Transport Process I: Heat and Mass Transfer
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Lecture – 01
Why do we study transport processes?

Welcome to this course on transport processes my name is V. Kumaran, I am at the Chemical Engineering Department at the Indian Institute of Science and this series of lectures will deal with mostly heat and mass transfer, but also some momentum transfer. At the beginning of the course it is useful to go back and try to explain why we need to learn transport processes, how it is useful for us, what exactly we will be learning and how we will be going about analyzing these processes.

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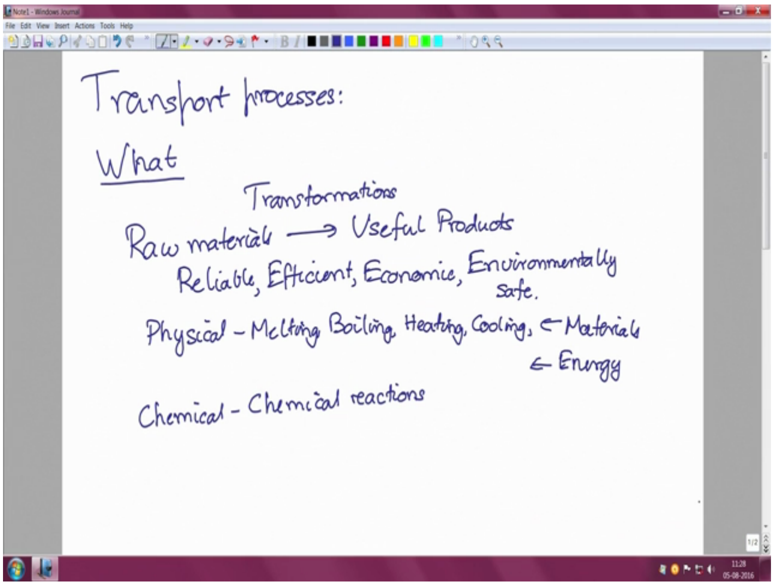

So first; now what exactly are transport processes? One of the major objectives in engineering design is to transform materials from raw materials to useful products, that is what many of the processes that we use aim to do to take materials that are raw then to convert them in some way into useful products.

Now, this is done by transformations, we not only have to transform the materials we may have to transform their them, physically we may have to transform them, chemically mix them together in such a way that what ends up is useful product and this has to be done in a reliable manner so that each and every time you do this transformation the product has exactly the same quality, it has to be efficient, it has to be efficient both in terms of a consumption of energy, in terms of consumption of capital, in terms of consumption of materials.

And in terms of cost it has to be economic, otherwise nobody will buy it and another important requirement is that it has to be environmentally friendly, that is the broad objective in a lot of process industries to convert raw materials to useful products in a safe reliable efficient and environmentally friendly manner.

And this transformation takes place by one of two ways; what are called physical transformations and what are called chemical transformations. Physical transformations do not involve change of the chemical species one from one species to the other whereas, chemical transformations do; physical transformations change only the form of the material and it could be for example, it could be phase change like melting, boiling, heating, cooling, changing the crystal structure of materials, mixing different materials physically and chemical transformations typically involve chemical reactions.

Each of these involves in some manner, the input and output of both materials and of energy and if you want to accomplish this economic efficient manner, you have to know how the heat or the chemical components in these materials are reaching the locations that they need to reach in order for these transformations to take place.

And of course, if you have to do it in an economic manner, you have to use large scale reactors and you know heat exchangers and pumps and so on in order to effect these transformations, because we are trying to do it in many little bits, the cost increases enormously. So, you have to buy in order to achieve it efficiency, you have to effect these equipment which handle large volumes at a time.

Let us look at some examples of these, let say you are taking carrying out a reaction in a reactor.

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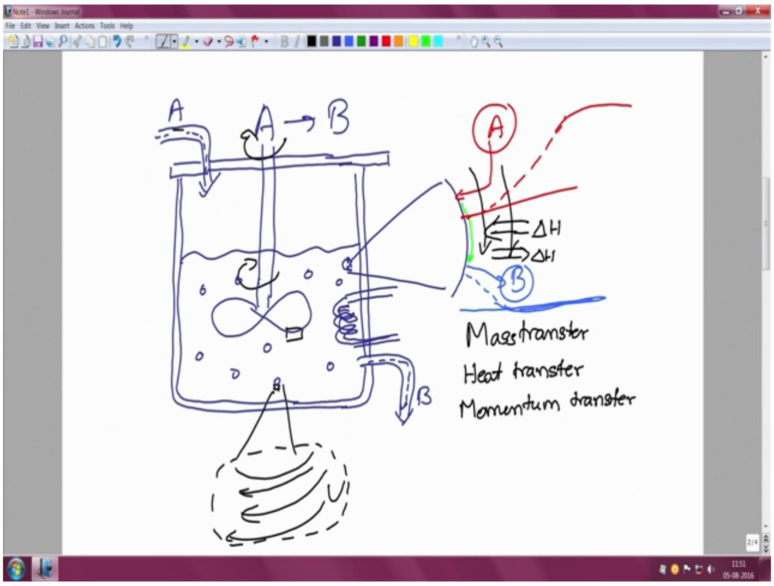

Where some material comes in the reactant A; the reaction is of the form A going to B and let say this is catalyzed reaction, so that the catalyst is a solid particle which is catalyzed in the reaction between the two react the conversion of A to B and this takes place in a chemical reactor which is usually a big tank into which the reactants come in and the products go out.

There is some fluid in this tank and of course, there are catalyst particles around and the reaction takes place on the surface of these catalyst particles, usually in all of the systems you will also have something in order to mix the system adequately so that reaction takes place it is called an impeller and you may have to either heat or cool the fluid in which case you will have coils which either heat or cool the fluid, in order to maintain the temperature. So, that you get the correct specification of the product and the correct yield.

Now, within this reactor system, it is not sufficient to ensure that the correct amount of A is fed in at the inlet and the correct amount of B is taken out at the outlet because just because you put in the correct amount of material, it does not mean that the conditions are created within the reactor for the reaction to take place at the correct rate so that you get the correct yield; after all the reaction itself is taking place at the surface of the catalyst particles.

If I look closely at the surface of this catalyst particle, the surface of this catalyst particle looks something like this; you have reactants which are coming to the surface of the catalyst particle. They are getting transformed at the surface of the catalyst particle to the product B and then the product B has to come out of the surface of the catalyst particle.

So, the rate of the reaction is essentially determined by how efficiently you can transport A to the surface and B of the surface, reactions very often are also either exothermic or endothermic, in which case you may have to add heat energy if it is exothermic sorry I am sorry you may have to heat add heat energy if it is endothermic or alternatively take out heat if it is exothermic.

The performance of this process essentially depends upon what is happening at the small scale. After all if the reactant does not reach the surface it is not going to take place. So, therefore, you have to make sure that there is sufficient the conditions are such that there is a flux of the material reactant to the surface.

After the reaction has taken place the product has to come out, after all if the product does not come off the surface there is not going to be any place for the more reactant to go in and react. So, unless the product comes off the surface the reaction is not going to take place. So, you have to make sure the conditions are such that there is sufficient flux of power off the surface of this catalyst particle.

In addition if the reaction is either exothermic or endothermic, one has to make sure that there is sufficient heat reaching the surface if it is endothermic and sufficient heat leaving the surface if it is exothermic. If the heat does not leave then the temperature of this catalyst particle will go on increasing and it could get hot spots and runaway reactions. On the other hand if it is an endothermic reaction and if the heat is not supplied to the surface then the temperature will decrease as the reaction absorbs heat and therefore, the reaction rates will decrease and once again the performance is not the desired performance.

So, ultimately the performance of this reactor depends upon what is happening at the small scales, the transport and of reactants to the surface, products of the surface, heat across the surface. In order to increase these transport rates your using an impeller to mix the material and this impeller of course, can generate a larger fluid flow across the catalyst surface, this impeller will because it is mixing this fluid as the across the catalyst surface, it will generate a flow of fluid with some velocity and thereby it will help in bringing the reactants and products to and from the surface. However, this impeller now consumes energy because energy is lost as you mix because of fluid friction, fluid viscosity and therefore, this impeller consumes energy and that consumption of energy is going to affect the efficiency of process.

So, in this process, in the simple process we have mass transfer, transfer of reactants to the surface, transfer of products away from the surface; we have heat transfer which is basically the transport of heat to or from the surface through these heating coils so that the there is sufficient either removal of energy if it is exothermic or sufficient addition of energy if it is endothermic. You have also mixing which basically transfers momentum from the impeller to the fluid, after all you are forcing the fluid by exerting a power on this impeller and at the surface of the impeller itself you have a stress that is the exerted on the impeller to due to the fluid flow and this stress acts exerts a resistive force to overcome that we need to apply a torque on this impeller.

Stress - force per unit area; it is the rate of transport of momentum transfer per unit area per unit time. Just as the mass flux is the mass transfer per unit area per unit time or the heat flux is the heat transfer per unit area per unit time. In this case this is the momentum flux per unit area per unit time.

So, simple process like this involves mass transfer, heat transfer and momentum transfer and they are often compromises that have to be made optimizations that have to be made you might think that if you increase the flow velocity enormously, there is a lot more of fluid flow across the surface and therefore, the transport mixing is more efficient the transport rates increase; however, as you increase the velocity, you also have to exert more force on the impeller and that adds to cost and to fuel costs and to environmental costs. So, these kinds of optimizations require a very good knowledge of what is happening very close to surfaces.

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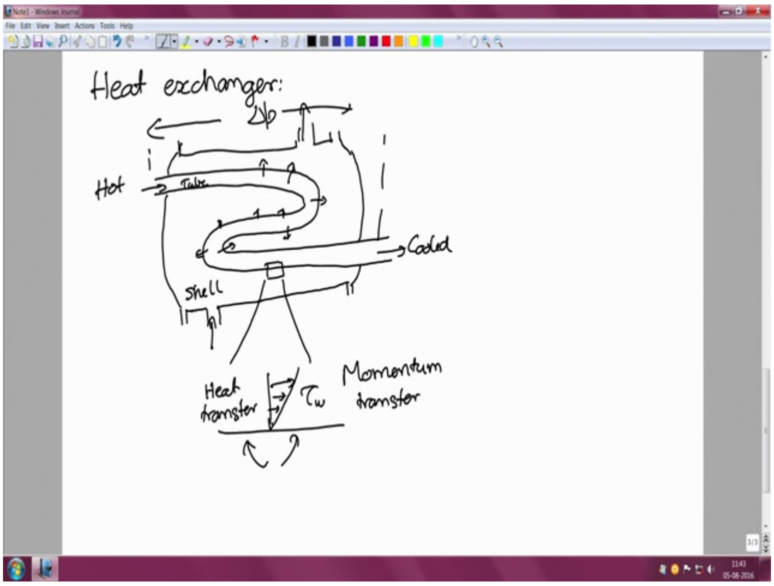

Let us take another example which is a heat exchanger. So, typical heat exchanger look something like this, there will be a shell there will be a tube going through, there could be of course, multiple bends in this tube, but I will just take one two for the moment that is the tube side and then there is a shell side.

So, what could happen in a typical situation is that you have hot fluid flowing in to the tube, this fluid is cooled down and this acts to transfer heat to fluid that is on the shell side. So, this is the shell and this is the tube. So, this acts to transfer energy to the fluid on the outside and heat exchangers have used quite often, they are often required in order because very often you may have a hot product stream which has a lot of energy in it, a thermal energy and you could increase the efficiency of your process by transferring that to an inlet stream which is cold, because if you do not use the product stream you would have had to burn fuel in order to heat up the inlet stream. Rather than do that you can use you can make use of the excess energy in the product stream and use that in order to heat up the inlet stream and so, there is an environmental angle as well to this because this enables you to conserve fuel and conserving fuel is good for the environment.

Now, to design this you have to know of course, what is the temperature difference and so on, but in order to cool the hot fluid sufficiently, you have to make sure that there is sufficient heat there is transported across the surface as this hot fluid is going through, such that at the outlet the temperature is the desired temperature either the desired temperature or the desired amount of heat has been transformed.

For that it is not sufficient to just pump in the fluid at the desired rates; you have to make sure that there is sufficient length of this tube and sufficient surface area so that all the heat that is desired to be transferred is transferred by the time the fluid comes out and this transport rate depends on what happens at the surface between the hot and cold fluid, you have a hot fluid that is flowing across this surface of the tube and you have cold fluid that is going around this tube, this transfer of heat from the fluid to the surface and then to the next fluid across is what is going to determine the efficiency of the process and this is something that you need to be able to predict in order to be able to design these processes.

Of course the heat that is transferred depends upon the conductivity of the wall; however, it also depends upon how the fluid is flowing across, because as the fluid flows across faster it is going to carry more heat with it as it comes along and to you might think simplistically that if I make the length of this heat exchanger of this tube larger and larger, there is going to be a larger and larger surface area and therefore, the heat transferred will keep increasing.

However there is a cost in order to pump the fluid through this tube, you need to apply a pressure difference across the two ends. So, across the two ends of the tube you need to apply a pressure difference in order to pump the fluid and this pressure difference increases as the length of the tube increases.

In the simplest approximation when the flows fully developed this pressure difference increases linearly with the length of the tube and therefore, there is a cost to be paid to make the tube longer and longer and that cost might overwhelm the cost the gains from increasing the length. So, you need to have a good understanding when a fluid is flowing, what is the rate at which heat is transferred across the surface? If I know the difference in temperature between the inner and the outer fluid and what is the pressure difference I need to apply in order to pump the fluid and that pressure difference is ultimately linked to the stress that is applied on the fluid, due to the pipe wall which tends to retard its flow when the fluid is flowing across the surface there is a wall shear stress acting at the surface.

And the pressure difference basically compensates for the backward wall shear stress that is exerted on the surface and to be able to predict the pressure difference, you would need to know what is the wall shear stress and how does it depend upon the flow rate of the fluid and the diameter of the pipe and the properties of the fluid. So, that is a momentum transfer problem.

After all, any friction loss in the fluid has to be compensated by energy that is put in from outside. So, this simply heat exchanger problem contains in it two problems: one is that of heat transferred across the surface, but this is intricately linked to momentum transfer as well because that has to tell you how much pumping you need to exert in order to transfer in order to achieve the desired flow rate and of course, for the heat transfer problem you need to know for a desired for a given flow rate or a fluid velocity how much heat is being transferred across this surface, given the temperature difference and the properties of the two fluids.

So, as I said as in the case of the previous example, in all of these cases the efficiency of the large process depends upon what is happening at each individual patch or surface along the surface of the tube and given the local conditions if you can predict what is the amount of heat transferred at each patch, what is the stress exerted on each patch and then add it up all together you will get what is the what should be the heat transfer rate and the pressure difference for the entire fluid.

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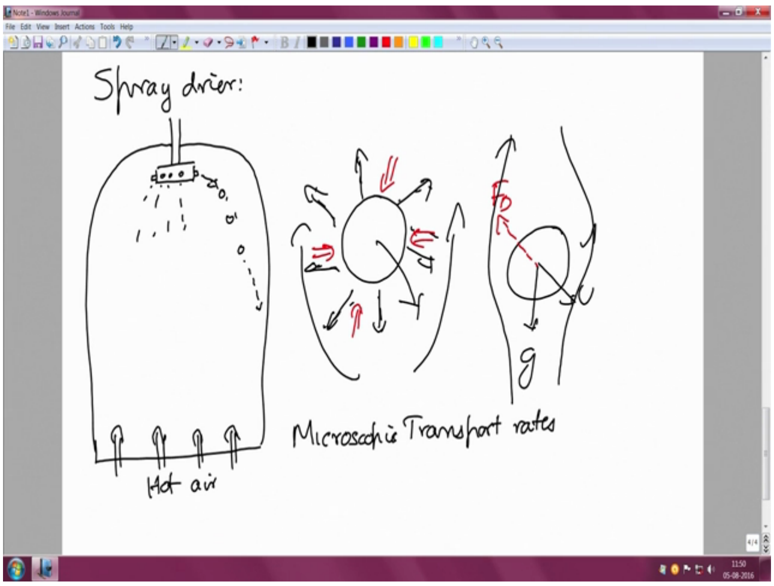

Let us take one more example. So, this is an example of a spray drier; spray driers are often used in food processing industries for example, for drying liquid droplets into powders. So, things like milk powder and so on are made in spray driers and what they basically consists of is a fluid that is ejected through nozzles in a large column from the top and there is hot air coming from below and this hot air dries from the droplets, before they hit the surface.

So, typical configuration would look like this will have some nozzles on this inlet manifold, through which droplets are ejected and all of this is enclosed in the large column through which you have hot air coming in from below. These droplets are typically of the order of 100 microns in size in diameter is about 0.1 millimeters in diameter, if you need still smaller droplets there are nozzles cannot be used you have rotating discs which spray the droplets, but in many case if you have a certain droplet that is coming out of this, we have to make sure that before it hits the wall it is completely dried so that it does not stick on the surface.

And if you look at the droplet itself as it is going out, it is a wet droplet it contains roughly 80 percent of water, now all of the water has to be evaporated out of the surface due to the hot air that is going around it, due to the hot air that is going around this droplet, all of the water has to be evaporated by the time it hits the wall of the or the bottom.

Now, this is a mass transfer problem since the hot air is dry there is a difference in the vapor pressure of water in the dry air and the vapor pressure of water on the droplet surface that acts in order to evaporate the moisture and therefore, dry the droplet through a flux of moisture that is coming out, but this also requires heat transfer because in order to evaporate the moisture you need to provide the latent heat, this latent heat is provided by the hot air, this latent heat that is required to evaporate the droplet is provided by the hot air.

We have to make sure that there is sufficient transfer of heat, so that all of the moisture is evaporated it is not sufficient to just ensure that the water vapor comes out, you have to also ensure that there is sufficient supply of heat so that it compensates for the latent heat of all the moisture that is within the droplet so that all of the moisture can be evaporated.

And there are often design constraints and things like this if you are using food products for example, the temperature difference between the droplet and the outside air cannot be more than about 40 degrees because at higher temperatures the food will spoil. So, there are constraints, working within those constraints we have make sure that there is sufficient heat that reaches the surfaces of the droplet and you have to make sure that the moisture comes out, it evaporates and there is sufficient flux of moisture out of the surface so that the droplet is completely dried.

There is one another thing that is also important and that is that you have to know how long it will take for a droplet to hit the surface or hit the bottom. This droplet of course, is being exerted by two forces: this droplet is under the action of a gravitational force, it has some initial velocity and you have to be able to predict how the velocity changes as the droplet is coming down, because in addition to the gravitational force there is also the air around the droplet and that air will exert a drag force in the direction opposite to the motion of the droplet.

The combination of these two forces the gravitational forces and the drag force will decide how long it takes travel a certain horizontal distance and how long it takes to travel a certain vertical distance. This drag force is exerted due to the fluid flow around the droplet, this drag force is exerted to do fluid flow around the droplet ok and this fluid friction acting at the surface of the droplet is what exerts a drag force. So, the fluid flow is exerting a stress on the surface of the droplet because it is flowing around and this stress is what slows down the droplet.

Therefore I need to know what is the stress exerted on the droplet, for a certain fluid flow around this droplet. Stress as I said is the rate of change of transfer of momentum and this rate of transfer of momentum is a momentum transfer problem. So, this example once again contains all three, it contains mass transfer, heat transfer and momentum transfer, in order to be able to predict what are the dimensions of the tank that I need to design, what is the velocity with which the droplet has to be ejected, in such a way that the droplet dries completely before it hits either the wall or the bottom.

So, what I have tried to explain to you here is that the efficiency, the economics, the environment friendliness of a large process depends upon what happens at the microscopic scale. So, basically in order to we have to design I need to know the microscopic transport rates in order to be able to design processes.

So, in all of these cases what we are doing basically is trying to find out given. So, given a catalyst particle with a certain concentration of reactants on the surface and a certain concentration far from the particle after all when you put in this material into the reactor, you end up with a certain concentration in the bulk fluid within this; however, close to the particle the concentration going to decrease because the reactant is being consumed. So, given this variation in concentration across the fluid down to the surface, from some bulk value what is the flux.

Similarly, for the product B there is a change in concentration as well ok. So, in the case of B the concentration is higher at the surface because B is being produced and then it goes to some concentration in the bulk given this difference in concentration what is going to be the flux.

Similarly, for heat transfer given the difference in temperature between the bulk and the fluid what is going to be the flux of energy to the fluid and in the case of momentum transfer as we will see later, momentum transfer takes place basically due to a difference in velocities, so given a difference. So, obviously, the impeller is moving at a higher velocity than the fluid because it is dragging the fluid along with it, given the difference in velocity what is going to be the stress that is required to be applied.

Similarly, in the case of heat transfer what you would like to know locally at each patch on the surface given a difference in temperature what is the heat flux, what does the pressure required to flow through each individual element of the tube and in the case of a the spray drier, what we would like to know is that given the difference in the vapor pressure of water between the inside and the outside, between the surface and the bulk what is the rate at which water vapor will be evaporated; what is the rate at which the energy will be transferred given the temperature difference and what is going to be the force exerted due to the difference in velocity between the droplet and the air.

So, that in nutshell is the questions that we will answer in this course and I would try to tell you what I will try to make those questions a little more precise in this next lecture, what precisely I will be going to try to calculate and how are we going to try to calculate it. So, we will continue with this in the next lecture.

Thank you.