Fundamentals of Fluid Mechanics for Chemical and Biomedical Engineers
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Lecture No. 01
Introduction

Hello. So, in this first lecture we are going to talk about some introductory stuff. So, before we begin to talk about the course itself let us do some introductory things.

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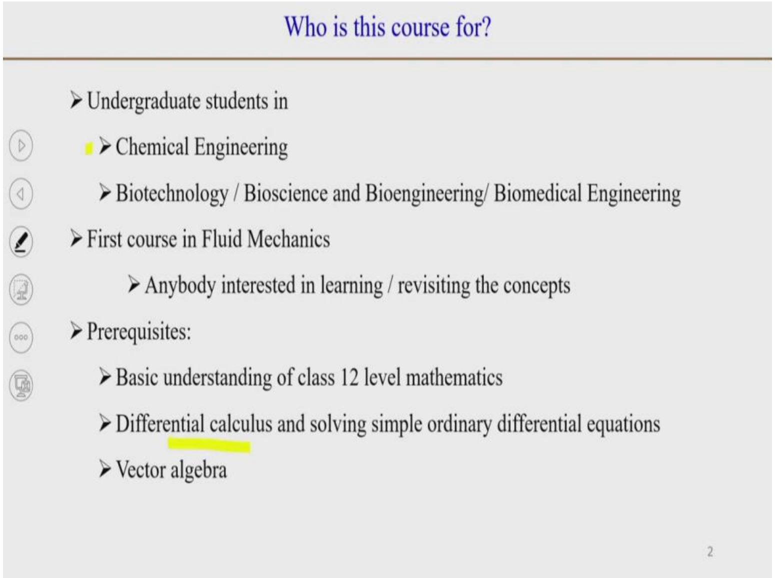

So, first thing is that who is this course for? Who is the target audience for whom keeping in mind the course has been designed? So, it is primarily a undergraduate level course for first or second year undergraduate students. Primarily, from Chemical Engineering or Biomedical Engineering discipline. Now these Biomedical Engineering can be Biotechnology, Bioscience and Bioengineering for all of these people because Bioengineering generally refers to where people are looking at Biochemical applications, Biomedical applications. So, this course will be useful for all such students.

Apart from it these disciplines, the course can be also useful for anybody who is interested in learning an undergraduate level of first course in fluid mechanics. He can be from a Mechanical Engineering background, a Civil Engineering background or from Mathematics background, Physics background or anybody in the industry who is interested in revising his fluid mechanics concept or he wants to understand some basics of fluid mechanics, he can also find the course to be useful.

So, next thing I would like to talk about what are the prerequisites of this course. So, basically the students should have learnt or should have an understanding of class twelve level mathematics and in particular what we will be interested in is because we will be using a lot of differential and integral analysis here. So, it will be helpful if the student can construct and solve differential equations, is aware of the concept of limit, can do differentiations or integrations and he is able to solve some simple ordinary differential equations.

The other thing the student should know is a bit of vector algebra. What is vector? What is a scalar and then different operations of vectors and vector calculus? But vector calculus as we go along we will be talking about or we will be discussing those concepts from vector calculus in the course itself. So, it is not mandatory but one should have understanding of some calculus as well as vector algebra.

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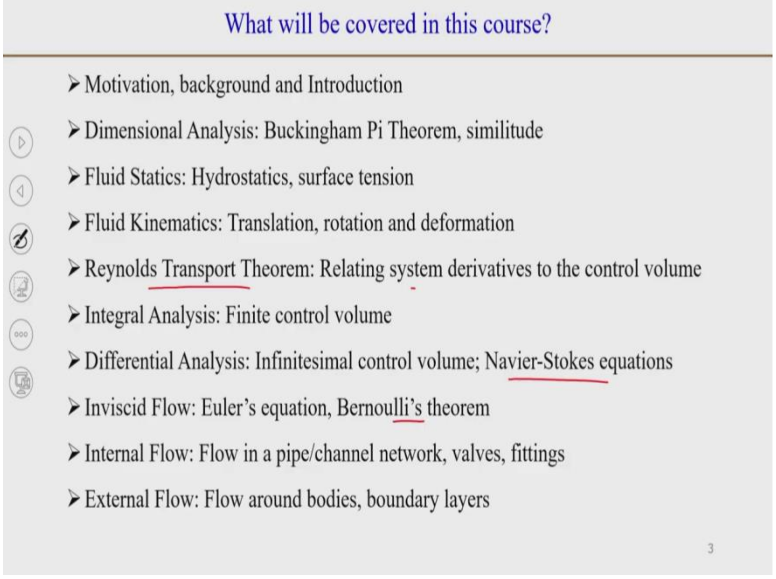

So, what we will cover in this course briefly? First we will be talking about some introductory stuff. Why as a chemical engineer or as a biochemical engineer or as a biomedical engineer we need to learn fluid mechanics? What are the basics of fluid mechanics? Where it is used in these disciplines? And then some basics, some fundamentals of this.

Then we will be looking at three different techniques to solve fluid mechanics problem and one of the most powerful and simplest technique is dimensional analysis which is not only useful in fluid mechanics but in any area of Physics so to say because there we are looking at the dependence of dependent variable on independent variable by looking at their dimensions and then similitude.

The next thing we are looking at fluid statics. So, where we will look at if the fluid is not moving, what is the pressure distribution and if there is if there are two fluids present gas and liquid or liquid and liquid which are immiscible the surface tension or interface tension in between them? So, we will be looking at these concepts in the topic fluid statics.

Then we will look at fluid kinematics. So, the translation, rotation and deformation of the fluids. It may be linear deformation or the angular deformation of the fluid and the rate of because when we talk about the fluid, we will be talking about the rate of deformation. Then another very important concept which is called Reynolds Transport Theorem in which we relate. So, as we go along we will be talking about two different approach to solve fluid mechanics problem, Eulerian approach and Lagrangian approach.

And the Reynolds transport theorem because most of the solid mechanics stuffs that we do, we do in a system approach or in a Lagrangian approach where we follow a mass of, a solid mass and follow its motion. Whereas, in a fluid we are generally concerned with a control volume or fixed volume in which the fluid comes in and go out and we are interested in the fluid flow phenomena in that particular volume.

So, we will be relating these formulations, system formulation in the Lagrangian description with the control volume formulation in Eulerian description and that will be done using Reynolds Transport Theorem. Then we will be looking at integral analysis which is another approach to solve fluid mechanics problem where we are looking at the forces or the motion of the systems at a macroscopic level.

And then we will be looking at differential analysis. So, this is a powerful tool which can provide us the flow field. Flow field means velocity field. Velocity as a function of x, y, z or as a function of coordinates in time in a domain, in a control volume and when we apply differential analysis what we get is the famous Navier-Stokes equations which are used to solve for fluid flow.

Then special case when we can neglect the viscosity of the fluid. So, we will be talking about Euler's equation and then how from this we can derive Bernoulli's theorem or Bernoulli's principles which I believe you would have studied in your school physics. So, once we have looked at the fundamentals we will look some applications in internal flow, flow in a pipe, flow in channel network, for turbulent and laminar regime both and pumps, valves and fittings, and solving basically the piping network problems.

And then we will also be looking at external flows briefly. So, where we will talk about what is a boundary layer, the fundamentals of boundary layer, flow over flat plate, the dependence of boundary layer on Raynold's number and so on and so forth and then we will look at the concept of drag and left and flow around bodies etcetera. So, that is pretty much the content of the course and we will be solving problems as much as possible.

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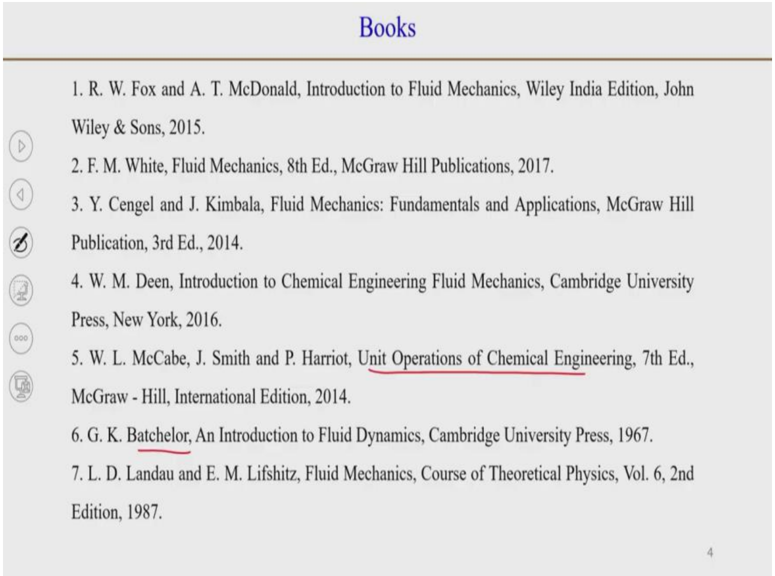

So, about the books as we will providing you the slides in PDF format, so I believe you might not need the books, but for additional reading I have listed down some of the books. So Fox and McDonald, Introduction to Fluid Mechanics or F. M. White, Introduction to Fluid Mechanics and Cengel and Kimbala, Fluid Mechanics: Fundamentals and Applications. All of these, all three books have been written with a mechanical engineer in mind but they are written in a very simple language and anybody from any background can understand this. And there are number of problems and examples in these books.

So, all three of them are very nice and good books. Then there is Introduction to Chemical Engineering Fluid Mechanics by Professor Deen, which talks about lot of Chemical Engineering applications of fluid mechanics. So, that is again a good book especially for chemical engineers and also those who are interested in Biological applications. Then there is this book called Unit Operations of Chemical Engineering. So, unit operations generally refers to physical operations in chemical processing and one can classify them as mechanical operations.

For example, crushing and grinding or then fluid flow operations or momentum transfer and heat transport and mass transport. So, this book covers all of these things in a single volume. So, it has lot of applications of fluid mechanics in chemical engineering discipline. So, this book is important from that perspective to look at the chemical engineering applications of fluid mechanics.

Then this is one of the classic book for fluid mechanics by Batchelor which is An Introduction to Fluid Mechanics and there is another book by Landau and Lifshitz on fluid mechanics.

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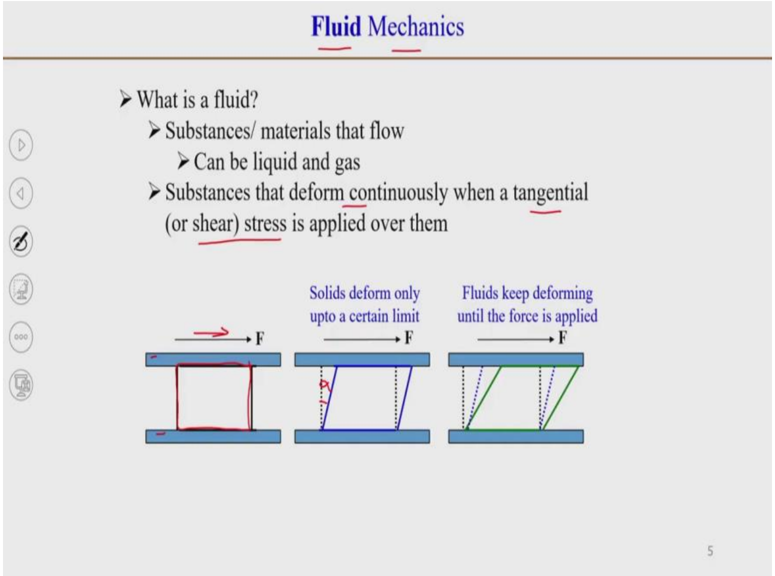

So, these are lot of additional texts which if you are interested you can go through. Ok, So, now let us look at the course Fluid Mechanics. So, as we can see fluid mechanics it involves two words - fluid and mechanics. So, we will look at the two words first. The fluid, what is a fluid?

So, in general, the first answer that comes to mind, we can say that something that flows, is a fluid. So, any material that flows is called a fluid. So, if we look at the three phases of a material, solid, liquid and gas, so out of these three we know that liquids can flow, or gases can flow. So, in fluid we have liquids and gases. Now in more technical terms we can define, the substances that deform continuously under a shear stress or tangential stress are called fluids.

So, when we apply a shear stress on a solid, the solid will tend to deform but it will deform up to a certain extent and then it will stop. So, there will be under strain, there will be a deformation and then it will stop. So, there will be no further deformation in the solid and we relate this with stress versus strain curve and the slope of this curve if you remember we call elasticity for perfectly elastic solids. The slope will be linear between stress versus strain or the curve will be linear.

Whereas for fluid it is deforming continuously. So, the deformation when a fluid is under a stress, it will keep deforming. So, there is a continuous deformation. So, unlike solids, we cannot talk about strain here, because there is continuous deformation. So, in place of strain what we will be talking about? Rate of strain or rate of deformation.

So, fluid and solid can be distinguished based on their deformation. So, here we have an example that a material of this in a 2D plane. We can say that there is a rectangular material between 2 parallel plates and a force is being applied on the upper plate. So, if the material is a solid, it will deform for a certain extent. Let us say, by an angle (α) and then it will stop. So, Solids deform only up to a certain extent. Whereas fluids will keep deforming as the forces until the forces being applied on them.

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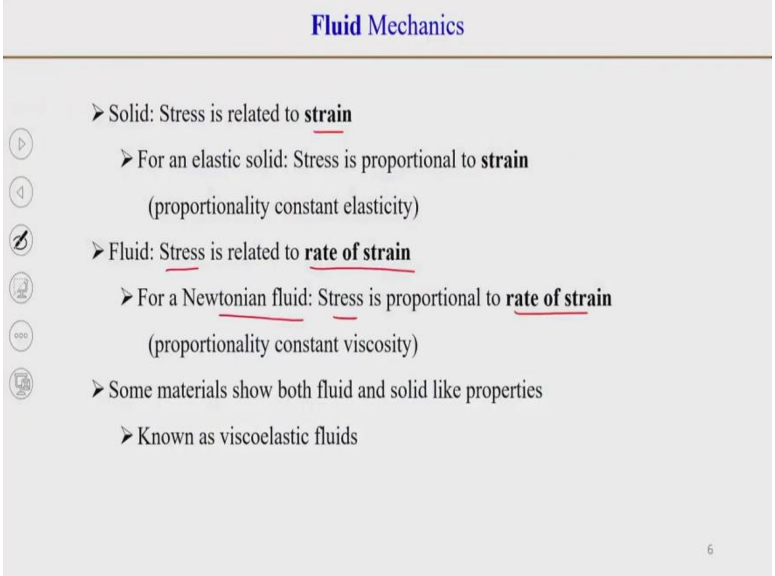

So, now as I said that, in solid what we do is relate the applied stress with the deformation in a non-dimensional form, which we call strain. The change in length divided by the initial length that is how we define strain. So, for an elastic solid we know, the stress is proportional to strain and this proportionality constant is called elasticity. Whereas for fluid, because it is deforming continuously, we relate stress not with the strain but rate of strain.

So, for a Newtonian fluid, it is a particular class of fluid which we will be talking about in the consequent or the subsequent lectures. So, for a Newtonian fluid, the stress is proportional to the rate of strain or if the fluid is not Newtonian even then what we do, when we study the rheological behaviour of the fluid. So, the rheological behaviour is characterizing the property of fluid where we relate stress and rate of strain. If it is linear, then we call it a Newtonian fluid, but if it is not linear then we call it Non-Newtonian fluid.

So in any case for fluids, we always study the relationship between stress and rate of strain and the branch of fluid mechanics in which we do this or we study this is called Rheology. And for a Newtonian fluid, the proportionality constant between stress and rate of strain is called viscosity. So, there are some materials for example bread dough they show both the properties, fluid and solid like properties. That means they will show elastic behaviour and viscous behaviour. And so, such fluid we term as viscoelastic fluids depending on that the behaviour which more toward elastic side, then we call it viscoelastic solids. If it is towards viscous side or fluid side, then we call them viscoelastic fluids.

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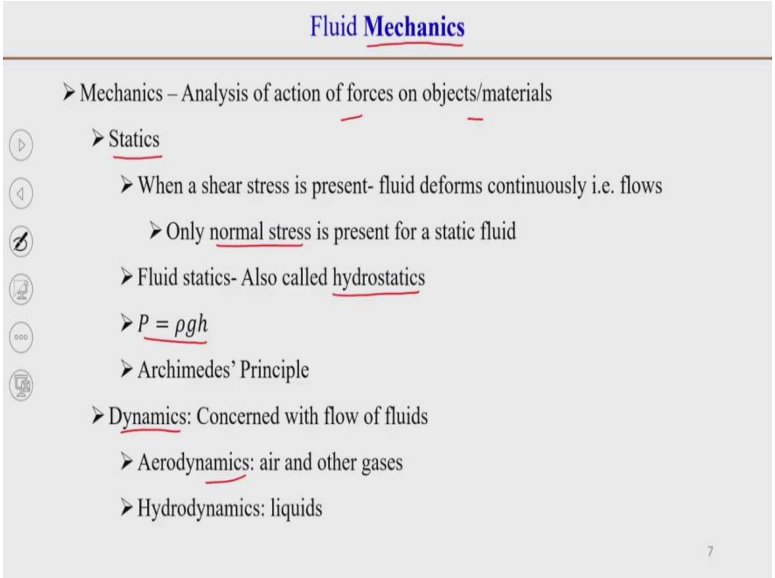

Now we will look at the second term in this, mechanics. So, mechanics as we know, mechanics is the analysis or study of the action of forces on objects or materials. So, when we apply force on a material, what happens to this material? What kind of motion does this material do or what is the pressure distribution, what is the stress distribution inside this material is what comes under mechanics?

Now mechanics can have two branches, depending on that when a material is under a force or it is subjected to a force or stress, stress is basically force per unit area. We will have the proper or more detailed definition of stress later on. But just for now we can think of a stress is force per unit area. So, when a force is applied on a material, it can undergo motion, or it can remain stationary. So, when it remains stationary, then we call it statics or the branch of mechanics which deals with stationary material or stationary fluid when we talk about fluids. So, branch of fluid mechanics, when the fluid is not moving is called fluid statics.

And as we just discussed by the very definition of it, if the fluid is under a shear stress or if a shear stress, that means a tangential stress is being applied on a fluid, then it deforms continuously. So, that means if a fluid is under shear stress, then it will keep moving. So, that will not come under statics. What can be the other form of stresses? It can be a tangential stress or there can be a normal stress. For example, pressure is an example of normal stress.

So, when we talk about a static fluid, it will have normal stress present in it. So, one of the common normal stress is pressure. So, we will look at fluid statics in detail and it is when we talk about statics, we also call it hydrostatics. And you might remember, pressure in a fluid because if a liquid is filled in a vertical column, the pressure distribution with height is,

$$P = \rho g h$$

where h is the depth in the fluid from the top surface.

So, that will come under statics and this is something, which probably you would have studied somewhere. Then Archimedes' principle, we will be able to derive from this so, Archimedes' principle also is under statics. The other branch is dynamics. So, when we talk about fluid mechanics, we have two branches, fluid statics and fluid dynamics. So, bulk of this course we will be looking at the velocity of the fluid, which will come under dynamics. So, we will be looking at when a fluid is subjected to a shear stress or a normal stress, what is the velocity field in this fluid.

So, one of the primary objective of ours will be, finding out the velocity of the fluid. Especially when we are talking about differential analysis, we will be looking at what is the velocity field. So, our unknown will be three components of velocity, u, v and w, if we are talking about Cartesian coordinate system. Now if it is air or other gases, then we term this branch as aerodynamics. Or if it is flow of liquids, then we call it hydrodynamics. So, in fluid mechanics we have two branches, fluid statics and fluid dynamics where statics deals with stationary fluid and fluid dynamics, we will be looking at flow of fluid.

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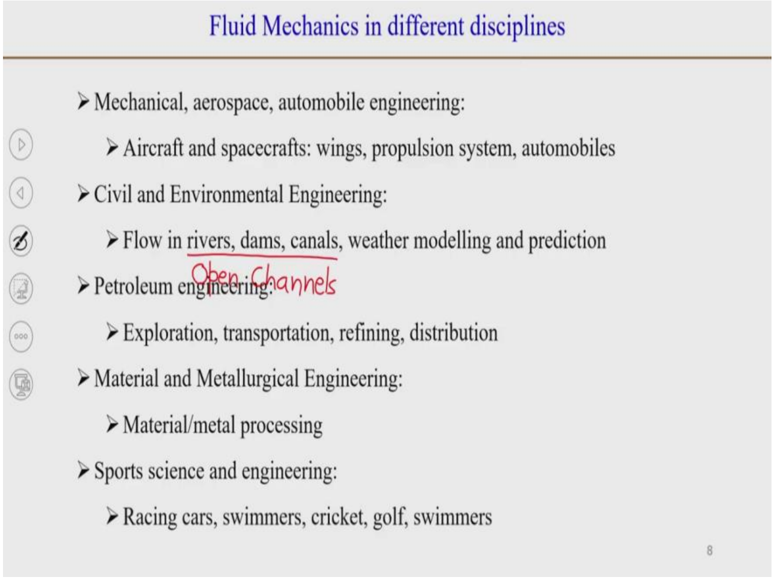

Now if we look at the application of fluid mechanics in different disciplines, so if somebody is looking at from mechanical engineer's perspective or aerospace or automobile engineering which can be sub branches of mechanical engineering, then they need to understand fluid mechanics. For example in aerospace application, design of aircrafts, and the spacecrafts' and rockets, design of wings, design of their propulsion systems, design of Engines, design of gas turbines, etcetera all that requires one to understand and know the principles of fluid mechanics, design of automobiles.

So, one need to understand internal as well as external flow, flow inside an engine, flow over an aircraft, flow over a wing or flow over the car so that the drag on the car can be minimized. All of us know that the, one wants to have a streamlined body, so that the drag on the car is minimized. Then from a civil and environmental engineering perspective, if we look at, one is concerned with flow in the rivers, flow in the dams, flow in the canals, all of these come under open channels.

So, in civil engineering, one of the topics that will be very important is flow in open channels. But we will not cover that in this course. Then from the environmental engineering perspective, one is concerned with weather modelling and weather prediction. So, that is again a very important and useful application of fluid mechanics. For example, predicting of different hurricane or storms and preparing it and that can be done by applying fluid mechanics principles and model the weather.

Pollution modelling or looking at the air pollution etcetra that also will come under the environmental engineering. Now petroleum engineering, so in petroleum engineering, one generally have the what classify three different stream that upstream. Upstream means the exploration of oil and gas from the site itself. So, the exploration itself requires that the oil is transported from underneath. It might be in the land or it might be under the sea. So, how the gas or oil can be transported from inside the earth to the surface, that requires flow in porous media or reservoir engineering what is called that from, so that reservoir engineering includes or it utilizes principles of fluid mechanics.

So exploration, once the oil comes up, it needs to be transported to the refineries so the transportation to the refineries, then during the processing, so, what is called midstream, so during the processing this oil needs to be treated and that is an example of a typical chemical engineering plant where one need to process the oil and during this process the oil is going to go through different heat exchangers, different reactors, different pipelines. So, one need fluid mechanic principles there. And then it needs to be, again transported from the refinery to the different distribution points. It might be via pipelines or it might be via trucks etcetera. In all of these cases one need to apply fluid mechanics principles at different stages.

For material and metallurgical engineering perspective, the processing of material and metals. Again as I said that in a material and metallurgical engineering, one need to, for example, for iron processing, one need to melt the iron and then transport it to different stages, process it to different stages where one need to do, handle liquid matters and liquid materials. So, that involves principles of fluid mechanics as well as heat and mass transfer. So, that is one area where material engineers need to understand the principles of fluid mechanics.

Even in the manufacturing of say computers or chips etcetera, one need to have fundamentals of fluid mechanics because they are again a different set of or different class of materials. So, what is called CVD reactors or chemical vapour deposition reactors, again there is a lot of fluid mechanics principles involved in there. So, in the traditional material engineering where one is looking at the metals etcetera as well as, in new age material where one is looking at manufacturing of electronic material, one need to understand the fluid mechanics principle.

Then Sports science and engineering and this is a relatively new but very fast developing area of fluid mechanics. Where for example, in the racing sports or in racing cars, cycling, one is aiming to achieve as high speed as possible. That means one need to reduce the drag on the car, on the bicycle as well as on the rider of the bicycle. So, again fluid mechanics principle come into play there and the design of racing cars involve lot of fluid mechanics.

Then if you look at and google some of the new technologies that are being used in swimming or swimming as a sport, again fluid mechanic principles come into play there. And then these games for example cricket, golf, basketball, so specially in cricket and golf one is looking at say spinning the ball and that will be depending on what is the force on the ball and that will be depend on the surfaces of the two sides and the pressure and stress distribution which will give a lift to the ball in one direction or that magnets effect when the ball is rotating the net force on the ball so that the ball drifts on towards one side. Again, in golf the ball is dimpled. There are lot of dimples on it which can reduce the drag on the ball. So, the ball can travel to long distances.

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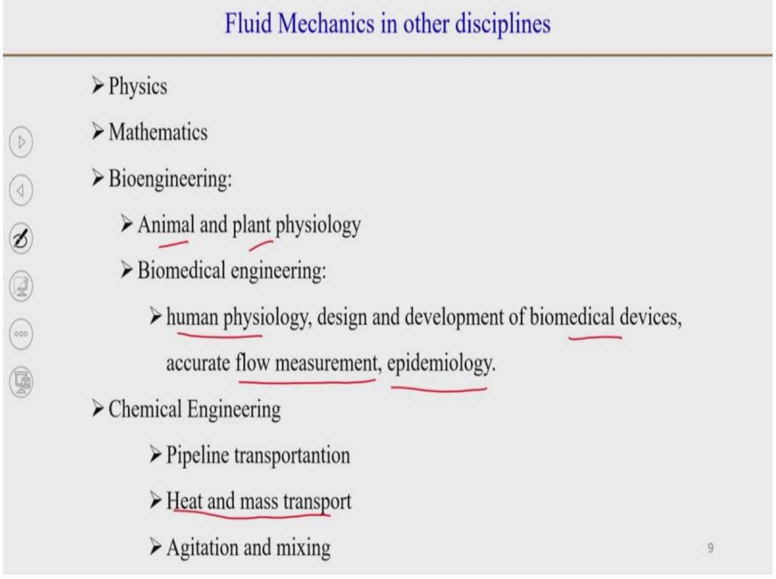

Then there are, fluid mechanics which of course a branch of Physics. So, the students of Physics, they need to understand fluid mechanics and it can be related with other disciplines. For example, when one studies fluid mechanics with the principles of electrical engineering or electrostatics, then it is called electrohydrodynamics, magnetism and fluid mechanics, magnetohydrodynamics. And right now, you might have heard of magneto rheological fluid.

So, the fluid which shows the magnetic property and how the rheology, as I said the rheology is the relationship between stress and strain. So, when there is a force on the fluid, and that force will be because of the magnetic property of the fluid. So, how does the stress versus strain relationship turn out for such magneto rheological fluid and subsequently their motion? That is again a newly developing area.

Then in Mathematics because when we derive the equations, the Navier Stokes equations or in general the Cauchy momentum equations, there will be partial differential equations because the velocity and the pressure, they will depend on x, y, z and time. So, it will depend on different variables. Now these equations are highly non-linear equations and solving these Navier-Stokes equations or momentum conservation equations is one of the most difficult problems in Mathematics itself.

So, lot of development that you see in fluid mechanics has come from mathematicians. And then in applied mathematics, one of the very useful and commercial applications of numerical methods has been in solving these differential equations, which we call computational fluid mechanics and with the advancement in computers, the computational fluid dynamics has developed in last 50 years very fast or very rapidly.

Then in Bioengineering, so if we look at Biology is basically studying living materials or living things or so we can classify living things, in plants and animals. So, the animal physiology and the plant physiology, they involve the flow of fluids. For example, if you talk about plants, they need to transport water from the surface, via roots, towards the leaves, so that the leaves can use the water in the process of photosynthesis. Now this transportation of water happens or it is done via the effect of capillarity. So, that transportation in plant or the movement of sap is based on the fluid mechanics principle.

Similarly, in animals, especially large animals like human beings or other mammals, the nutrient and oxygen, they flow through blood. Now this blood is pumped through heart to different blood vessels which we call arteries and veins, depending on their transporting blood away from the heart or bringing it to the heart. So, that transportation of blood, transportation of air into our lungs that also comes under fluid mechanics and all these physiological principles. So, one need to understand fluid mechanics principle.

Actually, one of the very commonly used equations in fluid mechanics Hagen Poiseuille equation was developed by a fluid dynamicist, by a physiologist, his name was Poiseuille. So, after him we call the equation as Hagen Poiseuille flow which gives the relationship between pressure drop and flow rate for laminar, fully developed flow in the pipe. So, not now, but for last few centuries physiologists have been interested in the principle of fluid mechanics.

Then biomedical engineering we can say, it is a subbranch of bioengineering and one need to understand the human physiology, the flow of blood, the flow of air, even flow of tears in the eye. We need to keep our eyes moist and the joints in the humans, they need to be lubricated, all that comes under or all that is governed by the principles of fluid mechanics.

So, when one wants to develop and design biomedical devices, it maybe for the diagnosis or it may be for a treatment design and development of biomedical devices is strongly dependent on fluid mechanics principle. For example, a artificial heart valve or a heart pump or the devices which we call spray devices inhalers in asthmatic patients etcetera, they all require fluid mechanics principle.

In cardio vascular mechanics one need to have a very accurate flow measurement, that how much blood is flowing to a particular artery is the amount of blood required being transported or not or more recently the epidemiology in tackling Covid-19 in guiding the principles of social distancing. For example, the distance of 6 feet it all comes from the principles of fluid mechanics. When one sneezes how far the droplets can travel, or one coughs how far the droplets can travel? What will be the size of the droplet that will be ejected? All these is decided by the fluid mechanics.

Then in Chemical Engineering, so in chemical engineering, because we have lot of, for the continuous production of chemicals, there is lot of transportation of fluids, reactants, products from one unit to another unit and that is done by pipelines. So, flow of fluids in these pipelines, the valves, fitting etcetera. The designing of the pipeline system, the pressure drop in the pipeline, the pumping power required to all these come under fluid mechanics principles.

Then another important areas of chemical engineering is heat and mass transport. Heat transport because the reactions can be exothermic, or the reactions occur favourably at a particular temperature. So, one need to maintain the reactor at a certain temperature and one need to either give or take heat from the reactor. So, heat exchange is required, and this heat exchange can be done by the principles of conduction, convection but radiation is generally at a very high temperature.

So, very rarely one need to use radiation but when we talk about the heat transfer, predominantly it is convection which is used as a mode of heat transfer. So, convection is basically the bulk flow of fluid and this fluid transports the heat. So, to understand convection one need to understand the fluid flow first. And then agitation and mixing, so when you have a reactor and you want the reactants to be perfectly mixed or you do not want the reactants to be mixed, all these.

So, we have two examples when we study chemical reaction engineering. There are two different reactors in two extremes. One we call plug flow reactor, another we call mixed flow reactor or perfectly mixed flow reactor or CSTR, continuously stirred tank reactor. So, CSTR or MFR, mixed flow reactor, there we are looking at the reactants are perfectly mixed. Whereas, in the plug flow reactor, we look at that there is no axial mixing between the reactants.

So, the reactant that has come inside the reactor at time t is equal to 0, at time t is equal to 1 second they do not mix each other which is what we say in a plug flow reactor which is what we assume in plug flow reactor. So, both of these reactors in an any reactor actually any real reactor will be between these two extremes. There will be some amount of mixing. It will not be perfectly mixed and it will not be that there will be any axial mixing.

So, characterising this mixing which we generally do in chemical reaction engineering is called using residence time distribution and all these will require the understanding or the knowledge of fluid flow behaviour inside these reactors. So, designing of reactors one need to do. Then for mass transport, mass again, mass transport will depend on the process of diffusion which happens say molecular diffusion or one can have turbulent diffusion because of the motion of the fluid.

So, again one need to understand the fluid flow behaviour for mass transport. So, fluid mechanics is an important part of chemical engineering. So, we will stop here and in the next lectures subsequent lectures we will be looking at some more detailed application of fluid mechanics in chemical engineering as well as in biomedical engineering.