Upstream LNG Technology
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Lecture – 14
Flow in Natural Gas Systems

Welcome back, today we shall take up a new topic after we have learned about the estimation methods of various types of properties, which will be utilized now for further analysis. Now today we shall be looking into the flow of the natural gas, and because this knowledge will be required for further analysis and design of the various types of fluid moving machineries; like compressor pumps etcetera and also the various types of flow measuring devices. So, we shall be looking into the fluid flow in natural gas systems

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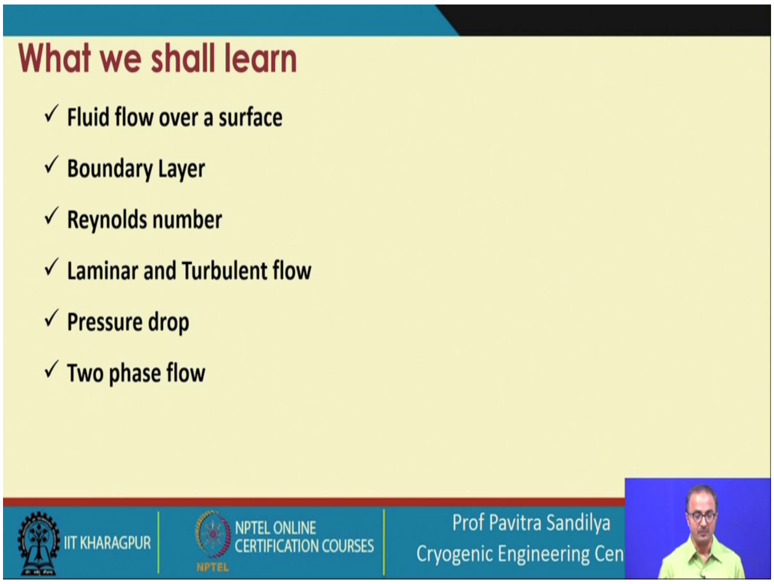

In this lecture we shall be learning about the fluid flow over a surface ah, then we shall go to some boundary layer concepts followed by Reynolds number, then laminar and turbulent flow pressure drop and two phase flow. First let us go to the fluid flow over a surface.

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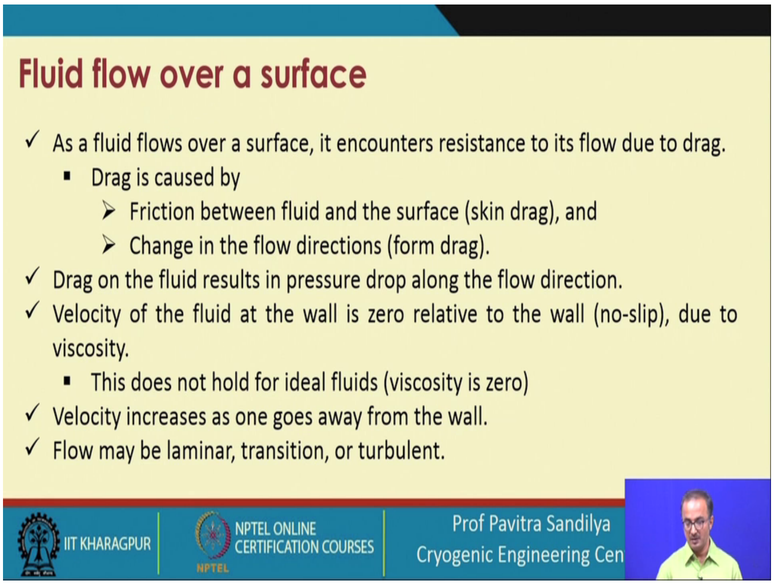

Now, whenever there is a fluid flow on the surface, the fluid encounters some kind of resistance to its part and this resistance is called some drag and this drag is caused by primarily two effects; one is the friction between the fluid and the surface which we call the skin drag, and then whenever a fluid is flowing there might be the, the fluid might change its direction during its flow ah. So, in that case we have the form drag. So, like for example, the fluid is flowing through some elbow or some T joint. So, in this case for what we will find that there is a change in the direction of the flow, so this causes form drag

Now, because of this drag there will be a reduction in the energy of the fluid; that means, this will be reflected in terms of the pressure drop. So, and this, if there is too much a pressure drop what will happen? The flow may cease at some point of time. So, we have to see to it that whatever pressure drop occurs, there should be compensated for form by supplying energy to the fluid from external sources; that is why it is important for us to understand the fluid flow, and generally the velocity of the fluid is taken to be 0 at the wall ah, this is because of a property called viscosity and this particular assumption is called no slip condition.

This no slip condition does not hold for ideal fluids ideal fluids means those fluids which have 0 viscosity and as we move away from the wall, we find that the drag effects reduces and the fluid velocity again starts increasing and ultimately it may attain the free stream velocity of the fluid

Now, flow may have different nature, it may be laminar, it may be turbulent or it may be somewhere in between, which we call the transition zone. Now we come to boundary layer.

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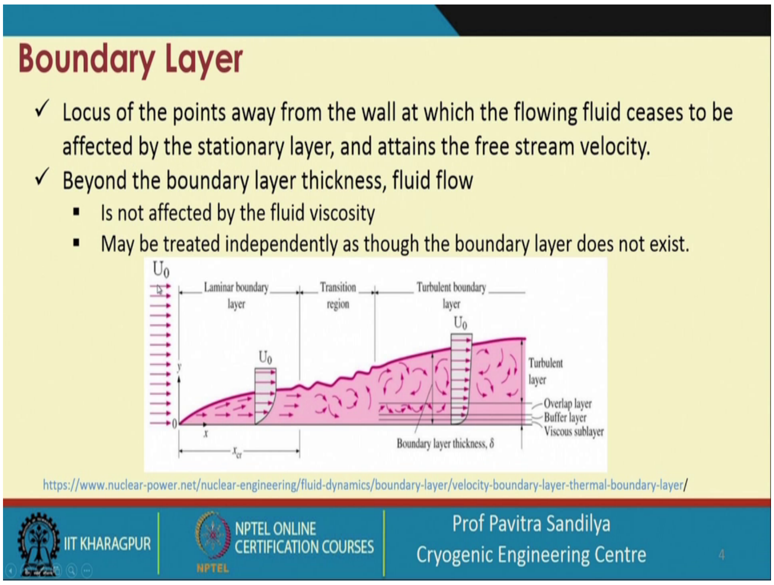

Now, boundary layer is a concept which was proposed by Prandtl, Ludwig Prandtl to explain some of these flow phenomena. So, first let us understand what is boundary layer. This boundary layer signifies the locus of the points away from the wall, where the fluid ceases to experience the drag effect from the wall and the fluid stream attains the stream velocity

Now, beyond this so, there is a particular thickness. We assume that there is a thickness of the fluid above the wall within which the effect of the drag exists and beyond this boundary layer thickness fluid flow is not affected by the fluid velocity and their, this bound, and in this conditions outside the boundary layer, the fluid is treated independently, as if there is no boundary layer

Now, here in this particular figure we see that how this boundary layer exists. See on this side or the left hand side we see the fluid is coming with a free stream velocity of U 0 and as it enters this particular surface that on the x axis, we show x direction and the perpendicular the surface we call it y direction so, initially what happens that the fluid comes in contact with the wall and the, because it has 0 velocity at the wall.

So, the whatever fluid elements are above the wall will get retarded by the fluid, which is below it and slowly and slowly we find is certain kind of layer is developing. And here in this particular figure we are showing that how the fluid velocity changes from the wall to 0 and up to the free stream velocity and this boundary layer keeps developing as we go inside the surface

And then, initially it may be a laminar boundary layer, then there would be some kind of transition where we are showing this some kind of disturbance is taking place. So, this in transition zone, it will be sometimes laminar, sometimes turbulent. So, it is always changing its nature and ultimately, we go to the turbulent boundary layer, as we move in still inside the surface and here we have, we are showing some layers like near the surface, we have a viscous sub layer then we have some buffer layer, some overlap layer and ultimately we have a turbulent zone.

So, this is the overall picture, we visualize to understand the fluid flow and this kind of things are purely conceptual. We try to put these concepts into use in explaining the various types of fluid flow phenomena

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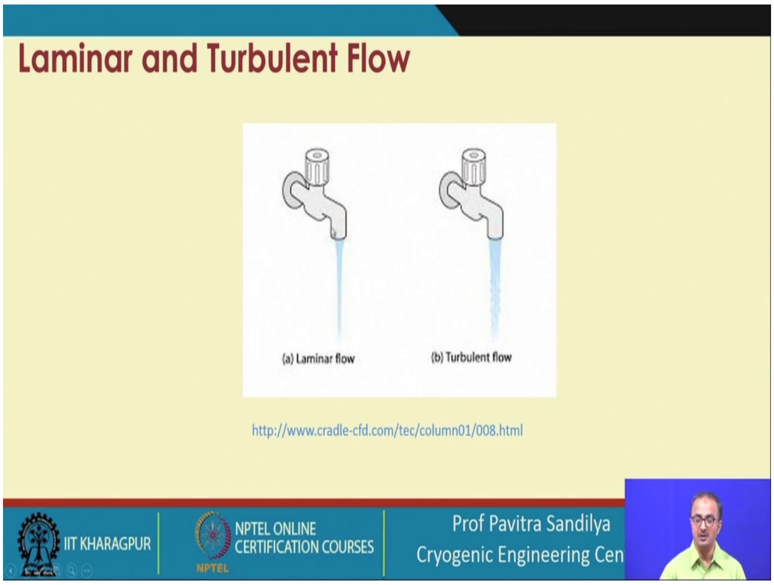

Next we come to some rudimentary knowledge about laminar and turbulent flow. Now this you can observe many a times in your, at your home, at your workplace around you. So, this you can see that we have taken a very simple example which you may find at your workplace or home that a water is flowing through a tap.

Now in this case we see that when the tap is opened a little we find, water will initially form some bubble and when at certain opening we will find a continuous flow of water starts and initially we will find this flow is very well systematic, which is not going to take a very very definite path.

So, this particular flow is the laminar flow, but as you keep opening the valve of the tap you find that the flow becomes more and slowly and slowly the flow becomes more and more irregular, and in this case you will find, ultimately you will find the flow is very irregular and you would approach the turbulent flow. So, this is a very general observation which you find in your day to day life

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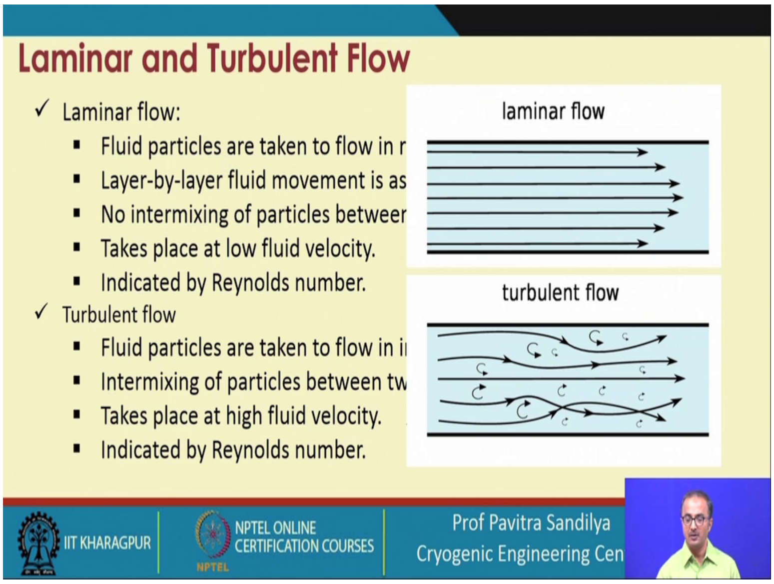

Now, this observation now we try to give some kind of definition to this that in laminar flow we assume that the fluid particles are going into a some regular paths. Now the when is the regular path it means that, it may going to a straight to the path or it may take some curved path, but it is going to a regular fashion and we also assume that the fluid is moving a layer by layer manner and each layer is having different momentum.

That means, a layer which is nearest to the wall, will be having less momentum and as we move away from the wall the momentum of the fluid particles will increase. So, there will always be some kind of momentum exchange between two consecutive fluid layers. And we also assume that there is no inter mixing of particles between two consecutive fluid layers and this kind of laminar flow takes place at low velocity.

Now, next this, all this phenomena is indicated by Reynolds number about which we shall be learning a bit later. Now here I have shown by a picture that how we visualize the laminar flow to take place in some kind of a conduit. Here we see that the arrows are indicating that is a quite regular flow and the length of the arrows, is indicating that the fluid velocity, magnitude of the fluid velocity. The smaller arrow means lower, lower velocity and the longer allow arrow means the higher velocity.

Now, next we come to turbulent flow. Now unlike the laminar flow in the turbulent flow, the fluid particles going to very irregular path and there will be inter mixing of the particles between two consecutive layers and it takes place at higher velocity and again it is indicated by Reynolds number.

Now, here I have shown in the picture that how we visualize the turbulent flow takes place. So, we can see that the fluid particles take various types of paths, zigzag path and there are these lots of disturbances, sometimes we call them vertices or eddies. So, these eddies and vertices are formed in the turbulent flow.

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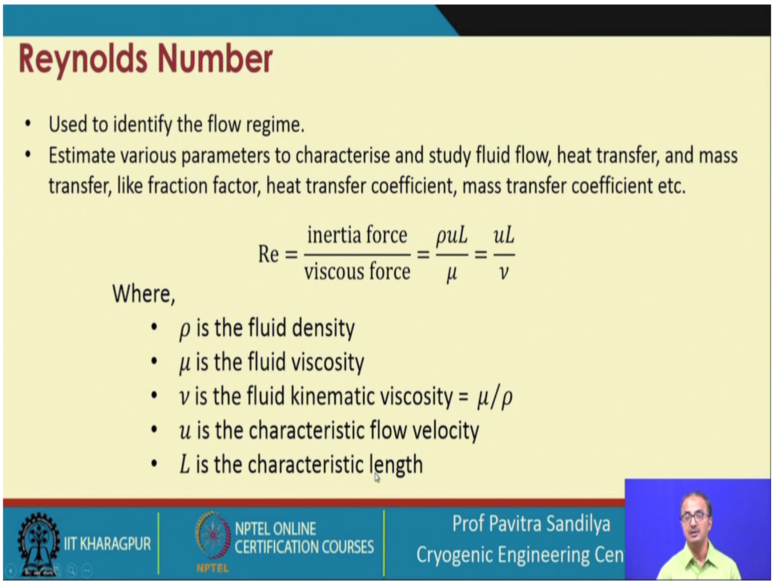

Next, we come to Reynolds number. The Reynolds number we will find has a very very big use in the study of the transport phenomena; that is fluid dynamics then heat transfer and mass transfer. So, Reynolds number is used to identify the various types of flow regimes, then this Reynolds number is also used to characterize and estimate the various parameters which are involved in the study of the transport phenomena. For example, in kind of fluid mechanics we find the friction factor.

In case of heat transfer we find the heat transfer coefficient and in case of mass transfer we find the mass transfer coefficient by the knowledge of the Reynolds number, and this is defined as some, the ratio of the inertial force to the viscous force and is given by this expression that rho uL by mu and rho is the fluid density, mu is the fluid viscosity, u is the characteristics fluid velocity and L is the characteristic length and this can again be written in other way uL by nu, where nu is the kinematic viscosity of the fluid and which is nothing, but the ratio of the dynamic viscosity and the density

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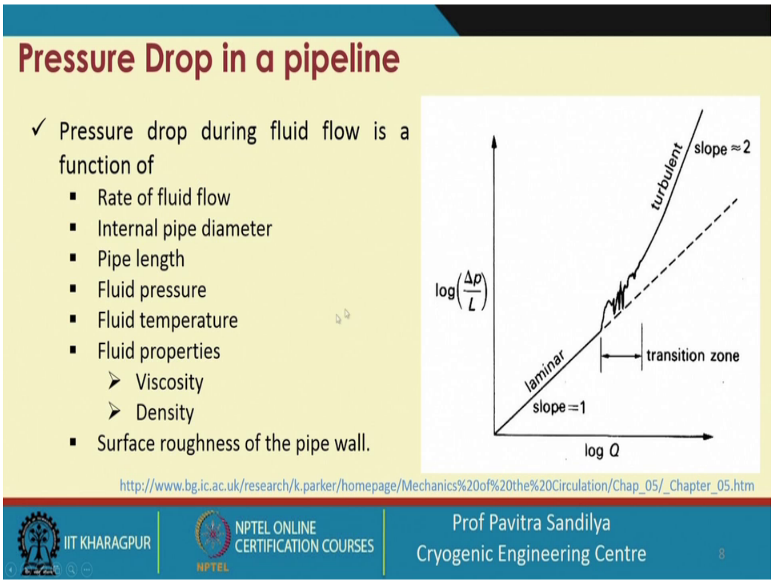

Now, let us come to the pressure drop. As I told you the pressure drop is caused by drag on the fluid while it flows. So, this particular pressure drop depends on the rate of fluid flow, the internal diameter of any closed conduit in through which it is flowing or for it can cause of a open channel. It depends on the length traversed by the fluid from the starting point on the surface and then pipe length, then fluid pressure, then fluid temperature, various fluid properties; like density and viscosity and then the surface roughness of the pipe wall.

As we know that the rougher the wall or the surface the more will be the drag effect, more will be the resistance to it flow. So, the this kind of the effect of the surface roughness, we also feel ourselves when we are walking on the sand or on a very smooth tile. So, you will find that the surface roughness makes us, makes our walking easier or difficult. In these two cases, in similar manner the surface roughness dictates the resistance that will be offered to the fluid by the surface

Now, in this particular figure we have shown the pressure drop per unit length as a function of the flow rate and here we find at lower flow rate, where the we have laminar flow. In between we have some transition zone and ultimately it goes to a turbulent flow and what also you find that the slope of this line changes from 1 to 2, where this is on a log scale we are plotting log ah, this is delta p by L that we. These are pressure difference per unit length; that is the pressure gradient and log of the flow velocity

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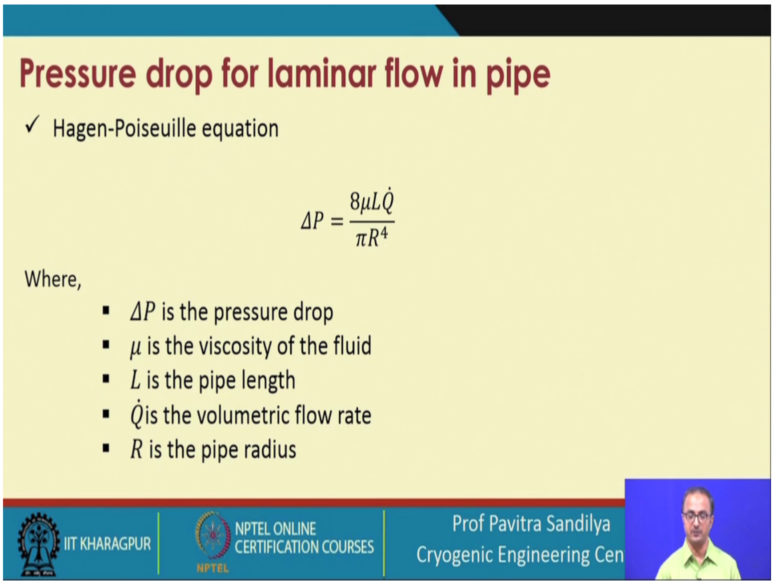

Next we come to the pressure drop for laminar flow. Now in the laminar flow we have many expressions can be, we can be derived theoretically and one of the expressions which is very commonly used is Hagen Poiseuille equation. In this it is given by this particular expression, this can be derived also. I am not going into derivation on this. This you can find in any standard fluid mechanics book

So, in this particular example we find that delta P is the pressure drop, mu is the fluid viscosity, L is the pipe length and Q naught is the volumetric flow rate of the fluid and R is the pipe radius. So, this expression is used to find out the pressure drop. In fact, this Hagen Poiseuille equation is also used to determine the viscosity of a fluid through a pipe line. So, we can, we can also use this Hagen Poiseuille equation to find out the viscosity of a fluid

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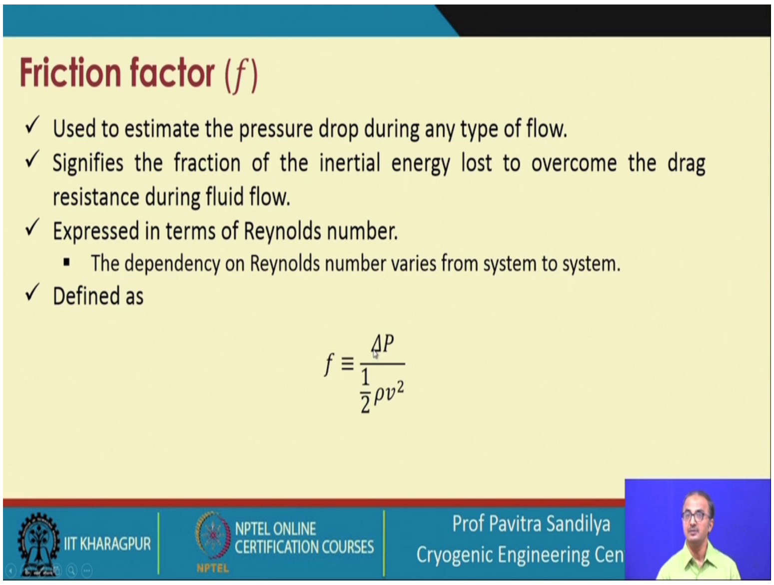

And next we come to the friction factor. Now the friction factor is used to determine the pressure drop through a on their surface. Now this friction factor may be used for both laminar flows as well as for turbulent flow. Now it signifies the fraction of the inertial energy of the fluid lost to overcome the drag resistance during the fluid flow; that means, whenever a fluid is flowing, it we take, it takes some energy which is the kinetic energy half rho v square; that is the kinetic energy per unit volume half rho v square and out of this total energy, the inertial energy how much is expended is lost to overcome the drag experienced by the fluid over the surface and during the flow path

So, this ah, this fraction is the friction factor and it is expressed in terms of a Reynolds number, and it depends on the Reynolds number and it varies from system to system; that is it might be something for single phase, something for the two phase, something in the packed bed, something like that. So, it depends the system we will have different types of friction factor expressions as function of Reynolds number.

It is defined as I told you that f is the friction factor, the is ratio of the pressure drop and divided, and the kinetic energy of the fluid. So, if I want to know the pressure drop, I can. If I know the friction factor then I can multiply this half rho v square into friction factor to get the pressure drop in the system

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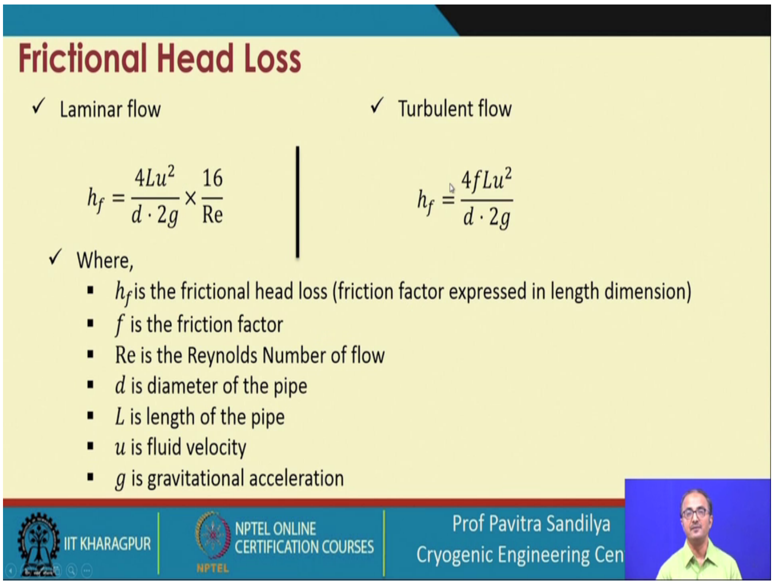

Now, sometimes we express the friction loss, friction drag in terms of head, head is in terms of length. Any kind of head mean we mean that we are talking terms of some length dimension. So, for laminar flow this is the expression for the frictional head loss and for the turbulent flow, this is the expression for the frictional head loss ah. And here we find that h f is the friction head loss and rest of the things, say f is the friction factor, Re is Reynolds number, d is the pipe diameter, L is the pipe length and u is the fluid velocity and g is the acceleration due to gravity. So, these are some expressions which have been obtained through some experimental data for the laminar flow and for the turbulent flow

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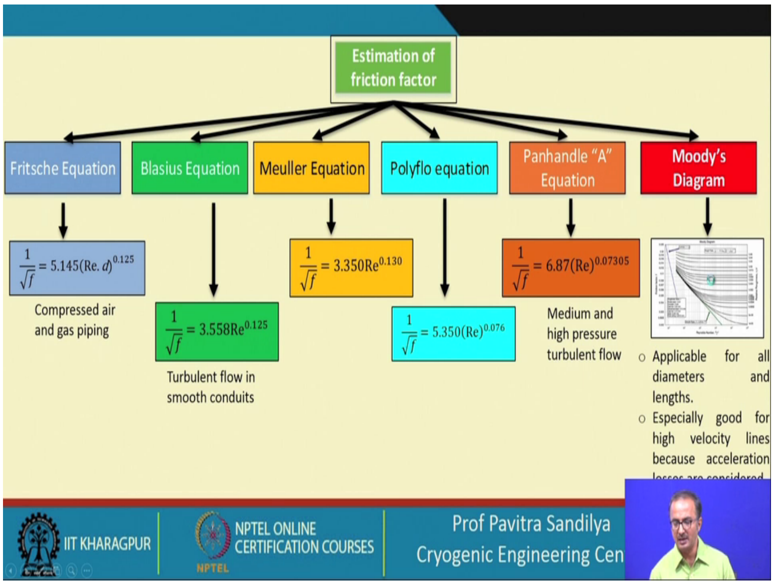

Next we come to the estimation of the friction factor. There are various correlations proposed to find out the friction factor ah, some of the commonly used correlations which are used in the natural gas sector are given here. First we come to the Fritsche Equation, then Blasius Equation, Meuller Equation, Polyflo Equation, for Panhandle A Equation, Moody's Diagram. And we shall see one by one what are these, these are the various types of equations you can find the expressions here and this is applicable for compressed air and gas piping, then the Blasius Equation, this is for turbulent flow in smooth conduits, then we have Meuller Equation with then Polyflo Equation Panhandle and the Moody's Diagram.

So, we can see that there are host of equations which are applicable under different situations in the case of natural gas flow, and nothing to cram these equations. You have to remember that there are many equations are existing and whenever needed you refer to the literature, to find out the expression and apply them appropriately.

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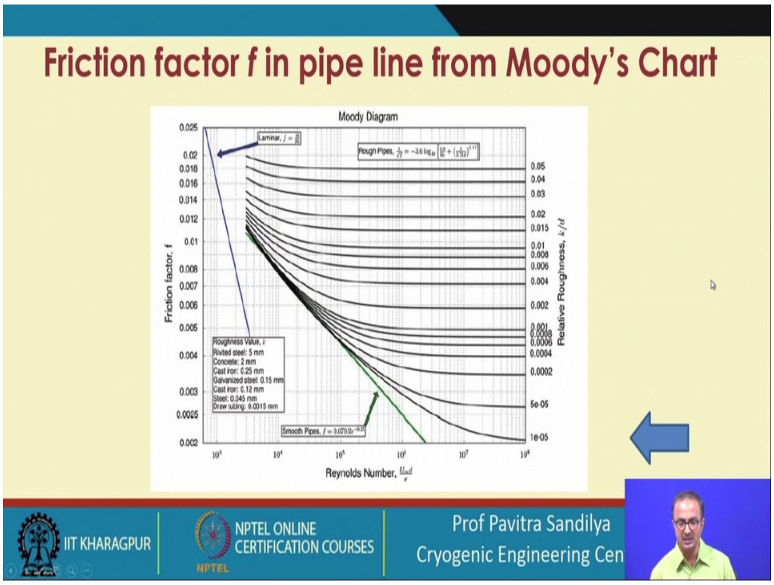

Now, here this particular Moody's diagram you can see, that which is very commonly used and we can see this in magnified view, that in this case we are plotting on a semi log scale; the friction factor and the Reynolds number and here you see that for laminar flow we have a pretty straight line. And in case of the turbulent flow we have several lines and all these lines are have a parameter which is the roughness factor

So, depending on the roughness we will find for a turbulent flow, we have for the same Reynolds number, but different roughness factor, we will be having different values of the friction factor. So, this Moody's diagram is very commonly used to estimate the friction factor. Other than that also we may have some other specialized correlation for that particular system

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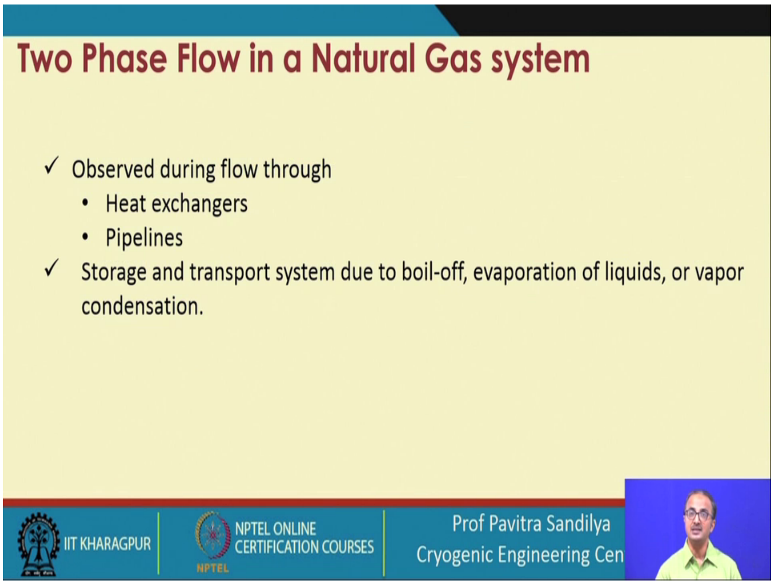

Now, next we come to two phase flow now two phase flow has many peculiarity and we encountered such kind of flow whenever there is a situation that two separate phases are flowing together, and these two phases may flow together, because we have two different kinds of fluids or in some systems a liquid may evaporated boil off generating the vapor or a vapor while flowing can get, can get condensed and generates liquid.

In that way also we can easy to generate a two phase flow and, especially in case of natural gas systems and when we are trying to store natural gas as liquefied natural gas; that is LNG all this kind of two phase phenomena are very common and they are, there in some heat exchangers in the pipelines, during storage, during transport, due to boil off evaporation or vapor condensation. So, these all generate two phase flow in a natural gas system and that is why it is important for us to understand, have some idea about the two phase flow.

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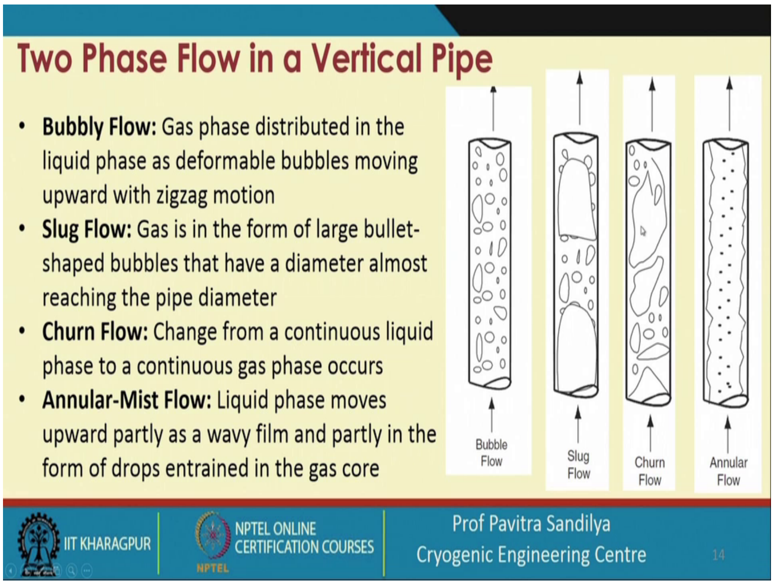

What we shall learned here that some of the flow regimes two phase flow give rise to different types of flow regimes as we shall see. So, first we shall come to bubbly flow. Now in this bubbly flow what we find that there are two things we can say; one is a continuous flow, another is a dispersed flow. In the bubbly flow the liquid is a continuous flow, whereas, the gas bubbles are the dispersed flow

So, we see in this particular figure that gas bubbles are getting dispersed in the liquid and then we have the slug flow what happens, that as we start increasing the gas flow rate, the bubbles coil is and they make a bigger bubble, we call them slug. So, that is how we get slug flow. And next we come to churn flow at still higher flow rate of the of the vapor. We find that now the big big slugs are formed and they now cover up churn, they disturb the, disturb the whole flow.

So, that we call churn flow; mixing, there is a lot of mixing the churn flow and lastly, we have annular mist flow ok. Let me tell you that in this case we have this, we in the churn flow we call them Taylor bubble. So, we will also find literature, they talk of Taylor bubbles.

Now, in the annual mist flow now, the statutory reverses in the mist flow what happens the liquid now becomes the dispersed phase; whereas, the vapor will become the continuous phase; that means, the, these are, what we are finding that the mist, the liquid is now formed in the vapor, because at this is the vapor flow rate has become much much high, so that the ratio of the vapor to liquid flow rate is now very high. So, at low vapor to liquid ratio we have bubble flow; whereas, at high vapor to liquid flow ratio we have annular flow.

So, various kind of flow regimes are possible and depending on the orientation of the pipe, whether it is vertical or horizontal we will have different types of flow regimes and each flow regime with have its different characteristics of fluid pressure drop and heat transfer and mass transfer; that is why it is important for us to know the various types of flow regimes.

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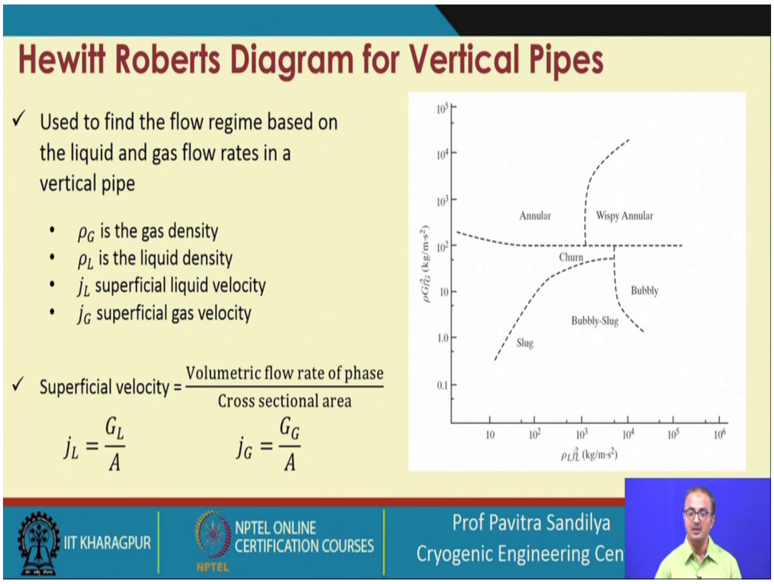

Now, here we have some Hewitt diagram which gives us, we can tell us that for vertical flow, what kind of flow regimes we can have. And you can see on the x axis we have some kind of a rho L and j L factor, this j L is given in terms of the gas flow rate and area of cross section and similarly on the y axis we have rho G and gj factor, j G factor which is given in terms of the gas flow rate and the area of cross section. So, all these things are used to find out that what kind of flow we shall be obtaining in this kind of two phase flow in a vertical pipeline

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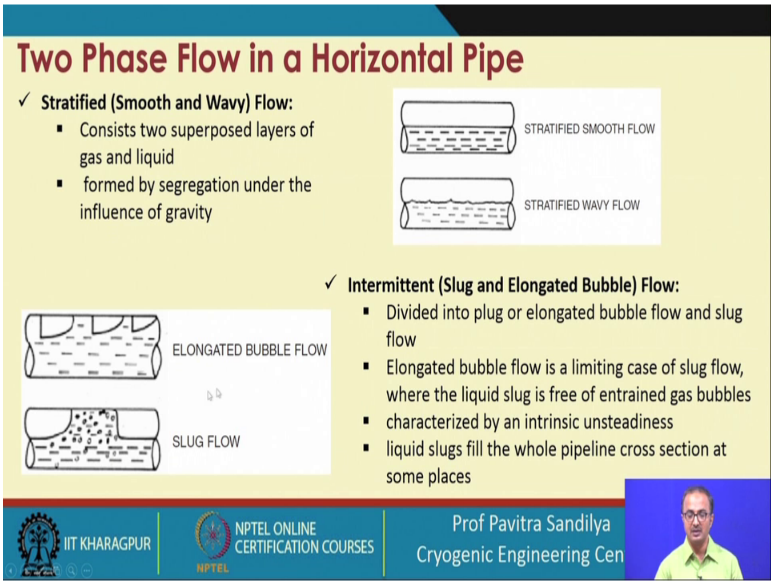

Next we go to two phase flow in the horizontal pipeline and here we have some stratified flow. These stratified flow means that the vapor is flowing over the liquid; that means, there are two strata or layer. So, the two layers are formed below, because the liquid is denser, it will be on the below and above that it will be vapor and again we have two types of stratified flow depending on the flow ratio. In one case the fluid top layer interface may be very very smooth without disturbed and another case we find that there become a waves formed, something like what you the waves you find on the reverse or the ponds or the sea, similar that at high vapor velocity it will disturb the interface between the liquid and the vapor.

And then we observed elongated bubbly flow and the slug flow. The things are similar they are also inter some intermitted flow. And here also we find that depending on the ratio of the vapor to liquid flow, we can have this bubbles and slug flow. And there may be these elongated bubble flow is a limiting case of slug flow, because this slug is free of any kind of entrained gas bubbles.

There is no, the liquid does not carry any bubble, so these becomes a, becomes a limiting case of the slug flow and there will be some. This will be unsteadiness, means it will be the steady, it will be sometimes the slugs the sizes of these bubbles will keep on changing from time to time. So, it is an unsteady flow, and this liquid side slugs will fill up the whole pipeline.

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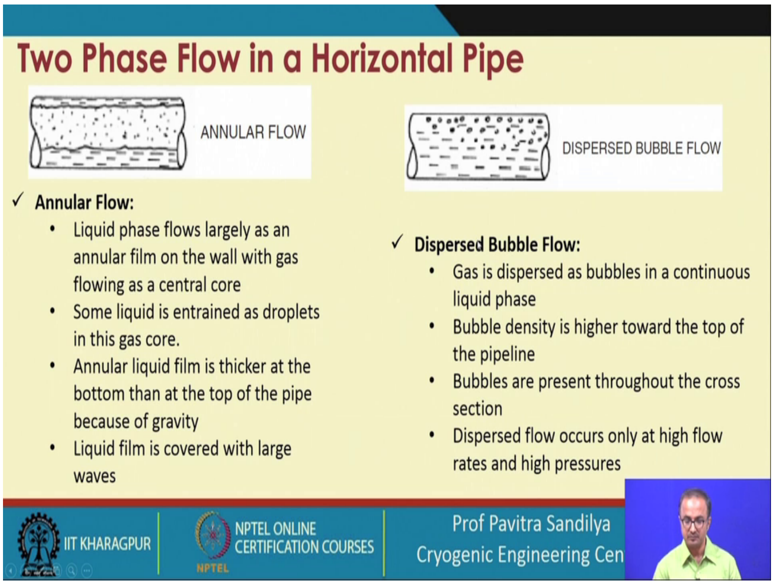

Now, next is the annular flow. In this annular flow we find that its annular is formed; that means, the vapor goes through the middle of the pipeline; whereas, the liquid is pushed to the walls. So, that is why it is called annular flow the. This is we find the vapor is going and on the wall we have the liquid is the annular flow. And here we have the dispersed bubble flow, is similar to the one we found for the vertical pipes that the bubbles, the vapor is now dispersed phase and the liquid is the continuous phase, and these bubbles are present throughout the cross section

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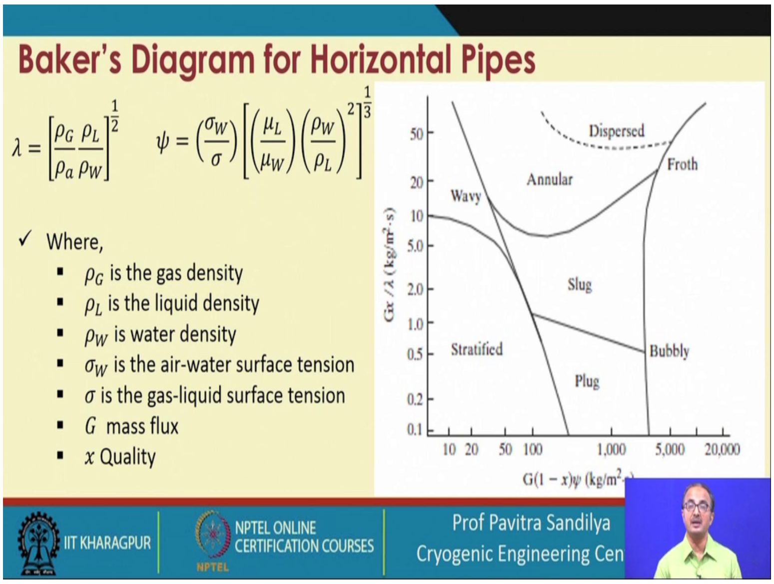

Now, here we show the Baker's diagram which is a very common diagram to identify the flow regimes. It is very commonly used in the two phase literature and on this vapor diagram again we have two parameters on ah. Here we have the G; that is the gas velocity and here x is the quality; that is the vapor fraction and lambda is given by this particular factor, and then on the x axis we have the gas flow rate, this 1 minus x is the liquid fraction and psi is given by this particular expression. Now you can see in here it also depends on, not only the viscosity and density, but also on the surface tension.

So, this surface tension also important property to decide the type of the two phase flow and this baker diagram can be used to identify that which regime we are in, and this will also help us to decide the liquid and vapor flow rates in practice

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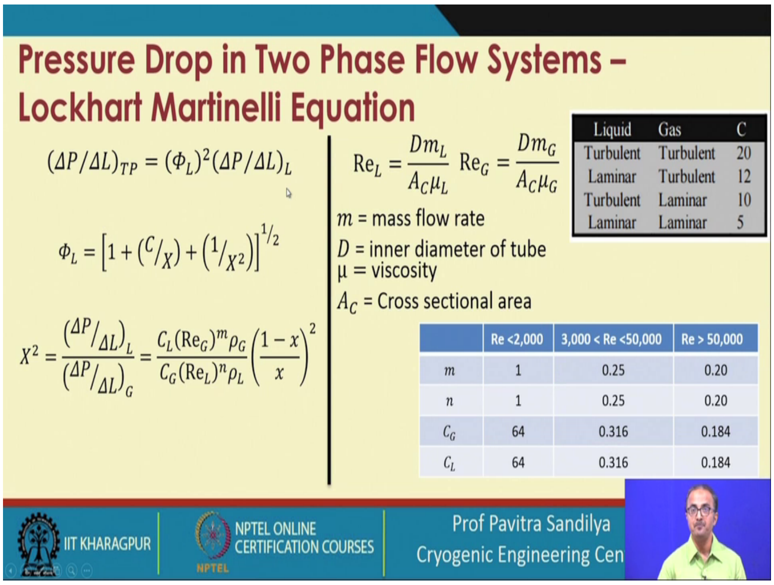

Now, another important parameter is the pressure drop in this system. And as we learned for the single phase flow, some expressions for the calculation of the pressure drop, in case of the two phase flow systems we have a very commonly used a expression; that is the Lockhart Martinelli equation.

There are many other expressions also, but this is very commonly used, and in this case we find the two phase pressure drop is related to the, pressure drop through the liquid only, and with some parameter phi L, where phi L is given by this particular expression and here we find that x square. This x square is given by some ratio of the pressure drop per unit length in the liquid to pressure drop per unit length, if the flow were only vapor.

So, this particular ratio is given by x x and then b of the Reynolds number for the liquid and for the gas and we are, here we have the mass flow rate, the inner diameter of the tube viscosity and area of cross section, and here we can have various types of combinations to determine the value of the C, which is used to find out the phi L, here we find for, if the liquid is turbulent, gas is turbulent we have some value of C. So, we have various combinations that liquid turbulent, gas turbulent, liquid laminar gas turbulent, liquid turbulent gas laminar and both are in laminar flow and we have different values of Cs here

And here in this case we find the values of the other parameters m n C G C L which are also used in this expressions. So, these are for various types of Reynolds number we have these values and the C L C G are appearing here. So, this m n C G C L they are dependent on the Reynolds number. So, this is the Lockhart Martinelli equation for the calculation of the two phase pressure drop.

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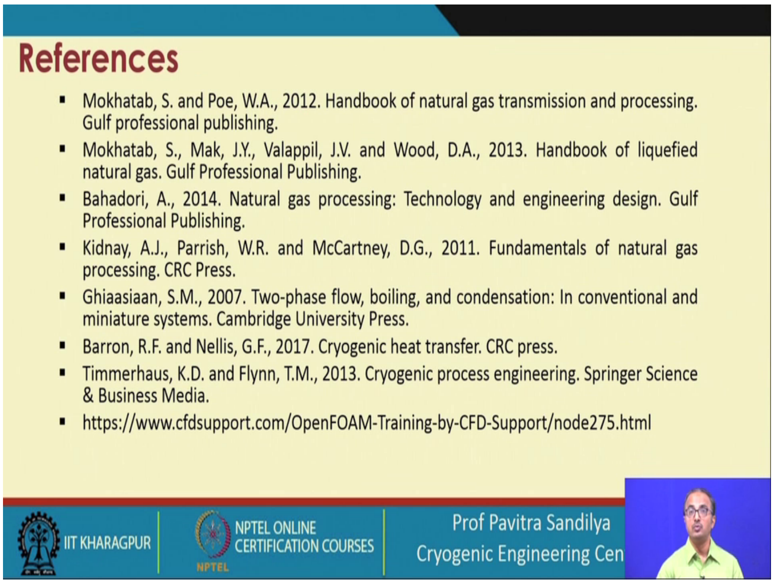

So, and to know more about this you can refer to some of these references and also any book on two phase flow or fluid mechanics to get more knowledge about this, all these topics.

Thank you.