Fuels, Refractory and Furnaces
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Lecture No. # 22
Macroscopic Energy Balance: Concepts

This lecture is in continuation to the previous lecture on transport phenomena in furnaces. I have discussed there the importance of fluid flow and heat transfer. So, as such today, I will be discussing fluid flow and in that the macroscopic energy balance. Macroscopic energy balance considers the properties of flow rather physical properties of the flow like density, viscosity, velocity at the inlet and at the exit. In the macroscopic balance what is happening to the flow inside the system is not being considered. Macroscopic energy balance comprises of the defining the physical properties that inlet and outlet and all forms of energy that are entering into the system and that are exiting the system they are to be considered.

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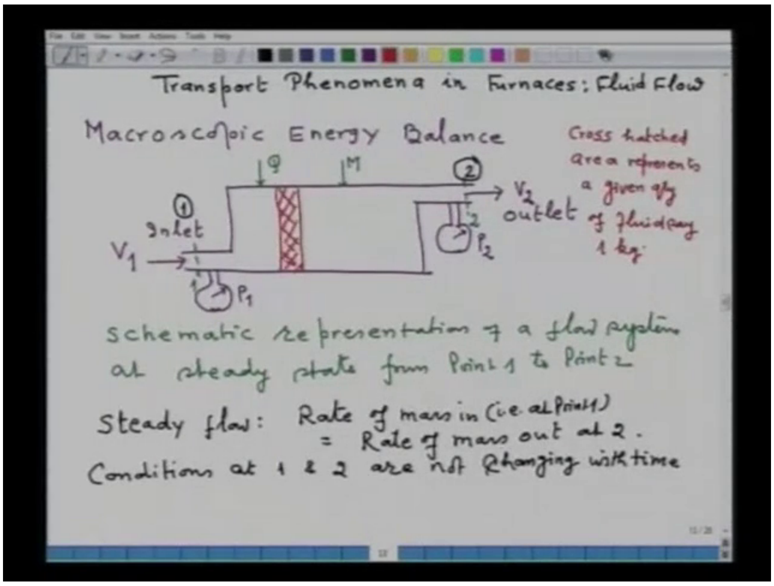

Now let us represent schematically what system under consideration. So for example, we consider a system a schematic representation of a flow system with a schematic representation of a flow system at a steady state. So, here the fluid is entering at velocity v 1 fluid is exiting at velocity v 2. So, this is the inlet, this is the outlet. Here we have put some pressure measuring device that measures pressure at inlet and similarly, we are putting pressure measuring device somewhere at the outlet and this is measuring pressure as p 2.

Now, in the system a certain amount of heat let us take q is entering into the system and a fan is also used which is in introducing certain mechanical energy into the system. So this is a system under consideration. Let us consider a flow of the fluid from inlet to outlet, somewhere we consider this is system at 1 and somewhere here it is 2. So, in fact this is the schematic representation of a flow system at steady state, mind you we are considering steady state from point 1 to point 2.

So, if you consider steady flow that means at steady flow rate of mass in, rate of mass in that is at point 1, we can consider this is point 1 and somewhere here is point 2 that will be equal to rate of mass out rate of mass out at 2. Also, we are assuming that considering conditions at 1 and 2, conditions means all the physical properties which are under consideration, conditions at 1 and 2 are not changing with time are not changing with time. In addition we are representing a cross hatched area in the flow system, this is the cross hatched area. So, this cross hatched area I am writing here, cross hatched area represents a given quantity of fluid, a given quantity of fluid say 1 kg during its passage through the system. That is considering 1 kg of the fluid. Now, as the topic under discussion is macroscopic energy balance so, we have to consider different kinds of energy and energy changes which are occurring as the fluid flows from point 1 to point 2.

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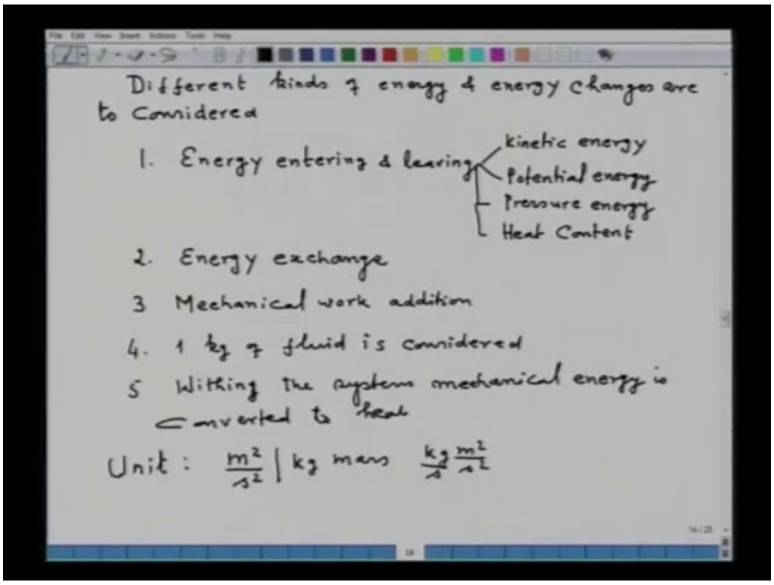

So, the different kinds of energies, different kinds of energy, different kinds of energy and energy changes are to be considered and energy changes are to be considered; so, from the energy entering and leaving say, energy entering and leaving the system; say one form is the kinetic energy by virtue of motion, kinetic energy. Second is the potential energy potential energy mitigates, in the figure say we consider this is the datum, datum point or this is the datum line, and here the system is at height Z 1 and here it is at height Z 2. So, kinetic energy, potential energy and energy entering and leaving pressure energy because pressure energy, when the fluid is entering into the system, it enters at a pressure so as such pressure energy is in and even when it exits the pressure energy also is out, then heat content.

Second energy exchange, second energy exchange between fluid flow system and surrounding that is transfer of heat; if the heat is entering from surrounding to system or system to surrounding. So, heat exchange or energy exchange between system and surrounding. Third mechanical work addition, mechanical work addition say for example, by a fan or pump. Fourth say 1 kg of fluid, 1 kg of fluid is considered. It may do the mechanical work on the fluid which is being surrounded by 1 kg of the fluid so as such the expansion work will also to be considered. Fifth say within the system, within the system mechanical energy, mechanical energy is converted to heat, is converted to heat. So, as such these energies are to be considered.

Now, another important thing is that say unit for energy flow calculation is meter square per second square per kg of mass or if you say per kg rate of mass then the unit will be kg meter square upon second square and the rate of the flow is kg per second. So this is what the unit. Now, potential energy of the fluid it possesses by virtue of the mass position and gravity.

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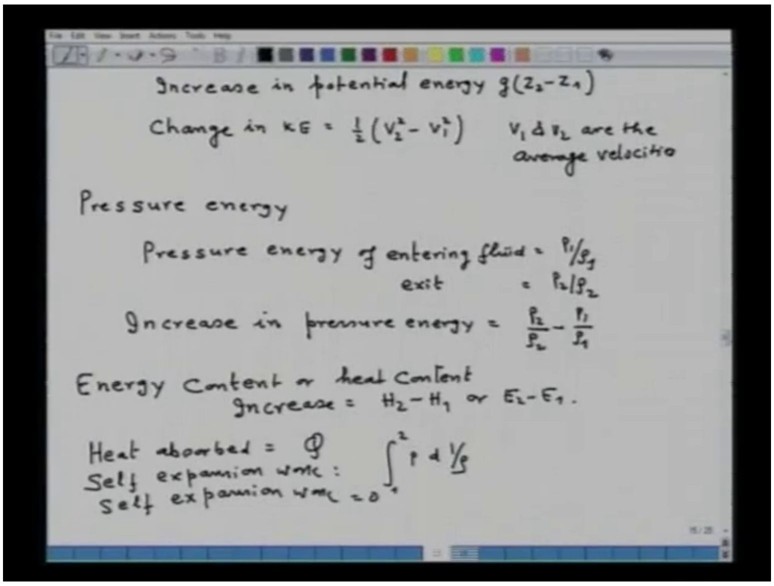

So, the increase in potential energy, increase in potential energy in our system under consideration that will be g into Z 2 minus Z 1 mind you we are writing per unit mass. Similarly, change in kinetic energy, change in kinetic energy that will be equal to half V 2 square minus V 1 square, again it is on per unit mass where V 1 and V 2 are the average velocities, are the average velocities at point 1 and at point 2. Third form of energy is pressure energy, is the pressure energy. Now, this pressure energy is there is mechanical energy possessed by the fluid because it is under pressure, at some pressure it enters, at some pressure it exits. So, it possesses some type of mechanical energy. So, the pressure energy of entering fluid, pressure energy of entering fluid that is at inlet whichever way you want to call, that is equal to P 1 upon rho 1 and at the exit that will be equal P 2 upon rho 2 therefore, increase in pressure energy, increase in pressure energy as the fluid flows from 1 to 2 that will be equal to P 2 upon rho 2 minus P 1 upon rho 1.

The energy content energy content or let us say heat content at 1 and 2 H 1 and H 2 they are the (( )). So, increase in energy content so increase that will be equal to H 2 minus H 1 or E 2 minus E 1. Now, if the heat enters on surrounding to the system then you have to consider so this heat absorbed, heat absorbed as shown in the figure that is equal to Q entering from surrounding to system. Then you have self expansion work, self expansion work and as I have said the self expansion work is due to the surrounding of the fluid concerning the 1 kg of the fluid, say we have considered 1 kg of the fluid and this is the mechanical work that 1 kg of the fluid done on fluid surrounding it as it expands because if the fluid flows depending on the density change there is an expansion also occur and as a result of expansion mechanical work will be done and that is called the self expansion work and that is equal to 1 to 2 P d 1 by rho. Now, the self expansion work, the self expansion work is equal to 0 when there are no density changes.

Remember when they are no density changes in self expansion work is to be 0. Another form of energy that we have to consider and that is the most important part in any mechanical energy balance is a friction or so called frictional forces and this frictional forces is responsible say conversion of mechanical energy into heat.

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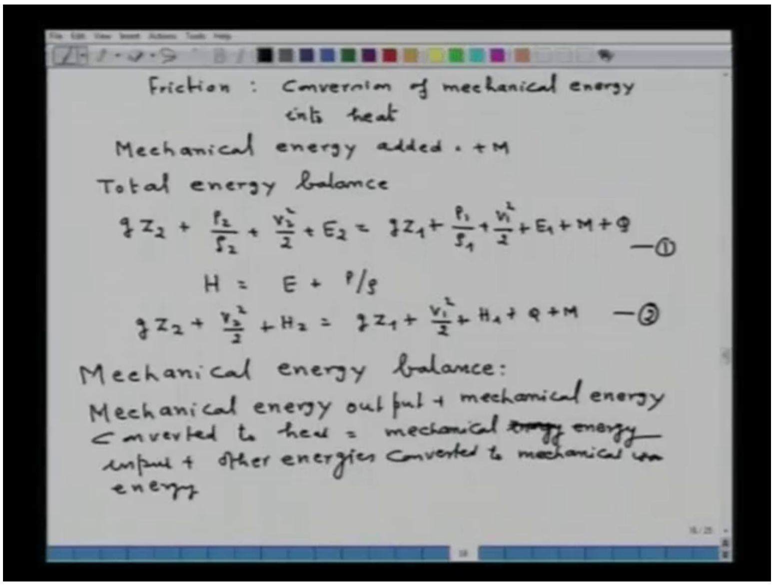

Conversion of mechanical energy, mechanical energy into heat because as the fluid flows there is a frictional forces exerted by the fluid on the wall depending on the roughness of the wall and there is an entrance and exit effect, all these they have to be considered in the friction and that is also being accounted in the so called mechanical in or in the so called macroscopic energy balance. Then mechanical energy, mechanical energy added say we incorporated some fan or by pump let us say that is equal to plus M, plus means that means we are adding into it. So, then we can write down now total energy balance, we can write down now total energy balance just we have to sum total at point 1 and point 2. So, g Z 2 plus P 2 upon rho 2 this is the pressure energy at point 2 plus V 2 square upon 2, this is the kinetic energy at point 2 plus energy content at 2 that will be equal to g Z 1 plus P 1 upon rho 1 plus V 1 square upon 2 plus E 1 plus M and plus Q and that is our equation number 1. So, that is how the total energy balance comprises of.

Now, you see that, we can also put it let us say H that is equal to E plus P by rho you know this thermodynamic equation then we can put it for example, g Z 2 plus V 2 square by 2 plus H 2 that is equal to g Z 1 plus V 1 square by 2 plus H 1 plus Q plus M and that is our equation number 2. Now, equation number 2 is in fact an energy balance. Now, this equation is useful only when there are heat content or changes in the heat are involved but, in our for example, in a steam engine. There is considerable change in the heat is involved then the equation 2 is helpful, but for gas flow systems at substantially atmospheric pressures in furnaces, fuse and ordinary metallurgical equipment and for liquid flow system the mechanical energy balance is much more useful. So, now alone mechanical energy balance say input and output of mechanical energy it cannot be equated as you have done in case of energy balance. Now, why we cannot equate it? Because conversion of heat into mechanical energy that has to be considered and other energy conversions occurring within the system.

So, these 2 things because of this a straight away mechanical energy balance input and output of mechanical energy it cannot be equated. So, mechanical energy balance which is useful for the design of the furnace equipment fuse, furnaces and so on that can be derived by considering the conversion say conversion of heat into mechanical energy and other energy conversions that are occurring. So, the useful form is the mechanical energy balance, mechanical energy balance and mechanical energy balance can be written that is mechanical energy output, mechanical energy output plus mechanical energy converted to heat. Mechanical energy converted to heat that is equal to mechanical energy input, mechanical energy input plus other energies converted to mechanical energy. So, that is what a mechanical energy balance is in qualitative statement.

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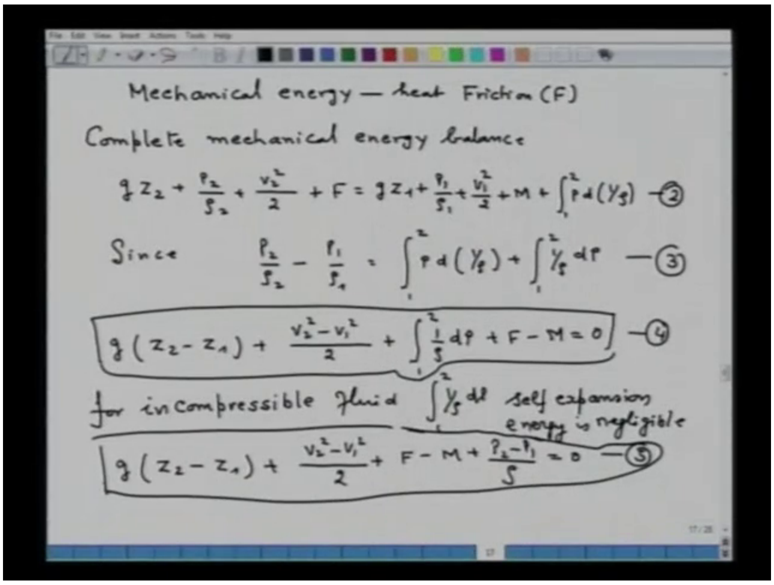

So, now in order to make a quantification of this, now say mechanical energy, mechanical energy converted to heat that is the friction, that is the friction and frictional forces are F. Say other forms of energy that has converted into mechanical energy is by expansion of the fluid which furnaces which furnishes so called self expansion work. So, accordingly the complete mechanical energy balance, complete mechanical energy balance, mechanical energy balance it can be written as g Z 2 plus V 2 upon rho 2 plus V 2 square upon 2 plus F that is equal to g Z 1 plus P 1 upon rho 1 plus V 1 square upon 2 plus M plus P d 1 by rho. Here, Z 2 and Z 1 they are the positions, P 2 is the pressure at point 2, rho 2 is the density of fluid at point 2, V 2 is the velocity at point 2, F is the frictional forces and P 1 pressure at the point 1, rho 1 is the density of the fluid at point 1, V 1 is the velocity at point 1 and M is the mechanical work added by pump or whatever the case maybe and P d 1, P d 1 by rho is the self expansion work.

Now, since you know, now since say P 2 upon rho 2 minus P 1 upon rho 1 it can be written equal to 1 to 2, P d 1 by rho plus 2, 1 by rho d P and let me put this equation is 2, this equation is 3. So, by combining 2 and 3 and by writing in terms of change in mechanical energy so the equation look g Z 2 minus Z 1 plus V 2 square minus V 1 square by 2 plus 1 to 2, 1 by rho d P plus F minus M that is equal to 0 and that is our equation number 4. Now, for incompressible fluids, say for incompressible fluids, for incompressible fluids say 1 upon rho into d P, 1 to 2 the self expansion, self expansion energy is negligible. Self expansion energy is negligible because by virtue of the incompressible fluid the density does not change. So, for incompressible fluid the mechanical energy balance is g Z 2 minus Z 1 plus V 2 square minus V 1 square by 2 plus F minus M plus P 2 minus P 1 upon rho that will be equal to 0 and this is our equation number 5.

So, as such we have this is the mechanical energy balance and for incompressible fluid its density is constant. So, we can integrate it and get it P 2 minus P 1 so this our mechanical energy balance and mind you that this mechanical energy balance has been derived by considering for unit of mass, that point is to be cleared.

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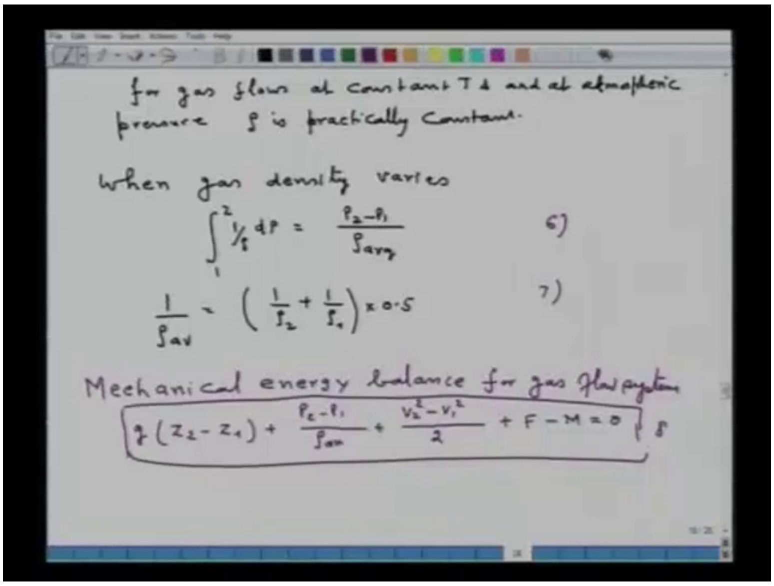

Now, for gas flows at constant say for gas flows, for gas, for gas flows say at constant temperature and atmospheric pressure and at let us say atmospheric pressures, at atmospheric pressures say rho is practically constant, rho is practically constant. So, then we can write down say equation 5 for considering this one then. Now, when gas density varies, when the gas density varies then we can evaluate the integral 1 to 2, 1 by rho d P that is equal to we can put it P 2 minus P 1 upon rho average where say rho average if suppose the gas passes through a duct and the temperature decreases from t 2 to t 1 then 1 upon rho average that will be equal to 1 upon rho 2 plus 1 upon rho 1 into 0.5 that is why you are taking the arithmetic average.

So, mechanical energy balance, mechanical energy balance for gas flow system, for gas flow system it will be g Z 2 minus Z 1 plus P 2 minus P 1 upon rho average, rho average plus V 2 square minus V 1 square by 2 plus F minus M that is equal to 0. So, this is the mechanical energy balance for gas flow system and let me put let me just again number the equation. Let us put it this is number 6, this is number 7 and this is number 8. Now, this equation 5 is or incompressible fluid I mean when the density is constant then the equation 5 can be used and for gas flow system this equation 8 is very useful.

Now, if you see into those equations say 5 and 8 you will find that frictional forces is the most important part and that are to be evaluated. Now, in the equation 8 or equation 5 if you look, you will find that g is acceleration due to gravity and is known. Z 2 and Z 1 you know the position of the inlet and position of the outlet with reference to a datum point. And by virtue of the mass of the position the potential energy is entered is entering or exiting Z 2 and Z 1 they are known to us.

Similarly, P 2 and P 1 they can be measured at the outlet and at the exit and one knows them. Rho average for gases you know the temperature at entry and temperature at the exit by invoking ideal gas law one can calculated, one can calculate the densities and one can find out the average density and in case of liquids one knows the density of the fluid and we are taking an incompressible fluid and density of the fluid is also known to us. Now, the most important part in the mechanical energy balance when it is applied to the flow systems for designing of the fluid, designing of the stack, designing of the flow measuring devices the most important parameters are the evaluation of frictional forces F. And if one can evaluate the frictional forces then one can also find out what should be the mechanical work or say if you require to add a pump then one can calculate. So, as such our next next thing would be the evaluation of frictional forces.

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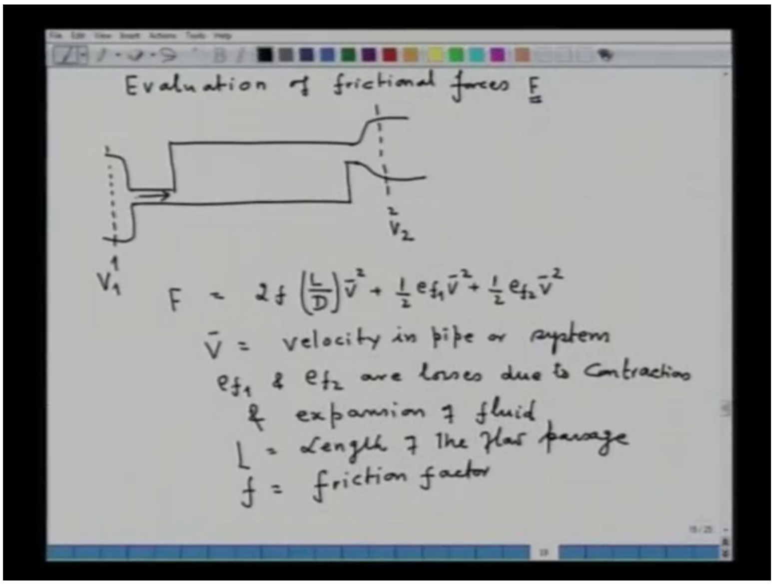

Evaluation of frictional forces F; now, say in the figure you see we represented a flow system at which the fluid is entering at point 1. I am slightly modifying this flow system say what I am doing now that the fluid is entering from a reservoir and here it is exiting into a some sort of a reservoir and the fluid is flowing into the system. So, now if this is my now position 1 and this is my position 2. Recall in earlier our position 1 and 2 was directly at the inlet. Now, in this 1 and 2 as you see from here there is as the fluid enters from 1 to the system, this is my system then there is a contraction.

As the fluid exits from the system there is an expansion and the frictional forces will act also along the walls of the system. So, in such the evolution of frictional forces is F that will be equal to 2 f L upon D, V bar square plus half e f 1 V bar square plus half e f 2 V bar square where this V bar that is equal to velocity in pipe, velocity in pipe if you are considering flow in a pipe or velocity in system.

Now, this point is to be very clearly understood that this V bar is different than V 1 and V 2. In this system V 1 is here and V 2 is here where V bar is the velocity in this particular case whereas, whereas, in this 13 whereas, in the figure you see the V 1 is at the inlet and V 2 at the outlet of the system. Whereas if the system is connected by a reservoir on those sides then as the fluid enters there is contraction, as it exits there is an expansion. So, accordingly one has to consider the losses because of friction occurring due to contraction as well as due to expansion so as such e f 1 and e f 2 are the losses due to contraction and expansion of fluid and expansion of fluid. L is the length of the flow passage. f is the friction factor, f is the friction factor. Now, again I must emphasize over here that while applying the mechanical energy balance to the flow system the differentiation between V 1, V 2 and V bar must be clearly understood as my experience with the teaching of this course I always found that students commit mistakes in understanding V 1, V 2 and V bar.

Now, note V 1 and V 2 they are the velocities at point 1 and at point 2. Whereas V bar is the velocity in the pipe for example, or velocity in the system. Physically you can also perceive that the frictional forces will act only there when the fluid is in touch with the surface. So, V bar will the velocity in the pipe whereas, V 1 and V 2 they are the velocities at the entrance and at the exit. So, that point should be very very clearly understood while applying the mechanical energy balance that is in F is equal to 2 f L by D V bar square plus half e f 1 V bar square plus half e f 2 V bar square. V bar is not equal to V 1 and V 2. V bar is the velocity in the system itself. So, that point is to be clearly understood.

Now, normally e f 1 and e f 2 values will be given while solving a problem. V bar is the velocity of pipe or in the system and it can be calculated by a flow rate divide by the cross sectional area that is sometimes also called empty tube velocity. So, the concept of friction that the frictional forces act only when the fluid touches the wall and therefore, this V bar has to be substituted by q upon a. So, the only thing which is unknown in evaluation of the frictional the frictional forces is the frictional factor that is the f.

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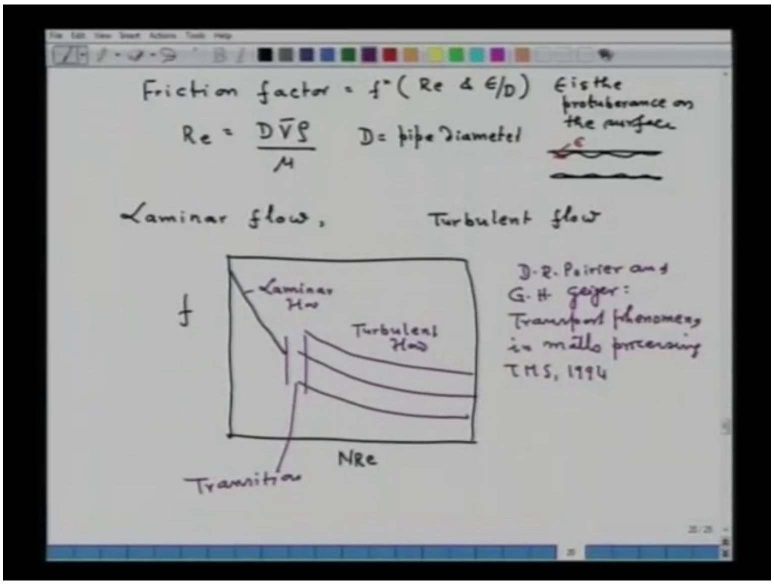

Now, this friction factor, friction factor it is a function of Reynold's number and surface roughness factor, where epsilon is the protuberances; protuberance on the surface. What does it mean? Say for example, if this is the surface, this is the pipe and this is the surface. Now, surface is never a plain which I have shown, it will be something like this; that is roughness. So, this height from here to here that is the epsilon that is what I wanted to say.

Now, the friction factor against the friction factor is the function of Reynolds number and Reynolds number is defined D mind you D V bar remember rho upon mu, D is the diameter, V bar is the velocity same as I have just now defined, rho is the density and mu is the viscosity of the fluid. D for example, if you have considered a pipe then it is a pipe diameter. Say pipe diameter. Now the variation of friction factor with the Reynolds number, it depends on the geometry of the system.

For example, if you consider friction factor for flow in tube which is long and smooth too then you know we have Laminar flow, we have Laminar flow and then we have Turbulent flow. For flow of fluid in tubes long and smooth normally the transition from laminar to turbulent flow occurs when the Reynolds number exceeds 2100. So, in books you will find a plot which is f against Reynolds number, I am just drawing symmetrically so the frictional factor for laminar flow is this 1, it decreases as the Reynolds number increases and then under the turbulent flow we have.

This is for the turbulent flow, this is for laminar flow and this is somewhere is the transition and for detail you can refer the book by D. R. Poirier and G. H. Geiger, name of the book Transport phenomena in materials processing. It is TMS publication, 1994 or in any fluid dynamic book you will find the friction factor plotted against Reynolds number for various geometries for pipes, for tubes, for sphere or rectangles and what not.

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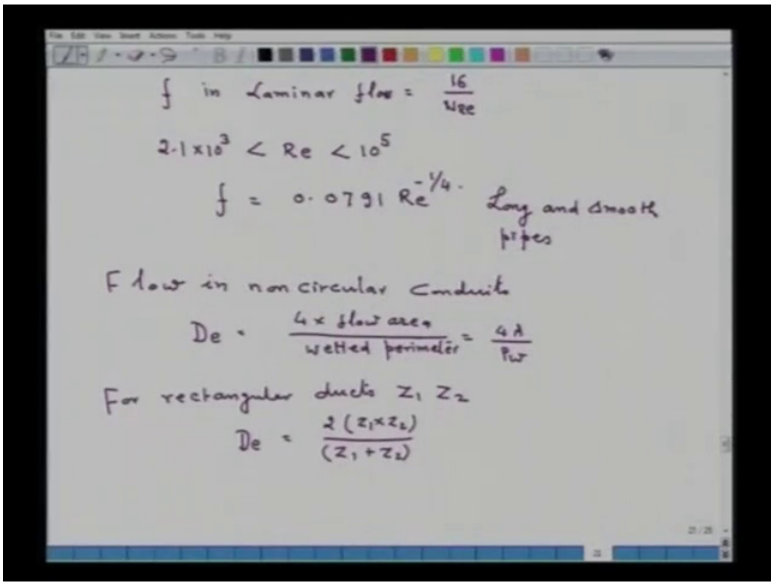

So, for for say friction factor f, for flow in tube in laminar flow, f in laminar flow for tubes it can be calculated from equation 16 upon N R e. 1. Now, when the Reynolds number is between 2.1 into 10 to the power 3 less than Reynolds number less than 10 to the power 5 then f can be calculated is equal to 0.0791 Reynolds number to the power minus 1 upon 4, this is for long and smooth pipes. I just given for laminar flow and turbulent flow this 2 equations. However, for all other geometries and depending on the type of problem, depending on the type of flow system the value of f can be determined from the standard charts which are available in any fluid dynamic book

Now, sometimes you will you may also come across the non circular type of geometries. So, therefore for flow in non circular conduits, flow in non circular conduits the problem comes what should be the diameter? So, here we take an equivalent diameter D e, D e is the equivalent diameter and that is defined as 4 into flow area upon wetted perimeter that will be equal to 4 A upon P w for example, for the rectangular ducts say for the rectangular ducts of dimensions Z 1 and Z 2 the equivalent diameter D e that will be equal to 2 into Z 1 into Z 2 upon Z 1 plus Z 2. So, while calculating the Reynolds number this thing has to be kept in mind the calculation of equivalent diameter because the friction factor calculation by the equation 16 by N R e or other equation that is that takes into account V is the diameter. So, one has to substitute so called the equivalent diameter for all non circular conduits.

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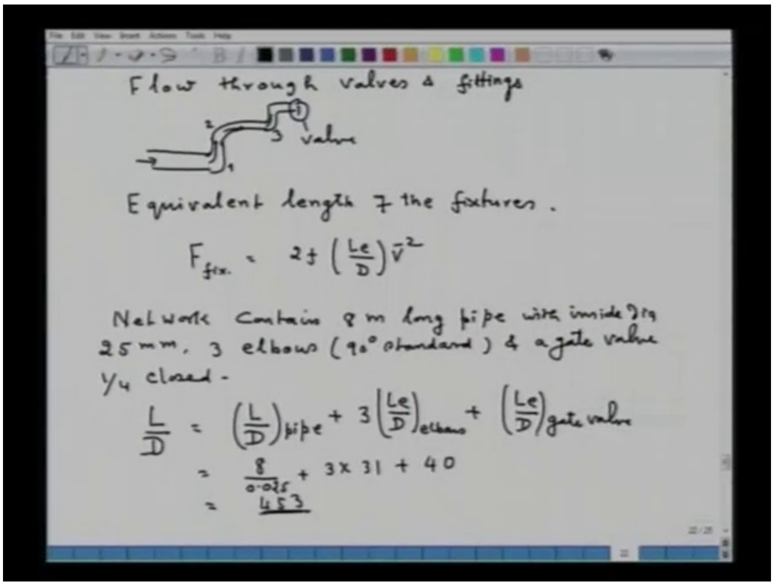

Now also there can be a situations also say flow through valves and fittings, flow through valves and fittings. Say, in several cases say we may have a flow a flow system has to be designed for example, this is a straight line and then 1 requires a sort of say bends and then again you have 1 bend, another bend and then further like this. So, it is many things are possible. So, to evaluate and then there is a valves are also attached in the flow system then what we have to consider, we consider the so called an equivalent length, an equivalent length, an equivalent length of the fixtures, of the fixtures. For example, we have here 1 elbow, then you have second elbow, then you have third elbow and then somewhere here we have a valve. So, fluid is flowing from here through the elbows, through the pipe, through the elbows and again valve. So, everywhere there will be frictional losses and these frictional losses are accounted by converting the fixtures into the respective equivalent lengths.

Now, this equivalent length concept is that the frictional forces through the fixtures that will be equal to 2 f L e upon D, V bar square. Now for example, say if a network, say if a network it contains 8 meter long pipe, 8 meter long pipe say within, with inside diameter let us say 25 millimeter, it has 3 elbows and elbows are 90 degree and standard one and a gate valve and a gate valve which is one fourth closed, then L by D for such cases will be equal to L by D of pipe plus 3 elbows and each elbow has a equivalent length elbows plus L e upon D of the gate valve. Now, for your information these fixtures could be of many types, standard elbow or 90 degree, 45 degree for all such cases a standard table has be consulted in order to find out the losses because what will happen because of the elbow, because of the valve there will be losses in the pressure and these losses are accounted by converting those fixtures into the equivalent length that is all.

So, in this case L by D which has to be substituted for calculation of the frictional forces that will be equal to 8 upon 0.025 plus 3 into 31, this value of 31 I have obtained from a table and as such you can see also those tables and from those tables these values are available and they can be substituted plus for the gate valve it is 40. So L by D for evaluation of the frictional forces in this case has become equal to 453 and this value of 453 that should be used in this particular equation. That is this is the L by D and this value of 453 that you have calculated, it has to be used in this expression.

Now, had there been no elbows and no gate valve, then L by D that is the length of the pipe divide by the diameter. So, this whole macroscopic energy balance it requires lot of exercise to solve the problem. So, as such we will see some of the illustrations in the forth coming lectures.