radiation from the surface of the Sun. If the surface temperature of the sun is 5778 Kelvin and if we know that the sun can be regarded as a black body and then the radiation energy per unit area can be expressed by like here q by A that will be equals to sigma into T to the power 4. Now, according to this equation, then what should be the amount of heat that is being radiated from the sun? So, since we know that surface temperature of the Sun is 5778 K, so you can directly substitute this temperature here for this temperature T.

So, in this case, you can then write that q by A will be is equal to sigma into T to the power 4, why q by A we are not actually calculating the surface area, but we can say that here what will be the radiating heat flux from the sun. So, here the rate of heat transfer by radiation by unit cross section sorry unit surface area of the sun, it will be is equal to then 5.6703 into 10 to the power minus 8, this is basically Stefan-Boltzmann constant into what is the surface temperature, it is 5778 Kelvin, then it will be to the power 4 here as per this equation.

Finally, after calculation it is coming as 6.32 into 10 to the power 7 watt per meter square. So, this is the example based on which you can say that how much heat is being radiated per unit surface area of the sun.

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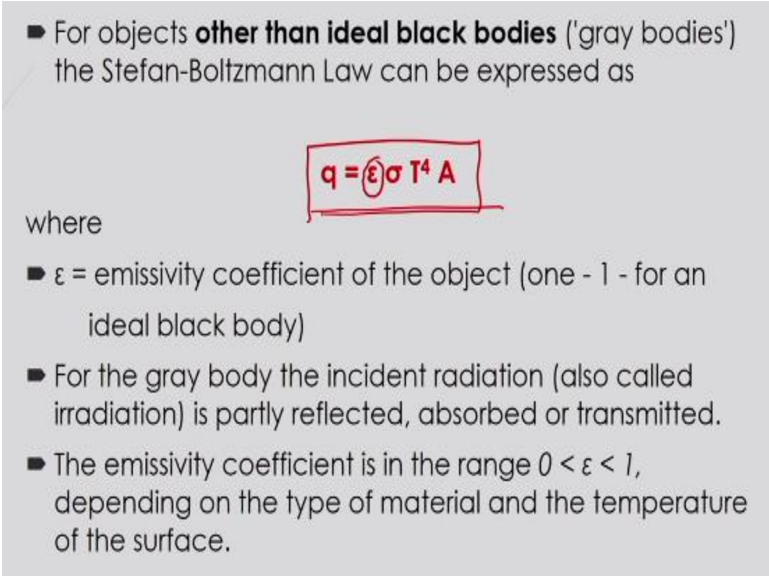

You know that for objects other than these ideal black bodies, it would be called as gray bodies. Now, the Stefan-Boltzmann law can be expressed here as per that, that q will be is equal to epsilon sigma T to the power 4 into A. Here, one important parameter is coming as epsilon, this epsilon is basically one coefficient, it is called as adjustment coefficient or it is called emissivity coefficient of the object where the object from which that heat is transferred is not the ideal black bodies.

So, other than this ideal of black bodies, we can say that the total heat transfer rate by the radiation it will be some fraction of that heat radiation rate of that black body. So, that is why this heat transfer rate per unit crosssectional area to be regarded as it transfer flux by radiation can be regarded as epsilon into sigma into T to the power 4 based on this Stefan-Boltzmann law. For the gray body, the incident radiation, it is also called as irradiation, is partly reflected and in that case absorbed or transmitted.

Now, the emissivity coefficient will be is in the range of you will see that the 0 to 1. There will be certain fraction of that heat will be radiated compared to that ideal black bodies, that is why this emissivity coefficient depending on the type of material and the temperature of the surface.

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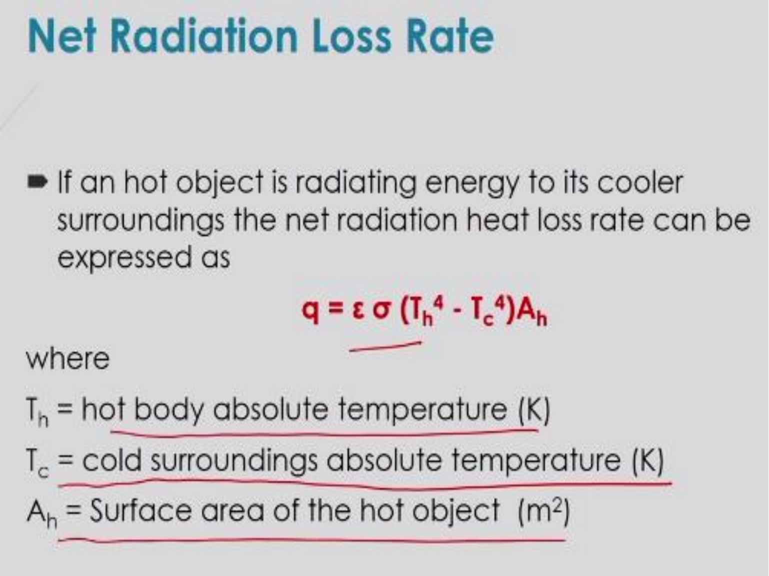

How to actually calculate the net radiation loss rate. If you know an object which is hot will be radiating energy to its cooler surroundings, then the net radiation heat loss rate can be expressed as q will be is equal to epsilon into sigma into Th to the 4 minus Tc to the power 4 into Ah. In this case, you have to know the temperature of these two bodies, one is hot body, another is that cold body.

So, in that case based on that temperature difference, what should be the radiation or heat transfer rate difference there, so you can calculate based on this temperature. In this case, Th is hot body absolute temperature and Tc is called cold surroundings absolute temperature and Ah will be is equal to surface area of the hot object.

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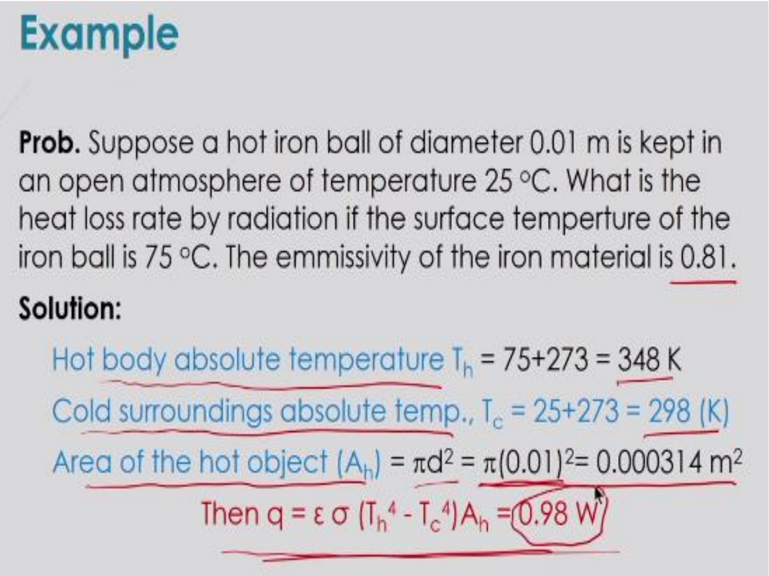

Let us do an example based on this. Suppose a hot iron ball of diameter 0.01 meter is kept in an open atmosphere of temperature 25 degrees Celsius. Then what is the heat loss rate by radiation if the surface temperature of the iron ball is 75 degrees Celsius. The emissivity of the iron material is given here 0.81, So according to that, you have to first find out what should be the hot body absolute temperature there. So, it will be 348 Kelvin whereas cold surroundings absolute temperature it will be 298 Kelvin and area of the hot object it is simply pi d square.

So, we can say that it will be pi into 0.01 whole square. Since, it is you know that spherical object, so you have to have this surface area as pi d square here. So, finally, we can calculate what should be heat transfer rate based on this temperature difference, it will be 0.98 watt.

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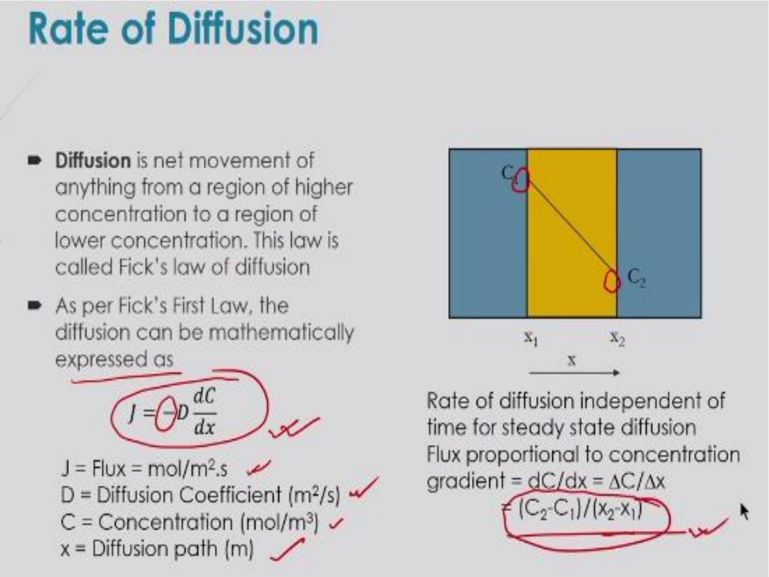

Now, let us consider that diffusion. Diffusion is one of the important chemical engineering processes based on which you can say that that there will be a transfer of molecules from one phase to another phase through the interface. So, in that case, this diffusion basically depends on the concentration differences of different location. So, in that case, the diffusion can be regarded as the net movement of anything from a region of higher concentration to a region of lower concentration and this law is called as Fick's law of diffusion.

As per Fick's law of diffusion, you can say that the diffusion can be mathematically expressed as J will be is equal to minus D to dC by dx where J is called flux that is how much molecules will be transferred per unit time per unit crosssectional area. Here D is called diffusion coefficient and C is called concentration and x is called diffusion path. Here negative sign is there because here the concentration is actually considered here they are higher concentration and lower concentration, but the difference of what the diffusion process is considering actually final minus initial.

So final is basically the low concentration and initial concentration is higher concentration. So, final minus initial is to be negative, that is why here you have to consider that the diffusion will be from higher concentration to the lower concentration in the negative direction. So, here in this case, this flux will be defined by this Fick's law. So, rate of diffusion independent of the time of steady state diffusion, flux proportional to the concentration gradient.

Then we can say that if there are two concentrations here C1 and C2, then C2 minus C1 will be regarded as negative one and then x2 minus regarding you can say that x2 minus x1 similarly here it will be coming. So based on which what would be the dC by dx you can calculate like this.

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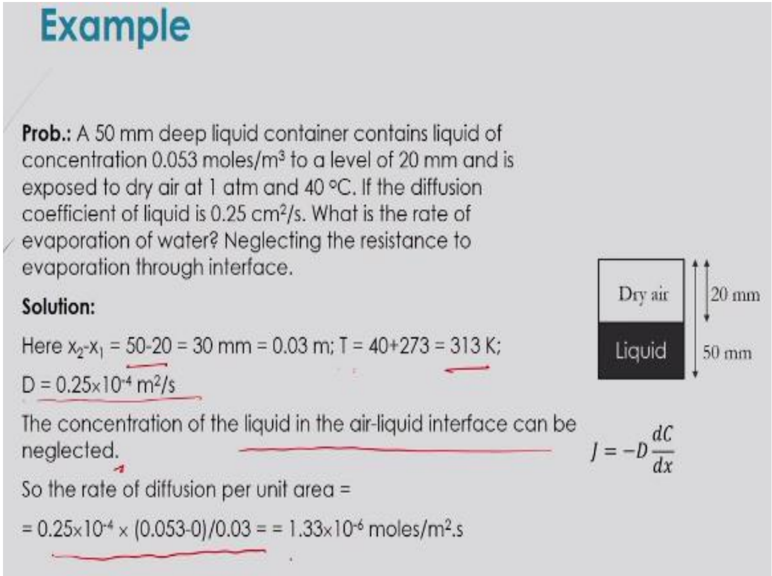

Now, let us have an example for this. A 50 millimeter deep liquid container that contains liquid of concentration here 0.053 moles per meter cube to a level of 20 millimeter and is exposed to the dry air at 1 atmosphere and 40 degrees Celsius. If the diffusion coefficient of liquid is 0.25 centimeter square per second, then what is the rate of evaporation of the water and neglecting the resistance to evaporation through interface. Very interesting that here that liquid the concentration is 0.053.

It is exposed to the dry air and because of this diffusion, you will see that the liquid will be evaporating to the atmosphere from this liquid and you have to find out then what should be the rate of evaporation of this water. This evaporation is basically a diffusion process. So, here in this case x2 minus x1 that will be is equal to your 50 minus 20 and also you can say that temperature is here 313 and diffusion coefficient is given to you and the concentration of the liquid in the air liquid interface can be neglected because initially there will be no concentration here.

So, only the evaporation starts from this liquid concentration to the 0 concentration of the air. So, the rate of diffusion per unit area can be calculated based on that diffusion equation of Fick's law. So, that will be is equal to 1.33 into 10 to the power minus 6 moles per meter square per second.

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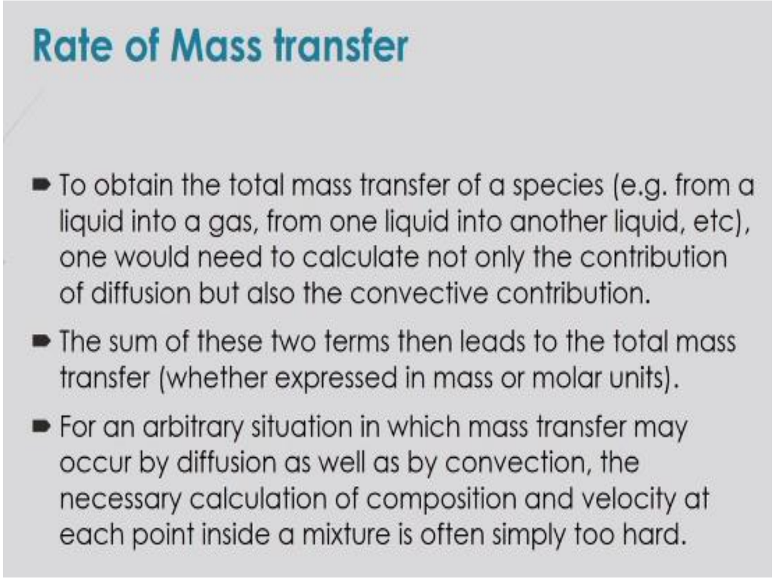

Another important aspects of chemical engineering process is that mass transfer. You see the mass will be transferred from one phase to another phase like I have given earlier the example like suppose there is a transfer of carbon dioxide gas molecules in air mixture that will be transported from this gaseous mixture to the liquid phase. Suppose sodium hydroxide solution. So, in this case there is an interface of this gas and liquid, gas air mixture of carbon dioxide and air and then you know that in the liquid there is sodium hydroxide.

Now carbon dioxide gas to be absorbed to the liquid sodium hydroxide solution. Now, in this case, there will be a mass of carbon dioxide transferred from this gaseous space to the liquid phase of sodium hydroxide solution. So, in this case what will be the mass transfer rate okay?

So, that you have to calculate. Now to obtain the total mass transfer of a species, example from a liquid into gas or gas into a liquid, you can say that one would need to calculate not only the contribution of diffusion, but also the convictive contribution there.

The sum of these two terms then leads to the total mass transfer whether expressed in mass or molar units. For an arbitrary situation in which mass transfer may occur by diffusion as well as by convection, now the necessary calculation of the composition and velocity at each point inside the mixture that is often simply too hard. So, that is why that you have to consider some overall mass transfer phenomena and from that overall mass transfer you have to define some mass transfer coefficient and based on which you can calculate the mass transfer rate.

So, based on that concentration difference of this gaseous phase and the liquid phase, you will see there will be concentration difference. Now, based on this concentration difference, this mass will be transferred from that one phase to another phase. Now, these mass transfer concentration difference it is called the driving force for the mass transfer.

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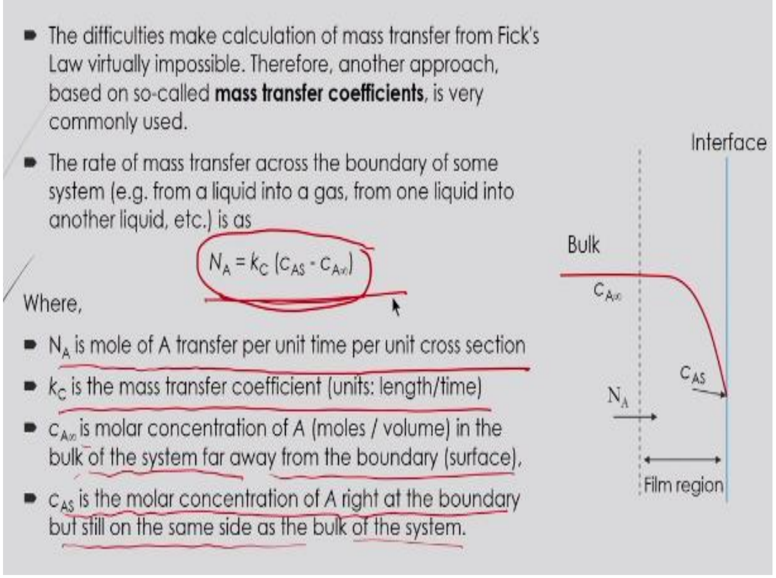

Now, if your mass transfer rate is proportional to that concentration differences, then proportionality constant will be regarded as mass transfer coefficient. Now, in that case so, the rate of mass transfer across the boundary of some of the system from a liquid into gas or from the liquid into another liquid or from the gas into the liquid, you can represent this mathematically as by this NA which will be is equal to Kc into CAS minus CA infinity, where this NA is the mole of A transfer per unit time per unit cross section.

KC is the mass transfer coefficient per unit length sorry length per unit time and also CA infinity is the molar concentration of A that is moles per volume in the bulk of the system that is far away from the boundary surface as shown in the figure in the slides, and CAS is the molar constitution of A that is right at the boundary but still on the same side as the bulk of the system, here as shown in the figure. So, in this way, you can define how that mass is transferred and what will be the rate of that mass transfer, how it can be expressed. So, by this equation given in the slide, you can calculate what would be the mass transfer rate.

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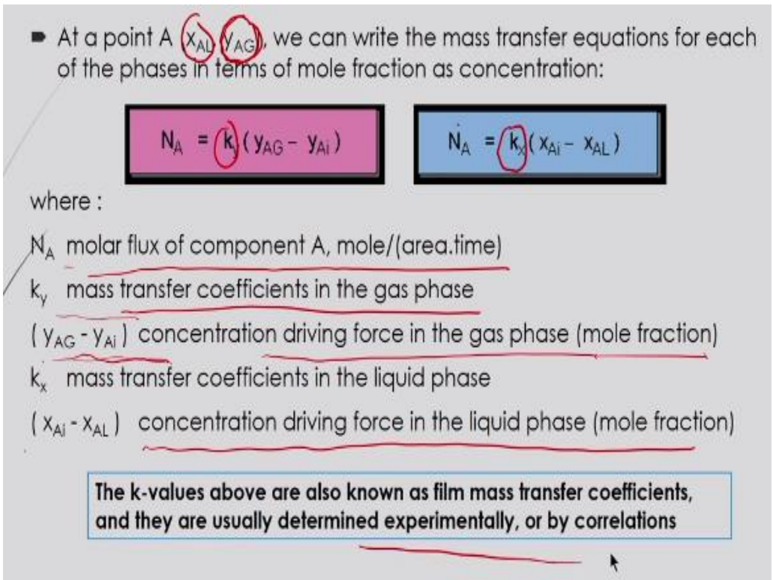

Now at a point suppose A where the concentration maybe mole in terms of mole fraction for the liquid as well as gas, generally for liquid it is expressed as XAX and for gas it is YY, so XAL and XAG. Suppose there is a mole faction in the two phases in the liquid and gas respectively, then we can write the mass transfer equations for each of the phases in terms of mole fraction as concentration like this NA is equal to Ky into YAG minus YAi and NA will be is equal to Kx into XAi minus XAL.

Here in this case, interesting that for a particular phase, we are considering the concentration difference of the bulk phase from its interface concentration. So, NA here molar flux of the component A that will be mole per unit area per unit time and also Ky will be called as mass transfer coefficient. If you are considering the gas phase, it will be Ky, if you are considering the liquid phase, it will be Kx. So, it will be called as individual mass transfer coefficient and YAG minus YAi that is the concentration difference, here mole fraction difference between bulk concentration and interface concentration.

So, there is a difference and this is called driving force in the gas phase, that is the mole fraction whereas in the liquid phase it will be XA minus XAL. So, it will be concentration driving force in the liquid phase in terms of mole fraction. Now, in this case, this Ky and Kx these are mass transfer coefficient of individual phases. So, it is called that individual mass transfer coefficient or film mass transfer coefficient since only we are considering that concentration difference from the reference of the interface.

Now, these K values above are also known as film mass transfer coefficient because of that, and also they are usually determined experimentally or by some correlations.

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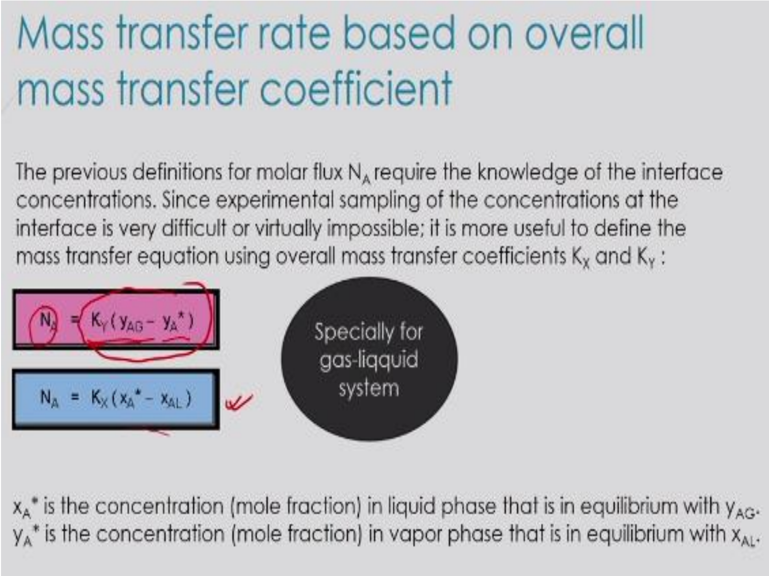

Now, mass transfer rate based on overall mass transfer coefficient. In this case, the concentration difference is to be considered, you know that from the gaseous phase to the liquid phase. So, in that case the overall mass transfer coefficient will be there and the rate of mass transfer to be defined as Ky into YAG z minus YA star, here it will be capital K, Y is for gaseous phase and YAG is the mole fraction in the gaseous phase in the bulk region whereas YA star it will be represented as what is that in the gaseous phase in that interface or at the you can say that equilibrium condition.

Similarly, for liquid you can express by this equation as shown in here in the slides. Here XA star and YA star are the concentration in the liquid phase that is in equilibrium with the gaseous phase and YA star is the concentration in the vapor phase or gaseous phase that is equilibrium with the liquid phase.

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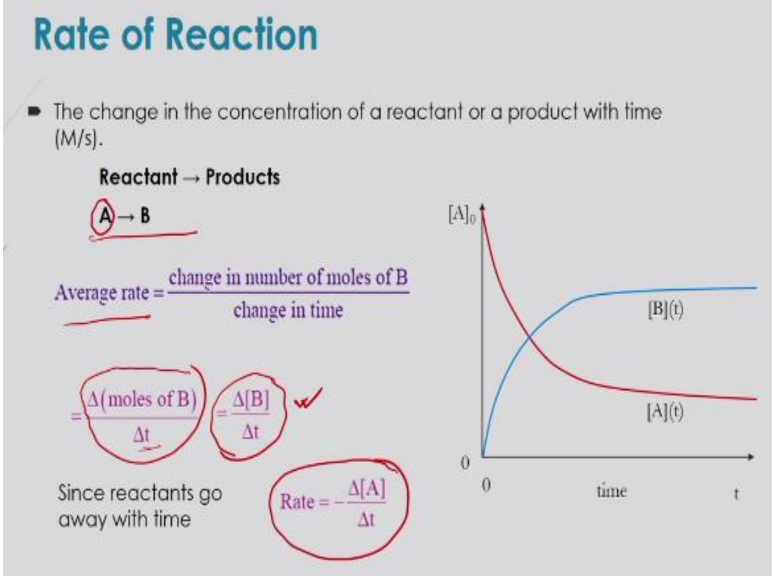

Then another important that most of the chemical engineering processes actually depends on is that reaction, so how to express that the reaction rate. Suppose there is a reaction that is or reaction is represented by this A is giving the product B and the change in the concentration of the reactant or a product with time here. So, in this case, the average rate of that reaction will be considered as change in the number of moles B per unit time of change. So, we can write this equation as delta moles of A, that is a change of moles A per unit time that is per unit delta t.

So, it will be regarded as delta B by delta t. In this way also by this symbol you can represent this reaction rate. Since reactants go away with time, so, we can write here rate of reaction will be is equal to minus delta A by del t. Here, you can also represent that reaction in terms of reactant concentration. Not only the product concentration you are expressing this reaction rate, you can express that reaction rate in terms of reactant concentration also. In this case, the change will be negative because you know that the A consumed whereas B is generated, that is why this rate of reaction will be positive there.

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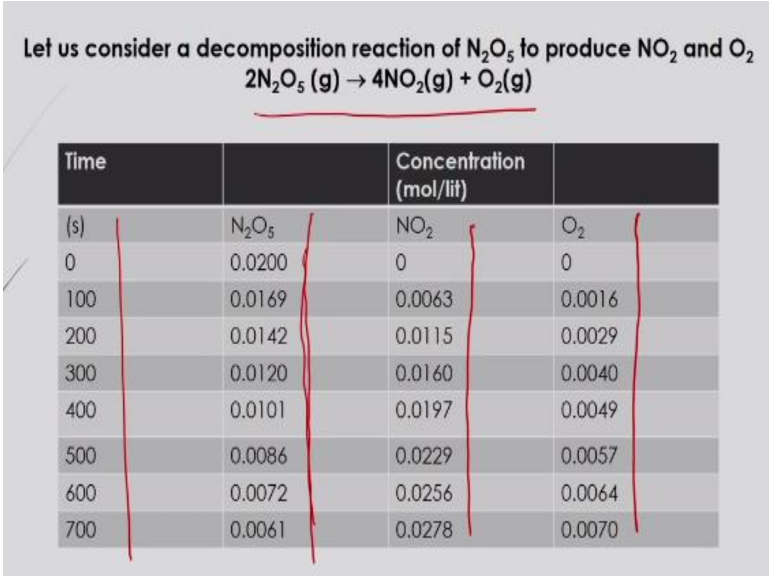

Let us consider a decomposition reaction of N_2O_5 to produce NO_2 and O_2

$$2N_2O_5\,(g) \rightarrow 4NO_2(g) + O_2(g)$$

Time		Concentration (mol/lit)	
(s)	N_2O_5	NO_2	O_2
0	0.0200	0	0
100	0.0169	0.0063	0.0016
200	0.0142	0.0115	0.0029
300	0.0120	0.0160	0.0040
400	0.0101	0.0197	0.0049
500	0.0086	0.0229	0.0057
600	0.0072	0.0256	0.0064
700	0.0061	0.0278	0.0070

Let us consider a decomposition reaction of nitrogen pentoxide to produce nitrogen dioxide and oxygen based on this reaction given in the slide. So, in this case as for time 0 to 700 seconds. This concentration of the components given here for nitrogen pentoxide that is consumed at the rate given here, whereas nitrogen dioxide it is produced at a rate here and also you know that oxygen that is produced based on this reaction as here at this rate, this rate is mole per liter it is expressed.

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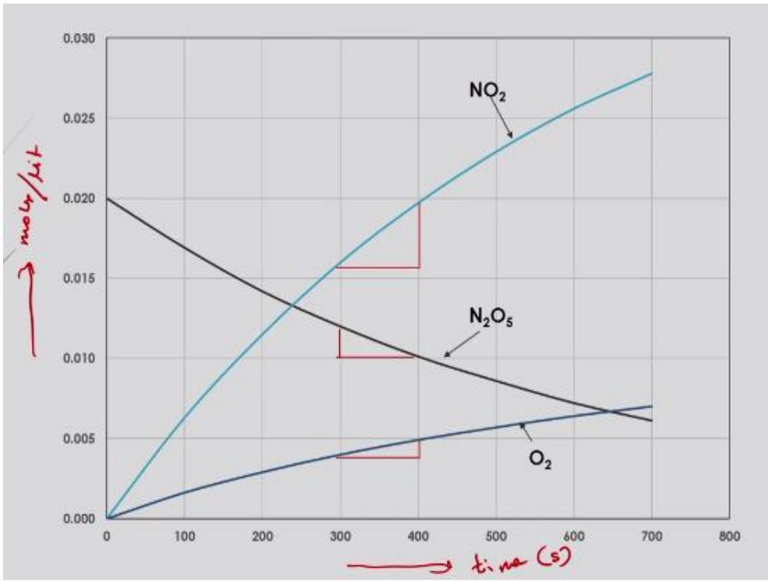

If we express this you know that happening of this reaction reactant and also products flow rate based on this consumption and also you can say that you know generation. So, we can express this by this graph here. In this, x axis is temperature and y axis is what would be the mole fraction, mole that is consumed per unit volume of litre. Then you will see that how this oxygen is actually increasing with respect to temperature, sorry it is not temperature, it is time, sorry this is time, this is in second.

This is here moles of A or B you can say per unit litre and in this case then how oxygen is actually increasing with respect to time and also nitrogen dioxide is increasing with respect to time, whereas this nitrogen pentoxide is decreasing with respect to time because nitrogen dioxide is consuming to give you that generation of nitrogen dioxide and oxygen.

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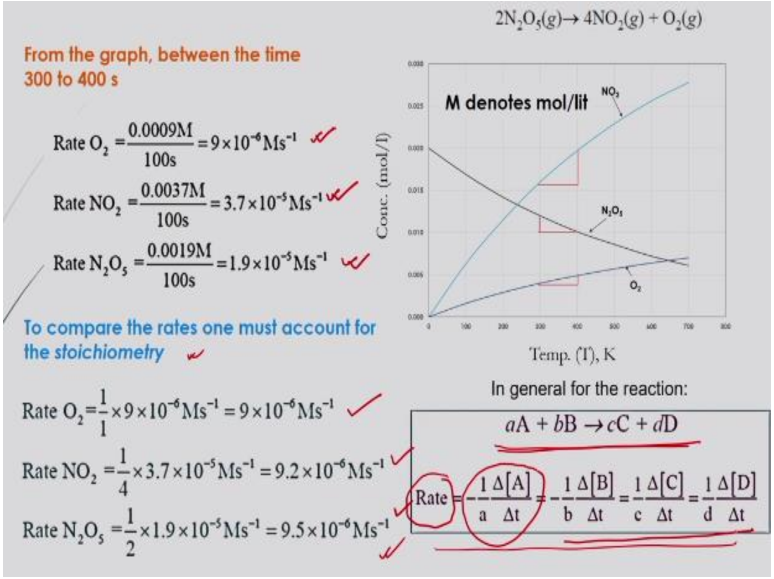

So, from the graph, we can say that between the time 300 to 400 second, the rate of oxygen can be expressed by this equation and rate of nitrogen dioxide can be expressed by this equation, the rate of nitrogen pentoxide can be expressed by this equation, and to compare the rates, one must account for the stoichiometry. Here in this case rate of oxygen can be expressed by this equation, rate of nitrogen dioxide can be expressed by this equation given in the slide, and rate of nitrogen pentoxide that is consumed can be expressed by this equation.

Now, in general for the reaction, you can express this aA + bB that will give you the cC and dD, the general reaction equation and based on these, you can also express the rate or you can compare the rate based on this stoichiometry. Here in this case, this rate will be here minus 1 by a delta A by delta t that will be is equal to similarly for other components here like this given in the slides. So, based on this general equation, you can express what should be the reaction rate based on this stoichiometry coefficient.

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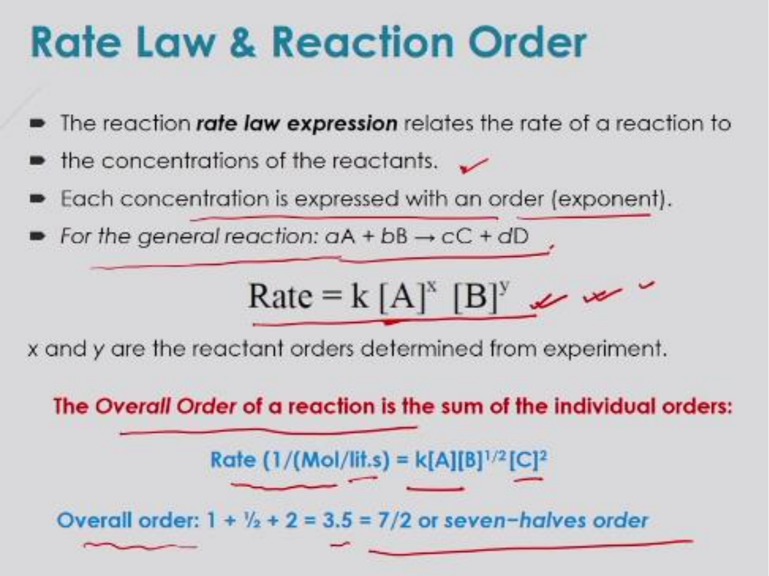

Now, what is the rate law and also reaction order? The reaction rate law expression actually relates the rate of reaction to the concentration of the reactants. Now, each concentration is expressed with an order like exponent and for that we can say for the general reaction of this shown in here in the slides, then rate can be expressed by this here for this reaction of aA + bB which will give you the cC plus dD. Based on this equation, you can express the rate of the reaction as k into A to the power x into B to the power y.

Here, in third bracket, we are writing this A and B, it does mean that the concentration of this component A and B respectively. So, the rate of reaction depends on this concentration of these reactants A and B and what will be the rate of that reaction. It will be proportional to the concentration of the A and B and it will follow some power law equation. Here in this case, it is expressed as k into A to the power x into B to the power y.

Here x and y are the reactant orders that is determined generally from the experiment and k is called reaction rate constant and overall order of reaction is the sum of the individual orders, here like here in this case rate in 1 by mole per litre second that will be equal to k into A suppose B to the power half into C to the power 2. Then we can say that overall order will be equal to 1 + here half + 2, that will be 3.5, then it will be equal to 7 by 2 or seven-halves order.

So, in this way, we can actually calculate what should be the overall order of a reaction. In this case, suppose rate is here came to A to the power x into B to the power y, in this case overall order will be x + y.

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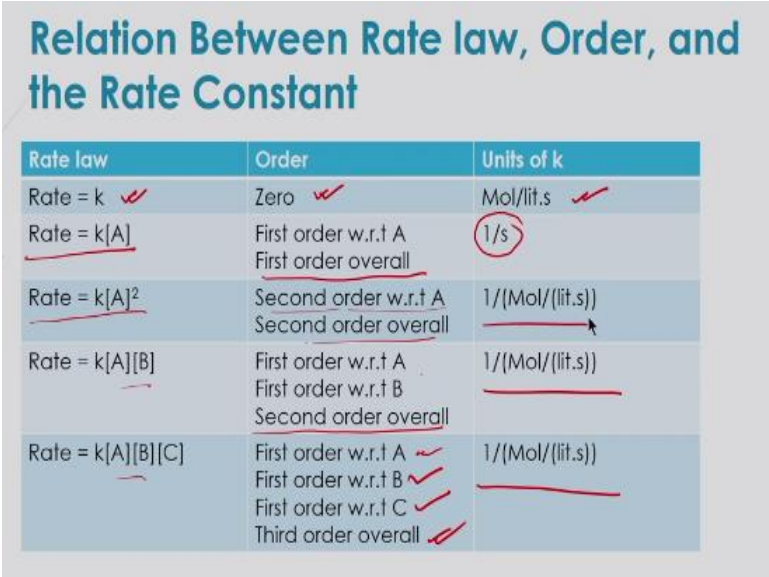

Now relation between the rate law, order, and the rate constant like this here. Zero order reaction will be regarded as or as per rate law as rate will be equal to constant, here unit should be like this. Here if rate is expressed as k into A, it will be called as first order with respect to component A or reactant A and first order overall reaction and unit will be 1 by s. Similarly, if rate is considered as k into A square, in this case it will be second order with respect to A and second order overall.

Similarly, if rate is expressed as k into AB, here first order with respect to A, first order with respect to B and will be second order overall. Similarly, rate if it is expressed as k into A into B into C, then it will be first order with respect to A, first order with respect to B, and first order with respect to C, and overall it will be third order reaction and then unit will be like here as given in the slide.

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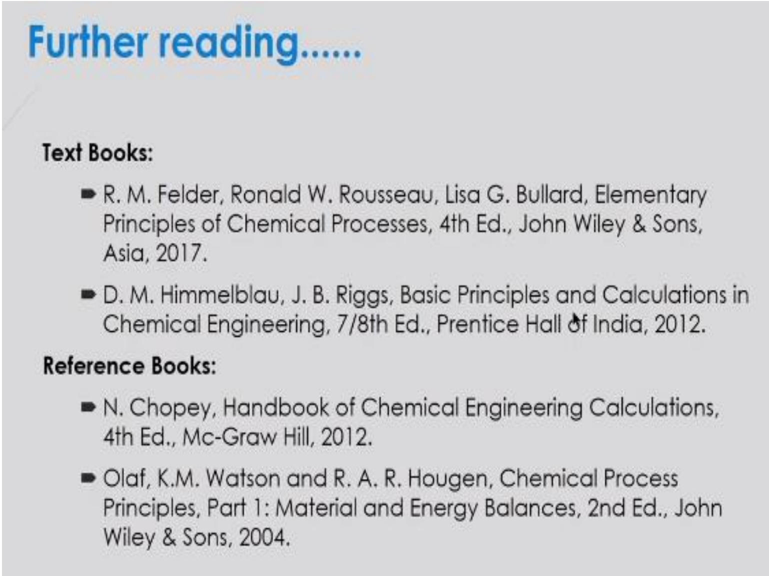

So, we have described different laws of the chemical engineering processes, like that mass flow rate, momentum, heat transfer rate, mass transfer rate, and also reaction rate. So, I think you have understood the basics of this rate equation. These will be required for further understanding of the chemical engineering processes or other subjects like you know heat transfer operations in details, mass transfer operations in details.

Also fluid flow phenomena where energy balance will be required to express that phenomena, that momentum equation, then there it will be helpful to further understand. So, we will describe more about this chemical engineering principles. In the next lecture, so we will describe that principles of material balance and its calculation based on this rate law. So, thank you for giving your attention here.