Mass Transfer Operation-I
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Module - 1
Diffusion Mass Transfer
Lecture - 2
Molecular Diffusion

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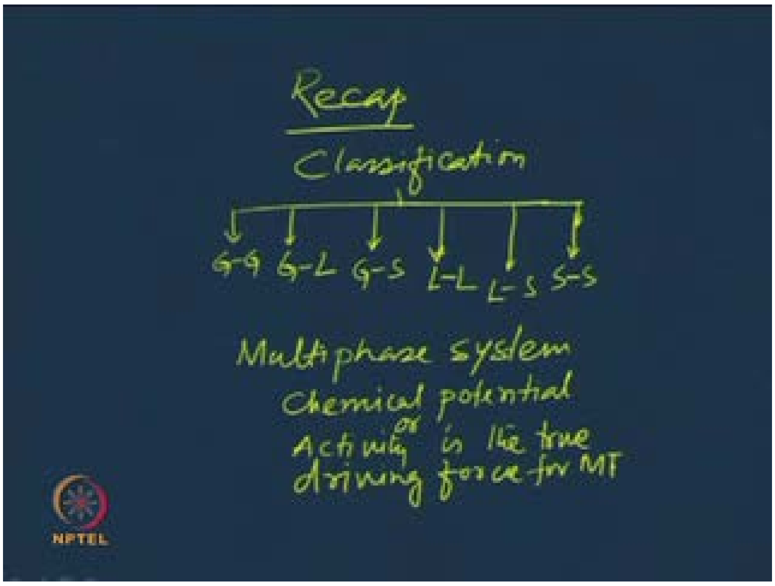

Welcome to the second lecture on mass transfer operation. Before going to the second lecture, we will just have a recap on the first lecture, what we have done. In this lecture, we have introduced you the objectives of the course, and then the overall plan of the course syllabus, and then we have given you the introduction to mass transfer. What is mass transfer and what are the common examples of mass transfer? For example, we said, if we add a lamp of sugar in a cup of tea, then there is a mass transfer, where sugar particles diffuses throughout and form the unit form solution. There are some industrial examples like the separations of CO2, which is a greenhouse gas; by using absorption is a mass transfer operation.

We have also classified the multiphase systems classification, and we have seen there are 6 phases of contact: Gas-gas system, gas-liquid system, gas-solid system, liquid-liquid system, liquid-solid system, and solid-solid system; and we have explained based on the thesis contact, what are the examples in each category. And then we have seen what are the mechanism of mass transfer, and then the concentration gradient or the chemical potential gradient for mass transfer. As we can see, if there is a multiphase system, for multiphase system, then we have seen the chemical potential or activity, or activity is the true driving force for mass transfer.

But in general, we consider mass transfer or we analyze mass transfer in a single phase system. In a single phase system or each phase, separately we analyze.

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So in each phase, concentration is the driving force. For a single phase, the driving force is the concentration difference.

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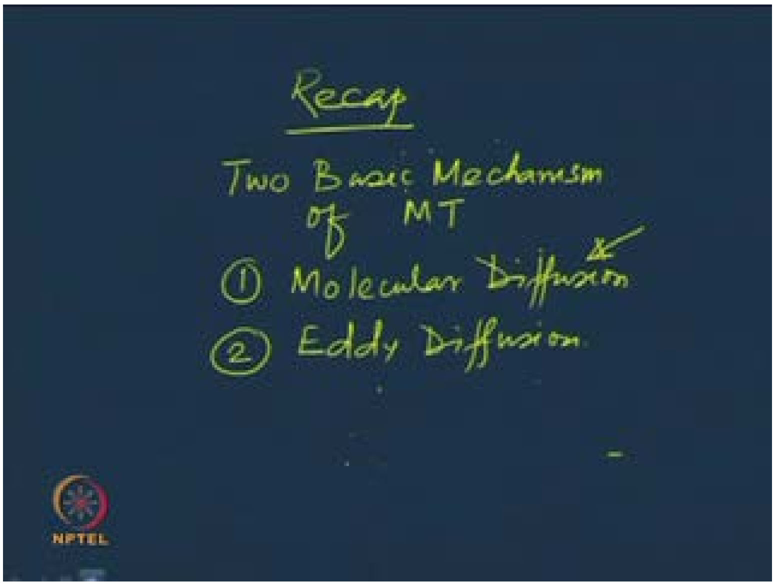

The mechanism of mass transfer as we said, there are two basic mechanism of mass transfer: One is molecular mass transfer, which is based on the molecular diffusion, and second mechanism is convective mass transfer, which is based on the Eddy diffusion. So in this lecture, we will start with the molecular diffusion phenomena and other related examples on this topic.

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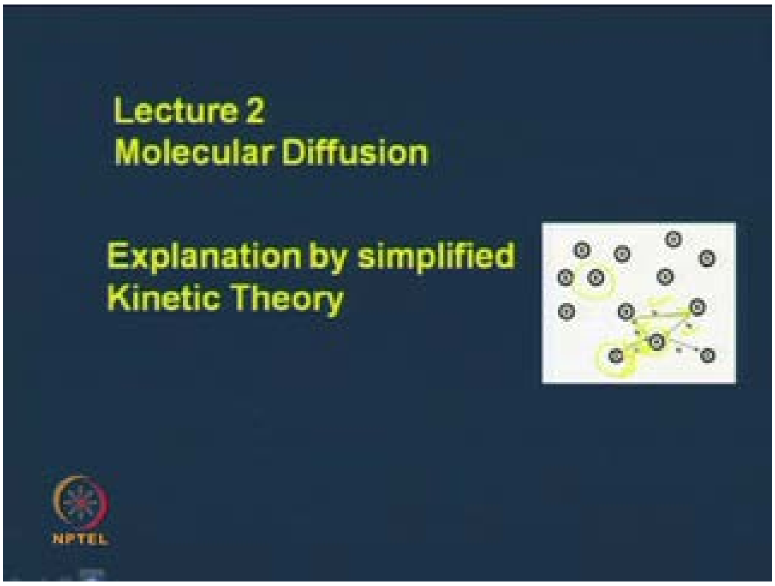

So molecular diffusion as we said in the last class, it is the diffusion of the molecules by virtue of their thermal energy. Since the diffusion of molecules by molecular diffusion occurs by thermal energy, the rate of diffusions is slow. We can explain this molecular diffusion mechanism by simple kinetic theory, like in case of gas molecules, suppose there are A and B type of molecules are present in a system. So, the A molecule diffuses in a straight manner until it collides with the other molecule in the system. And then, it changes its direction and path and then it again travels in a straight path. So, the motion is known as the Brownian motion and the path is zig-zag. But the total distance travel if we considered, suppose time t1, t2, t3, and t4. So, total time is t up to t4 and the molecule A travels up to this point. Then the net distance travel by the molecule is a fraction of the total distance travelled by the molecule.

The total distance travelled by the molecule is the mean free path of the molecule, and then the rate of diffusion is defined the total distance travelled per unit time. Since the total distance travelled by molecule is a fraction of the net distance travel, so the rate of diffusion is slow.

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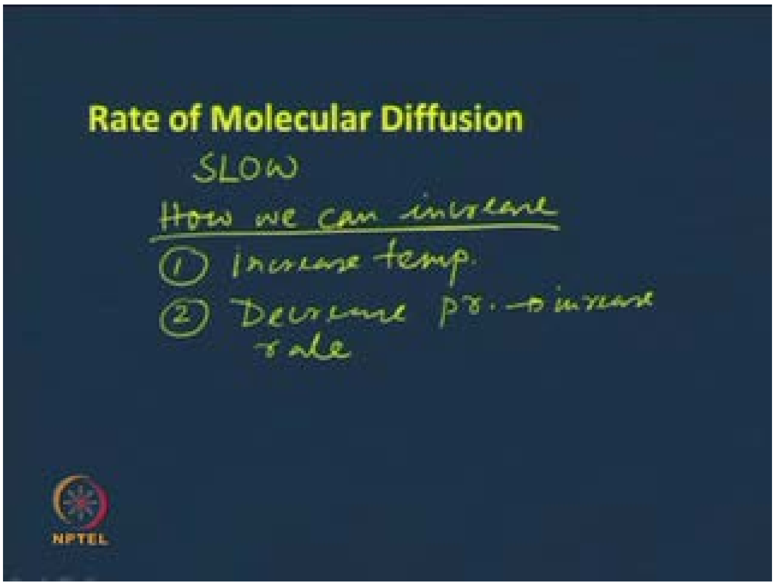

So, molecular rate of molecular diffusion is slow, how we can increase this rate? There are two ways we can increase this rate: One is increase temperature. If we increase the temperature, the molecular motion will increase and the rate of molecular diffusion will increase, and second, decrease the pressure. If we decrease the pressure of the systems, the number of collisions will reduce. If the number of collisions reduces, the net distance travel or mean free path of the molecule will be more or higher, and the rate of molecular diffusion will be more.

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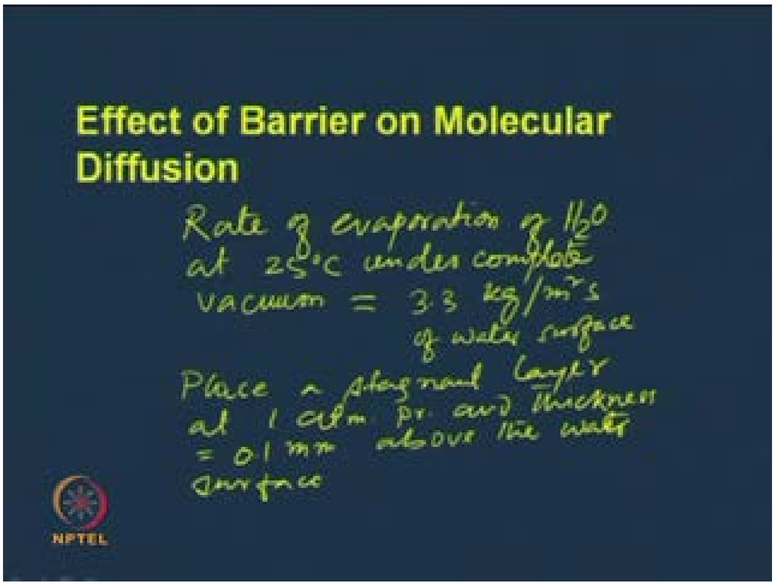

So, another effect on molecular diffusion is the barrier. Like if we consider rate of evaporation of water at 25 degree centigrade under complete vacuum, and it is roughly 3.3 kg per meter square second of water surface.

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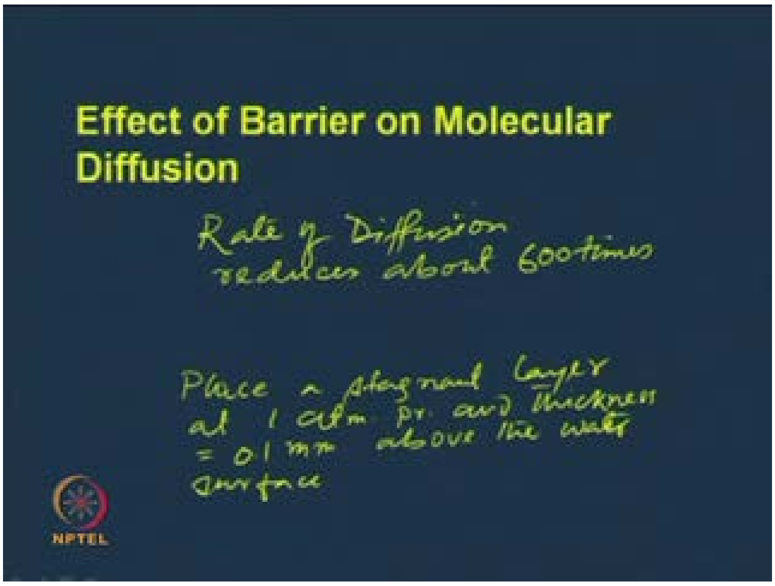

Now, if we place a stagnant layer at 1 atmosphere pressure and the thickness of the layer is around say 0.1 millimeter above the water surface, then the rate will decrease by about

600 times. The rate of diffusion reduces is about 600 times. So, the effect of barrier on molecular diffusion is very important.

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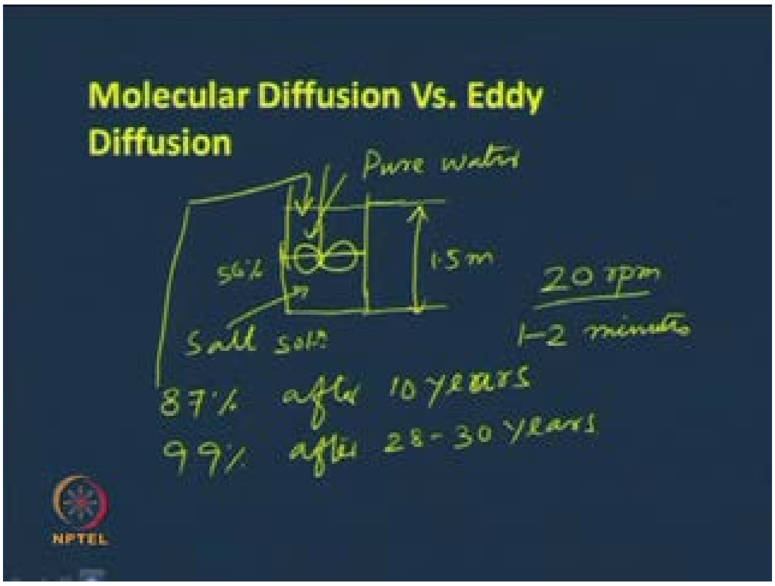

Now, if we compare the difference between the molecular diffusion and Eddy diffusion, which one is faster and how they compare each other? Now, consider tank of total height say 1.5 meter and 50 percent of it port with a salt solution. Without disturbing, if we place another 50 percent by pure water and then leave it undisturbed, it can be calculated that this salt concentration at the top layer will reach around 87 percent after 10 years, and it will reach around 99 percent after 28 to 30 years.

So, we can see how slow this process is and, but instead of keeping it stagnant condition undisturbed condition, if we place one-third between the 2 layer and star it with 20 RPM revolution per minute, then it will take hardly 1 to 2 minutes to reach complete uniformity. So the Eddy diffusion is much faster compared to the turbulent diffusion. Now in mass transfer, we have to have some units to represent the flux, and we know the concentration in each phase is the driving force for mass transfer. So, we need to know the concentration unit. The concentrations are represented in different ways.

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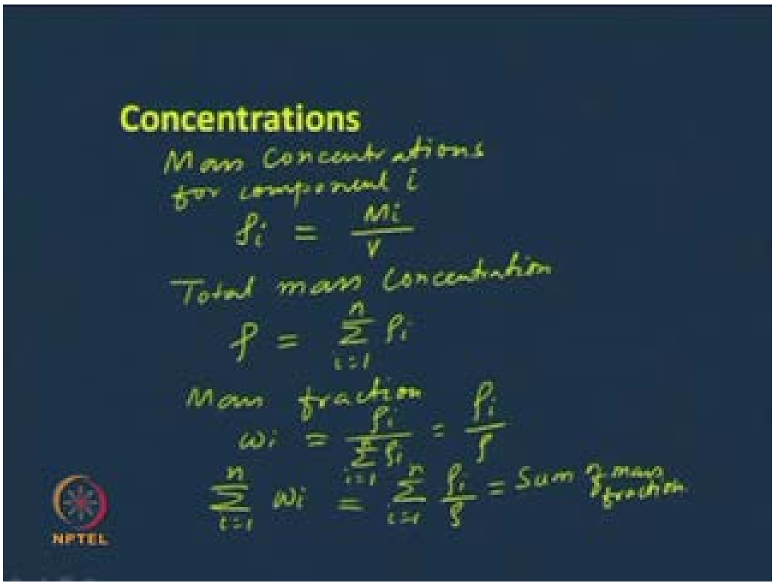

One is mass concentration. This is for component i. This is defined as rho i is equal to M i by v. So, the total mass concentration can be written as rho is equal to summation over i is equal to 1 to n, if there are n components in the mixture, it will be rho i; and the mass fraction is defined as w i which is equal to rho i, summation over i is equal to 1 to n rho i, so which is equal to rho i by rho; and sum of the mass fraction summation over i is equal to 1 to n w i will be equal to summation over i is equal to 1 to n rho i by rho. So, this is the total sum of mass fraction.

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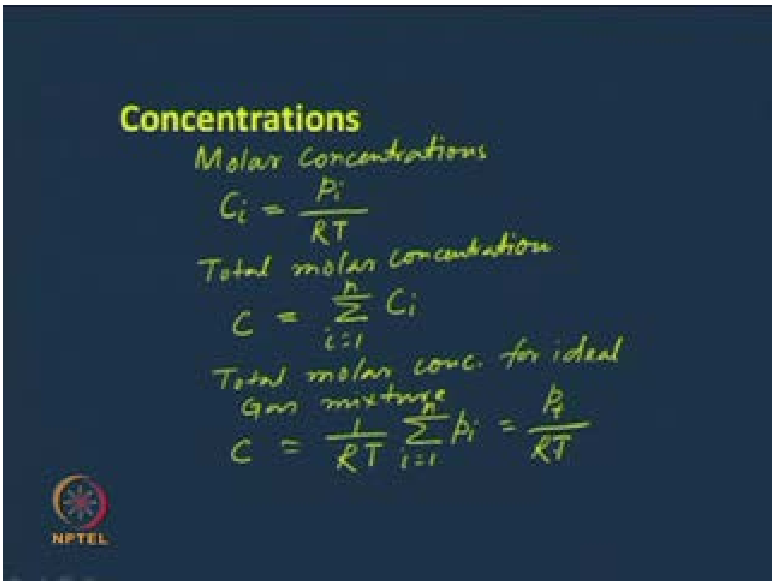

So, other concentration representation is the molar concentrations, and it is defined as C i for component i is equal to p i by RT. So, the total molar concentration we can represent it, C is equal to summation over i is equal to 1 to n C i. Total molar concentration for ideal gas mixture we can write, C is equal to 1 by RT summation over i is equal to 1 to n p i is equal to p t by RT.

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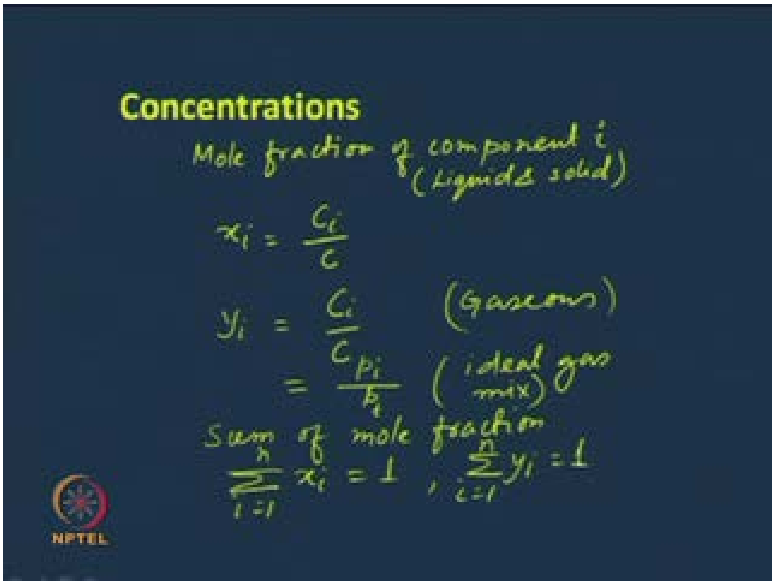

Mole fraction of component i for liquid and solid system can be represented as x i is equal to C i by C. For gaseous component, it is represented by y i which is equal to C i by C. If the gas components are ideal gas mixtures, then this will be p i by p t for ideal gas mixture, and then summation of mole fraction, we will get summation over i is equal to 1 to n x i will be 1, and summation over i is equal to 1 to n y i should be 1.

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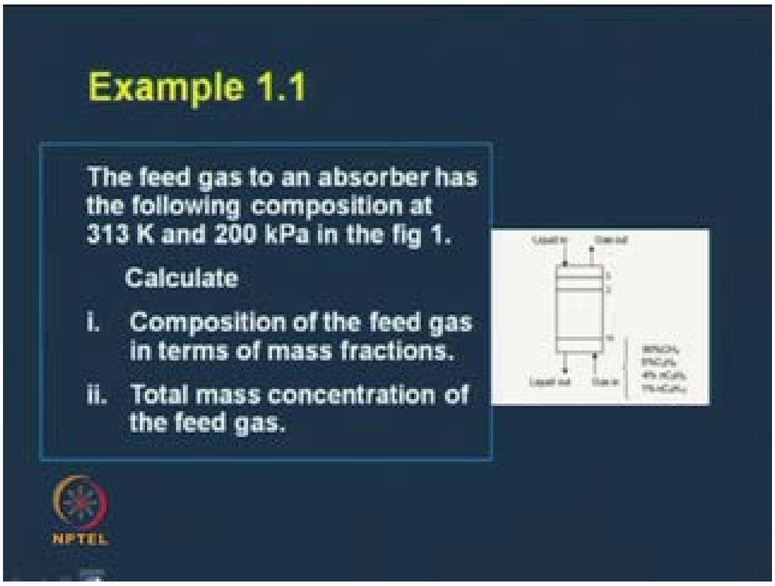

Now, let us take an example to calculate this mole fraction. Suppose the feed gas to an observer has the composition 90 percent methane, 5 percent ethane, 4 percent normal propane, and 1 percent butane. These are at following temperature: 313 Kelvin and 200 kilo Pascal pressure. Now, we have to calculate the composition of feed gas in terms of mass fractions and the total mass concentration of the feed gas.

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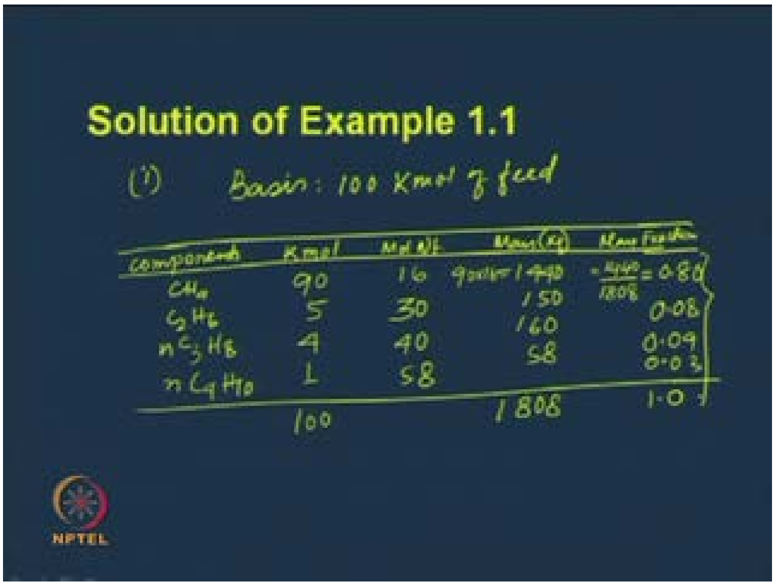

So for 1, for calculation of the mass fractions, let us take a basis. So, consider basis: 100 Kmol of feed.

So, let us develop the table. We have components and then Kmol, molecular weight of each component, mass in terms of kg, and then mass fraction. So, component we have CH4, C2H6, normal propane C3H8, C4H10 and this is as the basis is 100 mole Kmol of feed; so, 90 percent of this component. So, it will be 90, 5 percent of this, and then 4 percent of nC3H8, and 1 percent of. So, total will be 100 Kmol. As we have taken the basis, we know the molecular weight 16, 30, 40, and then 58.

We can calculate the mass Kmol of each. Each is, we multiplied by the molecular weight will give you the mass. So, 90 into 16 will be 1440, and then this one will be 150, 40 multiplied by 4 160, and then 58 multiplied by 1 58. So, total mass is 1808 kg, and then the mass fractions will be equal to 1440 divided by the total mass 1808. So, it will be 0.80. Similarly, the next one is 0.08, and then 0.09, and 0.03. So, sum of all these is 1.0. So, this is mass fractions; the first questions is answered and then the second one to calculate the total mass concentration.

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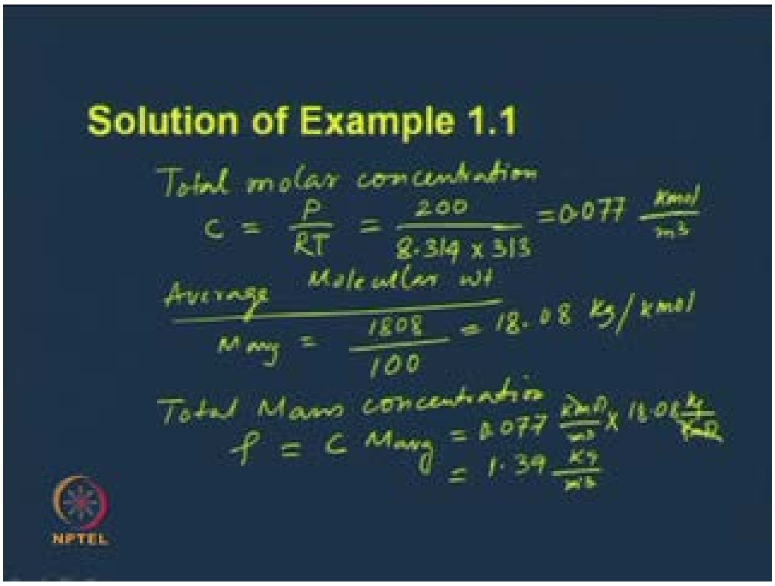

So to calculate the total mass concentration, we can calculate total molar concentration first. So, C is equal to p by RT. So, pressure is given 200 kilo-Pascal, and RT we can write, 8.314 into temperature 313 Kelvin. So, it will be around 0.077 Kmol per meter cube. Then average molecular weight we can calculate. M average will be the total molecular weight is 1, the mass is given 1808 divided by 100 is equal to 18.08 kg per Kmol. So that, the total mass concentration, which is rho is equal to C into M average will be equal to C is given, 0.77 Kmol per meter cube multiplied by M average 18.08 kg per Kmol; it will be Kmol, Kmol cancel out. So, it will be 1.39 kg per meter cube. So, this is the total mass concentration.

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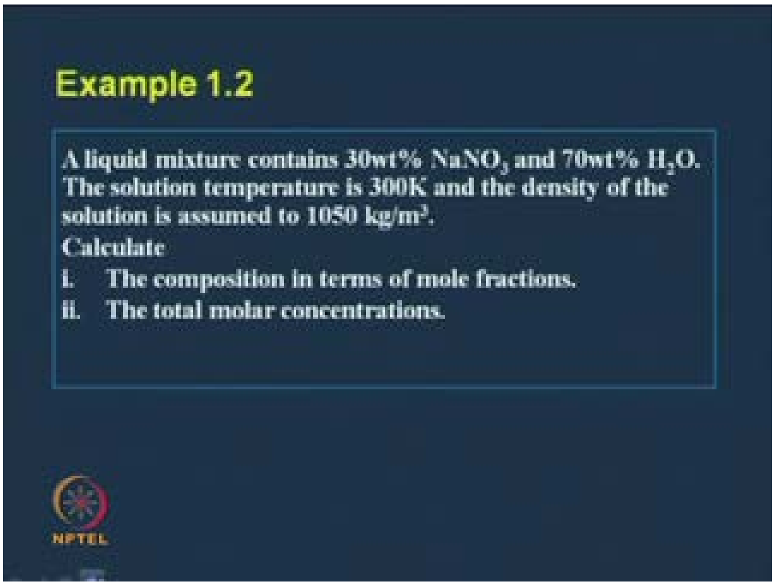

Now, let us take another example to calculate the mole fractions and total molar concentrations. A liquid mixture contains 30 weight percent sodium nitrate, and 70 weight percent water. The solution temperature is 300 K, and at this temperature, the density of the solution is assumed as 1050 kg per meter cube. Now, calculate the composition in terms of the mole fraction and the total molar concentrations.

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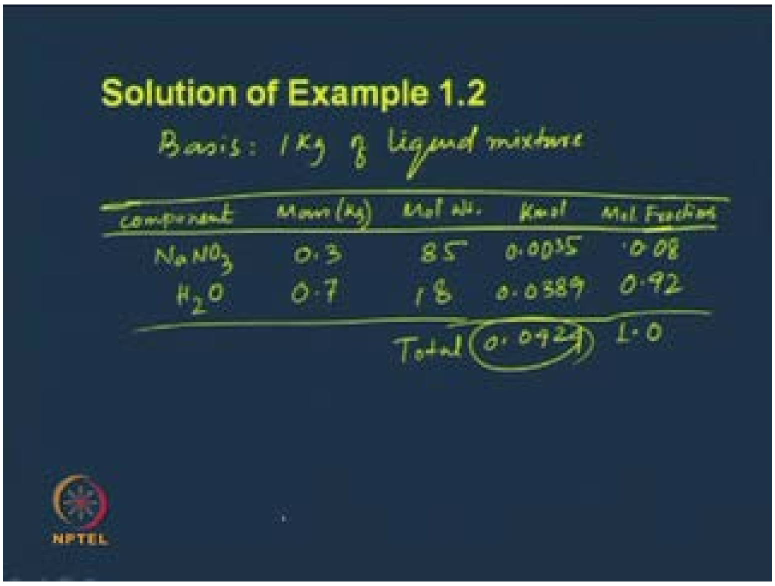

Similarly like previous case, we can take a basis, say 1 kg of liquid mixture. We can develop the table like earlier: Component, mass, molecular weight, Kmol, and mole fraction. So component is sodium nitrate and water; the percentage is given 30 weight percent. So, this is 0.3 kg and this is 0.7 kg. Molecular weight is 85 and 18, and this is Kmol if you calculate, it will be 0.0035 and this is 0.0389. So, the total Kmol is 0.0424, and then mole fraction is this Kmol 0.0035 divided by total mole, this is the total mole 0.0424. So then, this is will be equal to 0.08 and similarly for this Kmol, the mole fractions will be 0.92. So, the total mole fraction is 1.0.

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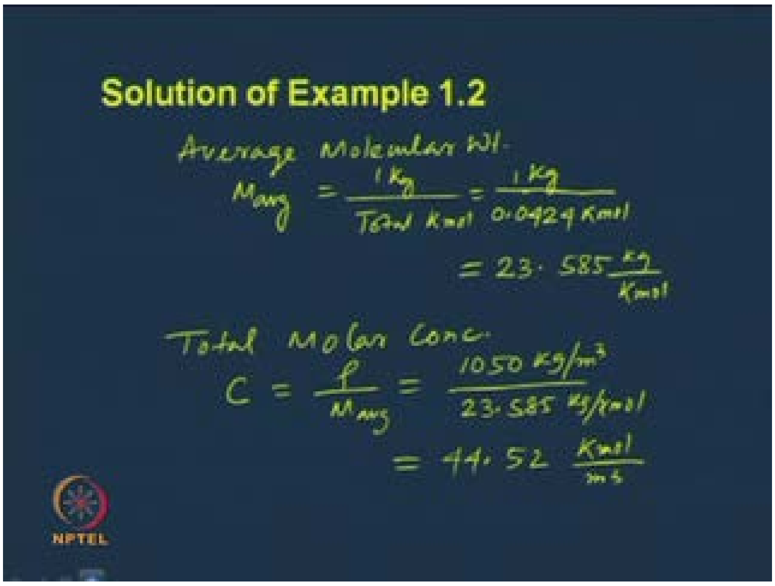

Now, to calculate the total molar concentration, we can calculate average molecular weight. So, this is M average is equal~~s~~ to 1 kg is the basis divided by total Kmol is equal to 1 kg divided by 0.0424 Kmol. So, this 24 k mole. So, this is equal to 23.585 kg per Kmol. Now the total molar concentration is defined as C is equal to rho by M average. So rho is given, which is 1050 kg per meter cube divided by M average, which is 23.585 kg per Kmol. So, this is 44.52 Kmol per meter cube. This is the total concentration. So, this way we can calculate the molar and mass concentration.

Now, another term in case of mass transfer is the velocity of diffusion or diffusion velocities. The diffusion velocities are defined either in terms of mass average velocity or molar average velocity.

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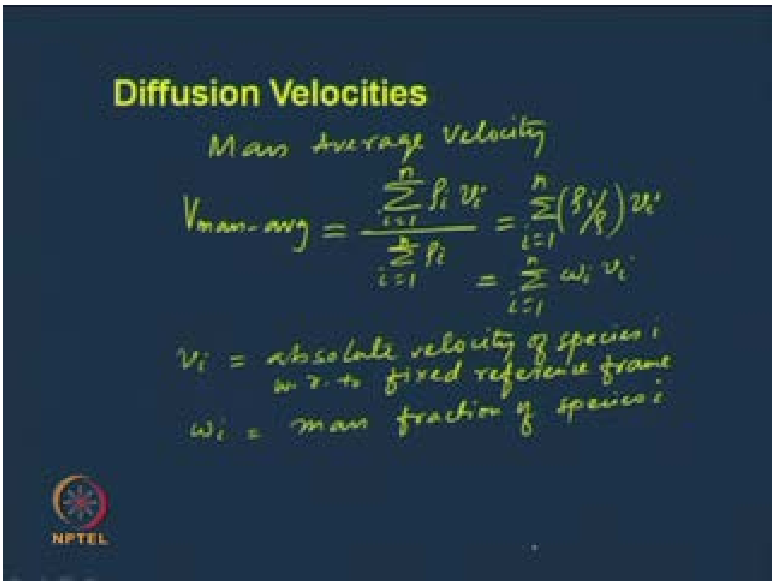

So for mass average velocity, it is defined in terms of mass concentration V mass average is equal to summation over i is equal to 1 to n rho i V i divided by summation over i is equal to 1 to n rho I, which we can write equal to summation over i is equal to 1 to n rho i by rho into V i is equal to summation over i equal 1 to n w i V i. V i is equal to absolute velocity of species i with respect to fixed reference frame, and w i is the mass fraction of species i.

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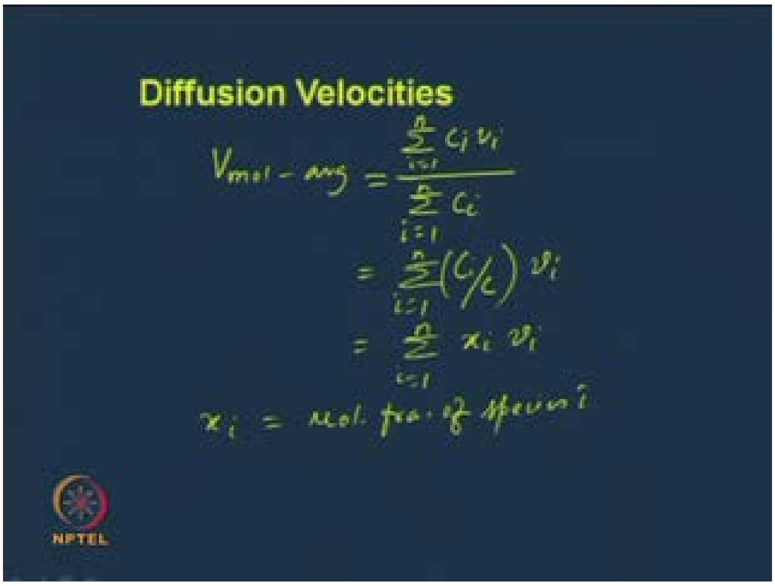

Now molar average velocity we can define Vmol average is equal to summation over i is equal to 1 to n C i v i divided by summation over i is equal to 1 to n C i. So, this equal to we can write, summation over i is equal to 1 to n C i by c into v i, is equal to summation over i is equal to 1 to n x i v i; xi is the mole fraction of species i.

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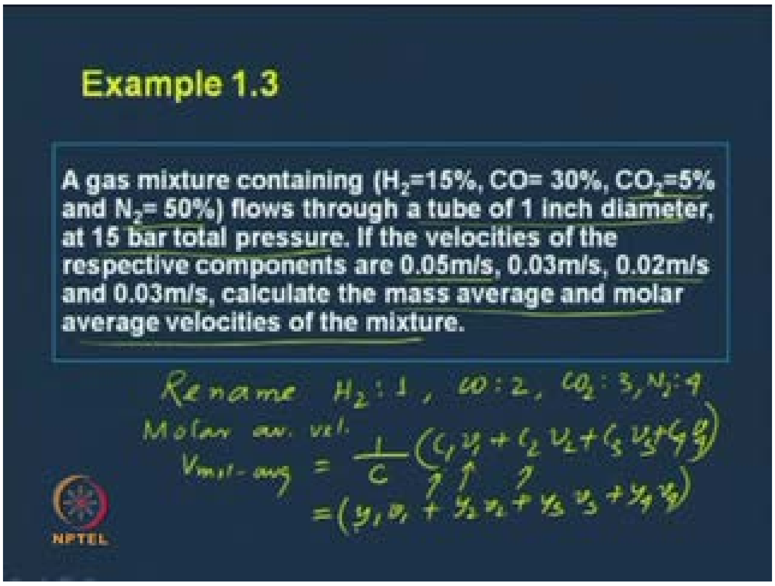

Now, let us take an example to calculate the average velocities. A gas mixture contains 15 percent hydrogen, 30 percent carbon monoxide, 5 percent CO2, and 50 percent nitrogen. This flows through a tube of 1 inch diameter at 15 bar total pressure. If the velocities of the respective components are given as 0.05 meter per second, 0.03 meter per second, 0.02 meter per second, and 0.03 meter per second; then, calculate the mass average and molar average velocities of the mixture.

Now, rename the components as H2 is 1, CO as 2, CO2 as 3, and nitrogen as 4. So, we can write the molar average velocities, that is Vmol average; from the definition it is 1 by C summation over we can just expand the summation like c 1 v 1 plus c 2 v 2 plus c 3 v 3 plus c 4 v 4. Now if we substitute, the velocities are given and the concentration of each term if we substitute, then we will be able to calculate the total molar average velocity. So in this case we can write, this will be y 1 v 1 plus y 2 v 2 plus y 3 v 3 plus y 4 v4.

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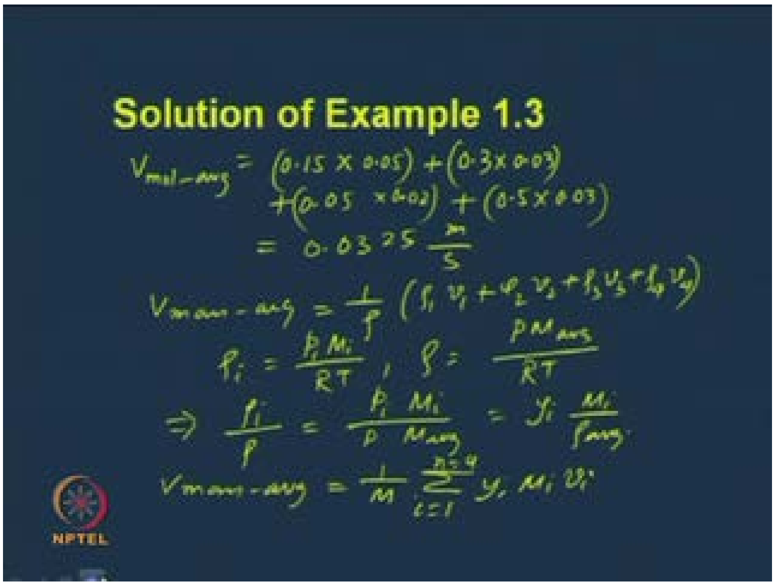

Now after substitution in this relation, Vmol average will be 0.15 into 0.05, plus 0.3 multiplied by 0.03, 0.05 multiplied by 0.02, plus 0.5 multiplied by 0.03. So, this will give you the total 0.0325 meter per second.

Now, to calculate the mass average velocity; so, V mass average we can calculate, and we know this is 1 by rho, rho 1 v 1 plus rho 2 v 2 plus rho 3 v 3 plus rho 4 v 4, and we know rho i is equal to p i M i divided by RT if it is ideal gas, and then rho is equal to p M average by RT. So, we can get rho i by rho, is equal to p i M i by p M average. So, we can write y i M i rho average. If we substitute here, the equations would be V mass average, is equal to 1 by M summation over i is equal to 1 to n n is equal to 4 y i m i V i.

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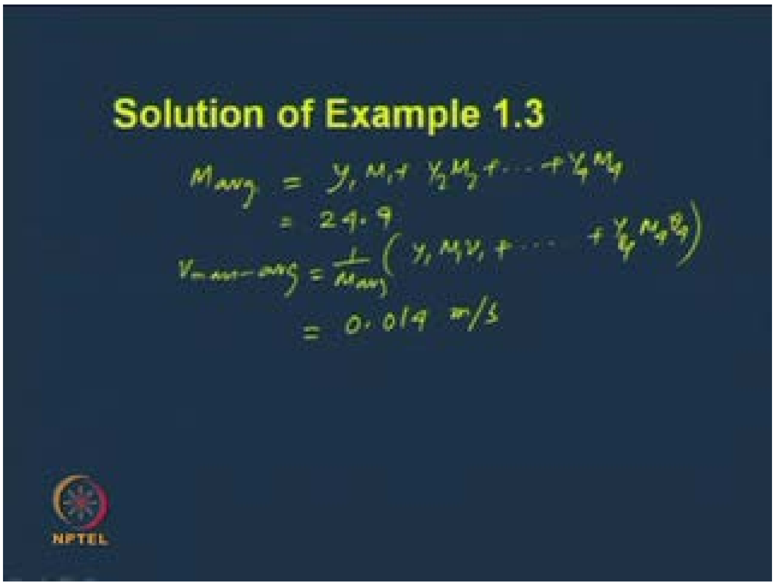

So then we can calculate, M average as per our given data, which will be y 1 M 1 plus y 2 M 2 and y 4 M 4; after substitution, it will be 24.9. So, V mass average we can calculate using this correlations, which is 1 by M average into y 1 M 1 v 1 plus y 4 M 4 v 4. After substitution, both M average and all this data, it will be 0.014 meter per second. So, this way, we can calculate the molar average velocity and mass average velocity for a given system.

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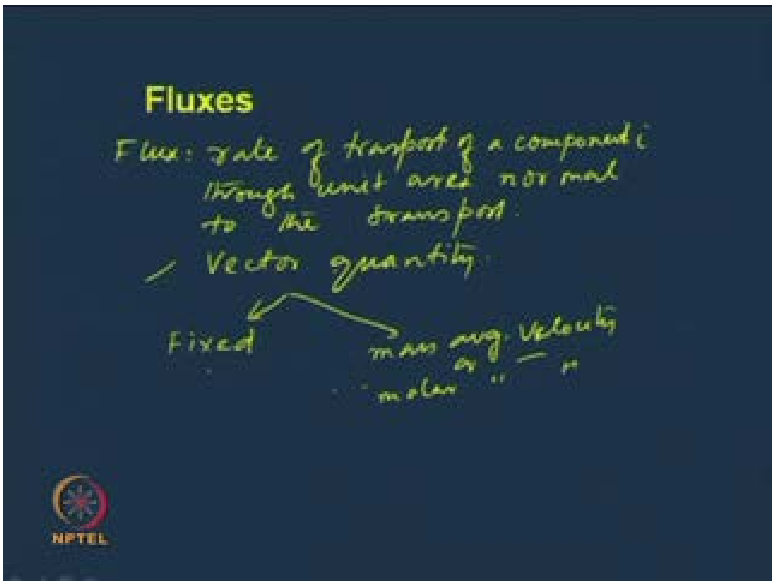

So now, we will discuss on the flux. The flux is defined as the rate of transport of a component through unit area normal to the transport, and this flux is a vector quantity. This flux maybe defined with respect to co-ordinate fixed in step fixed co-ordinate, or it may be defined with respect to a moving plane, moving with a mass average velocity or molar average velocity.

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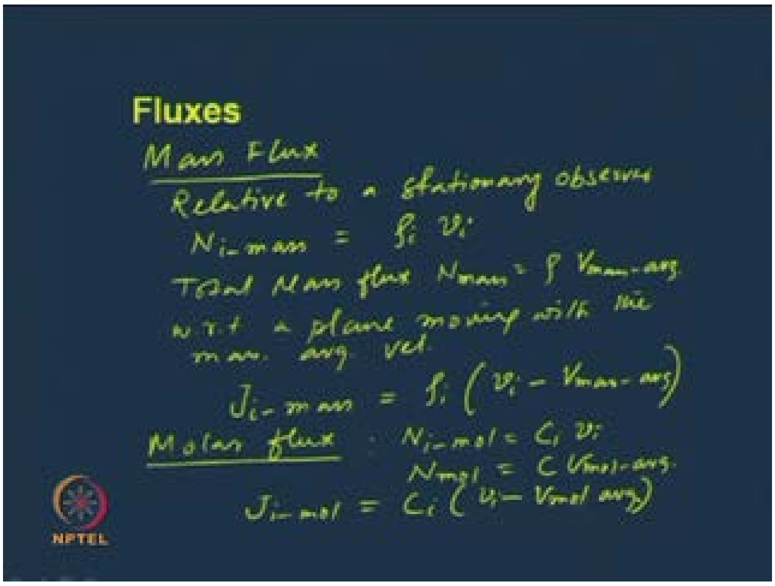

So, mass flux we can define relative to a stationary observer or plane. So N i mass is rho i v i, and the total mass flux N mass is rho V mass average. Similarly, if we calculate the mass flux with respect to plane moving with the mass average velocity, then we can define, J i mass is equal to rho i v i minus V mass average.

Similarly, the molar flux we can define with respect to fixed plane and that we can write, N i mol is equal to c i v i, and the total molar flux N molar total is c into V mol average, and if the flux is defined with respect to the molar average velocity, then J i mol we can write c i v i minus V mol average.

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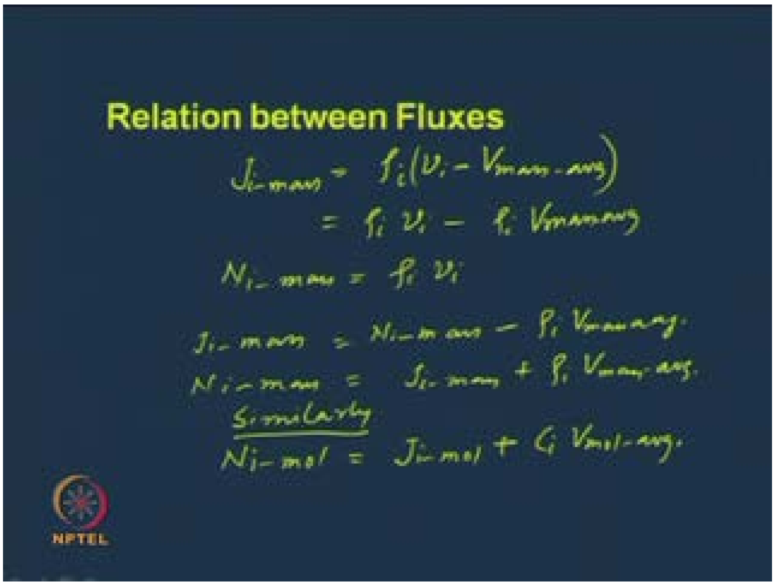

The relations between these mass average and molar average velocities, we can write from the above correlations, J i mass is equal to rho i v i V mass average. So we can write, rho i v i rho i V mass average, say N i mass we know rho i v i. So, J i mass is equal to N i mass minus rho i V mass average. So, N i mass will be J i mass plus rho i V mass average. Similarly, we can derive molar flux N i mol is equal to J i mol plus c i V mol average.

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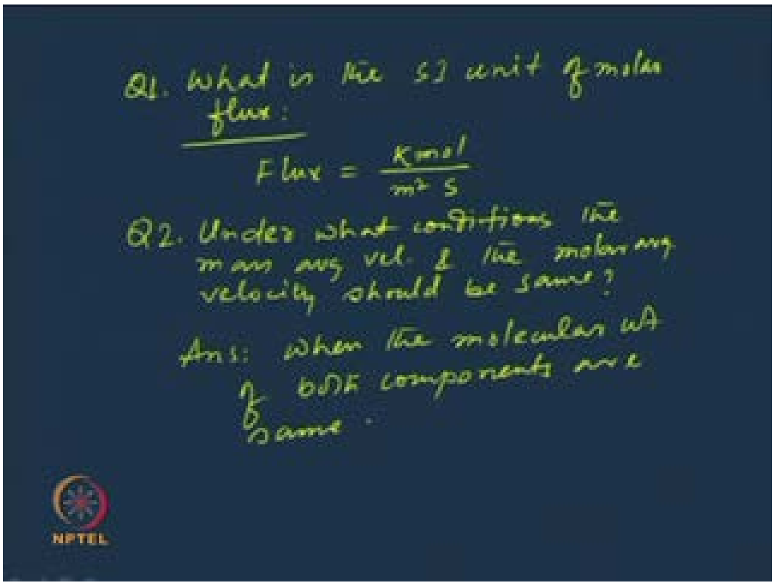

So if we ask the question, what is the SI unit of molar flux? As we define, it is the rate of transfer per unit area per unit time. So, it will be Kmol per unit area and time; so Kmol per meter square second. Second question: Under what condition, the mass average velocity and the molar average velocity should be same? The answer is, when the molecular weight of both the components are same then the total mass average velocity and the molar average velocity should be same.

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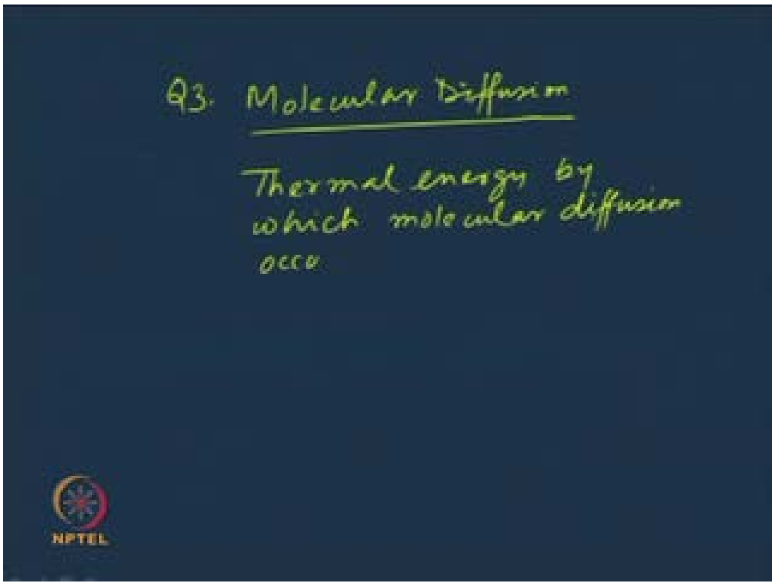

Another question if we ask, what are the basis for molecular diffusion or what are the driving force for molecular diffusion or the cause of molecular diffusion? It is the thermal energy by which diffusion occurs.