Fundamentals of Transport Processes

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Module No. # 01
Lecture No. # 01
Fundamentals of Transport Processes

So, welcome to this course on the fundamentals of transport processes. At the beginning of the course, it is always useful to examine why we are learning this course, what we are going to learn and how. So, these are the three questions that one should have a clear understanding before we even go on to a new course.

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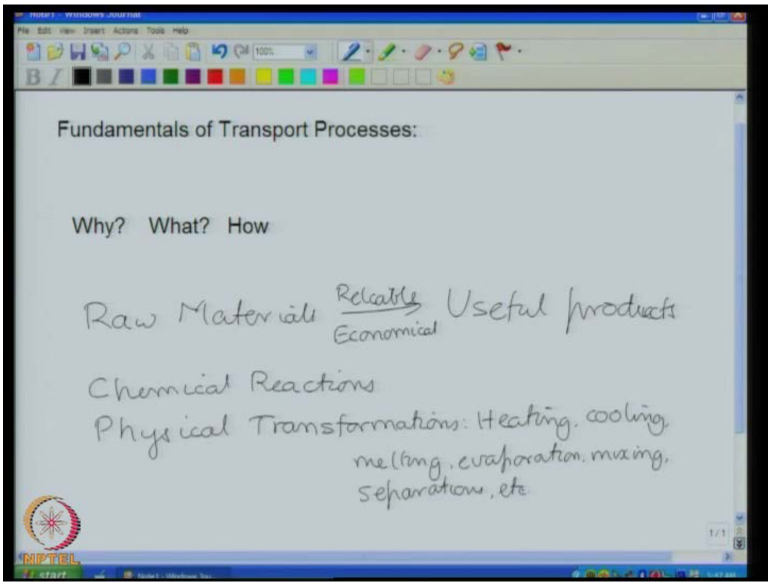

That is, why are we learning this course, what are we going to learn and how. So, the question why basically tells us the motivation for understanding for studying this particular course. Why do we want to study the fundamentals of transport processes and what influence does it have on our design ability to design engineering processes. Why is transport process a core part of engineering in general and chemical engineering in particular.

Engineering is broadly concerned with the conversion of raw materials ((No audio from 01:24 to 01:35)) to useful products. It is not sufficient to just carry out this conversion, one has also got to be able to do in reliable and in economical fashion. And these conversion processes can be broadly classified into two types; one is chemical reactions, chemical reactions typically involve the conversion of one type of substance into another, and the second is physical transformation. Physical transformations involve processes where there is no change in the chemical composition of the materials, but there is a change in their form. For example, heating, cooling, melting, evaporation, mixing, separations, etcetera.

Now, all of these processes innovatively involve the transfer of materials from let us say, one fluid to another or from one fluid to a solid surface, transfer of energy. Very often reactions are either exothermic or endothermic and therefore, one has to transfer energy for the reaction to take place or remove energy which was generated in the reactions.

Most of these also involve what is called momentum transfer. The rate of change of momentum in the applied force and therefore, momentum transfer will involve generation of forces. So, during this course, we will primarily be concerned with fluid systems.

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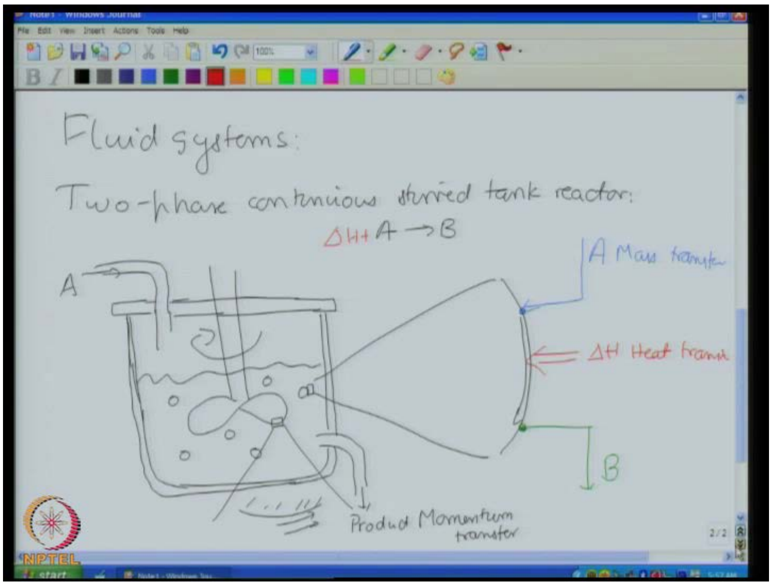

Fluid systems involve both liquids and gases. In many processes, it is preferable to undertake operations in fluids, simply because mixing is easy. Diffusion in fluids takes place very quickly. In gases it is extremely fast, in liquids, it is a little slower, but both liquids and gases have diffusion times which are much smaller than that of solids. So, for example, in solids, the diffusion takes place over very long time scales, over decades and centuries and therefore, in cases where there is transfer of mass required, solid phase is not a good phase to work with.

Solid mixing and transportation is a very important part of many chemical engineering processes, but in the present course we will deal exclusively with fluid systems.

Now, I said all processes involve chemical reactions as well as heat and mass transfer. Let us look at some concrete examples of this. So, first thing is let us take a two phase continuous stirred tank reactor. So, in this reactor, we have inlet of some reactant A, the reaction is of the form A going to B, and is catalysed by a solid catalyst. This A comes in through the inlet of the reactor, ((No audio from 05:30 to 05:39)) and then in a continuous process, you take out the exit strain; you take out the product. And this happens in a reactor in a continuous manner. ((No audio from 05:51 to 06:03))

So, there is some fluid in the reactor, you have reactant A coming in, and the product is taken out. And typically, in all of these systems, one will also have some kind of a mixing system; an impeller which is rotating in order to increase mixing. And I said that this reaction takes place in the presence of a solid catalyst; a catalyst particle in the form of pellets. So, the reactant is catalysed on the solid surface, the product is ejected, and the project product comes out in the product stream.

Now, for this system, it is not sufficient to just ensure that there is sufficient concentration of A coming in and sufficient concentration of B going out. If you just engineer this just based upon the amount of A coming in B going out, there is no guarantee that you will get the conversion that is necessary. Now the reaction actually is taking place at the surface of the catalyst particle. So, if you look very close to the catalyst surface,...

Now, there is reactant A that is coming in. At the surface, this reactant is getting converted into a product B. So, even though the reaction itself may be fast, if the rate at which A is coming to the surface is going to be slow, the reaction is going to be slow and one will not get the desired yield. So, in addition to providing all the reactants in sufficient quantities and mixing them, it is also necessary to ensure that the transport rates are such that the rate at which A comes to the surface is sufficient to ensure a sufficient yield of the product B.

So, A comes to the surface, the reaction takes place at the surface, and then the product B comes out. It is also necessary to ensure that the product B comes from the catalyst surface back into the fluid at a sufficiently fast rate, because if the B does not come out of the catalyst surface, and it just sits there, there is going to be no place for A to come back on to the surface; for more A to come back on the surface. So, for the reaction to take place in a continuous fashion, one has to ensure that the rate at which A is transported to the surface, the rate at which reaction take place, and the rate at which B comes out to the surface is sufficient to ensure that the desired yield is obtained.

In addition to this, the reaction may be either exothermic or endothermic. So, for example, if it is an exothermic reaction, the reaction actually generates heat. And if heat is generated at the surface, we have to ensure that there is a sufficient heat transfer away from the surface, the rate at which heat is transferred away from the surface should be such that there is no net heat accumulation at the surface resulting in a temperature increase, because if the heat transfer rate is not sufficient, then the heat will generated will not be transported out. It will accumulate at the surface resulting in the formation of a hot spot.

Alternatively, one could have endothermic reaction, where heat is necessary in order for the reaction to take place. In this case, it is necessary to ensure that there is a sufficient rate of transport of energy to the surface, because if energy is not transferred to the surface, the energy that is absorbed by the reaction will cool down the interface. So, the reaction rate will decrease and you would not obtain the desired yield.

So, this is actually a problem of heat and mass transfer to the catalyst surface; mass transfer of the reactants to the surface, mass transfer out, heat transfer to or from the surface as necessary for carrying out the reaction at the desired rate. And in order to design the reactor, it is not sufficient to just know what is the amount of material that has to go in and the amount of material that has to come out of the reactor.

One also has to engineer at this location; the catalyst surface is are the conditions such that the sufficient, there is sufficient rate of transport of reactors to the surface, sufficient transport of products away from the surface, and sufficient heat transfer to or from the surface as decided.

But wait, there is one another thing. And that is that, in order for the reaction to take place sufficiently fast, there has to be adequate mixing. This mixing is carried out in this case through the use of an impeller which is rotating within the fluid. And in order to design the system, one has to one has to design the power that is required for running this impeller to generate sufficient mixing. Why is power required, because there is energy absorption due to the fluid friction at the interface between the impeller and the surface? So, if I look closely at the interface between the impeller and the fluid, there is the impeller surface, and there is fluid that is flowing past the surface.

At the surface itself, the fluid has to have the same speed as the impeller. And then there is a variation of fluid of the velocity of the fluid away from the surface. Now this generates, this fluid motion generates fluid friction, and that exerts a backward force on the impeller. In order to compensate for that, you have to exert a power on the impeller. The force or rather the stress, which is the force for unit area that is exerted on the impeller surface, is actually a frictional force; stress. Stress is force per unit area and force is rate of change of momentum.

So, the shear stress at the surface is actually the rate of change of momentum per unit area per unit time. So, it is transfer of momentum to the surface in order to compensate for the frictional losses in the fluid. So, this is a problem of momentum transfer. This is a problem of mass transfer, and this is a problem of heat transfer. And it is necessary to study all of these, and ensure that there is sufficient transport of all of these in order for the reaction to take place at the desired rates.

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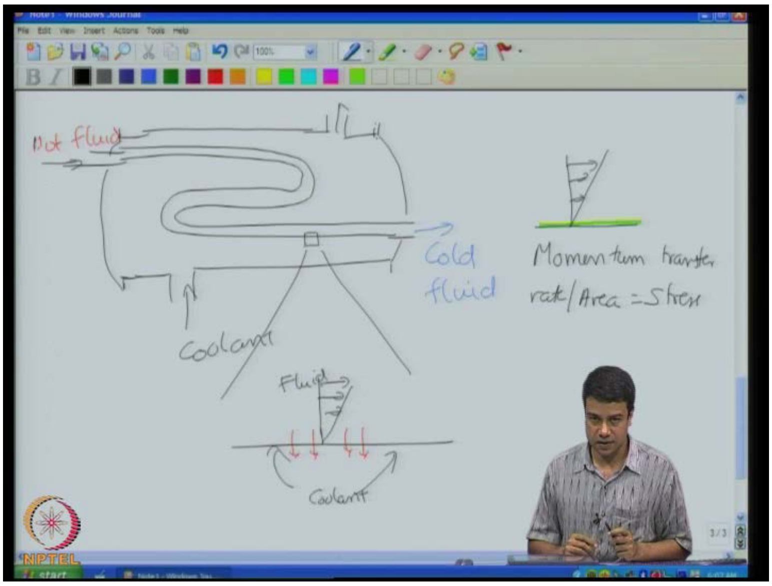

Let us look at another example which is a shell and tube heat exchanger. So, we have, the typical configuration looks something like this. There is a tube which is enclosed in a shell. ((No audio from 13:10 to 13:24)) And on the shell side, you have an inlet of fluid. ((No audio from 13:30 to 13:50)) So, there is hot fluid coming in, and it gets cooled by the coolant, and the fluid that comes out is cold fluid. So, that is the system and because you want to cool this hot fluid, you have to ensure that there is sufficient heat taken out of the hot fluid that the final temperature is the desired temperature that you want. And that heat that is taken out with this coolant can now be used for other useful purposes.

And once again, in this, it is not sufficient to ensure that there is sufficient quantity of heat coming in going out. If you look locally at the interface between the hot and the cold fluids, there is a fluid that is flowing through the tube, and there is the coolant that is going all the way around the tube.

And the transfer of heat actually takes place across the surface of the tube. So, the transfer of heat would of course, depend upon the conditions; the temperature of the fluid inside, the temperature of the fluid outside, as well as the speed with which the fluid is flowing through the tube.

So, it is necessary to ensure that you get a sufficient transfer of heat through the interface between the through the tube that the temperature at the outlet is the desired value. And this is the transfer of, this is a problem of heat transfer; transfer though the tube. And actually the conditions are of course, changing everywhere along the tube. The temperature is gradually decreasing as we go down the tube, and at each patch of the tube, there is some amount of heat transfer that is taking place. And in order to ensure that the temperature is sufficient is the desired value at the outlet; one has to make sure that in each patch of tube, the amount of heat that is transferred is sufficient that cumulatively the amount of heat transferred is going to be the desired value.

Now, the amount of heat transferred will of course depend upon the temperature difference between the shell and tube side. That itself is varying with position. It will depend upon the speed with which the fluid is flowing through and it is also going to depend upon the length of the tube. Naively, one may think that it is best to have as long a tube as possible because the longer the tube, the more heat is transferred in. So therefore, you can get a much higher transfer rate.

However, this transfer of heat is inextricably linked with the transfer of momentum as well, because for the fluid to flow through a tube, it is necessary to apply a pressure difference across the ends of the tube; either by a pressure head or a pressure pump or some other means. And that pressure difference is going to increase as the length of the tube increases.

Apart from developing section at the very inlet, the pressure difference is going to increase proportion to the length of the tube and therefore, even when you have a very long tube, there is going to be a much higher pressure difference and therefore, the cost of that has to be optimized against the gains in the greater heat transfer rates from the surface.

Now, this pressure difference compensates for the frictional stress exerted due to the fluid flow at the walls of the tube. The total frictional stress multiplied by the total surface area has got to be equal to the difference in pressure times the cross section across the tube, and this frictional stress as I said; force per unit area, momentum transported per unit time per unit area, it is a momentum transfer rate; rate per area is equal to the stress.

Therefore, for the heat transfer problem, I need to design the heat transfer rates based upon the temperature differences, the flow rates and the length of the tube, but inextricably linked with it is also the momentum transfer rate because the longer the length of the tube, the more pressure is required to pump the fluid across and that is going to increase the costs.

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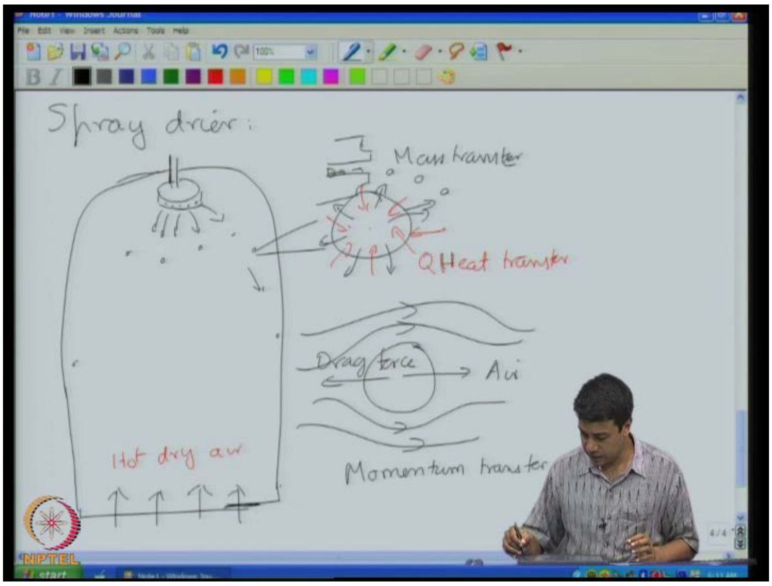

Let us take another example which involves only mechanical transformation, no chemical transformation, but which still involves both momentum, mass and heat transfer and that is a spray dryer. So, a spray dryer is typically used for drying liquids into powders, usually in the food product industry for example, milk powder is dried in spray dryers and what they do is that they spray out a fine droplets of the liquid. As these droplets of the liquid fall in the spray dryer, they come in contact with hot dry air and that dries the droplets and gives you solid particles.

The key crucial thing in the spray dryer is that the particles have to be fully dry by the time they settle on the walls of the dryer, otherwise they will agglomerate and form sludge. And for this reason, spray dryers actually very tall columns. They typically are ten meters in height and one meter in diameter.

We will see when we do dimension analysis; the reason for why these are of such large dimensions, but back to the spray dryer, it looks something like this. There is an inlet and there is a disk. And this disk has fine nozzles on it and droplets are ejected out of these nozzles into a chamber. As I said, the chamber is a fairly large one with large heights and from the bottom, there is hot dry air coming in, and these droplets contact with the hot dry air and they get dried up before they come to the surface and settle to the bottom. So, that is the basic picture.

The droplets are usually 100 microns or larger 0.1 millimetres or larger, if you want finer droplets, you have other kinds of mechanisms; you cannot use a nozzle for that, you have rotating disk. And as I said, the dimensions are very large. The dimensions are large because as the droplets is sprayed out, it is usually sprayed out at speeds of the order of one meter a second. You have to ensure that by the time it hits the surface, it has fully dried. So, you have to allow sufficient time for the droplet to dry before it hits the surface, and that is the reason you have to have a large size.

Let us look at what happens at the microscopic level. This is a droplet. Initially as it came out of the nozzle, comes out as liquid stream, and then its ejected as droplets out of the nozzle. The droplets; it is about eighty percent of water in it, for example, if you spray dry milk, it will typically contain eighty or more percent of water and the rest will be solids content and finally, you want to get a powder from which all of that water has dried up; that means, that all of the water that was within the particle has to come out into the air.

The rate at which the water comes out of course depends upon many things. It depends upon the speed with which the particles is moving through the air because the faster it goes, the faster the speed of the air around it, and therefore, more water can get evaporated. It will also depend upon the difference in humidity between the inside of the droplet and the outside.

If you have dryer air, you will get a greater transfer. However, there is one other thing that is important and that is that this water in the droplet was on a liquid phase, and it has to be evaporated before it can come out; that means that you have to supply all of the latent heat that is required for evaporating all of the water inside. So, this heat has to go in. It has to go in sufficient quantity that by the time it hits the wall, the heat supplied is sufficient to evaporate all of the water and the water all gets evaporated and the mass transfer rate is sufficient that all of the water leaves the droplet.

The heat transfer rate of course, will depend upon the difference in temperature between the air and the droplet which is why it is necessary to supply hot dry air at the inlet. The mass transfer is driven by difference in the concentration or the humidity; the humidity at the surface of the droplet and in the air that is coming in. So, that is an issue of mass transfer which is driven by differences in concentration. Both the heat and mass transfer are also affected by the speed with which the droplet is moving through the air. I said that we have to allow sufficient time for the drying to take place; that is, the particle has to be in the air sufficiently long that it has lost all of its water.

Now, the transfer rates will only tell you how much time it takes. It would not tell you how much distance it travels. In order to find out the distance that travels, you have to know what is the speed with which an ejected droplet will travel through the air. Now that speed is determined by a balance of forces. If there is gravitational force acting downwards because of the weight of the droplet, there is also what is called a drag force which tends to oppose the motion of the droplet.

So, if a droplet is moving through the air, it is exerting a drag force in the opposite direction. So, this droplet is moving through the air and therefore, you will have some fluid velocities in the region around the droplet, and this fluid moving past the droplet is going to exert a friction force, it is going to exert a friction force at every area element along the surface of the droplet, not just at one location.

This friction force, the frictional stress per unit area is a function of the speed with which locally the air is moving past the droplet, and if I inter-create the frictional stress over the entire surface, I will get the net frictional force on the entire droplet. And once I know the frictional force, I can then calculate the speed with which is going through the air and therefore, the amount of time required for it to travel a certain distance. And that will be the basis for designing the dimensions of this spray dryer.

The stress acting on the surface is a problem of momentum transfer. So, this involves heat transfer, this is am sorry mass transfer of the moisture out of the droplet, heat transfer of the latent heat required for evaporation, and momentum transfer to find out what is a drag force acting on the droplet.

Now, there are empirical correlations that might tell you that for a given equipment, what are the dimensions are required to get a certain result, but that will work only for that particular equipment; a thumb rule. So, in many design applications, it is necessary to have some thumb rules and to make some microscopic models and then go to larger and larger systems, but those rules that are devised will work only for that particular system.

If I change the system, then I have to have another set of rules and I have to do another set of experimentation, another set of modelling, another scale up; however, if I had a good understanding of the microscopic processes which affect these transfer rates, the transfer rate of heat into the transfer rate of mass out of transfer of momentum, if I had a microscopic understanding, if the microscopic particle level in this problem, alternatively at the interface level in this problem, alternatively at this catalyst surface level in this problem, if I had that microscopic understanding, I could utilize that to get some idea of what is what is likely to be the conversion for the macroscopic system for the entire flow system. So, this microscopic understanding is a subject of this course, fundamental understanding of the transport processes that take place.

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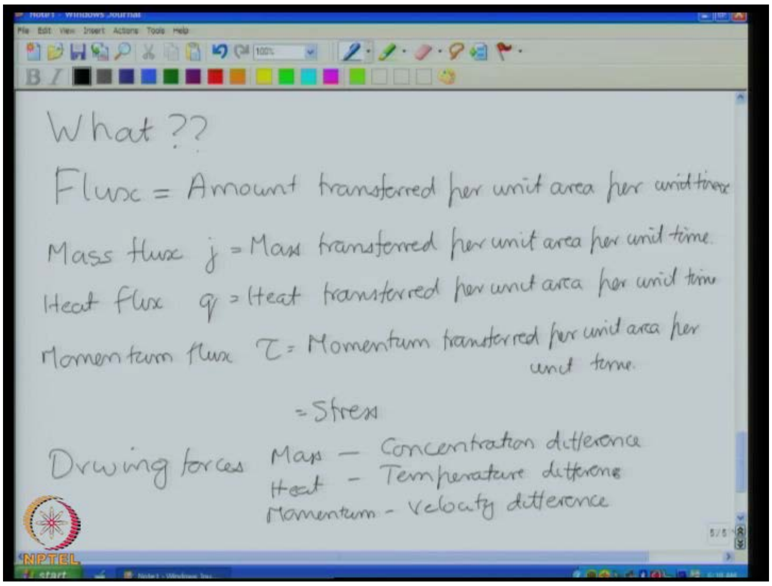

Now what are the fundamental quantities here? So, the next question is what are we going to study in this course? So, what are the fundamental quantities? Basically I want to know for a given inlet and outlet conditions, how much conversion takes place. So, let us for example, go back to the reactor situation. For a given set of conditions, inlet outlet stream, how much conversion takes place. So, the conversion that takes place is going to be determined of course by how much material is present, the number of catalyst particles present and so on. The conversion itself is taking place at the catalyst surface.

So, rather than asking how much conversion takes place over the whole thing, I can ask the question how much conversion will take place at each catalyst bulk, but that once again will determine on the size of the palette and the conditions around it and so on. And in order to get a quantity that is invariant of these things, it is better to define what is called a flux which is defined as amount transferred per unit area per unit time. So, this will be the fundamental quantity.

So, the mass flux usually written with the symbol j; is the mass transferred per unit area per unit time. Heat flux usually written with the symbol Q; is the heat transfer per unit area per unit time. Momentum flux tau is equal to momentum transfer per unit area. ((No audio from 30:18 to 30:28)) Rate of change of momentum, change in momentum per unit time is a force. So, momentum transfer per unit area per unit time can also be written as force per unit area which is the stress. So, this is equal to stress. So, these are the fundamental quantities that we will be dealing with; the mass flux, the heat flux the momentum flux.

These things of course, depend upon conditions. So, for example, in the reactor problem, the mass flux of A to the surface is of course, going to be depend upon the difference in concentration of A between the bulk of the fluid and the surface, because mass always travels from regions of higher concentration to lower concentration. So, it is necessary to have a higher concentration at the surface in order to ensure that there is a sufficient mass flux.

Similarly, for the transport of B, the flux of B depends upon the concentration difference between the catalyst surface and the bulk of the fluid. So, you have to have difference in concentration between the surface and the bulk in order to get the sufficient transport rate. Heat transfer takes place from regions of higher temperature to regions of lower temperature. Therefore, the temperature at the surface has to be higher than the temperature in the bulk in order to generate the heat transfer.

Momentum transfer; we will come back to later, depends upon difference in velocities. One has to have a difference in velocity between two locations to have momentum transfer. So, for example, in this reactor problem, there has to be a difference in temperature between the fluid inside and the fluid outside to have a flux of heat. There has to be a difference in temperature between the fluid and the wall for having momentum transfer. The fluid has to be travelling with the certain velocity, the wall is stationary. There is a difference in velocity therefore, you get momentum transfer.

Similarly, in this problem, there has to be a difference in the temperature for the heat to go in, the temperature of the air outside has to be higher than the temperature of the droplet in order to have heat transfer from the outside to the droplet.

Alternatively, in order for the mass transfer to take place, the humidity or concentration of water on the surface has to be higher than the concentration in the air. And momentum transfer takes place when the droplet is moving relative to the air. There is a difference in velocity between the droplet and the outside.

So, all of these involve driving forces which are basically differences in quantities between two locations. I will tell you later that this is not exactly the driving force. The driving force is actually the gradient, but for the present, we will continue this discussion assuming that the driving force is actually the difference between two different locations.

So, for mass transfer, the driving force is concentration difference. For heat transfer, this is temperature, and for momentum, this is velocity difference.

So, the next question is how do we take these into account when analyzing this system? So, for example, for mass transfer, we have to ensure that the system is designed in such a way that you have a sufficient concentration difference. That requires some knowledge of how the transfer rates depend upon the differences.

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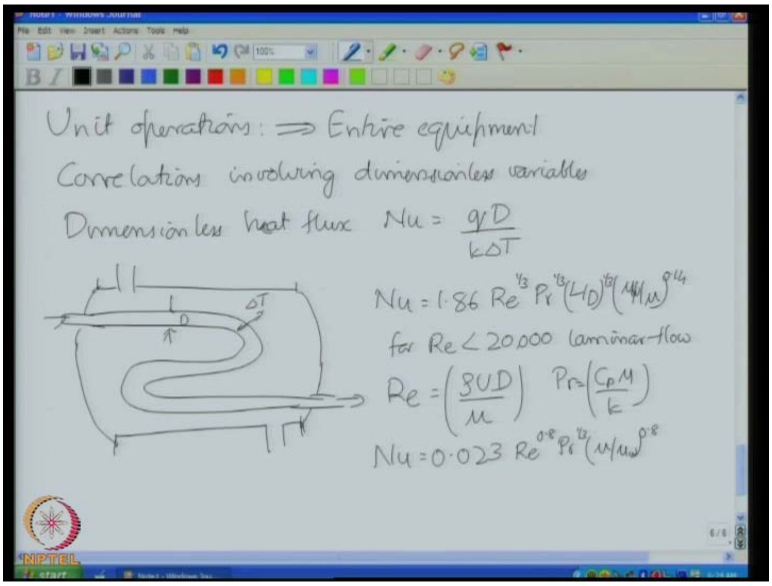

Now for the entire at the level of unit operations, these things are written for the entire equipment. For example, for the shell and tube heat exchanger that I had earlier, what one would do is write down an equation which tells you how much how the transport rate depends upon the average difference between the temperature on the shell side and the tube side. So, these are usually written in the form of correlations involving dimensionless variables.

As I will show you in the next lecture, it is preferable to use dimensionless variables because there we can use the Buckingham pi theorem to reduce the number of variables in the problem. So, dimensionless heat flux ((No audio from 35:38 to 35:46)) which is called the nusselt number is written as Q D by k delta T, where Q is the heat flux; the amount of heat transferred per unit area of the surface, average heat flux averaged over the entire surface, D is the diameter of the pipe, k is the thermal conductivity and delta T is the average difference between the shell side and the tube side.

So, to draw the shell and tube heat exchanger once again, ((No audio from 36:18 to 36:40)) I have fluid coming in and fluid going out. So, D is the diameter of the pipe, k is the thermal conductivity of the fluid, delta T is the difference in temperature between average difference in temperature between the shell and the tube side.

So, you define this dimensionless heat flux and this of course depends upon many things. This depends upon for example, the temperature difference, the difference in velocities between the shell and the rate at which the fluid is flowing and so on as far as the properties of the fluid, the specific heat, the thermal conductivities, the viscosities and so on, but once you express it in dimensionless form, you get only a small number of variables in it.

For example, the correlation for the Nusselt number is of the form 1.86 Reynolds number power one third prandtl number power one third l by D power one third mu by root of mu w by mu power 0.14 for Reynolds number less than about 20000 laminar. Now this correlation has neatly packaged the dependence of the heat flux on various things; the conductivity, the temperature difference, the diameter, the viscosity, the specific heat; all into these dimensionless numbers, the nusselt number, the Reynolds number and the prandtl number and the ratio of lengths to diameter of the pipe and the ratio of viscosity at the wall to the viscosity of the bulk. This is standard correlation for the dependence of the of the heat flux on the various parameters in the system.

Here the Reynolds number is equal to rho u D by mu, where rho is the density, u is the average velocity and D is the diameter, where prandtl number is equal to C p mu by k, where C p is the specific heat, mu is the viscosity and k is the thermal conductivity. This of course is valid only when the Reynolds number is less than about 20000. When the Reynolds number becomes larger, you get a different correlation which is of the form 0.023 R e power 0.8 p r power one third times mu by mu w power 0.8.

These correlations are derived by doing a large number of experiments and actually derive and using dimensional analysis to reduce the number of variables, from the original list that I had, all the fluid properties; the velocity and so on, to a reduced list which contains only dimensionless groups. We would see how to do the analysis in terms of dimensionless groups a little later, but this contains only dimensionless groups.

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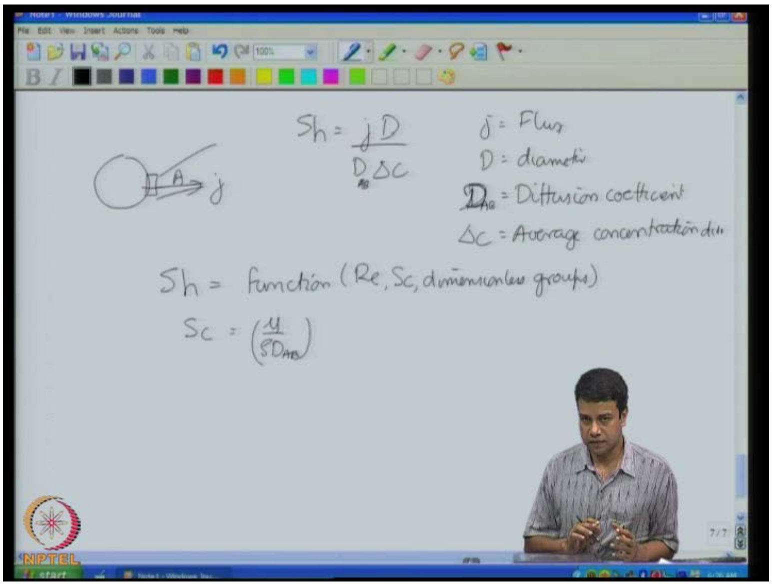

Now, similarly, one can also define a transport rate for mass, mass flux at the surface if you have some material A coming out from the surface into the bulk. It is preferable to work in terms of mass flux because it tells you the flux that is coming out per unit area of the surface j.

I can define the Sherwood number as a dimensionless mass flux; j D by D delta C diffusion coefficient and T if e times delta C, where j is equal to the flux, D is equal to diameter, this diffusion coefficient gives you the relative diffusion of A and B. I will use a script for that, and delta C is equal to the average concentration difference.

In a similar manner to the correlations that we obtained for mass transfer, we can also obtain sorry correlations we obtained for heat transfer; we can also obtain correlations for the mass transfer. In the mass transfer, these correlations will have a Sherwood umber is equal to some function of the Reynolds number, Schmidt number and various other dimensionless groups, where the Schmidt number is the ratio of diffusivities is equal to mu by rho D a p.

So, these are dimensionless relations that are obtained. The dimensionless groups for momentum transfer are a little more complicated. Momentum transfer results in an exertion of a force on a surface.

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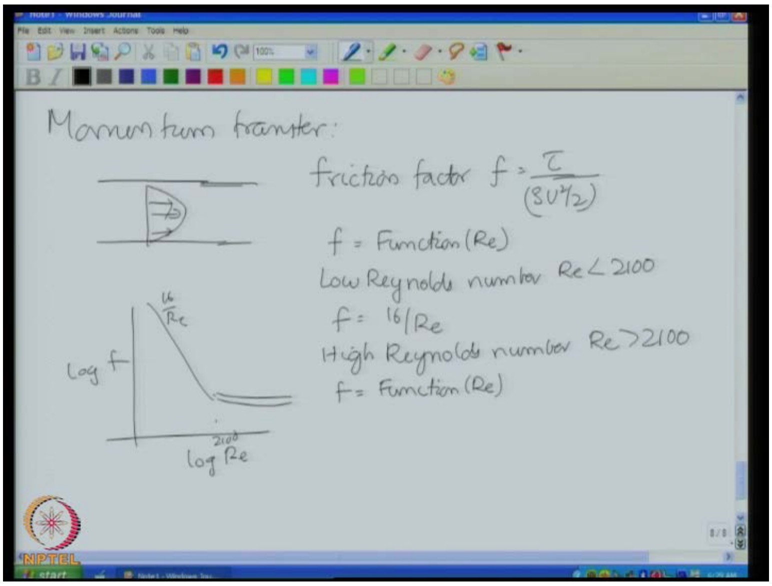

So, for momentum transfer, the dimensionless groups are defined as follows. If we had the flow in a pipe for example, the fluid velocity exerts a stress at the surface. Stress is force per unit area. Therefore, the dimensionless groups should involve the force per unit area suitably non dimensionalized. The friction factor f is written as tau by rho u square by 2, where for the flow in a pipe, where rho is the density and u is the average velocity.

This is the dimensionless group and this friction factor for the flow in a pipe is some function of the Reynolds number.

The correlations that are derived are of the following form: low Reynolds number; R e less than about 2100, friction factor is equal to 16 by R e. This is true only for a cylindrical pipe. If you had a square cross section or some other cross section, then this would change. At high Reynolds number, ((No audio from 43:23 to 43:31)) R e greater than 2100, when the flow becomes turbulent, then you has a different form of the friction factor. It is still a function of the Reynolds number, but it also depends upon things like the friction at the roughness at the pipe and so on. And if you have charts which show log of friction factor versus log of Reynolds number, if this is 16 by R e on a log plot and then at 2100, that is a transition to a turbulent flow; it is called moody plots.

Now, these are obtained by doing experiments on a large number of such systems and then finding out what the relationship is between these dimensionless groups. So, these will be valid only for the particular configuration for which they are obtained. They will not be valid in general. Change the configuration, change the properties, you will get different results.

The correlations will still be correlations between these dimensionless groups. For all heat transfer problems, you will still get a correlation between the nusselt number, the Reynolds number, prandtl number and dimensions, but the form of the correlation will change if you change the geometry; if you make it a square cross section tube instead of a circular cross section tube.

So, we have to do experiment for the particular geometry in order to find out the correlation, and then use that as an input in unit operations.

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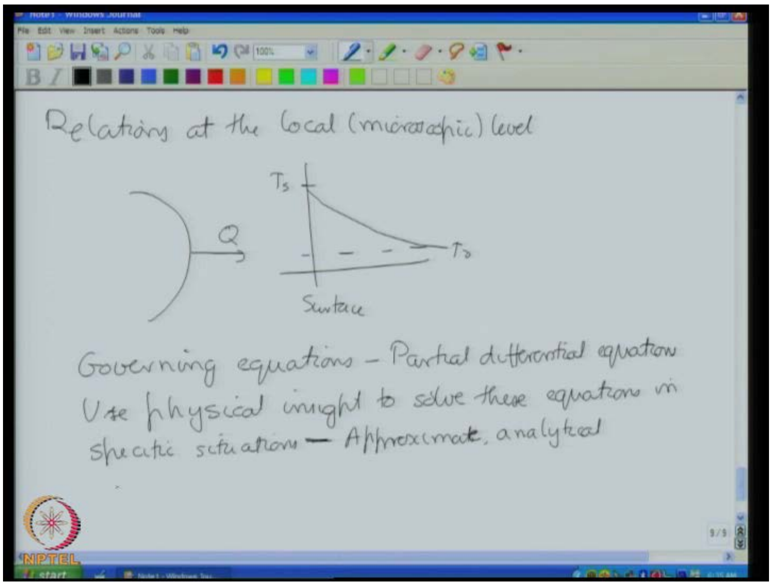

Now in this course, we will try to go further and what our attempt will be in this course is to obtain relationships at the local level; microscopic between the fluxes and the driving forces. Previously, the correlations for the entire unit operations had average quantities, for example, the correlation for heat transfer in a heat exchanger contained the average flux over the entire heat exchanger as a function of the average temperature difference, but of course as the fluid is flowing through, the temperature is decreasing.

If I knew locally at every point how the transfer rate of heat was related to the temperature difference at that point, and then I added up the transfer rate over the entire geometry, then I would get the transfer rate for the entire system. In that case, I would not be limited to applying correlation only for a particular geometry. I could change the geometry, change the system, if I knew what happened at the microscopic level, I could then add up everything that happens at the microscopic level over every small patch of surface, and then get an average value over the entire system.

So, what we will do is try to obtain relations at the microscopic level between the forces and the fluxes. Now this relations at the microscopic level, now they are going to tell you how locally, for example, at the catalyst surface, the flux depends upon the variation in temperature of heat say; it is going to tell you how the locally the flux of heat depends upon the variation temperature at that surface.

Temperature of course, is a continuously varying thing. It is high at the surface and it is slow far away, but of course, undergoes a gradual decrease in temperature. So, this is the surface. So, this is the temperature at the surface, and this is the temperature in the fluid far away. It is going to decrease continuously and of course, the heat transfer rate is going to depend upon the way in which this decreases continuously.

So, we are going to find out, obtain relations for how the heat flux depends upon the temperature variation at the surface in such a way that we can get entire picture of the entire temperature field around this object. Now the way in which the heat flux or the mass flux varies with position, and how that is related to the fluxes is given by what is called as set of governing equations, which basically tell me given a set of conditions on bounding surfaces, how does the temperature internally within the fluid change with position and with time.

So, this basically contains information about the change in temperature with both position and with time. So, these governing equations are what are called partial differential equations, which tell me basically how the temperature, the concentration or the velocity vary as a function of position all round the object or all within the entire tube. And these partial differential equations; they are different from ordinary differential equations in the sense that they have multiple independent variables. So, because of that they cannot be solved that easily.

However, presently there are computational techniques available that will actually solve these partial differential equations. So, given geometry, a configuration, a set of boundary conditions with some very complicated boundaries, one can solve them subject to initial conditions to find out what is the velocity field everywhere within the flow. But however, that does not provide physical insight into the processes that are taking place.

So, one part of this cause will be how to derive these governing equations for heat, mass and momentum transfer; the partial differential equations. The second part of it will be how to use physical insight to solve these equations in specific situations. These solutions first of all, because we are using physical insight, we have to make a judgement about what is important and what is not. So, because of that, we will be retaining the most important physical effects in the problem and neglecting those that are not important. So, these will be approximate; in the sense that, we have used our physical insight to make a judgement about what is important and what is not.

However, these will also be mostly analytical. We will not be just putting it to computer and getting solutions out. You will be actually sitting and solving the equations and because we are using an analytical solution, we will get a more fundamental insight into the transport processes that are going on in the system.

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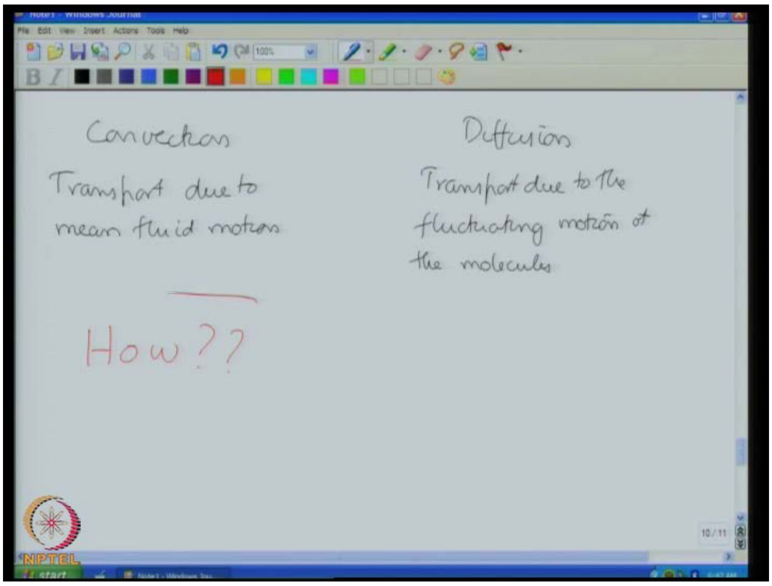

Now, an important analytical insight in all of these situations is a balance between two important effects in almost all of transport phenomena; that is, the two effects are convection and diffusion. We will be examining situations in which convection is dominant and try to neglect diffusion, examining situations in which diffusion is dominant try to neglect convection, in that way simplify the problem, and then formulate a set of tools which we can use for solving these problems. Difference between convection and diffusion; convection is transfer transport due to mean fluid motion.

So, for example, in the problem of the reactor, convection is what carries the fluid; the reactant A into the reactor. Convection is what carries the product B out of the reactor where as the motion of the fluid itself carries the material with it. Even around the particle, if there is some fluid velocity field, that fluid velocity is going to convect material around the particle. So, that convection is the motion due to the motion in the mean flow.

For example, in this heat transfer problem, convection is what carries heat into the into the heat exchanger because that is due to the mean motion of the fluid. Convection is what carries heat out or the cold fluid out. And in the case of the droplet problem, convection is what transports the energy due to the mean motion of the hot air from the bottom to the surface. Convection is what carries along with the air the moisture out. So, that is convection; transport due to the mean motion.

The second important part is what is called diffusion. Diffusion is basically transport due to the fluctuating motion of the molecules. In any fluid, the molecules are in constant motion. The fluctuating velocity is given by half m v square is equal to 3 by 2 k T and we will calculate that a few lectures down the line, but if you actually calculate the fluctuating velocity, the magnitude of the fluctuating velocity is of the order of probably of the order of a 100 to a 1000 meters per second.

So, the molecules are constantly in rapid motion with very large velocity. And this velocity can add to transport material; so long as is the difference in concentration or transport heat when there is a difference in temperature. So, if there is a difference in concentration between two parcels of fluid, and the molecules are in fluctuating motion, there is going to be a net flux from one parcel to the other, and that is due to the diffusion motion of the molecules. And diffusion is a very important part in all transport processes.

For example, if we take this reactor example, convection can transport material from the inlet to the fluid surrounding this catalyst particle; however, there is no fluid velocity perpendicular to the catalyst surface because the fluid cannot penetrate the surface. So, there is no fluid velocity that occurs perpendicular to the surface; that means that the motion to the catalyst surface which has to occur in a direction perpendicular to the surface can take place only due to diffusion. Same thing with heat; the transport perpendicular to the surface which will only result which is the only form of transformation result in transfer of heat has to take place due to diffusion.

So, at surfaces where there is no convective transfer perpendicular to the surface because the fluid cannot travel perpendicular to the surface, it cannot penetrate the surface, transfer ultimately has to take place due to diffusion.

Similarly, in the heat exchanger problem, convection can bring hot fluid into the tube, but for that heat to get across the surface, that has to take place due to diffusion. If you cannot have convected transport perpendicular to the surface because there is no fluid going perpendicular to that surface. And the same thing in the droplet drying problem; ultimately one has to have transfer perpendicular to this droplet to either transfer heat in or to transfer mass out, and that ultimately has to happen due to diffusion. So, these are the two important mechanisms that are important in that whose balance will determine the transport processes.

So, we will we will look at regimes where convection is dominant, and we expect diffusion to be a small effect, other regimes where diffusion is dominant and you expect convection to be a small effect and see how we can simplify problems in these two regimes and try to obtain a solution. And this we will do first for heat and mass transfer, and then for momentum transfer.

So, the next lecture, I will focus on how we are going to solve these problems. What is the exact procedure that we are going to adopt to solve these problems?

So, I hope in this lecture, I have provided you some motivation for why it is important to study transport processes. Whenever you want to design or engineer equipment for carrying out some useful transformations, it is important that you understand the transport that takes place at the microscopic level.

It is not sufficient to just make sure that the material that comes in is adequate and the material that goes out is adequate, the heat to or from the system is adequate, it is also necessary to ensure that the microscopic level, it is sufficient transfer to the surface or away from the surface so that the reaction proceeds at the desired level.

This involves a coupling between mass transfer which is required for the material to either react or to change its form from water to vapour for drying the system. There has to be heat transfer because physical transformations involve energy, reactions involve energy either to or from the system.

Third important point is momentum transfer. Inevitably, all of these processes involve a net force that is exerted on some part of the equipment. The impeller in this case, the walls of the tube in this case, or the liquid droplet in this case; they always involve transfer of a net force exerted, and force is just the rate of transfer of momentum. So, you need to ensure that there is sufficient momentum transfer rate in order to accomplish the transformation that you desire.

So, this is a brief introduction to transport phenomena, why we needed and what exactly is involved. And in the next lecture, I will go into the question of how exactly we analyze systems. And after that, we will have a lecture on start with dimension analysis and then go on to actual analysis of transport and in real physical systems. Thank you very much and we will see you next time.