Chemical Process Utilities
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Lecture – 39
Natural Gas Transmission-I

Welcome to the new concept of natural gas transmission under the aegis of chemical process utilities. Now, before we go into the detail, let us have a brief outlook about that what we studied in the previous lecture. We discussed about the various elements of pipeline design. Under this, we discussed about the fluid properties, we discuss about the impact of environment, we discussed about the effect of temperature and pressure.

We discussed about the typical flow equations for liquid and gas and gave you an idea about the various codes and standards. We discussed the different societies those who design those codes and standards. And apart from this, we discussed about the environmental and hydrological consideration. Now, in this particular chapter we are going to discuss about the natural gas transmission.

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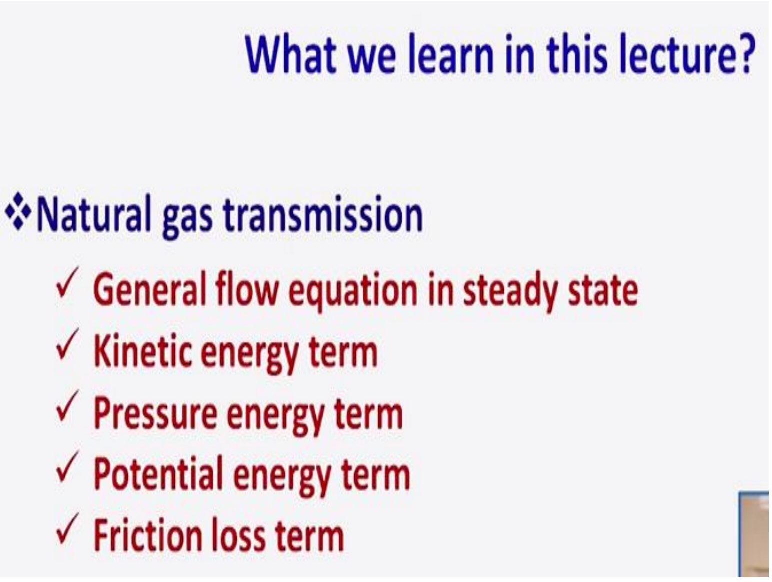

Here we will discuss the general flow equation in steady state. We will discuss about the kinetic energy term. We will discuss about the pressure energy term. We will have an idea about the potential energy term and then we will discuss about the frictional loss term.

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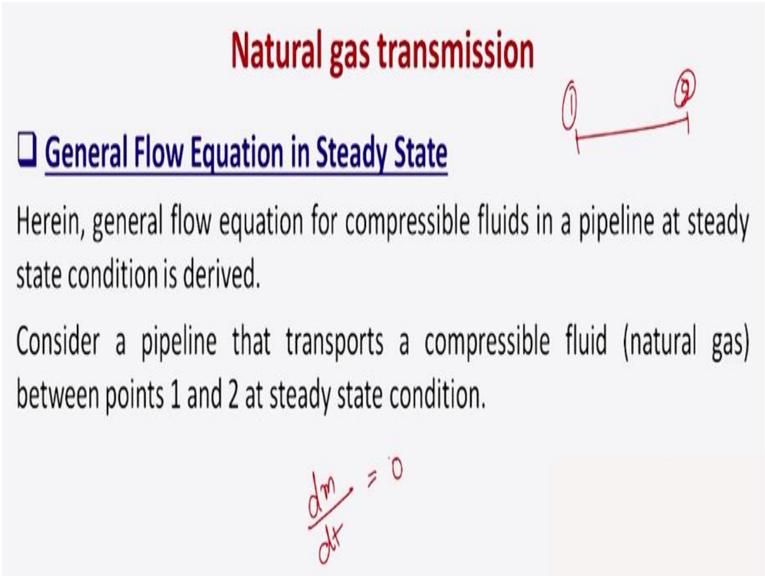

So, let us talk about the general flow equation in the steady state. Now, the general flow equation for compressible fluid in pipeline at steady state condition is usually derived. Now, let us consider a pipeline that transports compressible fluid from point, maybe this is a natural gas from point number 1 to point number 2 at a steady state condition. So, the equation can be written as dm over dt = 0.

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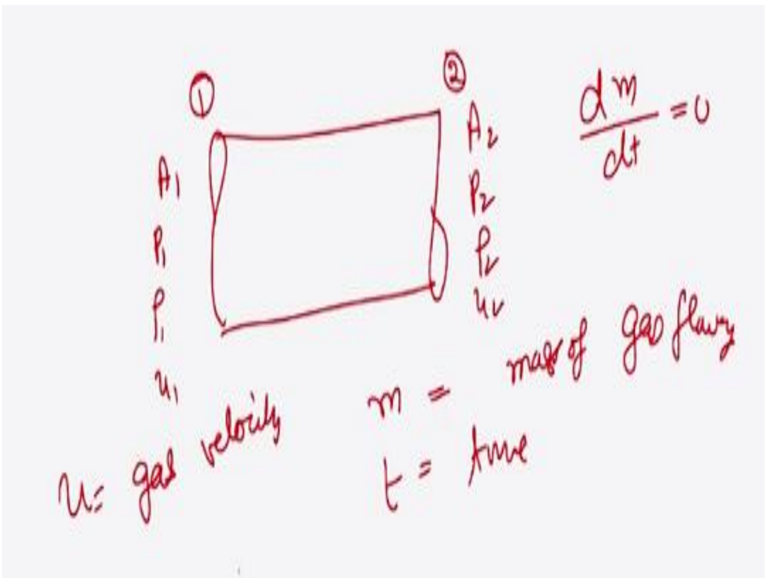
At steady state condition:

$$\frac{dm}{dt} = 0$$



Now, let us give you an idea about the pipeline. Now, this is the station number 1 and this is the station number 2. Now, here the A 1, P 1, rho 1, and u 1. This is the area of cross section A, P is the pressure, rho is the density and u 1 is the velocity that is the gas velocity and here this is the A 2, P 2, rho 2, u 2. So, u is the gas velocity, m is the mass of gas flowing and t is the time for this equation dm over dt is = 0.

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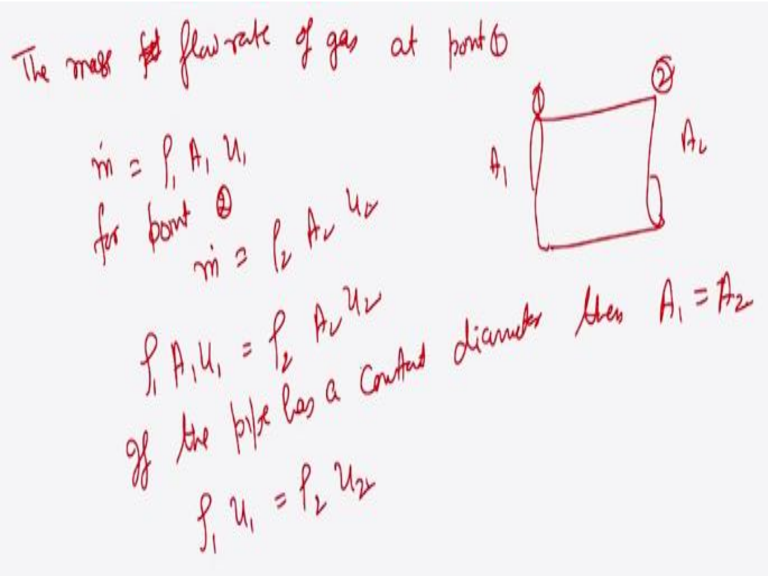

Now, the mass flow rate of gas at point 1, again I am drawing this can be defined as rho 1 A 1 u 1 and for point 2 rho 2 A 2 u 2. So, if the above equation we can take rho 1 A 1 u 1 = rho 2 A 2 u 2. If the pipe has a constant diameter, then obviously A 1 will be equal to A 2, so in that case rho 1 u 1 = rho 2 u 2.

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The mass flow rate of gas at point 1 can be defined as;

$$\dot{m} = \rho_1 . A_1 . u_1$$

Similarly, mass flow rate at point 2 is;

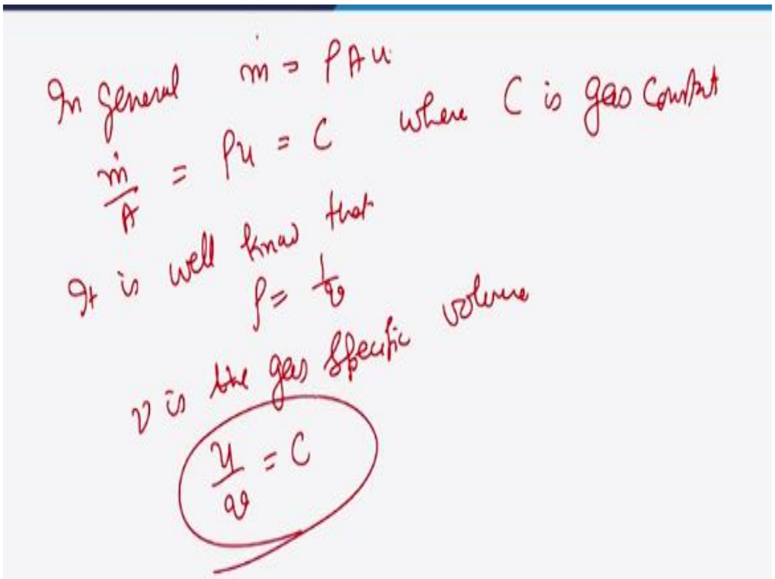
$$\dot{m} = \rho_2 . A_2 . u_2$$

From the above equation we have;

$$\rho_1 . A_1 . u_1 = \rho_2 . A_2 . u_2$$

If the pipe has a constant diameter, then

$$\rho_1 . u_1 = \rho_2 . u_2$$



So, in general if we say that m = rho A u, now m upon A = rho u and that is equal to C where C is gas constant. Now, it is well known that rho = 1 upon v, now v is the gas specific volume. Therefore, u upon v = C in this particular equation.

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In general

$$\dot{m} = \rho . A . u$$

$$\frac{\dot{m}}{A} = \rho u = C$$

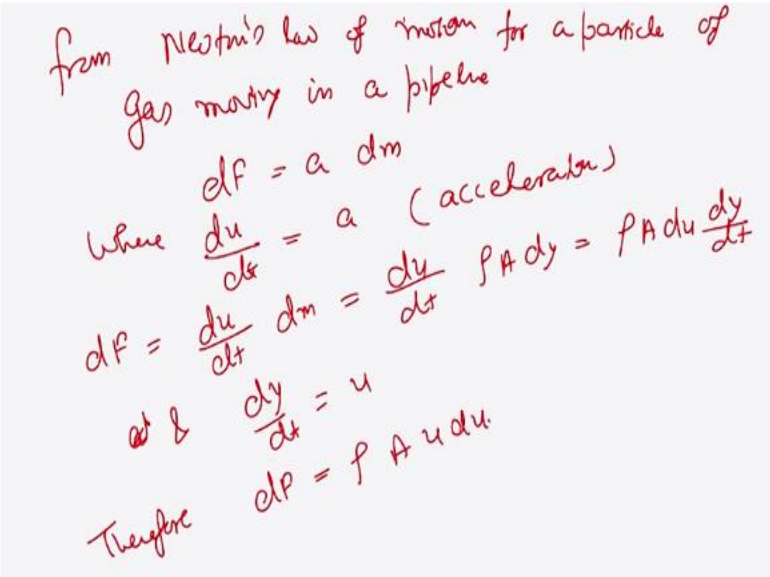
Where, C is gas constant

It is well known that;

$$\rho = \frac{1}{\nu}$$

Where ν is gas specific volume, so;

$$\frac{u}{v} = C$$



Now from Newton's law of motion for a particle of gas moving in a pipeline, then df = a dm where du over dt = a that is acceleration. So, df = du over dt dm or du over dt rho A dy and that is rho A du dy over dt and dy over dt = u. Therefore df = rho A u du.

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From Newton's law of motion for a particle of gas moving in a pipeline

$$dF = a.dm$$

Where, $\frac{du}{dt} = a$ **is the acceleration;**

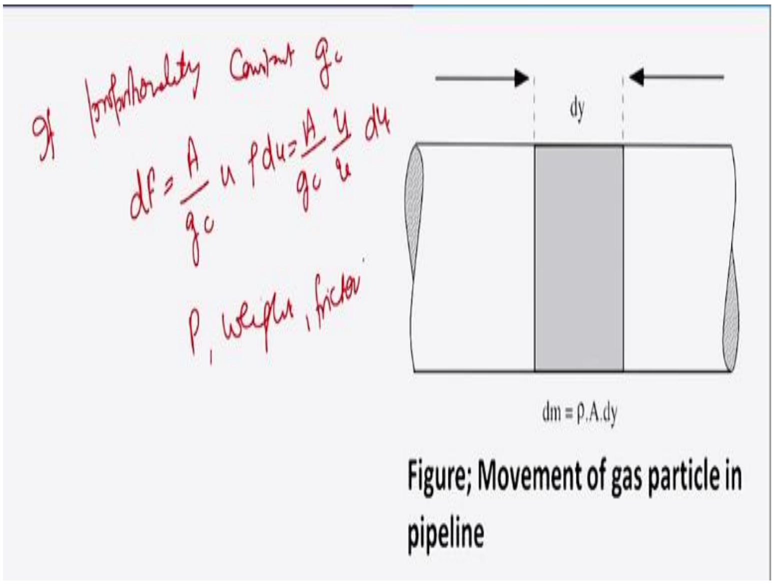
$$dF = \frac{du}{dt}dm = \frac{du}{dt}\rho.A.dy = \rho.A.du.\frac{dy}{dt}$$

And,

$$\frac{dy}{dt} = u$$

Therefore,

$$dF = \rho.A.\ u.\ du$$



Figure; Movement of gas particle in pipeline

Now, if by using the proportionality constant g c, if we use the proportionality constant g c so we can write this equation df = A over g c u rho du = A g c u v du. So, the impact of all existing forces that is pressure, weight, friction exerted on a particle of gas in a non-horizontal law pipeline this can be considered in different equation.

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By using proportionality constant g_C above equation can be written as;

$$dF = \frac{A}{g_C}.u.\rho.du = \frac{A}{g_C}.\frac{u}{v}du$$

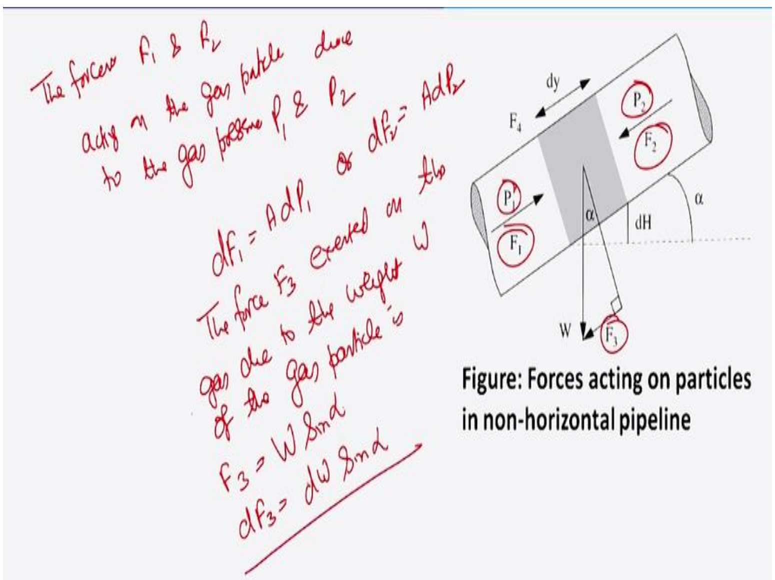

Figure: Forces acting on particles in non-horizontal pipeline

Now, let us take the forces f 1 and f 2. This is the f 2 and f 1 acting on the gas particle due to the gas pressure P 1 and P 2. This can be defined as df 1 = A d P 1 or df 2 = A d P 2. So, this is the force acting on particles in non-horizontal pipeline. Now, the force f 3 exerted on the gas due to the weight W of the gas particle is f 3 = W this is the angle sine alpha or we can write in the differential form that is df 3 = dW sine alpha.

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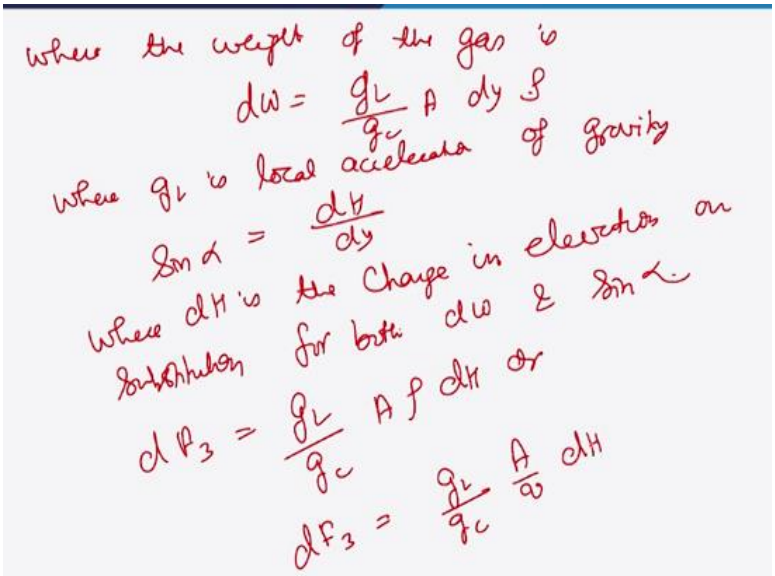
The forces F_1 and F_2 acting on the gas particle due to the gas pressure P_1 and P_2 can be defied as;

$dF_1 = AdP_1$ ***or,*** $dF_2 = AdP_2$

The force F_3 exerted on the gas due to the weight W of the gas particle is

$F_3 = W.\sin\alpha$ ***or, in deferential form;*** $dF_3 = dW.\sin\alpha$



Now where the weight of the gas dW = g L over g c A dy rho, now where g l is local acceleration of gravity. Now, sine alpha = dH upon dy where dH is the change in elevation on substitution for both dW and sine alpha. So, df 3 = g L over g c A rho dH or dF 3 = g L over g c A over v dH.

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Where, the weight of the gas is

$$dW = \frac{g_L}{g_C}.A.dy.\rho$$

Where, g_L is local acceleration of gravity,

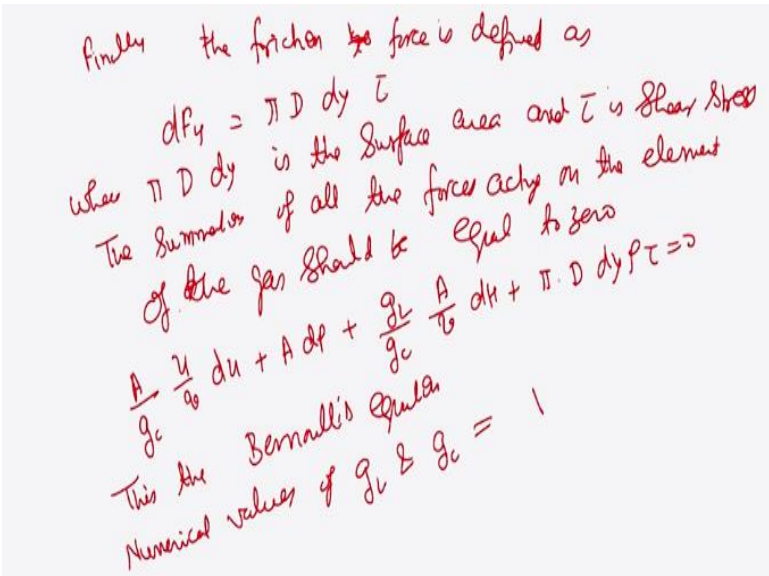
Furthermore;

$$\sin\alpha = \frac{dH}{dy}$$

Where, dH is the change in elevation,

on substitution for both dW and $sin\,\alpha$

$$dF_3 = \frac{g_L}{g_C}.A.\rho.dH \; or \; dF_3 = \frac{g_L}{g_C}.\frac{A}{v}.dH$$



Now, finally the friction force is defined as df 4 = pi D dy tau where pi D dy is the surface area and tau is shear stress. Now, the summation of all the forces acting on the element of the gas should be equal to 0. So, therefore A upon g c u upon v d u + A dP + g L over g c A over v dH + pi D dy rho tau should be equal to 0. This is the generalized form of Bernoulli's equation. Now, in most cases the numerical values of g L and g c it is equal to 1.

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Finally, the friction force is defined as;

$$dF_4 = \pi . D . dy . \tau$$

Where, $\pi . D . dy$ is the surface area and τ is the shear stress.

The summation of all the forces acting on the element of the gas should be equal to zero, therefore;

The summation of all the forces acting on the element of t equal to zero, therefore;

$$\frac{A}{g_C} . \frac{u}{v} . du + AdP + \frac{g_L}{g_C} . \frac{A}{v} . dH + \pi . D . dy . \rho . \tau = 0$$

$$\frac{A}{g_C} . \frac{u}{v} . du + AdP + \frac{g_L}{g_C} . \frac{A}{v} . dH + \pi . D . dy . \rho . \tau = 0$$

This is general form of Bernoulli equation. In most cases the numerical values of g_L and g_C are equal to **1**.

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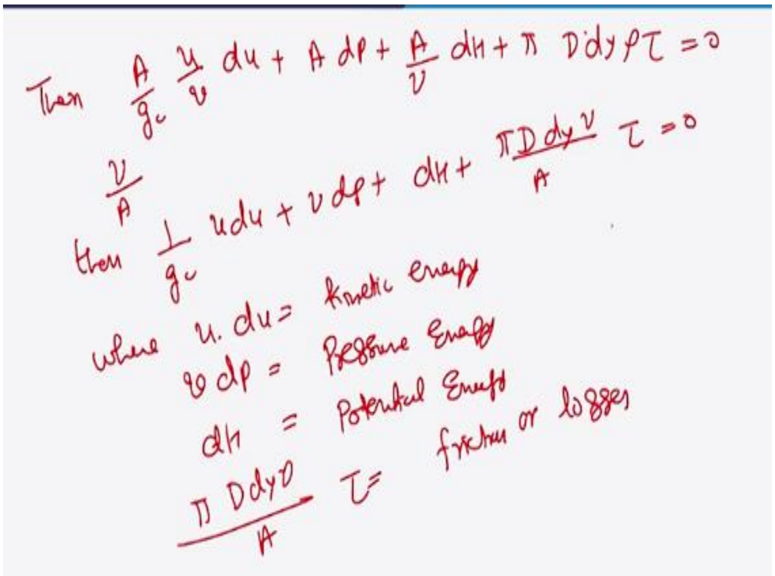

Now if you take this value then A over g c u upon v du + A dP + A upon v dH + pi D dy rho tau = 0. Now, if we multiply both sides by v upon A, then 1 upon g c u du + v dp + dH + pi D dy v upon A tau = 0, now where u dot du is equal to kinetic energy, v dp is equal to pressure energy, dH is equal to potential energy and pi D dy v upon A tau is equal to friction or losses.

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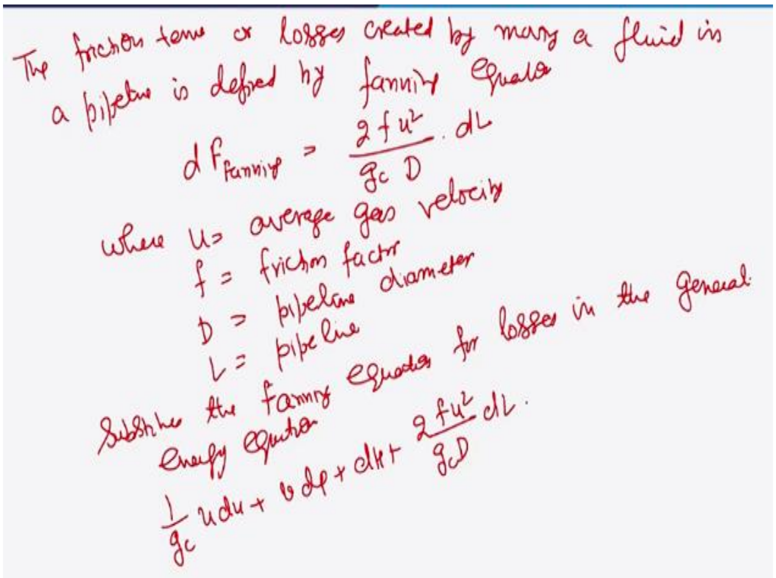
Then,

$$\frac{A}{g_C}.\frac{u}{v}.du + AdP + \frac{A}{v}.dH + \pi.D.dy.\rho.\tau = 0$$

Multiplying both sides by $\frac{v}{A}$

$$\frac{1}{g_C}.u.du + vdP + dH + \frac{\pi.D.dy.v}{A}.\tau = 0$$

Where, $\boldsymbol{u.du}$=kinetic energy; $\boldsymbol{vdP}$=pressure energy; $\boldsymbol{dH}$=potential energy; $\frac{\pi.D.dy.v}{A}\ \boldsymbol{\tau}$ =friction or losses.



The friction term or losses created by moving a fluid in a pipeline is defined by Fanning equation and this is d Fanning = 2 f h square upon g c D dL where u is equal to average gas velocity, f is equal to friction factor, d is pipeline diameter, L is pipeline. Now, if you substitute the Fanning equation for losses in the general energy equation this equation will result like 1 upon g c u du + v dp + dH + 2 f u square upon g c D dL this is equal to 0.

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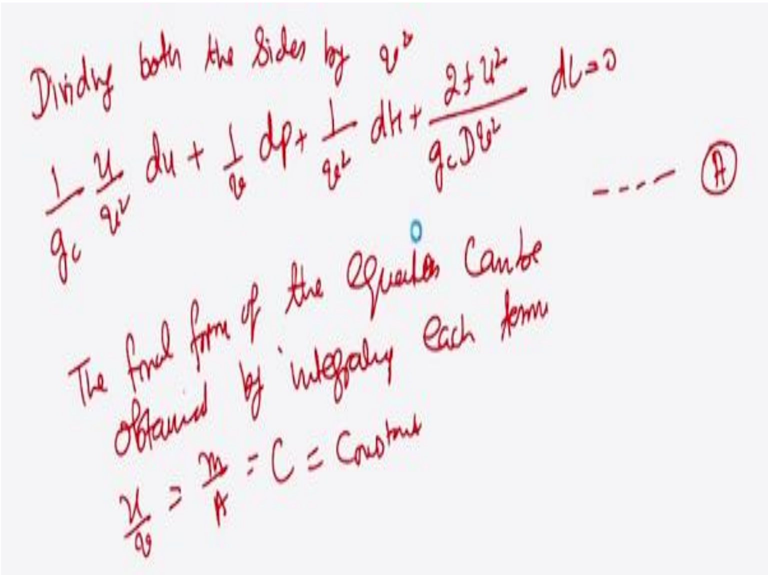
The friction term or losses created by moving a fluid in a pipeline is defined by the fanning equation as follows:

$$dF_{Fanning} = \frac{2fu^2}{g_C.D}.dL$$

Where, $\boldsymbol{u}$ =average gas velocity, f =friction factor; $\boldsymbol{D}$= pipeline diameter; $\boldsymbol{L}$ = pipeline;

On Substituting the fanning equation for losses in the general energy equation will results in;

$$\frac{1}{g_C}.u.du + vdP + dH + \frac{2fu^2}{g_C.D}.dL = 0$$



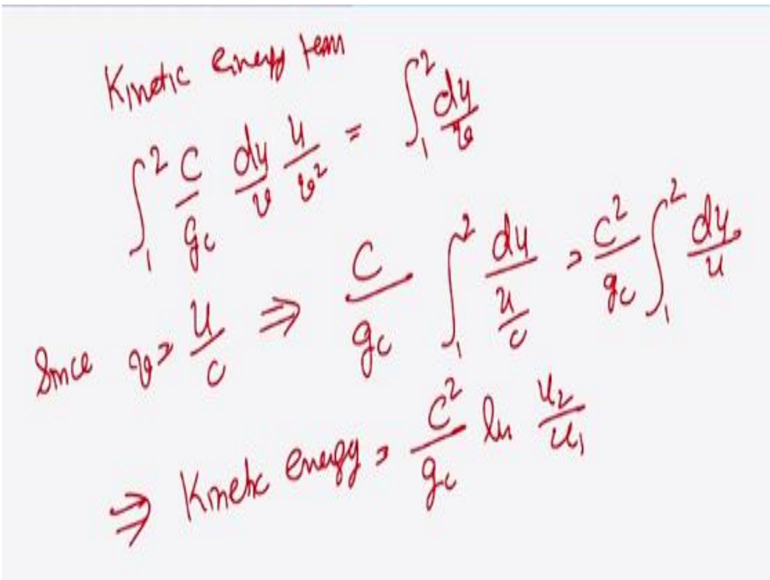
Now, if we divide both the side by v square then equation becomes 1 upon g c u upon v square du + 1 upon v dp + 1 upon v square dH + 2 f u square upon g c D v square dL that is equal to 0. Let us say that this is our equation number A. The final form of the equation can be obtained by integrating each term by assuming u upon v = m upon A = C and that is constant. **(Refer Slide Time: 17:49)**

Dividing both sides of the equation by $\boldsymbol{v^2}$;

$$\frac{1}{g_C}.\frac{u}{v^2}.du + \frac{1}{v}dP + \frac{1}{v^2}dH + \frac{2f}{g_C.D}\frac{u^2}{v^2}.dL = 0$$

Note:

The final form of the equation can be obtained by integrating each term, assuming $\frac{u}{v} = \frac{\dot{m}}{A} = C = constant.$



So, the kinetic energy term that can be written as integration from 1 to 2 C upon g c du over v u over v square and that is equal to 1 to 2 du over v. Since v = u upon C this can be represented as C or g c integration from 1 to 2 du u c and that is C squared upon g c integration 1 to 2 du u and that is the kinetic energy = C square g c ln u 2 over u 1.

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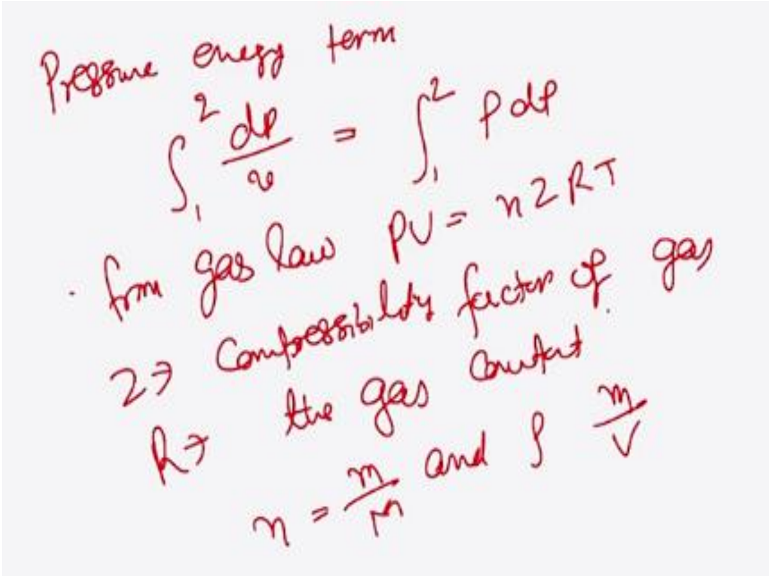
Kinetic energy term;

$$\int_1^2 \frac{C}{g_C} \cdot \frac{du}{v} \frac{u}{v^2} = \int_1^2 \frac{du}{v}$$

Since; $\quad v = \frac{u}{C} \quad \Rightarrow \frac{C}{g_C} \int_1^2 \cdot \frac{du}{\frac{u}{C}} = \frac{C^2}{g_C} \int_1^2 \frac{du}{u}$

$$\Rightarrow \textit{Kinetic energy} = \frac{C^2}{g_C} \ln \frac{u_2}{u_1}$$



Let us talk about the pressure energy term. So, it is from 1 to 2 dp upon v 1 to 2 rho dp. Now, from gas law P V = n Z RT, Z is the compressibility factor of gas and R is the gas constant. So, n = m upon M and rho = m upon V.

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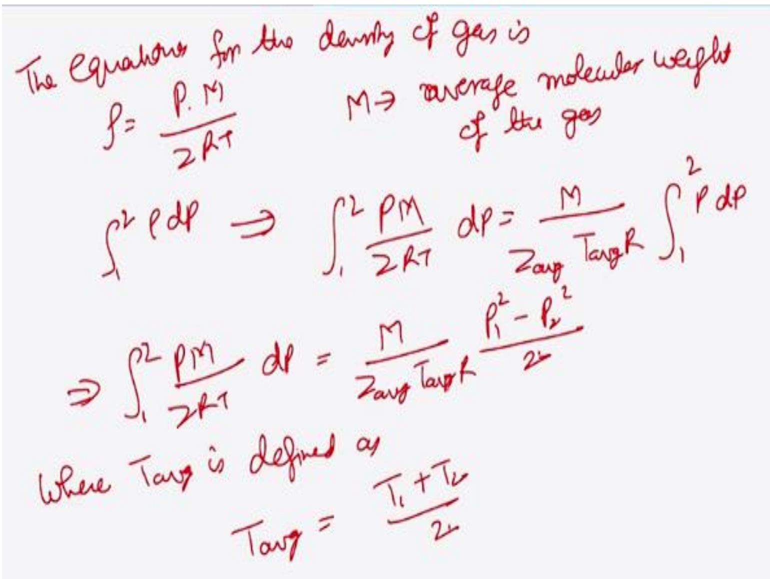
<u>Pressure energy term</u>;

$$\int_1^2 \frac{dP}{v} = \int_1^2 \rho . dP$$

From real gas law; $PV = nZRT$

Where Z is the compressibility factor of the gas and R is the gas constant for;

$$n = \frac{m}{M} \; and \; \rho = \frac{m}{V}$$



The equation for the density of a gas is rho = P M upon Z RT, M is the average molecular weight of the gas. So, if we substitute this into the integration 1 to 2 rho dp that it becomes 1 to 2 P M upon Z RT dp = M upon Z average T average R 1 to 2 P dp. This can be 1 to 2 P M Z RT dp that is equal to M Z average T average R P 1 square – P 2 square upon 2 where T average is defined as T average = T 1 + T 2 upon 2.

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The equation for density of a gas is; $\boldsymbol{\rho = \frac{P.M}{Z.R.T}}$

Where, M is the average molecular weight of the gas;

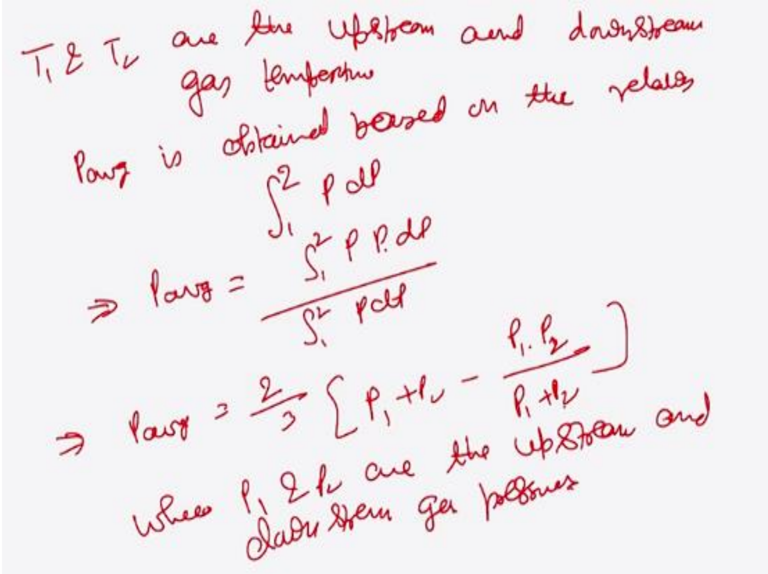
After substitution into $\int_1^2 \boldsymbol{\rho.dP}$

$$\Rightarrow \int_1^2 \frac{P.M}{Z.R.T}.dP = \frac{M}{Z_{avg}T_{avg}R}\int_1^2 PdP$$

$$\Rightarrow \int_1^2 \frac{P.M}{Z.R.T}.dP = \frac{M}{Z_{avg}T_{avg}R}\frac{{P_1}^2 - {P_2}^2}{2}$$

Where T_{avg} is defined as follows;

$$T_{avg} = \frac{T_1+T_2}{2}$$



Now T 1 and T 2 are the upstream and downstream gas temperature and P average is obtained based on the relations 1 to 2 integration P dp that is P average = integration 1 to 1 P dp upon integration 1 to 2 P dp and that is P average = 2 upon 3 P 1+ P 2 – P 1 dot P 2 upon P 1 + P 2 where P 1 and P 2 are the upstream and downstream gas pressures.

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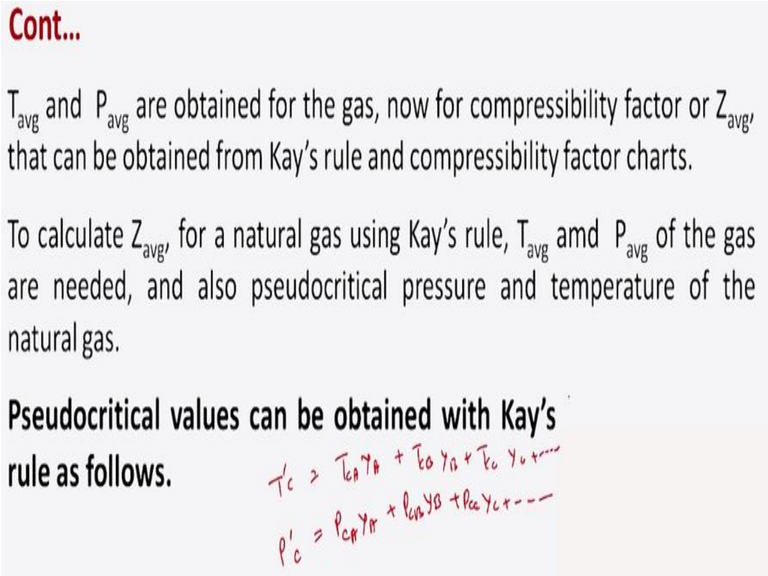
T_1 and T_2 are the upstream and downstream gas temperature and P_{avg} is obtained based on the relatio

$$\Rightarrow \boldsymbol{P_{avg}} = \frac{\int_1^2 \boldsymbol{P.P.dP}}{\int_1^2 \boldsymbol{P.dP}}$$

$$\Rightarrow \boldsymbol{P_{avg}} = \frac{\mathbf{2}}{\mathbf{3}}\left[\boldsymbol{P_1} + \boldsymbol{P_2} - \frac{\boldsymbol{P_1.P_2}}{\boldsymbol{P_1} + \boldsymbol{P_2}}\right]$$

Where, P_1 and P_2 are the upstream and downstream gas pressure.



Now, T average and P average they are obtained for the gas for the compressibility factor Z average that can be determined from the Kay's rule and the compressibility factor chart. TO calculate the Z average for a natural gas using Kay's rule T average and average P of the guests are needed and also pseudocritical pressure and temperature of the natural gas. So, if we talk about the pseudocritical values this can be obtained by the Kay's rule which is as follows T dash C = T CA Y A + T CB Y B + T CC Y C and P dash C = P CA Y A + P CB Y B + P CC Y C + and so on.

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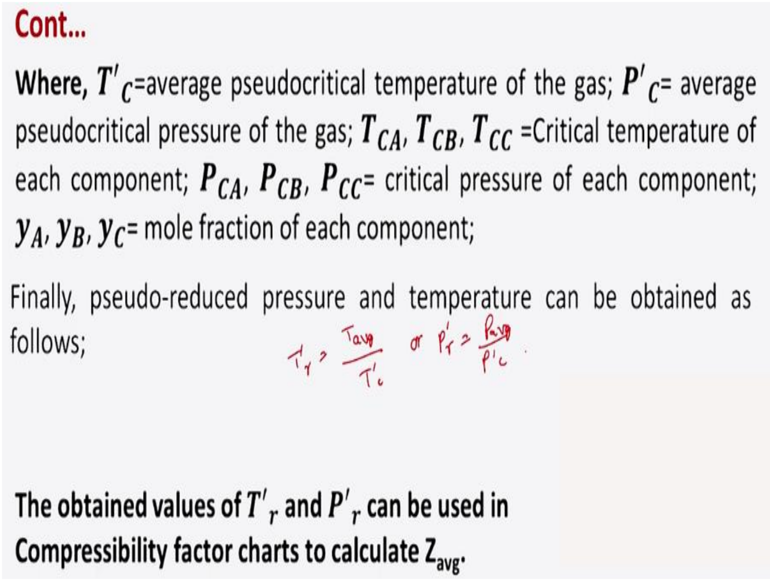
Pseudocritical values can be obtained with Kay's rule as follows.

$$\boldsymbol{T'_C = T_{CA}.y_A + T_{CB}.y_B + T_{CC}.y_C + \cdots}$$

$$\boldsymbol{P'_C = P_{CA}.y_A + P_{CB}.y_B + P_{CC}.y_C + \cdots}$$



Now, where T dash C this is the average pseudocritical temperature of the gas. P dash C this is the average of pseudocritical pressure of the gas and T CA, T CB, T CC these are the critical temperatures of each component. Where P CA, P CB, P CC these are the critical pressures of each component; Y A, Y B, Y C these are the mole fraction of each component. So, finally pseudo-reduced pressure and temperature can be obtained as T dash r = average T upon T dash C or P dash r = average P upon P dash C. Now, to obtain the values of T r dash and P r this can be used in the compressibility factor chart to calculate Z average.

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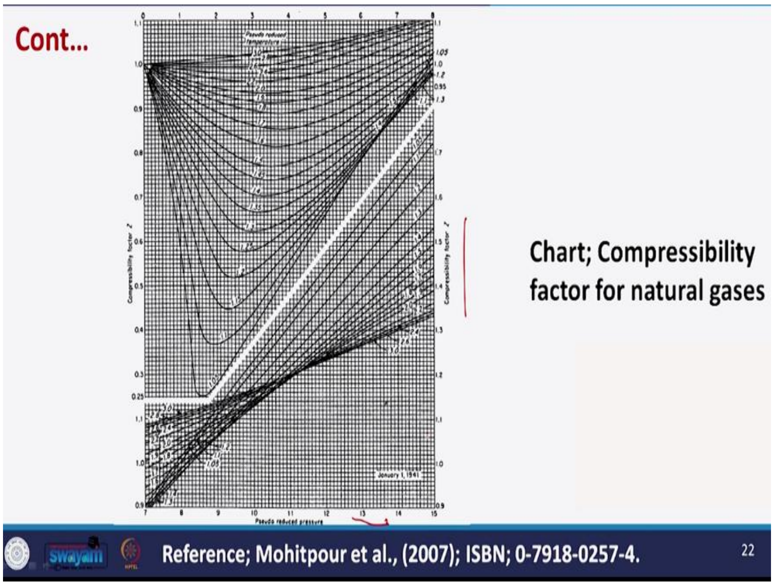
Finally, pseudoreduced pressure and temperature can be obtained as follows;

$$T'_r = \frac{T_{avg}}{T'_C} \quad \text{or} \quad P'_r = \frac{P_{avg}}{P'_C}$$

The obtained values of T'_r and P'_r can be used in Compressibility factor charts to calculate Z_{avg}.



Now, this is the compressibility factor chart for natural gas and you can see here this is the compressibility factor and this is the pseudoreduced factor. So, by substituting the values you can get the values of either Z or pseudoreduced pressure whatever required.

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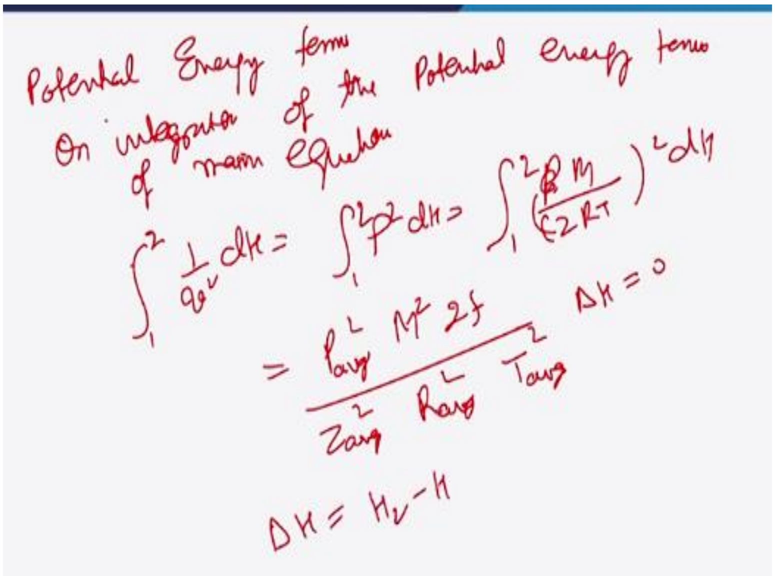

Now let us talk about a potential energy term. So, on integration of the potential energy term of main equation which we derived earlier, so it will result integration 1 to 2 1 upon v square dH = 1 to 2 rho square dH 1 to 2 P M upon Z RT squared dH and that is equal to average P square M square 2 f upon average Z square average R square average T square into delta H = 0 where delta H = H 2 – H 1.

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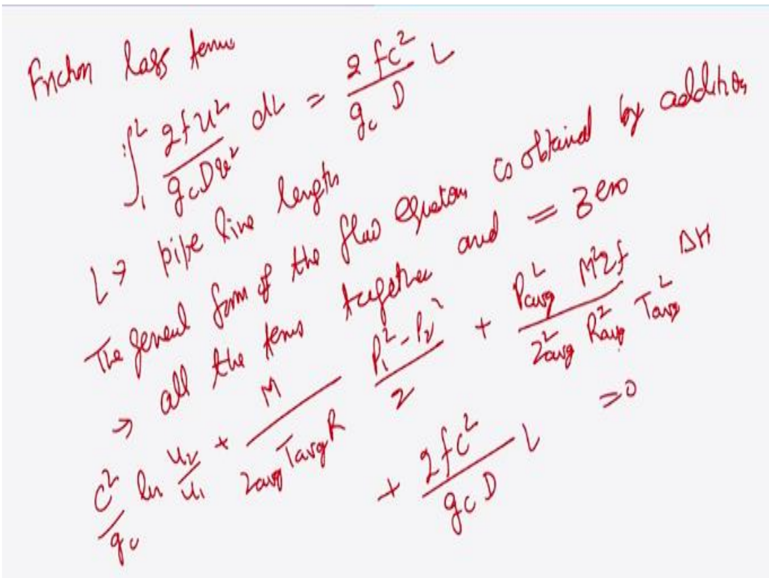
Potential energy term

On integration of the potential energy term of main equation will result in;

$$\int_1^2 \frac{1}{v^2} dH = \int_1^2 \rho^2 dH = \int_1^2 (\frac{P.M}{ZRT})^2 \, dH = \frac{P_{avg}^2 . M^2 2f}{Z_{avg}^2 . R_{avg}^2 . T_{avg}^2 .} . \Delta H = 0$$

Where, ΔH=H_2-H_1.



Now, let us talk about the friction loss term. So, if we integrate the energy loss energy losses, this can be evaluated as 1 to 2 2 f u square upon g c D v square dL this is equal to 2 f C square upon g c D L, L is the pipeline length. So, the general form of the flow equation is obtained by adding all the terms together and equating them to zero. So, it is C square upon g c ln u 2 upon u 1 + M upon average Z average T R P 1 square – P 2 square upon 2 + average P M square 2 f upon average Z average R T average delta H + 2 f C square upon g c D and that is equal to 0.

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Friction loss Term

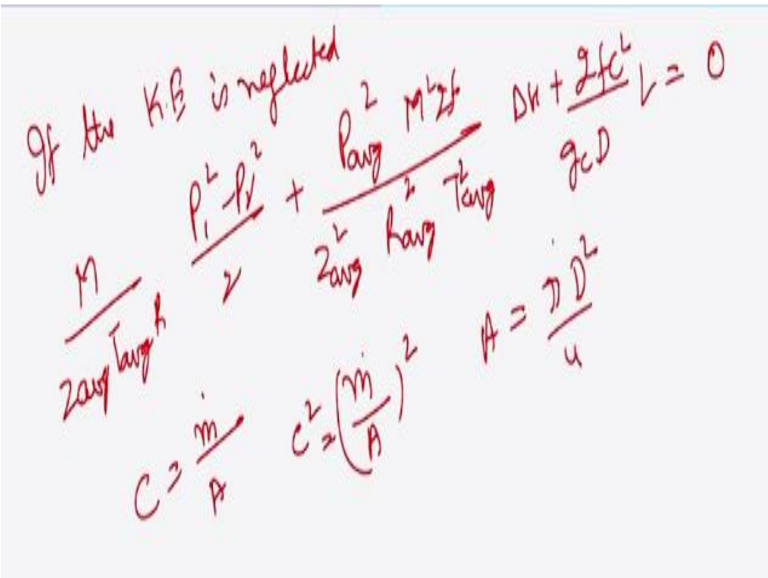
On integration of energy losses can be evaluated as follows;

$$\int_1^2 \frac{2f}{g_C . D} \frac{u^2}{v^2} . dL = \frac{2fC^2}{g_C . D} L$$

Where, L is the pipeline length.

The general form of the flow equation is obtained by adding all the terms together and setting them equal to zero.

$$\frac{C^2}{g_C}ln\frac{u_2}{u_1}+\frac{M}{Z_{avg}T_{avg}R}\frac{{P_1}^2-{P_2}^2}{2}+\frac{P_{avg}^2.M^2 2f}{Z_{avg}^2.R_{avg}^2.T_{avg}^2.}.\Delta H+\frac{2fC^2}{g_C.D}\mathrm{L}=0$$



Now, if the kinetic energy term is neglected for all high-pressure gas transmission lines, the contribution of kinetic energy term compared to other terms is insignificant. So, we can write M upon Z average T average R P 1 square – P 2 square upon 2 + P average square M square 2f upon Z average square R average square P average square delta H + 2 f C square upon g c D L that is equal to 0. Now, this equation can be further simplified upon if you take the following assumption or following substitution. C = dot m upon A, C square = dot m upon A square and A = pi D square upon 4.

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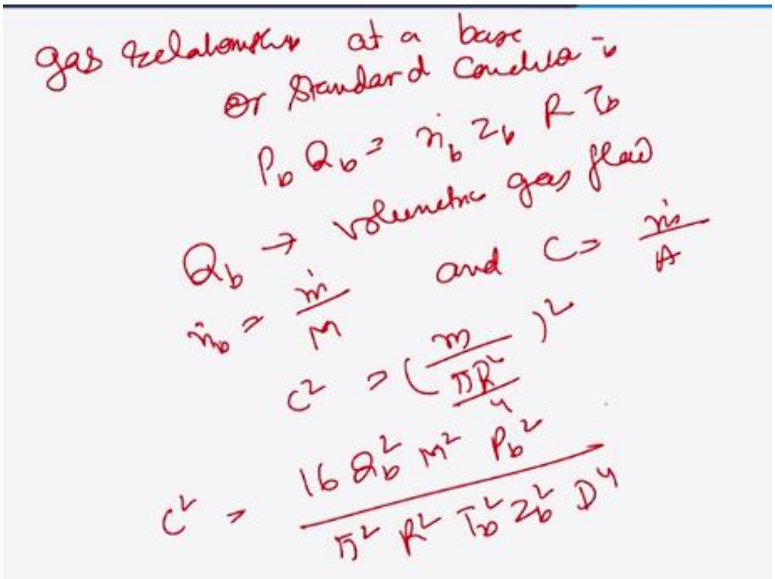
If the kinetic energy term is neglected (for all high-pressure gas transmission lines, the contribution of the kinetic energy term compared to other terms is insignificant), so;

$$\frac{M}{Z_{avg}T_{avg}R}\frac{{P_1}^2-{P_2}^2}{2}+\frac{P_{avg}^2.M^2 2f}{Z_{avg}^2.R_{avg}^2.T_{avg}^2.}.\Delta H+\frac{2fC^2}{g_C.D}\mathrm{L}=0 \;\ldots\ldots(2)$$

The above equation can be further simplified upon the following substitutions;

For pipe $$C = \frac{\dot{m}}{A},\ C^2 = (\frac{\dot{m}}{A})^2,\ A = \frac{\pi D^2}{4}$$



Now, the gas relationship at a base or the standard condition is P b Q b = dot n b Z b R T b. Q b is the volumetric gas flow. So, if dot n b = dot m upon capital M and C = dot m upon A, then C square = m upon pi D square by 4 whole square and C square = 16 Q b square M square P b square upon pi square R square T b square Z b square D to the power 4.

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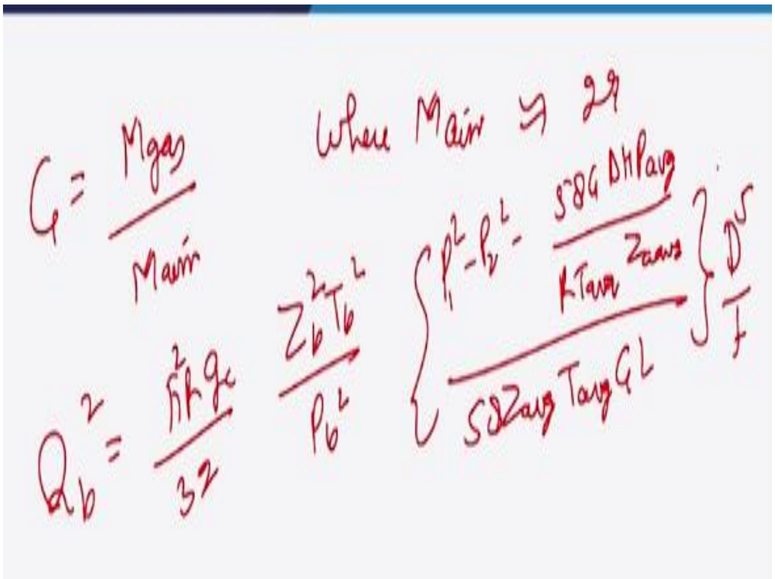
Gas relationship at a base or standard condition is;

$$P_b.Q_b = \dot{n}_b.Z_b.R.T_b$$

Where, Q_b is the volumetric gas flow

If $\dot{n}_b = \frac{\dot{m}}{M}$ and $C = \frac{\dot{m}}{A},\ C^2 = (\frac{\dot{m}}{\frac{\pi D^2}{4}})^2$

Then, $$C^2 = \frac{16Q_b^2.M^2.P_b^2}{\pi^2.R^2.T_b^2.Z_b^2.D^4}$$



Now, gas gravity is defined as G = M guess upon M air where M air is approximately 29. Now, if we substitute and rearrangement to solve Q b, then the equation becomes Q b square = pi square R g c upon 32 Z b square T b square upon P b square P 1 square – P 2 two square – 58 g delta H P average upon RT average Z average upon 58 Z average T average G L D to the power 5 upon f.

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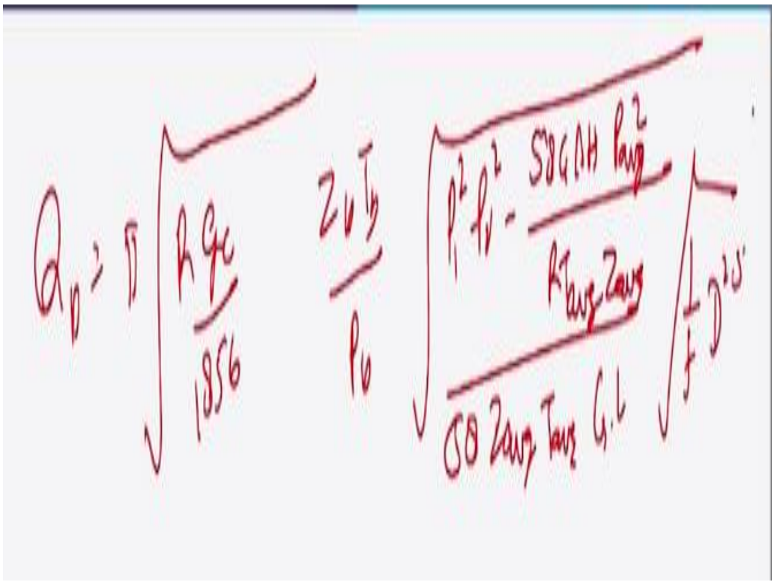
Gas gravity is defined as

$$G = \frac{M_{gas}}{M_{air}} \qquad \text{Where, } M_{air} \approx 29.$$

Upon substitution and rearrangement to solve for Q_b, the equation (2) becomes;

$$Q_b{}^2 = \frac{\pi^2 . R . g_c}{32} . \frac{Z_b{}^2 T_b{}^2}{P_b{}^2} \left\{ \frac{P_1^2 - P_2^2 - \dfrac{58G . \Delta H . P_{avg}^2}{R . T_{avg} . Z_{avg} .}}{58 Z_{avg} . T_{avg} . G . L} \right\} . \frac{D^5}{f}$$

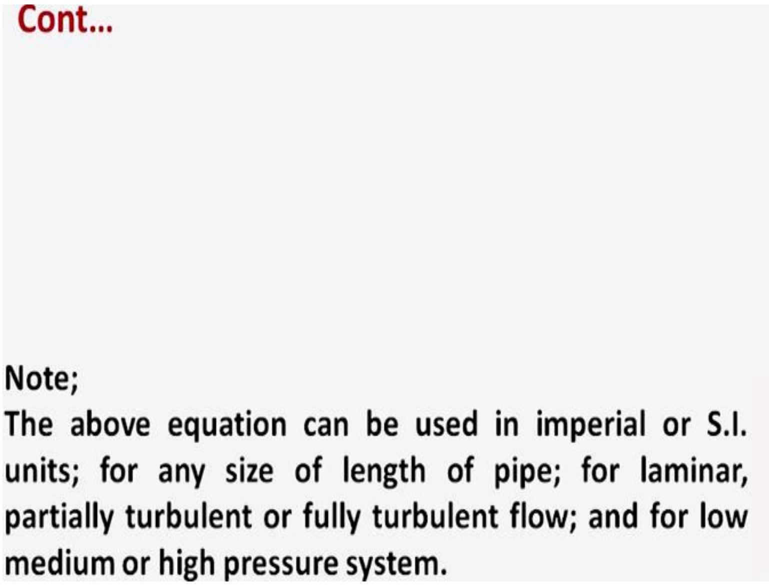


Now, after taking the square root of Q b, the general flow equation of natural gas in pipeline can be Q b = pi R g c upon 1856 Z b T b upon P b whole square root P 1 square – P 2 two square – 58 G delta H P average square upon RT average Z average 58 Z average T average G L 1 upon f D to the power 2.5.

(Refer Slide Time: 33:26)

After taking square root of Q_b, the general flow equation of natural gas in a pipeline is;

$$\boldsymbol{Q_b = \pi\sqrt{\frac{R.g_c}{1856}}.\frac{Z_b.T_b}{P_b}\sqrt{\frac{P_1^2 - P_2^2 - \frac{58G.\Delta H.P_{avg}^2}{R.T_{avg}.Z_{avg}.}}{58Z_{avg}.T_{avg}.G.L}}.\sqrt{\frac{1}{f}}D^{2.5}} \quad \ldots\ldots(3)$$



Now, this equation can be used in the imperial or you can say S.I. units for any size of length of pipe, for laminar, partially turbulent or fully turbulent flow and for low medium or high-pressure system.

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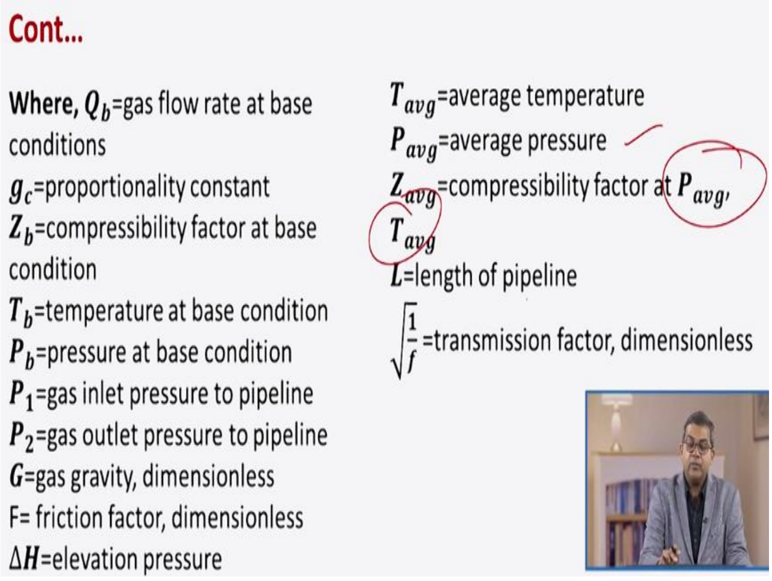

Now, as far as the notations are in question then Q b is the gas flow rate at base condition, g c is the proportionality constant, Z b is the compressibility factor at base condition, T b is the temperature at base condition, P b is the pressure at base condition. P 1, P 2 these are the gas inlet and outlet pressure in the pipeline. G is the gas gravity which is dimensionless. F is the friction factor, again it is dimensionless. Delta H is the elevation pressure.

Average T is the average temperature, P average is the average pressure, Z average the average compressibility factor at P average and T average and L is the length of pipeline whereas 1 upon f square root that is the transmission factor which is dimensionless.

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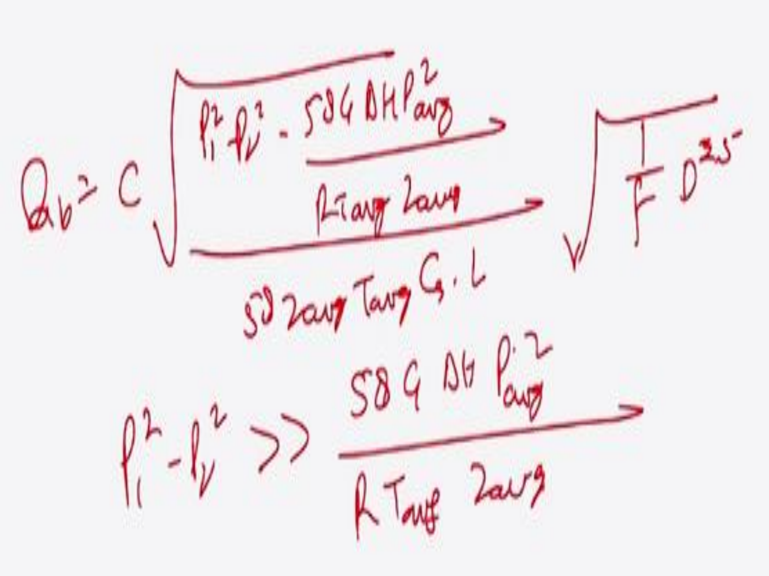


So, I am taking all constant as a C. So the previous equation becomes Q b = C P 1 square –P 2 square –58 G delta H P average square upon RT average Z average whole divided by 58 Z average T average G L 1 upon f D to the power 2.5. If the pipeline is horizontal delta H is insignificant to compare the value of P 1 square – P 2 square, so, P 1 square – P 2 square is greater than greater than 58 G delta H P average square upon RT average Z average.

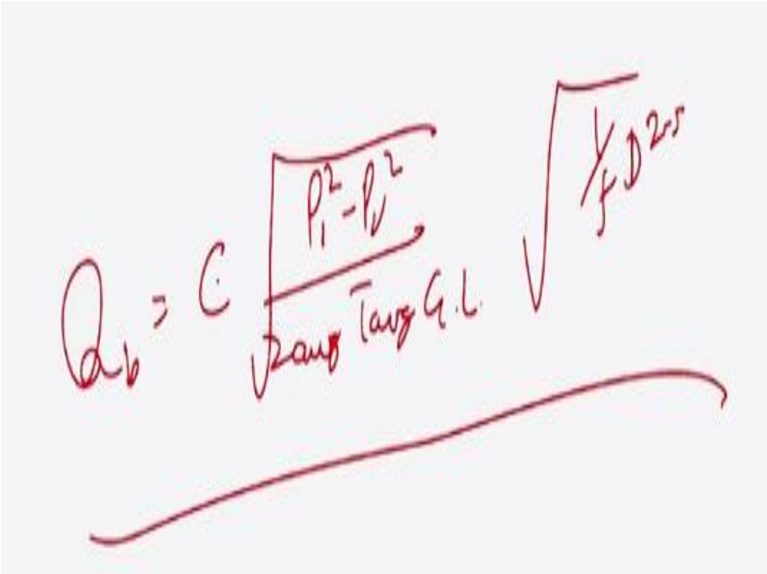
(Refer Slide Time: 35:43)

On taking all constant as C, the equation (3) becomes;

$$\boldsymbol{Q_b = C.\sqrt{\frac{P_1^2 - P_2^2 - \frac{58G.\Delta H.P_{avg}^2}{R.T_{avg}.Z_{avg}.}}{58Z_{avg}.T_{avg}.G.L}}.\sqrt{\frac{1}{f}}D^{2.5}}$$

If the pipeline is horizontal or ΔH is insignificant compare to the value of $P_1^2 - P_2^2$

$$\boldsymbol{P_1^2 - P_2^2 \gg \frac{58G.\Delta H.P_{avg}^2}{R.T_{avg}.Z_{avg}.}}$$



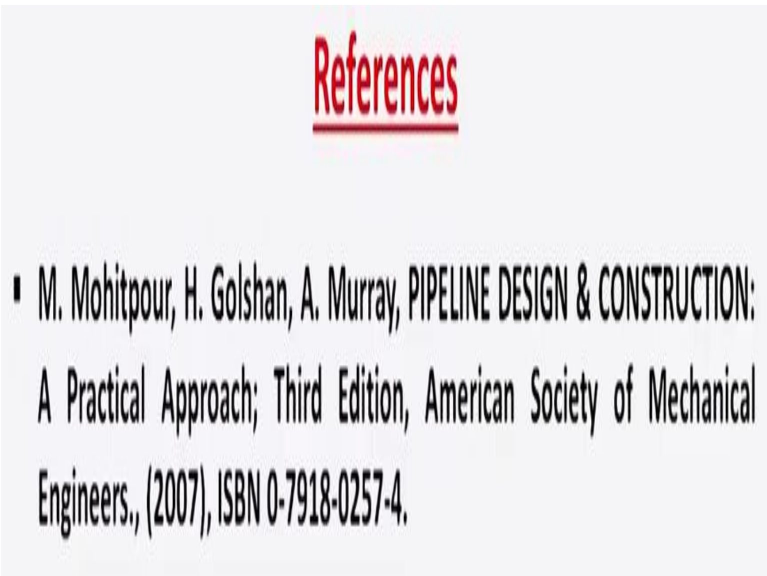
Then the elevation term is omitted and the final equation becomes Q b = C 1 square – P 2 square upon Z average T average G L 1 upon f D to the power 2.5. So, this equation shows the effect of transmission factor and the diameter of the pipeline on flow of gas in pipeline.

(Refer Slide Time: 36:12)

Then the elevation term is omitted and the final equation becomes;

$$Q_b = C.\sqrt{\frac{P_1^2 - P_2^2}{Z_{avg}.T_{avg}.G.L}}.\sqrt{\frac{1}{f}}D^{2.5}$$

The above equation shows the effect of transmission factor and diameter of pipeline on flow of gas in pipeline.



Now, in this particular segment we discussed about the design equations and especially the impact of kinetic energy, potential energy, friction terms, etc. For reference we have listed a reference for your convenience. If you wish to have further reading, you can take the help of this particular reference. Thank you very much.