

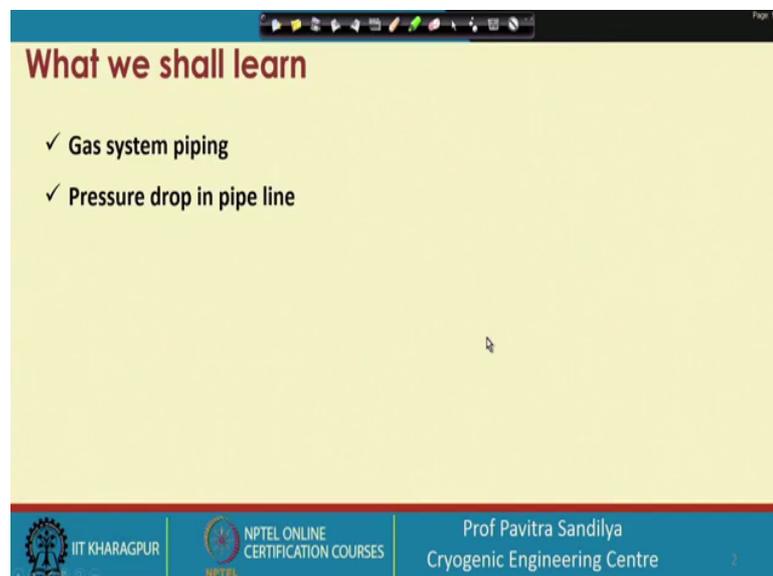
Upstream LNG Technology
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Lecture – 83
Piping in natural gas systems – I

Welcome, after learning all about the processing of the natural gas it is, but an important issue to see to it that whenever, we are talking of the various types of connections in the various, systems in the natural gas plant and we have been using many of the correlations to find out the, pressure drop, inside the pipeline in the various processing systems.

Now, you will find that there are some special type of equations which are used in the natural gas systems to, estimate the pipeline inside the, the, pressure drop inside the various types of pipelines. So, in this particular lecture, we shall be looking into the pressure drop calculations in the, pipelines in the natural gas systems. So, in this thing we shall studying the piping in natural gas systems.

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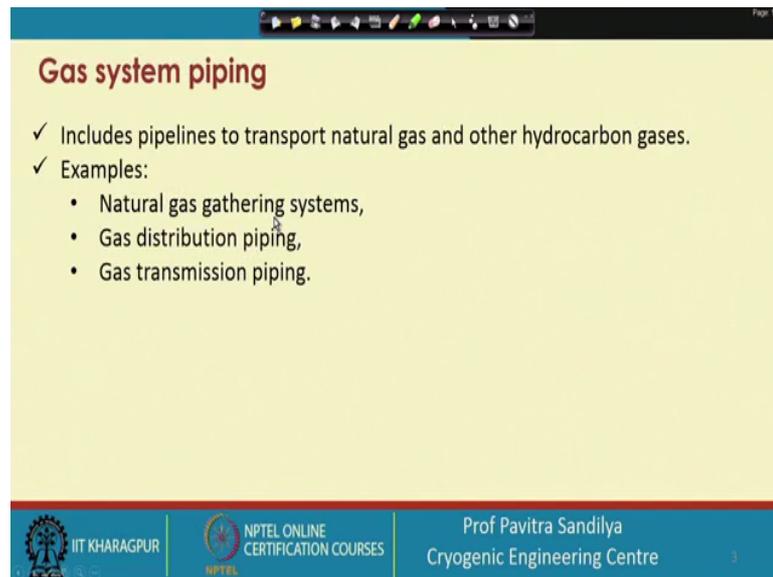
What we shall learn

- ✓ Gas system piping
- ✓ Pressure drop in pipe line

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And we shall be looking into the various piping systems under pressure drop in the pipeline.

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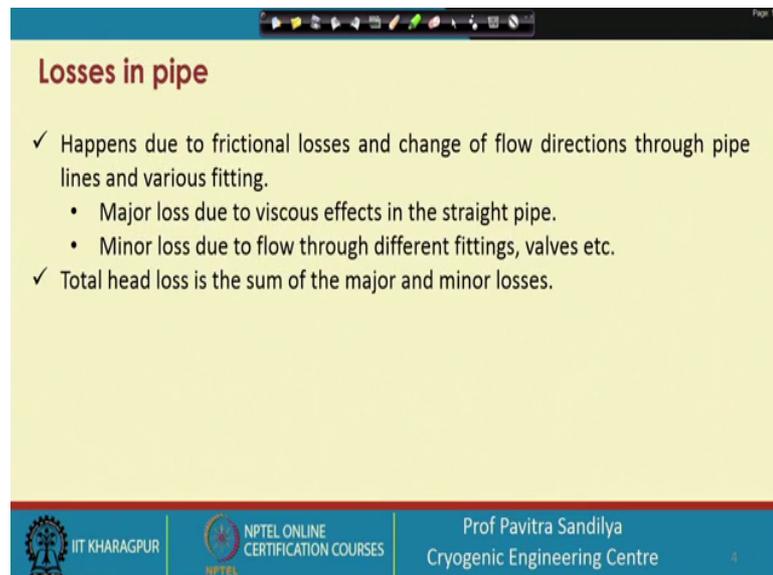
Gas system piping

- ✓ Includes pipelines to transport natural gas and other hydrocarbon gases.
- ✓ Examples:
 - Natural gas gathering systems,
 - Gas distribution piping,
 - Gas transmission piping.

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Now, this will be including the, we know that the pipelines are included for transportation of natural gas and other hydrocarbon gases like LPG. So, and examples are like Natural gas gathering systems, Gas distribution piping and the Gas transmission piping. So, at various places we are using these pipings.

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Losses in pipe

- ✓ Happens due to frictional losses and change of flow directions through pipe lines and various fitting.
 - Major loss due to viscous effects in the straight pipe.
 - Minor loss due to flow through different fittings, valves etc.
- ✓ Total head loss is the sum of the major and minor losses.

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So, we find that the in a piping whenever there is some fluid is flowing, there will be some frictional losses and also some losses will happen whenever there is any kind of change in the direction of the flow.

So, this frictional losses is generally called the skin friction and the, loss of the pressure due to the change in the flow direction is called the form drag. So, these kind of drags results in the loss of energy of the flowing fluid and which necessitates to use a compressor or some kind of pump during the flow of the, fluid over a long distance. So, in case of natural gas you also need to have some kind of compressor from, what we what we call the compressor stations we need, from distance to distance to, again reenergize again give the external energy so, that the gas can keep flowing.

So, there are various types of losses we have some Major loss, which are generally in the straight pipelines and there are Minor losses and these are something through the fittings and valves. Now, major minor does not mean that, one is greater than the other it is just that we are, nomenclature has been made in such a manner that major loss, when we say major loss we mean the straight line pipe losses and the minor loss we talk in terms of the fittings and valves etcetera or there could be something like entrance affect exit losses whenever something is, or there is some diverging section the converging sections.

In all these, changes in the, area of cross section of the flow also causes some losses; all these things are coming under the minor losses, and the Total head loss is the summation of the major loss and the minor loss.

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Bernoulli's equation

- ✓ Gives the energy balance during the fluid flow.
- ✓ Considers
 - i. Potential energy
 - ii. Kinetic energy
 - iii. Pressure energy
- ✓ Can give the flow rate through the pipeline based on inlet and outlet pressures of a pipeline segment.
 - ✓ Considering two points A and B, Bernoulli's equation, we have

$$Z_A + \frac{P_A}{\rho_A} + \frac{V_A^2}{2g} + H_p = Z_B + \frac{P_B}{\rho_B} + \frac{V_B^2}{2g} + h_f$$

H_p : Equivalent head added to the fluid by a compressor/pump
 h_f : Total frictional pressure drop

The diagram shows a pipe with flow from point A to point B. At point A, the velocity is V_A and pressure is P_A . At point B, the velocity is V_B and pressure is P_B . The elevation of point A is Z_A and the elevation of point B is Z_B . A horizontal line below the pipe is labeled 'Datum for Elevations'. The flow direction is indicated by an arrow labeled 'Flow'.

Now, here to understand these calculation of losses first you go back to the Bernoulli's equation and, we know that in the Bernoulli's equation we have the Potential energy the

Kinetic energy and the Pressure energies and other than that we also have some modifications in the made in the Bernoulli equation to account for the frictional losses in the pipeline.

So, this is basically an energy balance equation that is the first law of thermodynamics and in this, we know that we suppose we take this kind of a pipeline and here we see that the pipeline, in a general case it may have some Elevation. So, this is the Elevation of the pipeline Z_A and the Z_B and this Elevation is generally measured by considering the centerline or the central axis of the pipeline. So, this is this particular, curve is giving the central axis of the pipeline.

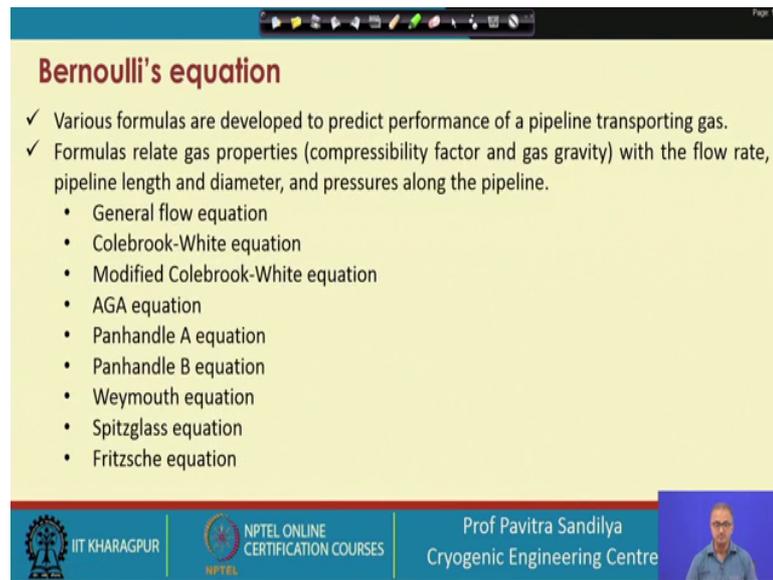
So, we are measuring the Elevation with respect to the some datum some Datum and the this centerline, and then at the inlet it might be having some Velocity and some Pressure and at the outlet again it might be having some other velocity and pressure. Now, you understand this we have, shown that this particular cross section of the pipeline may not remain constant during the flow of the fluid. So, here we see that on this side it is smaller and on this side it is bigger.

So, what happens that whenever the cross section is changing it would mean that even if, the mass flow rate is constant, but depending on the, pressure temperature and the cross sectional area the velocity of the fluid may undergo a change and as we know that for incompressible fluid if the cross sectional area is constant, if the mass flow rate is constant, then in that case velocity would remains same in the 2 sections.

So, here we are writing the Bernoulli's equation. So, this first term is signifying the Potential head and this is showing the Pressure head this is the, Kinetic head and this H_p is the Equivalent head added to the fluid by the compressor; that means, if you are using some compressor. So, this compressor itself is adding some energy to the fluid. So, that is accounted for on this side inlet side and the outlet side we again have the Potential head the Pressure head the Kinetic head and now, we are adding the frictional losses which are taking place during the flow of the fluid through this particular section.

Now, this is the energy balance which we shall be using time and again to find out the pressure loss in the pipeline.

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Bernoulli's equation

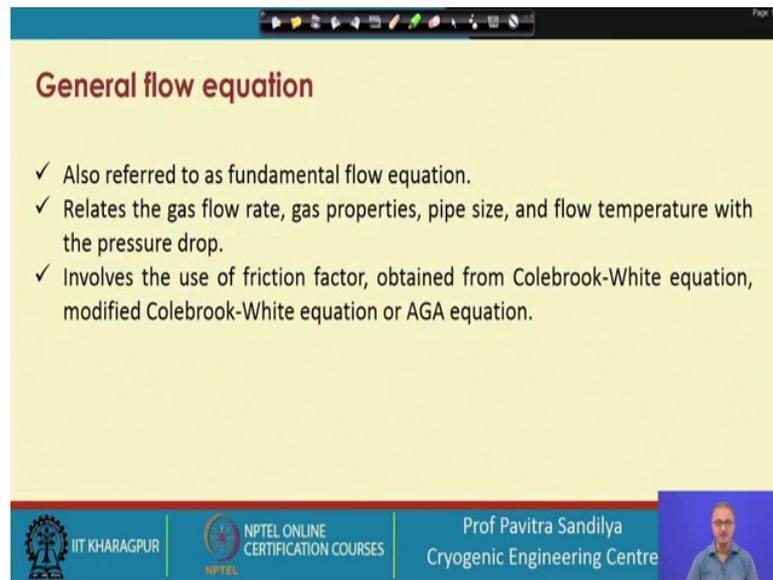
- ✓ Various formulas are developed to predict performance of a pipeline transporting gas.
- ✓ Formulas relate gas properties (compressibility factor and gas gravity) with the flow rate, pipeline length and diameter, and pressures along the pipeline.
 - General flow equation
 - Colebrook-White equation
 - Modified Colebrook-White equation
 - AGA equation
 - Panhandle A equation
 - Panhandle B equation
 - Weymouth equation
 - Spitzglass equation
 - Fritzsche equation

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Now, in this pressure loss there are various formulas are, developed based on the Bernoulli's equation to find out the, performance in terms of the pressure drop and these, all these formula whichever formula we may be encountering, we will be using some kind of gas properties like a compressibility factor, the Gas gravity and with the Flow rate the pipeline length the diameter and the pressure along the pipeline.

So, these are the parameters based on which various types of formula have been derived like these are the various types of formula which have been given in the literature, but other than these also there are plenty many. So, we have just come we are just considering a few of the commonly used, formerly which are used in for the, piping calculation in the natural gas systems and we shall be looking into these equations one by one.

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General flow equation

- ✓ Also referred to as fundamental flow equation.
- ✓ Relates the gas flow rate, gas properties, pipe size, and flow temperature with the pressure drop.
- ✓ Involves the use of friction factor, obtained from Colebrook-White equation, modified Colebrook-White equation or AGA equation.

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So, first let us go to the General Flow equation and this is also called the fundamental flow equation because the because fundamental because this is the one which is based on the theory, theory that is the energy balance and from that we derived various other types of equations and this relates the gas flow rate, the gas properties, pipe size, flow temperature with the pressure drop.

So, we want to calculate pressure drop and this pressure drop is related to all these the operating parameters of the fluid and it involves some friction factor and whenever we talk of friction factor we need against some other formula to find out the friction factor and again there are some formula which are again, we shall look into like Colebrook white formulas and modified Colebrook-White equation and the AGA equation. So, these kind of formula are used to find out the friction factor.

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General flow equation

✓ Steady state isothermal flow in a gas pipeline is given by:

$$\dot{Q} = 38.77F \frac{T_s}{P_s} \sqrt{\frac{P_1^2 - P_2^2}{\gamma_g T_f L_e Z}} D^{2.5}$$

Where \dot{Q} : Volumetric flow rate (SCFD), F : Transmission factor (dimensionless), T_s : Standard temperature (R), P_s : Standard pressure (psia), P_1 : Upstream pressure (psia), P_2 : Downstream pressure (psia), T_f : Average gas-flow temperature (R), L_e : Equivalent length of pipe (mile), Z : Gas compressibility factor (dimensionless), D : Pipe inside diameter (inches), γ_g : Gas gravity

So, to develop this a particular, flow equation we will not go into detail of this because these details have been given in any standard fluid mechanics books and the reference I have also given some, standard fluid mechanics books. So, you can look into those books you find out how one derives these equations here I shall just mention you that the basis of the derivation that here we find that, we take some kind of pipeline with a diameter, D and this is the inside diameter of the pipeline and then some Pressure at the inlet and some Pressure P_2 at the outlet and the length of this particular section is taken to be L .

The fluid is at a temperature of T_f and the Flow rate is Q and in this case we are assuming that the temperature is remaining constant, but the pressure is varying from the inlet to outlet and please understand that if, the pressure is remaining constant or pressure is not varying then there cannot be any flow. So, in that way the P_1 has to be more than P_2 that inlet pressure has to be more than the outlet pressure.

Now, here we have the, isothermal equation that is if, we consider the T_f to remain constant then, this is the equation we shall be able to derive. So, this is the equation by which, we can find that, what is the flow rate and here we take some standard temperature sometimes we need to take some base temperature pressure because, the gas is generally compressible. So, its density changes with both temperature and pressure. So, that is why, we need to define the, or we need to mention the flow rate with respect to some standard or base temperature pressure.

So, here in this case this T_s and P_s are the, some Standard temperature, pressure and these are the actual, pressures in the pipeline this γ_g is the compressibility factor, T_f is a fluid temperature L_e is the length of the section of the pipe and Z is the compressibility factor, D is the inside diameter of the pipeline. Now, in this case you will find that there is some kind of this constant. Now this constant value may change depending on the units we are using somebody may use the SI unit system and sometimes we may use the FPS that is the foot pound second. So, British units; what we call.

So, depending on the kind of units unit system we are using to, derive these equations this, the magnitude of this particular constant will remain same and in this case you see that this has been, defined in terms of the fps system that is the flow rate is in the, standard cubic feet per day thus pressure is in psia, that is the pounds per square inch absolute the temperature is in Rankine and the L_e the length of the pipelines in miles and diameter is in inches.

So, whenever you are using this particular equation you have to, be careful that you are sticking to this particular, units, where to, find the, Flow rate.

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General flow equation

✓ In SI unit,

$$\dot{Q} = 5.474 \times 10^{-4} F \frac{T_s}{P_s} \sqrt{\frac{P_1^2 - P_2^2}{\gamma_g T_f L_e Z}} D^{2.5}$$

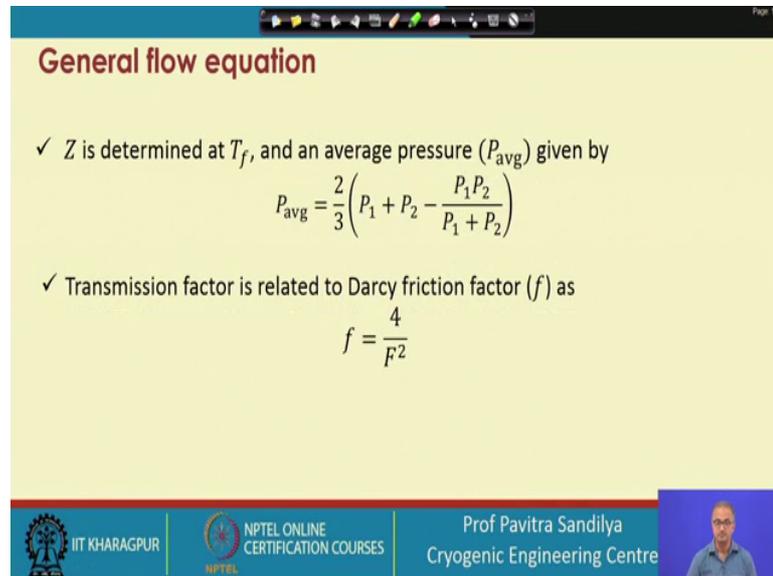
Where \dot{Q} : Volumetric flow rate (SCMD), F : Transmission factor (dimensionless), T_s : Standard temperature (K), P_s : Standard pressure (kPa), P_1 : Upstream pressure (kPa), P_2 : Downstream pressure (kPa), T_f : Average gas-flow temperature (K), L_e : Equivalent length of pipe (km), Z : Gas compressibility factor (dimensionless), D : Pipe inside diameter (mm), γ_g : Gas gravity

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So, if you are making any kind of mistake in unit then you will get wrong result. Now, here in similar the same equation has been put in terms of the, SI unit now you can see here that other remains the same except that this particular ,thing, is changing the,

constants changing and of course, there is something called the Transmission factor and we shall look into Transmission factor later on.

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General flow equation

- ✓ Z is determined at T_f , and an average pressure (P_{avg}) given by
$$P_{avg} = \frac{2}{3} \left(P_1 + P_2 - \frac{P_1 P_2}{P_1 + P_2} \right)$$
- ✓ Transmission factor is related to Darcy friction factor (f) as
$$f = \frac{4}{F^2}$$

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Now, as we said that the pressure is varying while we are considered the temperature to be constant now because the pressure varies. So, does the compressibility of the gas. So, to find out the compressibility of the gas earlier we learned many methods, in our earlier lectures. So, in these lectures we found that this compressibility is determined maybe from some equation or using some kind of figures and in these sometimes we need the reduced pressure.

So, whenever we are talking about this reduced pressure reduce temperature. So, we need to fix the temperature we need to fix the pressure. So, in this case because the pressure is varying. So, what is done for a quick estimation the pressure is taken to some average and some somebody can use the arithmetic average, but better than the arithmetic average we can use this particular expression which has been given here. So, this has been found to be better representation of the average pressure inside the pipeline.

So, that is why this particular in this you see that it is P_1 plus P_2 minus $P_1 P_2$ divided by $P_1 + P_2$. If, you look at this expression you will find that this is some kind of a harmonic average and this is particular thing if you divide by 2 and multiply by 2 this is some kind of an, of a arithmetic average. So, it is; that means, is this expression is considered in both the arithmetic average and the harmonic average of the pressure and

then this Transmission factor f this is related to this Darcy's friction factor and this, we will find that there are different types of friction factor later on.

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General flow equation: Effect of elevation

- ✓ Equivalent pipe length (L_e) is used to account for the change in elevation of the upstream end (1) and downstream end (2) of the pipe line. Assuming *single slope* between 1 and 2, it is given by

$$L_e = jL, \quad j = \frac{e^s - 1}{s}$$

Where L : Actual length of the pipeline between upstream and downstream ends, j : Elevation correction factor.

- ✓ If there are series of slopes between elevations 1 and 2, then j has to be determined for each slope of each pipe segment (L_i). Thus

$$L_e = j_1 L_1 + \sum_{i=2}^{N_{\text{seg}}-1} j_i L_i e^{s_i}$$

Where N_{seg} : Number of segments between 1 and 2.

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Now, in that, equation earlier equation the elevation effect was not taken into account that is the difference between Z_A and Z_B . Now, in this case if, you take the elevation in effect is the account then what will find; we land up in such an equation and you see that this, length this Equivalent length is taken to be j into L and this j is given by this particular expression e to the power s that is exponential to the power s minus 1 divided by s and this L is the Actual length of the pipeline between stream upstream and downstream ends and this is a Equivalent; that means, because of elevation this is the equivalent length even though this is the Actual length.

Now, this elevation correction factor, will be defined later on and this is this is what we this is the elevation correction factor and we shall see that if, there are many, segments means the pipeline the whole pipeline consists of many segments and each segment has different elevations. So, what we need to do? To find out the Equivalent length over the whole system what we do we use this particular equation and in this equation we find that this L_i represents the various sections and for each L_i we have some particular j_i and one particular s_i value. So, this way we are able to account for the elevation.

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General flow equation: Effect of elevation

✓ With the elevation correction factors between 1 and 2, we have in FPS unit

$$\dot{Q} = 38.77F \frac{T_s}{P_s} \sqrt{\left(\frac{P_1^2 - e^s P_2^2}{\gamma_g T_f L_e Z} \right)} D^{2.5} \text{ where } s = 0.0375 \gamma_g \frac{H_2 - H_1}{T_f Z}$$

Where \dot{Q} : Volumetric flow rate (SCFD), F : Transmission factor (dimensionless), T_s : Standard temperature (R), P_s : Standard pressure (psia), P_1 : Upstream pressure (psia), P_2 : Downstream pressure (psia), T_f : Average gas-flow temperature (R), L_e : Equivalent length of pipe (mile), Z : Gas compressibility factor (dimensionless), D : Pipe inside diameter (inch), γ_g : Gas gravity

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And this s is also given, in various manners in, for the type of unit system we are using. So, if we are using FPS unit then, this is the particular expression we are using to find out the, flow rate and here you see that the only thing we find that the outlet pressure has got some kind of modification due to the elevation this particular thing is taken to be one when we do not have any elevation effect.

So, and this s is given by this particular expression and this H_2 , H_1 are the elevations; that means, at the inlet and outlet the difference between the inlet and outlet elevation is given by this H_2 and H_1 and we see that again this, for calculating the s again we have to use the particular system of a units and the in this case the we are using the FPS unit.

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General flow equation: Effect of elevation

✓ In SI units, we have

$$\dot{Q} = 5.747 \times 10^{-4} F \frac{T_s}{P_s} \sqrt{\left(\frac{P_1^2 - e^s P_2^2}{\gamma_g T_f L_e Z} \right)} D^{2.5} \text{ where } s = 0.0684 \gamma_g \frac{H_2 - H_1}{T_f Z}$$

Where \dot{Q} : Volumetric flow rate (m³/d), F : Transmission factor (dimensionless), T_s : Standard temperature (K), P_s : Standard pressure (kPa), P_1 : Upstream pressure (kPa), P_2 : Downstream pressure (kPa), T_f : Average gas-flow temperature (K), L_e : Equivalent length of pipe (km), Z : Gas compressibility factor (dimensionless), D : Pipe inside diameter (m), γ_g : Gas gravity

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A similar expression can also be given for the SI unit. So, this is the expression of the s and again you find that the constant value has changed for both the Q and the s for the SI unit.

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Compressibility factor

✓ Is estimated by correlations like:

- Standing and Katz method (*already covered in previous lecture*)
- Hall-Yarborough method
- Dranchuk, Purvis, and Robinson method
- AGA method
- CNGA method

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Now, for the Compressibility factor, we have many equations we will not be going to the all the equations this Katz method we already studied in our earlier lectures. So, here we shall be looking into only a few of those which are very common that is the Hall, Hall-Yarborough equation and the CNGA equation.

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Compressibility factor: Hall-Yarborough method

✓ Gives Z in terms of reduced density (ρ_r)

$$Z = \frac{1}{\rho_r T_{pr}} \left(-0.06125 P_{pr} \exp \left[-1.2 \left(1 - \frac{1}{T_{pr}} \right)^2 \right] \right)$$

ρ_r is obtained from

$$-0.06125 P_{pr} \exp \left[-1.2 \left(1 - \frac{1}{T_{pr}} \right)^2 \right] + \frac{\rho_r + \rho_r^2 + \rho_r^3 - \rho_r^4}{(1 - \rho_r)^3} - A \rho_r^2 + B \rho_r^{\left(2.18 + \frac{2.82}{T_{pr}} \right)} = 0$$

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So, this is the Hall-Yarborough equation. Now, in this case you find this is the particular expression given for the Hall-Yarborough equation, in this case we find the Compressibility factor which is given in terms of the reduced density and the, pseudo reduced temperature about which we learnt earlier and this Pseudo-reduced temperature is obtained by, dividing the actual temperature by the Pseudo critical temperature.

And then we have the Pseudo-reduced pressure. So, using the pseudo, reduced temperature Pseudo-reduced pressure and the reduced density we find the expression for the Z and in this case this pseudo reduced density is unknown and which is obtained from again solving this particular expression. So, here you see that this is a highly non-linear, equation and to solve this particular equation for this Pseudo-reduced density what you need to do is that you have to use some, suitable numerical technique to find out the root of the equation for example, you may use the Newton Raphson method to find out this, value of the, Pseudo-reduced, sorry reduced density.

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Compressibility factor: Hall-Yarborough method

✓ Hall-Yarborough method:

$$A = \frac{14.76}{T_{pr}} - \frac{9.76}{T_{pr}^2} + \frac{4.58}{T_{pr}^3}$$
$$B = \frac{90.7}{T_{pr}} - \frac{242.2}{T_{pr}^2} + \frac{42.4}{T_{pr}^3}$$

Where T_{pr} : Pseudo-reduced temperature
 P_{pr} : Pseudo-reduced pressure

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Now, in this equation you have these two parameters A and B over. So, this A and B parameters can be found out from this A and B here. So, these two parameters again can be given in terms of the Pseudo-reduced temperature. So, using this particular, values you can, use the Hall-Yarborough method.

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Compressibility factor: CNGA method

✓ CNGA: Compressibility Natural Gas Association
✓ For $P_{avg} > 100$ psia

$$Z = \frac{1}{1 + 344400 P_{avg} 10^{1.785 Y_g} / T_f^{3.825}}$$

Where T_f : Average gas temperature (R)
 P_{avg} : Average pressure (psia)
✓ $P_{avg} < 100$ psia, $Z = 1$

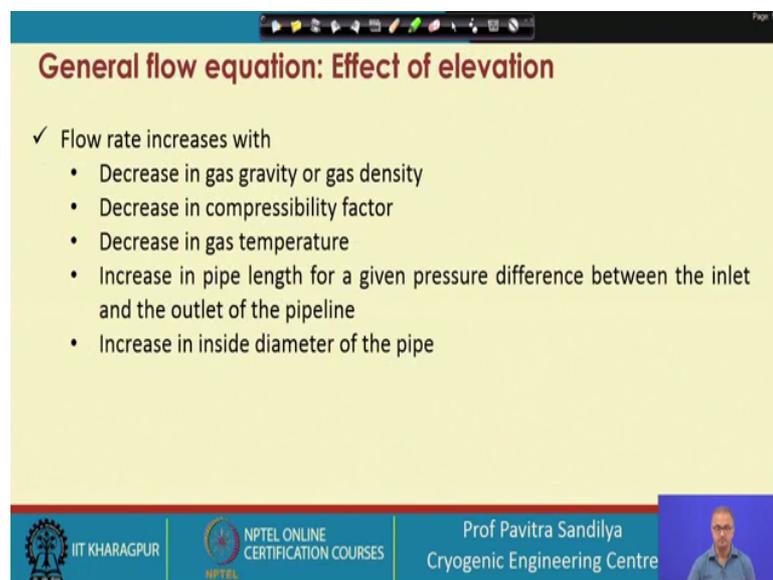
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Another very common method is the, CNGA method and this method is generally used for a pressure, of more than 100 psia. So, for this the Z is given by this particular

expression and you see this expression is much simpler than the Hall-Yarborough and in fact, it is much simpler than the other expressions I have just shown.

So, this is a very popular expression in the natural gas systems and the. So, we find that this the CNGA stands for the, California Natural Gas Association ok. So, this is the here we are using the temperature of the fluid directly and here we have the average pressure and here, is the gas gravity and for pressure less than 100 psia, the Z is taken to be almost equal to 1 that is we are we may take it to be an ideal gas.

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The slide is titled "General flow equation: Effect of elevation" and lists factors that increase flow rate. It includes logos for IIT Kharagpur, NPTEL Online Certification Courses, and Prof. Pavitra Sandilya from the Cryogenic Engineering Centre.

General flow equation: Effect of elevation

- ✓ Flow rate increases with
 - Decrease in gas gravity or gas density
 - Decrease in compressibility factor
 - Decrease in gas temperature
 - Increase in pipe length for a given pressure difference between the inlet and the outlet of the pipeline
 - Increase in inside diameter of the pipe

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Now, we find that the flow rate increases with the decrease in the gas gravity or the gas density and decrease in the compressibility factor a decrease in the gas temperature, increase in the pipeline the pipe length for a given pressure drop between the inlet and the outlet and increase in the inside diameter. So, these deductions we have made from the earlier equations I have shown you. So, you can easily see from the equations how the, flow rate would vary with the pressure temperature and the pipeline dimension.

And here we also find that the, if the temperature of the gas is higher we find the flow rate will decrease. So, for higher flow rate we need to see to that the gas remains at a lower temperature.

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Frictional pressure drop

- ✓ Factors determining the friction pressure drop:
 - Fluid flow rate
 - Fluid specific gravity
 - Fluid viscosity
 - Inside diameter of pipe
 - Pipe length
 - Pipe roughness

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Now, the frictional pressure drop we had which we have found in the expression in the expressions of the flow rate coming now this depends on the Fluid flow rate, the specific gravity of the fluid, the Fluid viscosity, the Inside diameter of the pipe, the Pipe length and the Pipe right roughness. So, these are the common factors which determine the pressure drop through a pipeline.

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Gas velocity

- ✓ Relative velocity between the gas and the pipeline wall dictates the pressure drop through the pipeline.
 - Since the wall velocity is zero, the relative velocity is the absolute velocity of the gas.
- ✓ Velocity is generally denoted by the superficial gas velocity (v), given by
$$v = \frac{\dot{Q}}{A}$$
Where \dot{Q} is the volumetric flow rate of the gas, and A is the cross-sectional area of the pipe.
- ✓ Since \dot{Q} varies with temperature and pressure, it is related to the volumetric flow rate at standard conditions (\dot{Q}_s)
$$\dot{Q}_p = \dot{Q}_s \rho_s$$

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For that, first we need to know, the gas velocity why because this gas velocity is related to the flow rate and also the kind of fluid regime flow regime we are having whether it is

a Laminar flow or a Turbulent flow or Transition flow that will also be determined by this Gas velocity through the Reynolds number. So, we need to know that how to, find out this Gas velocity.

Now, this Gas velocity is generally should be the Relative velocity between the, pipeline and the fluid. Now, in this case the pipeline is generally, a static it is not moving though because the pipeline is not moving. So, the relative velocity between the fluid and the pipeline is the absolute velocity of the gas relative velocity means we subtract one from the other. So, pipeline velocity is 0 and the gas velocity is a, it is own value.

If, I subtract some value from 0 it is remains the same. So, the absolute velocity of the fluid itself is the relative velocity of the fluid and the velocity is generally given by this particular expression in terms of the volumetric flow rate and the cross-sectional area. Now, generally the gas is compressible throughout the volumetric area varies with both temperature pressure. So, what we do? We relate this total this mass flow rate for the standard condition and the given condition because mass flow rate will remain the same no matter what the temperature and pressure are.

So, we said that is $\dot{Q} \rho$ is the mass flow rate at the given condition and \dot{Q}_s and, ρ_s are the, mass, is the this product is the mass flow rate at some standard condition.

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Gas velocity

- ✓ Now

$$\rho_s = \frac{MP_s}{RT_s Z_s}$$

- ✓ Hence

$$\frac{\rho_s}{\rho} = \frac{P_s T Z}{P T_s Z_s}$$

$$\dot{Q} = \dot{Q}_s \frac{P_s T Z}{P T_s Z_s} = \dot{Q}_s \frac{P_s T Z}{T_s P Z_s}$$

$$v = \frac{\dot{Q}_s P_s T Z}{A P T_s Z_s}$$

Generally $Z_s = 1$. Also, $A = (\pi/4)D^2$, where D : Pipe inner diameter

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So, we will equate this and after putting this, it is, this equation of state in terms of the Z value that is to consider it to be a non ideal gas we find that this is the, if, you do some kind of mathematical manipulations we find ultimately we arrive at this expression which gives us the velocity in terms of the standard, volumetric flow rate the pressure and the temperature and the compressibility factor.

And generally for the standard temperature and pressure this Z is this compressibility factor is taken to be unity.

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Gas velocity

✓ In FPS unit,

$$\dot{Q} = 2.122 \times 10^{-3} \dot{Q}_s \frac{P_s T}{T_s P} Z$$

Where D is in inch.

✓ In SI unit

$$\dot{Q} = 17.7349 \dot{Q}_s \frac{P_s T}{T_s P} Z$$

Where D is in mm.

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Now, depending on the type of unit system we are using again we find we have different expressions for the Q dot and here we have it is for the FPS system and this is for the SI unit ok. So, depending on that we are finding that we have different types of units. So, these units have to be taken care of and now, we have some something called.

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Erosional gas velocity

- ✓ Denotes maximum velocity gas velocity
 - Higher velocity causes vibration and noise during gas flow.
 - Higher velocity causes more erosion in the interior of the pipe over a long period.
- ✓ Maximum pipe velocity, in FPS unit:

$$u_{\max} = \frac{100}{\sqrt{\rho}} = 100 \sqrt{\frac{ZRT}{29Y_g P}}$$

Where D is in inch, u_{\max} is in ft/s, $R = 10.73 \text{ ft}^3\text{psia}/(\text{R}\cdot\text{lb-mole})$ and ρ is in lb/ft^3 , T is in R, P is in psia

- ✓ Generally $u_{\text{operational}} = 0.50u_{\max}$

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Erosional gas velocity and what it means? What it means is this is just whenever is gas is, flowing through the pipeline we, suppose we want higher flow rates what, but we find that as we keep increasing the gas velocity, it causes some kind of vibration and noise in the pipeline during the gas flow.

And the more the velocity of the gas the more the chances of Erosion of the from the wall of the pipeline. So, we need to be careful whenever we are trying to increase the velocity of the gas. So, this is the expression that has been suggested, to find out the maximum allowable gas velocity and this is in the FPS system it is given by 100 divided by root square of the density and, after putting the equation of state this is the expression we are getting.

And in this case, the R is taken with the, universal gas constant is taken to be this value and this is a density, my density, is in this particular, pounds per cubic feet the temperature is Rankin and P is in psia. Now, generally the operational velocity is taken to be about 50 percent of the maximum allowable velocity that is, we are keeping a buffer of 50 percent for the any variation due to some kind of abnormality then variation we are keeping this buffer.

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Major loss – Pressure drop due to friction

✓ Darcy equation is generally used:

$$h = f \frac{L v^2}{D 2g}$$

Where h : Frictional pressure drop
 f : Darcy friction factor
 L : Pipe length
 D : Inside diameter of pipe
 v : Superficial fluid velocity
 g : Acceleration due to gravity

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Now, the Major loss is given in by the Darcy's equation here we have this expression and this v square by $2g$ is signifying the kinetic rate; that means, this head loss is, found out in terms of the loss in the kinetic head of the fluid and here we have is something called the friction factor and this friction factor has been can be found out by, using different types of expressions and has been related by different, researchers.

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Friction factor

✓ Depends on the Reynolds number that dictates the flow regime.
✓ Two types of friction factor

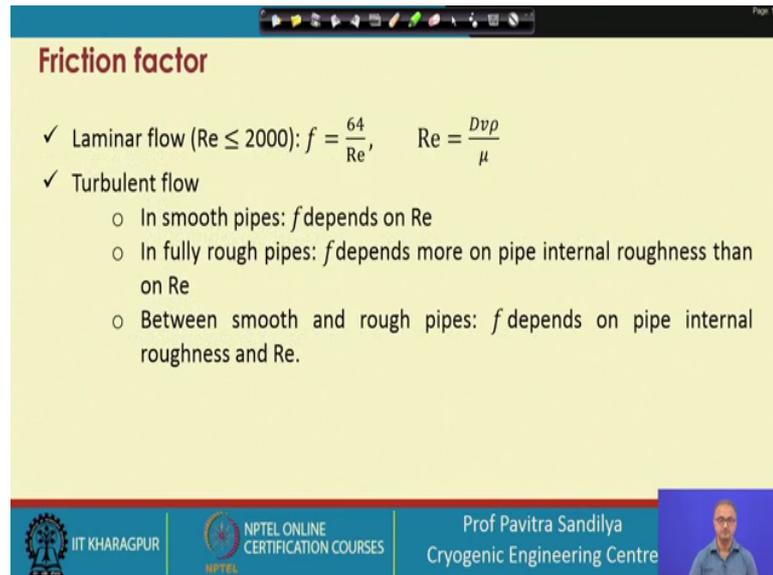
- Darcy friction factor (f_D)
- Fanning friction factor (f_F)
- $f_D = 4 \times f_F$
- We shall be using f_D , so that f would denote f_D

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Now, we have the Reynolds number which determine the type of flow regime and depending on the flow regime we will have different types of friction factor and there are

2 types of friction factors what is the Darcy friction factor and the fanning friction factor and these two are related by this that the Darcy friction factor is generally 4 times the fanning friction factor and in our, subsequent lectures, we shall be using the Darcy friction factor and we shall not be using $f D$ anymore, we shall be using only f , and we shall understand that we are talking about the Darcy friction factor.

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Friction factor

- ✓ Laminar flow ($Re \leq 2000$): $f = \frac{64}{Re}$, $Re = \frac{Dv\rho}{\mu}$
- ✓ Turbulent flow
 - In smooth pipes: f depends on Re
 - In fully rough pipes: f depends more on pipe internal roughness than on Re
 - Between smooth and rough pipes: f depends on pipe internal roughness and Re .

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Now, here we have an expression for the Laminar flow friction factor and this you can also find out in any standard fluid mechanics book and this is for the Darcy friction factor it is 64 by Re . In some books you may find it to be 16 by Re and then understand that they are talking about the fanning friction factor.

So, you may find both type of expressions in the fluid mechanics book. So, since we are using Darcy friction factor we are using 64 by Reynolds number and Reynolds number as you know it is the, $Dv\rho$ the D is a diameter inside diameter of the tube, v is the velocity of the fluid, ρ is the density and μ is the viscosity or the dynamic viscosity.

And we have different types of Turbulent flow. Turbulent flow maybe in the smooth pipes and in this case the friction factor depends on the Reynolds number alone; in case of a rough pipe it depends more on the roughness of the pipe than the Reynolds number and in between some roughness and, smooth pipe the f may depend on both the roughness and the Reynolds number.

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Friction factor

- Reynolds number in terms of pressure, temperature, flow rate, pipe inner diameter and fluid density and viscosity is obtained as
 - SI Unit

$$Re = 0.5134 \frac{P_s \gamma_g \dot{Q}}{T_s \mu D}$$

Where P_s : Standard pressure (kPa), T_s : Standard temperature (K), γ_g : Gas gravity, \dot{Q} : Gas flow rate (Sm^3/d), D : Inner diameter of pipe (mm), μ : Gas viscosity (Poise)

- FPS unit

$$Re = 4.778 \times 10^{-4} \frac{P_s \gamma_g \dot{Q}}{T_s \mu D}$$

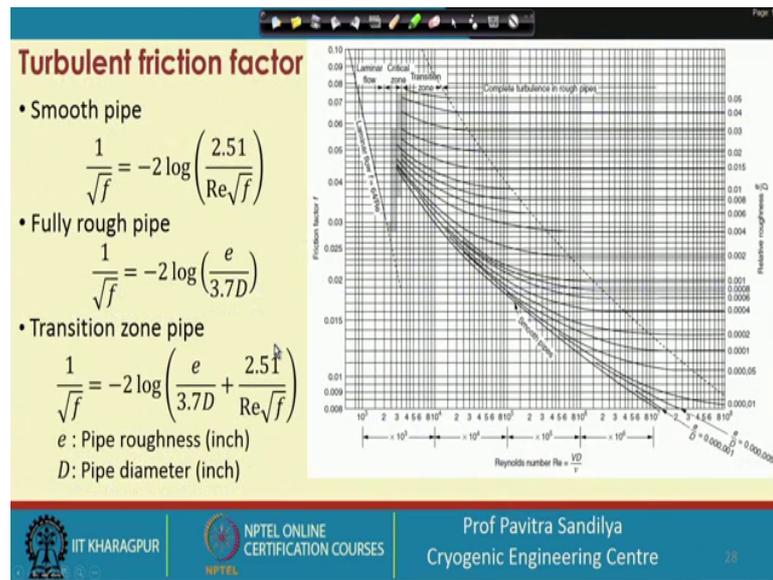
Where P_s : Standard pressure (psia), T_s : Standard temperature (R), γ_g : Gas gravity, \dot{Q} : Gas flow rate (SCFD), D : Inner diameter of pipe (inch), μ : Gas viscosity (lb/ft.s)

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So, here we have the Reynolds number expression for different types of units again. So, here we have the if, you have the SI unit then this is the particular expression for the Reynolds number and in this case what we have done we have substituted it the area of cross-section in terms of the pi by 4 D square. So, that is how we are getting this particular expression, for the Reynolds number here you find the, diameter of the tube is coming in the denominator and it is expressed in terms of the volumetric flow rate of the gas and the temperature pressure.

And the FPS units we find that rest of the things remains constant only the, this, even this value has changed ok. So, if, you take care of these, units then we have the different types of expressions.

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And here for the Turbulent, friction factor we have various types of mathematical expressions or we can use this moody's chart to find out the directly the, friction factor from this graph. So, using this, graph we can find out the friction factor.

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Pipe roughness

✓ Roughness factor = $\frac{\text{Absolute or internal roughness}}{\text{Inner pipe diameter}} = \frac{e}{D}$

Pipe material	Roughness	
	in	mm
Riveted steel	0.0354–0.354	0.9–9.0
Commercial steel/welded steel	0.0018	0.045
Cast iron	0.0102	0.26
Galvanized iron	0.0059	0.15
Asphalted cast iron	0.0047	0.12
Wrought iron	0.0018	0.045
PVC, Drawn tubing, Glass	0.000059	0.0015
Concrete	0.0118–0.118	0.3–3.0

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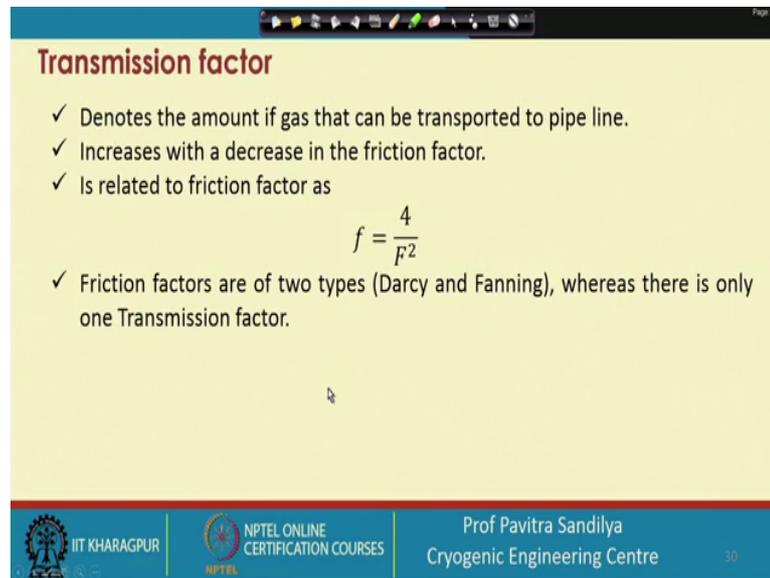
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And the, the Pipe roughness is given like this that the, Absolute or internal roughness divided by the Inner pipe diameter.

So, this is the particulars Roughness factor we use in this particular expression here you, find that in this expression we need e by D value and this e by D value has been is

defined like this and here in this particular table we find we have the various types of Roughness, given in terms of the inches or in terms of the millimeter for various types of material like Wrought iron, Galvanized iron, Cast iron, Concrete etcetera.

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Transmission factor

- ✓ Denotes the amount of gas that can be transported to pipe line.
- ✓ Increases with a decrease in the friction factor.
- ✓ Is related to friction factor as

$$f = \frac{4}{F^2}$$

- ✓ Friction factors are of two types (Darcy and Fanning), whereas there is only one Transmission factor.

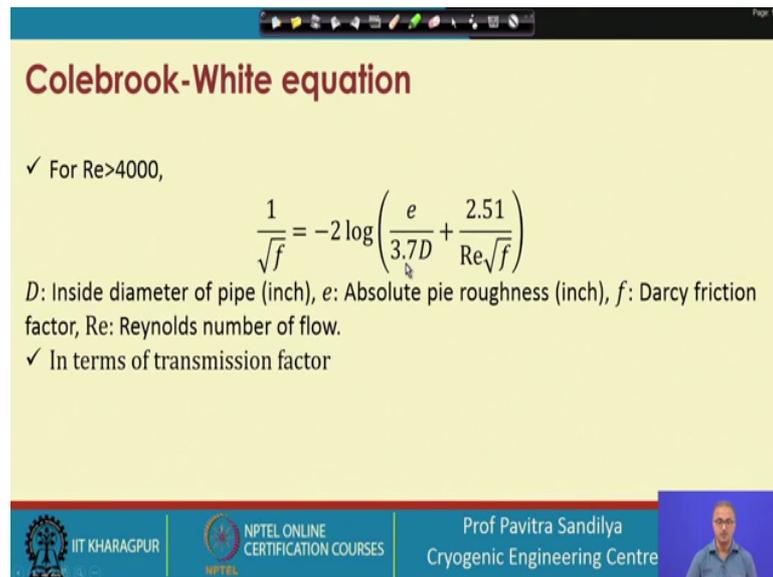
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So, we are given this and again we have a Transmission factor which is given by this particular thing and this is, kind of opposite of the friction factor. Friction factor tells us the, the resistance and the whereas, transcription of the factor says that how much gas can get transmitted or, transported through the pipeline.

So, the greater the Transmission factor the more will be the flow rather the, a less the friction factor more will be the flow and this particular expression is given by this f equal to 4 by F square when we are putting in terms of the Darcy friction factor. Now, please understand even if, we are using the fanning friction factor the value of f will change the, the value of the Transmission factor will remain the constant.

So, we find that if this f is in terms of fanning friction factor then we know that, this, 4 into fanning is the, Darcy. So, this 4 4 will get cancelled. So, fanning friction factor will be simply inverse of the square of the Transmission factor.

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Colebrook-White equation

✓ For $Re > 4000$,

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}} \right)$$

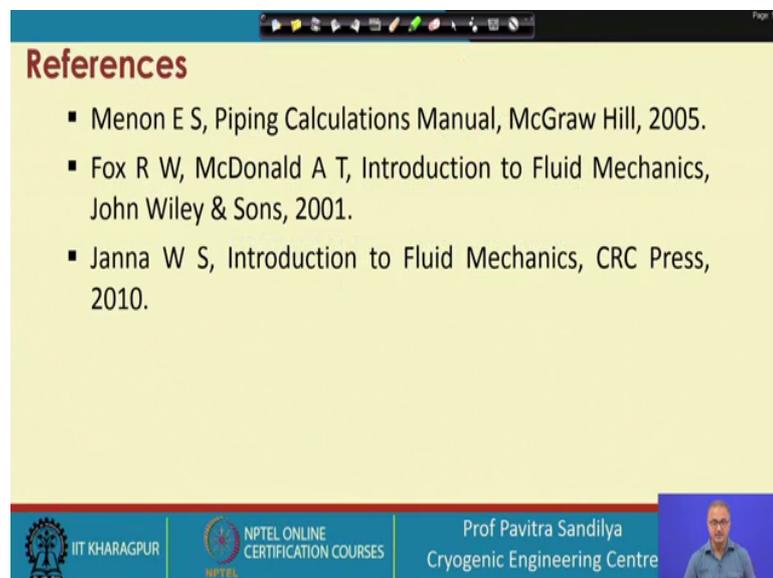
D : Inside diameter of pipe (inch), e : Absolute pipe roughness (inch), f : Darcy friction factor, Re : Reynolds number of flow.

✓ In terms of transmission factor

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So, before we go there, we will see more of these particular expressions in our subsequent lectures.

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And, we find that these are the, references which you may refer to find out more detail about this particular, the friction factor and other rest of the equations for the, gas flow rate and the pressure drop.

Thank you.