Momentum Transfer in Fluids
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Good morning. Welcome to the NPTEL certification course-Momentum Transfer in Fluid. This course will be taught by two faculty members, myself Professor Sunando DasGupta, and Professor Somenath Ganguly. Both of us are teaching this course for quite some time, and this course should be equally divided between two major parts-one that deals with fluid dynamics, that is fluids in motion which would be covered by me, and the second part to be covered by Professor Ganguly, would mostly deal with fluid statics, structures, fluid structure, interactions and so on. We are faculty members of the chemical engineering department, and our research interest also lies in fluid mechanics, and so therefore, this course is extremely close to us, and I hope that you would be able to learn something about fluids in motion, and which could be used in various areas not only in chemical engineering, but in several upcoming areas as well.

So, let us move on to the next slide, and where we would see that the first question for any new course is why should I learn about this course. So, I am just going to give you a brief overview of the topics which are going to be covered in my part of the course, but initially I am going to give a general introduction of the exciting area of fluid mechanics, and its application specifically in chemical industries, but as you understand, that these days the separation or the boundaries between different streams are getting blurred. So, applications in chemical engineering will not be limited to just flow of fluid through pipes applications in refineries and so on, but there are many exciting areas in which the knowledge of fluids in motion would be important.

But, let us first start with something which is very traditional, something which is close to chemical engineering- it is almost like the heart of chemical engineering which is a distillation process. You will learn more about the mass transfer operations involved in any distillation process which would result in several components, number of products, which we use in our daily lives starting from the gasoline, aviation fluid fuel to motor fuel, and on the other extreme, we have tars and bitumen's. So, everything is produced by the fractional distillation of the crude oil in a distillation column, what you see on the right of the slide. Now, if you look closely, you will see there are number of pipes in which either the crude will flow into the distillation column, and amount of exits/number of pipes through which the products are going to come out to be stored based on their composition, and all these will require a very delicate balance of flow heat transfer and mass transfer. So, the amount of pipeline which you would see in any chemical plant or any reactor specifically in a distillation column is mind boggling.

So, how do you make the fluid, the aviation fuel flow through a pipe? what kind of resistances it would encounter, and whenever there is a flow, there is going to be to make the products reach at the desired location, there would be a specific length of the pipeline. It is not going to be a straight pipe, there is going to be bends, there is going to be metering devices which would measure the flow rate through the pipe at any given point of time, and there is other draw of lines which would take the product for further analysis. So, the pumps that are needed to make the fluid flow from one point to the other, will have to be sized, you need to calculate what is the power to be supplied by the pump to overcome the friction, to overcome the gravity head. Like that means, you can see in the figure that the fluid is to be delivered at the top in some cases or the fluid is going to be extracted from the bottom, and all these may involve working against gravity. So, how do I calculate that and secondly, when a fluid flows through a pipe, there is going to be a velocity distribution.

The velocity is not going to be identical in the pipe, there is going to be a variation in velocity inside the pipe, and intuitively, you can sense that the maximum velocity is going to be at the centre line of the pipe. So, all these would need a fair knowledge of fluid mechanics, fluid flow through a pipe, and how it is going to depend on the properties of the fluid. The most important properties which we deal with in this part of the course, would be the density, and the viscosity. So, we all are aware of what is a density, and you know you can easily understand that to pump a denser fluid, you would require more power of the pump. The viscosity is a unique property which would tell us the nature of the fluid in terms of resisting the motion.

So, when you try to initiate a motion in a stagnant fluid, the viscosity will always try to bring order to the system. So, the resistance to flow is to some extent dependent on the viscosity, and this course would give you the fundamentals needed in order to calculate these pressure drops, the pumps, what is the flow pattern inside the tube and so on. So, this is traditional chemical engineering, but there are applications of these concepts equally important in a in number of areas. One such example is as you could see in the next slide, which is human body. So, in our body there are number of arteries, veins, the arteries then branch out into smaller arteries, and so on till it reach the capillaries which supply the nutrients and oxygen to every living cell of our body.

And the one that drives this flow of blood and other materials through this intricate network of veins and arteries, is the heart. So, how much a heart has to pump the blood through these would depend on various physiological factors, but still in this case the viscosity and the density will play a major role. Now, when you go to a very small-scale flow for example, the flow in a capillary, there we enter into the realm of micro fluidics which is fluid mechanics on a small scale. So, when blood or any fluid flows through a tiny capillary whose dimensions could be of the order of hundreds of microns at the most, then apart from the viscous forces which oppose the flow, there could be other forces which appear due to the reduced length scale. So, fluid mechanics deals with bulk flow as you could see in a distillation column, or for a macro sized reactor to the domain of micro fluidics where we deal with flow at the very small scale.

And the applications from traditional engineering to newer areas for example, in many situations, we you probably have heard about lab on a chip. So, on a single chip, how can we measure different constituents of blood. So, the blood will flow through prescribed geometries in different parts, and reach the end point where a reagent would be kept, and the blood is going to react with the reagent, and through the change of colour you could determine what is the sugar content, what is the creatinine content, and other parameters that commonly are measured for blood characterization. So, small scale flow, and large-scale flow we will deal with both, but in this specific course our emphasis will mostly be on the flow at larger dimensions. But, to give you an idea that we have an all-encompassing field of fluid mechanics where physics, chemistry and engineering intersect, and the most important contribution these days are coming from biology.

So, truly fluid mechanics is the first step of an exciting interdisciplinary field of study. So, I would try to give you some glimpses of the intricacies involved in the study of fluid mechanics. But, any course would require certain books text books which you are going to follow, which this course is going to follow. So, the two text books which are to be used in this are Transport Phenomena by Bird, Stewart and Lightfoot. This is a text book which is extremely important in many facets of chemical engineering, heat transfer, mass transfer and momentum transfer.

The second book is also equally good which is Fluid Mechanics by Fox and McDonald. So, these are the two books which you would follow, and initially for the first part of the course, I would mostly teach from Bird, Stewart, Lightfoot, and later on, I will shift to Fox and McDonald, and for each such transition, I will tell you that where you can find examples or the portions that I have taught. You can read them in any one of these books which I will specify. So, what are the topics that will be covered in this course? The first one is the conservation of mass. So, we will talk about continuity equation, and which is nothing but a statement of conservation of mass, and we will introduce the concept of control volume control surfaces.

So, what is a control volume? A control volume is an enclosed space defined by several control surfaces. So, if you can think of a box, it has 6 sides. Each side can be called a control surface, through which the fluid can enter or leave without encountering any resistance. So, control surface does not have any mass. Whereas, control volume defined by all these control surfaces has a mass of its own. So, the conservation equations which you can write for a control surface and a control volume would be different. For a control surface "mass in" will be equal to "mass out" there is not going to be any accumulation.

Whereas, for a control volume some amount of mass may come in through a control surface, some may leave through another surface, you may have multiple "in"s and "out"s of mass in a control volume. There could be a reaction which is taking place inside the control volume which can change the density as well. So, the net algebraic sum of all the mass "in" and "out" plus any accumulation of mass in the control volume would be zero, and that is what is the statement of conservation of mass. So, we will talk about this continuity equation which as a once again is nothing, but the conservation of mass principle. Then the type of fluid-incompressible fluid is defined as the fluid whose density is constant.

So, there are many fluids of engineering interest where this incompressible assumption is going to be valid. So, the density of incompressible fluid is constant. The second comes what are the different types of forces which a fluid would encounter. So, if you think of a mass of fluid, it is going to experience a force which is gravity, which is equally applicable all mass elements which are present inside the control volume. In that sense, the force on the control volume is a function of the volume. It works on all parts of the control volume.

So, that is why it is called a body force. So, the most common example is gravity, but there could be other examples. for example, electrostatic force which also acts on every point of the fluid inside the control volume. So, that can also be termed as a body force. Second comes the surface forces. The surface forces apply as the name suggests only on the surfaces, only on the control surfaces.

So, if you apply pressure to a control volume, they are going to be applied only on the surfaces, and the product of that pressure multiplied by the area would give you the force due to pressure which is acting on the surface. So, that is an example of a surface force. Similarly, if you have a fluid flow in between two plates, the viscous forces are going to be active only at the bounding surfaces. So, that is why the force due to viscosity is termed as a surface force. Then comes the conservation of momentum which in other words is a statement of the Newton's second law.

So, if you have some force which is acting on the control volume, the Newton's law suggests that the sum of all forces acting on the system must be equal to the mass times the acceleration of the control volume. So, this concept when applied to a control volume containing a specific fluid, is known as the equation of motion and a special case of equation of motion is Navier Stokes equation. This Navier Stokes equation would allow us to write the governing equation which defines, or which tells us about flow inside the system in terms of all the forces which are acting inside at the surface or as a body force. So, we will deal with Navier Stokes equation in this course as well. Another one which with which you must be familiar with is Bernoulli's equation.

So, Bernoulli's equation is applicable for an ideal fluid. An ideal fluid which does not have any viscosity. So, you could understand that it is just an approximation of an ideal situation, and therefore, in order to bring in the viscous nature of the fluid some modifications to the Bernoulli's equation will be required. So, what is Bernoulli's equation? From your high school physics, you know that it is the sum of all heads the pressure head, the velocity head, and the gravity head would be equal to 0.

So, if I have a pipe this is point 1 and this is point 2. So, sum of pressure head, velocity head, and gravity head would be equal to the sum of all these 3 heads at this point for an ideal fluid. But, we all know that in order to make a fluid even in a horizontal pipeline of constant cross section, you need to have a high pressure on one side and low pressure on the other side. This pressure changes between point 1 or point 2 or in other words the pressure drop needed for the fluid to flow from 1 to 2 is because of the non-ideal nature of the fluid.

So, what kind of modifications are to be incorporated in Bernoulli's equation which you tell us something about the pressure drop in such a system. So, this course will deal with that as well. Then we will talk about integral equation. So far what we have discussed is essentially you take a small volume of the fluid. You try to write a differential equation which is the governing equation, integrate that differential equation to obtain the velocity at every point. But, for engineering calculations you do not need the velocity at every point.

Most of the times, if you get an overall approximate behaviour of the fluid. Your purpose would be met. So, what is going to be these integral equations which would not give you velocity at every point, but would give you the parameters necessary for engineering calculations. So, we will deal with that as well, and then as I mentioned it is extremely important the pump calculations. What is the power of the pump needed to make a liquid flow in an intricate pipeline which may contain a change in elevation, which may contain a change in the size of the pipe, it goes from a larger pipe to a smaller pipe, and to make the fluid reach the point of interest, there may be bends in the path, there may be flow meters which are added to the path. All these would give rise to pressure drops. So, these cumulative pressure drops are to be calculated to obtain the power to be delivered by the pump. So, we will deal with those calculations as well. And secondly, as I mentioned flow meters. Whenever there is flow in a pipe you need to have a measure of how much the flow is taking place.

So, there are different flow meters which are to be added to the circuit, and how do we calculate the flow rate, what are the principles of operation of those flow meters will have to be known to find the right flow meter for the application at hand. So, in short. these are the 6 topics which would be covered in my part of the course. Concepts that are needed to understand fluid mechanics is shear stress, viscosity, and molecular transport of momentum. So, in this slide I will try to give you some idea of what is shear stress, what role viscosity plays with shear stress, and how does this concept give rise to the molecular transport of momentum. So, if you look at this slide, you have tau which is shear stress, and we know that when two layers of fluid slide past one another, then the molecules of this layer would try to drag the slower moving layer.

On the other hand, molecules on the slower moving layer would try to reduce the motion of the top plate which is moving with a higher velocity. So, essentially this kind of slip of one plane of fluid above the other will create and mutual interaction between these and viscosity is the invisible string which binds these two surfaces slowing down the faster moving one, and making the slower moving one move at a higher velocity. So, this is what viscosity does. So, therefore, a stress is exerted by the slower moving layer to the faster moving layer, and a momentum gets transported in a direction perpendicular to the motion. So, two fluid layers are moving towards you-one moving at a faster speed, the other moving at a slower speed, but this kind of interaction the shear stress essentially can be thought of as a momentum transfer in a direction perpendicular to that of the flow.

So, you can think of a molecule which is sitting over the smaller the lower slower moving layer, it jumps due to molecular motion to the upper layer. When it does that, it carries some momentum with it which is equal to the velocity times mass of the molecule for this slower moving layer. So, when it comes to the faster moving layer, it would try to reduce the velocity, the momentum of the top moving layer which is moving at a faster velocity. So, this kind of exchanges of molecules without any net motion can create a momentum getting transported in a direction perpendicular to the velocity that is what effect of shear stress is this kind of transport in a direction perpendicular to the flow due to the molecular motion is also termed as the molecular transport of momentum. So, please keep in mind that molecular transport of momentum is in a direction perpendicular to the flow expressed as τ_{yx} with two subscripts.

The first subscript x refers to the direction of movement. Let us say, this is the x-direction. The momentum gets transported in a direction perpendicular to the flow- that is in the y direction. So, x-direction movement imparts a flow of momentum in the y-direction. So, if you look at y, it is the direction in which the linear momentum is being transferred. So, always right tau with the proper subscripts-the first one is the direction of motion, the second one perpendicular to the direction of motion in which the momentum gets transported.

So, shear stress is nothing but molecular transport of momentum between two layers where there is a non-zero relative velocity, and if it is a fluid where there is linear relation between the shear stress τ, and the velocity gradient $(dv_x)/dy$,when there is a linear relation, it is called a Newtonian fluid because it follows Newton's law of viscosity where τ_{yx} is $-\mu$, μ is the property, the viscosity of the liquid solution, and the minus sign denotes is that the momentum is always getting transported in the direction of slower velocity. So, that is why we have a minus sign in there where the flow of momentum is expressed, the shear stress is expressed in terms of velocity gradient, it is proportional to velocity gradient. If it is linearly proportional to velocity gradient, it is called a Newtonian fluid, and the μ that you see the proportionality constant, is essentially the viscosity of the fluid. So, any liquid that follows this law, this linear relation between the shear stress and the shear rate which is (dv_x)/dy is called Newtonian fluid.

Of course, if there is Newtonian fluid there is a bunch of liquids, many liquids which follow this role there will be some liquids which will not follow this role, and they are called non-Newtonian fluids. Now, there are the shear stress is essentially the gradient of the velocity (dv_x)/dy, the velocity is a vector. So, when you take the gradient of a vector, it becomes a tensor. So, tensor has 9 components. I will discuss about it in later part. So, I will skip that right now, but just keep in mind that shear stress is not a vector, velocity is a vector, and the shear stress is it something new which is called a tensor I will discuss that later.

But, as I mentioned that there are 2 kinds of fluids- which are Newtonian fluid and non-Newtonian fluid. So, if you look at the black curve where the stress is proportional to strain, and it passes through the origin that is the Newtonian fluid. There are 2 different kinds of fluids-one is a shear thickening or dilatant, and the shear thinning or pseudo plastic with examples of them which are given. So, latex paint is a shear thinning fluid. So, it does not follow the straight-line relationship which is expected of a Newtonian fluid, and mixture solution of water and corn starch is a shear thickening fluid.

There are applications important applications which are related to these 2 types of fluids. There is a fourth type of one, which is known as Bingham plastic. Now, all of us are aware of the effort needed to initiate the motion for a tooth paste. You press it lightly nothing comes out of it. You put some shear rate, but there is no flow of the of the toothpaste out of the tube. So, you have to exert certain higher pressure in order to make the flow, but once it starts the flow, the relation between stress and strain is going to be linear.

So, Bingham plastics will have a yield stress, as you could see over here. This yield stress, once you cross the yield stress, it will start to behave like a Newtonian fluid. So, that is an important class of fluid which is known as Bingham plastic. So, these are the different types, and there are some efforts to express shear stress as mu times the velocity gradient to the power something. So, there are different models in which where the flow behaviour index and consistency would try to bring these different types of fluid, and have a universal relationship which is similar to that of a Newtonian fluid. We will discuss that later, but suffice to say at this point is that there are 4 different types of fluids-which are Newtonian, shear stress is proportional to strain, pseudo plastic, dilatant, and Bingham plastic.

Another very important concept which comes in fluid mechanics is that whenever there is a motion close to a solid surface, which you see many times when a car moves there is going to be a layer of air very close to the surface of the car in which there is going to be a steep gradient in velocity. When the car moves, the velocity of air very close to the car will mimic or will be almost equal to the velocity of the car itself, but if you think of a point far from it the velocity of that will be if it is a still day, the velocity would be equal to 0. So, every transport process, every viscous interaction between the moving object and a stationary air film will be confined to a layer very close to the solid surface. This has given rise to the concept of boundary layers. So, a boundary layer as you can see in this picture-there is let us say this time there is an approach velocity. The fluid the air comes with certain velocity, and then the blue one that you see is the solid plate.

So, when it encounters the solid plate, there is going to be the formation of a very thin layer. it is extremely thin, but I have drawn it in a thicker way so as to highlight certain features of it. Normally, these boundary layers are extremely thin of the order of a few millimetres. If it is a very long object it could it could be as few centimetres. So, on the surface of the solid at the solid fluid interface, the velocity would be equal to the velocity, the relative velocity would be 0. So, the velocity would be equal to the velocity of the solid plate which in this case is stationary. So, therefore, the velocity starts from 0, and then as we move away from the solid plate the velocity starts to increase, and then will asymptotically merge with the free stream velocity.

So, there are few terms which I would like to highlight here. Approach velocity v is the constant velocity with which the fluid comes towards the solid stationary solid plate. When the boundary layer forms, beyond this boundary layer, the flow velocity is constant again which is called the free stream velocity, where the stream is free from the viscous effects which is confined within this thin layer. The thickness of the boundary layer as denoted by delta; it is it is a function of x. So, higher the value of x, the value of the boundary layer thickness would be higher.

So, the boundary layer so to say grows on the solid plate, but the rate of growth of the boundary layer is very steep at the beginning, and as you move to the larger distance, that rate of increase of boundary layer thickness is rather small. So, the flow inside the boundary layer is governed by viscosity. So, it is viscous flow, and v_x, the velocity in the x-direction is a function both of x and y. Whereas, v_x outside of the boundary layer where the flow is free of any viscous effects, it is a constant which is the free stream velocity u infinity, and how do we define this thickness of boundary layer? Traditionally it is defined where the velocity of the fluid reaches 99 percent of the free stream velocity. There are scientific reasons of why this has been chosen, but it is now a common practice to term the thickness of the boundary layer is where the velocity inside the boundary layer reaches 99 percent of the free stream velocity.

This concept of boundary layer has many interesting applications specially in the design of cars, in the design of any moving objects. So, you heard about the term-streamlining the shape of a car. So, you do work on the shape of the car so as to minimize the frictional drag experienced by the car when it moves at a high velocity. Same applies to the design shape of an airplane, and a ship and everything else, and the application of boundary layer is very common. I mean, the concept is very common in different fields of sports as well.

So, when a cricket bowler bowls a swing ball, so he or she uses the concept of boundary layer. So, there is a seam in a cricket ball in which way it is directed towards the first slip or towards the leg depending on that there would be two different pressures on two sides of the ball. So, while in air, it will move away from the batsman which is the outswing, or from outside the off stamp it will come towards the batsman which is the in swing. So, when you see a free kick in football that is also the use of the formation of different thickness of boundary layers having a spin in the ball which would induce other forces, and make the ball swerve, and get into the target in the case of a perfect free kick.

So, the examples are very exciting. So, we may not have enough scope to discuss about the boundary layer induced phenomena in sports, but it is a very relevant in terms of the interaction between a solid, between a moving solid, and stationary air. So, I thought that I will just give you this idea of what is boundary layer thickness, how it is defined and so on. Next comes the concept of velocity distributions in laminar flow. This is something which we will continue for quite some time, and for that we are going to make something bring in a concept which is a shell momentum balance. Now, what is a shell momentum balance? You define a shell- let us say this mobile this is a shell. It has some width some length, but one of the dimensions is very small.

So, this is a shell, and we are going to figure out how much of mass that is coming in through this face, how much of mass that is going out of this face, and what are the forces acting on this shell. So, a shell of fluid is defined by 3 dimensions- 2 of them are large-the width and the length, one of them is small. This is a shell there could be forces acting on it for example, body force surface force and so on. So, a shell is an imaginary piece of fluid where one of the dimensions is going to be the smaller dimension, and we are going to make a momentum balance on that shell. So, this type of shell momentum balance where you write the physics of the forces, the physics of the different mechanisms by which momentum can come into this shell, and then express that in the form of a differential equation which becomes the governing equation. In the next lecture I will go very slowly on the shell momentum balance, how it is done, and how it can give rise to a governing equation for the system in at hand.

But this shell momentum balance if you could see so, this Δy is the smaller dimension ok, it has a length L and width W. So, if you think of this face through this face, the momentum comes into the shell, through this face the momentum goes out of the shell. So, we will have to do this kind of shell momentum balance, and I will explain in the next lecture- how did I get the form of momentum in, and momentum out. So, I will discuss that in the in the next part, but when you derive the equation, when you get the governing equation, how do we get the governing equation will be the topic of the next lecture, but when you arrive at a governing equation, then you have to solve it and differential equation when upon integration requires boundary conditions.

The boundary conditions come from the physics of the problem. So, what is the physics that is involved in here that would give rise to specific boundary conditions. One such boundary condition I have explained some of it in terms of my discussion of boundary layers is that a solid in contact with a liquid. there is no relative velocity at the solid liquid interface. So, at the solid liquid interface the relative velocity is 0, or if the solid is at rest then the velocity is going to be equal to 0. So, that kind of boundary condition is known as the no slip boundary condition. The fluid does not slip over the solid surface in most of the cases. There are instances which we will not discuss in this course where there can be a slip velocity, but forgetting about that, the no slip is one of the most commonly used condition in fluid mechanics where the relative velocity is assumed to be 0 at the solid liquid/solid fluid interface.

The other type of boundary condition is known as no shear boundary condition. If you have a liquid and a vapor as you could see in the light blue which is the liquid, and the vapor at the interface between the liquid and the vapor. Since the viscosity of vapor is extremely small, the density is very small. So, if the viscosity is small, the shear rate would be small because you have seen that the shear stress is μ times the velocity gradient. The absence of any appreciable viscosity of a vapor or gas can allow us to use the condition that at the liquid vapor interface the shear is 0. So, these two are the most common boundary conditions to be used while solving the governing differential equation for fluid flow in any conduit or geometry.

No slip that means, relative velocity is 0 at the liquid-solid interface and no shear at the liquid-vapor or liquid-gas interface. So, these two boundary conditions will use extensively in this course. So, that is what I wanted to cover in the first lecture, and we will continue with our study of shell momentum balance in subsequent lectures. Thank you.