Natural Gas Engineering
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Module No # 04
Lecture No # 17
Transportation of Natural Gas – I

Hello everyone and welcome to the class of transportation of natural gas 1 this class is going to be two parts transportation of natural gas 1 and 2. So far we had understood how natural gas is being produced from reservoir to surface and at this surface how it is purified to meet the requirement of customer. To send this natural gas which is purified at the surface to customer we have to adopt certain type of transportation mechanism.

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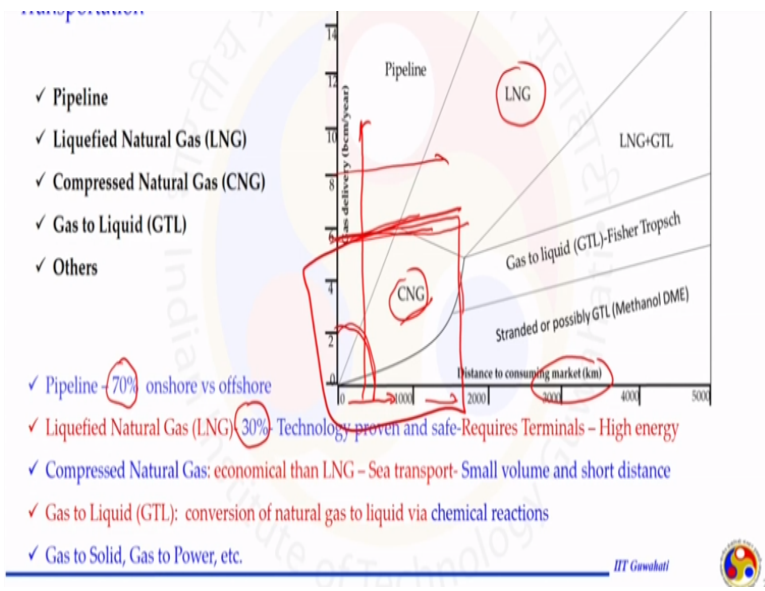

There could be several ways of transporting purified natural gas meeting the customer specification which is required record in terms of water removal in terms of contamination removal. In case of takeout valuable hydro carbon and selling them separately as well as same time of the customer needs the natural gas that is having certain amount of energy more than the pure gas even the traces amount of significant amount of higher hydro carbon where also supplied to customer.

So it depends on the regulation specification of the transportation as well as what could be separated out and at what extent that could be done in the separation facilities. The transportation can be accomplished by several means this chart shows on the X axis distance the natural gas is being supplied from its source to consumer or from its processing plant to consumer and the Y axis is having gas (()) (02:28) means how much amount of the gas is being transported.

The unit is BCM per year billion cubic meter per year and the X axis is having distance in globe meter. So this relationship shows when we are choosing an option to transport the natural gas it depends on several factor one of the factor is how much quantity is being transported and how long it is going to travel. If it is of very high amount that needs to travel not very far distance, not very far in the sense somewhere in this region we can choose either the small pipeline design system or can compress this natural gas and send it in CNG mode or it could be converting into some other liquid form all the option can be chosen.

And when the distance is going high we can see depend on the quantity if the quantity somewhere in this region we can still choose pipeline or CNG or the GTL process. But when the amount is too high for short distance, short distance means around 1000 kilometer it is not like 1 meter or 1 kilo meter or the 10 kilo meter it is a 1000 kilo meter distance significant high compared to one continent to other continent or somewhere one country to other country where it needs to be transported to a sea line then the mode will be different.

So if the distance can be covered by the land and the pipeline can be lay out even on the onshore offshore and the quantity is significant high we should choose the pipeline system. And pipeline system is something that mostly adopted so far for the transportation of natural gas compared to other means it accounts around 75% natural gas being transported from it is from one place to other place by the pipeline transportation mode.

These are the crude data but approximately pipeline is dominating the transportation mode when the quantity is high as well as distance is also too high like more than 1000 we cannot just lay out the pipeline at certain(()) (05:03) certain reason because of the geographical or political reason or by some other possibilities of facing the problem in terms of bay of fry or other things in the pipeline design.

Another mode that is mostly used is LNG liquefied natural gas and if we see on the crude data those are available in the literature and summarizes the liquefied natural gas accounts the remaining balance of the transportation around 30% it does not mean other modes are not being practiced.

So LNG mostly account 30% of the gas that is being transported this is a proven technology at safe mode but very energy intensive required the terminal where it can be deep freeze or the temperature can go down up to – 160 where this natural gas that is being transported and the gas which is being transported mostly methane and methane needs much lower temperature to go the liquid phase.

And when we going to – 160 degree Celsius temperature and liquefying this natural gas terminal are required for the purpose and when it is in a special type of the tanks transported from one place to other place in a special type of the tank system again at the other side terminals are required where it again be converted into gas phase. CNG also a mode of transportation and this is stand for compressed natural gas it is economical compared to LNG because we do not need to go to that much low temperature.

However the compressor is required to compress that thing but the handling equipment shipping from one place to other place the type of the tanker or the shell of vessels are required allow us to send gas in compressed manner in much economical manner than the LNG. Sea transport can also be accomplished while we are compressing the natural gas and sending it in the CNG mode the small volume and short distance when the volume is not too high and when the distance is also not very high that mode should be adopted and that is here in this region where the CNG is occupying significant part of this graph.

CNG is used in the vehicles now so there are significant number of vehicles on the road those are running on compressed natural gas if further modification can be some in the mechanisms of using the CNG this miss here a larger part it is having a better future prospective. Other technique could also be possible when can convert this natural gas or methane to liquid that can be done by GTL process we can do it with Fisher Tropsch process using a specialize catalyst and temperature pressure condition this lighter hydro carbon compound can be converted into heavier compound or other petro chemical compound those can be used for other purposes.

Like DME Di-methyl ether methanol those can be generated at the source itself and the liquid it is being transported through the tanker or by other media. We will be discussing the processes like LNG, CNG, GTL in little bit more detail at the later part of this transportation natural gas lectures. Let us focus on pipeline that account 70% and mostly used mode of transportation for natural gas to transport from one place to a very long distance.

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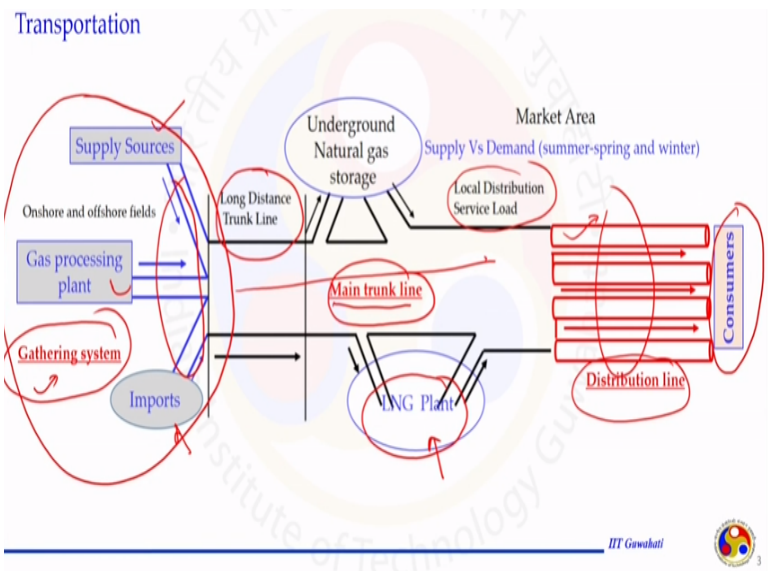

When we focus on the transportation on the pipeline we can see a symmetric diagram that shows now natural gas can be transported from one pace to other place. This figure shows on the left hand side the places from where the natural gas is getting accumulated or gathering station we can call it and the pipeline are called gathering pipeline. Here I had mentioned gathering system and when the gathering system is collecting the gases from various sources like the supply from other source from gas processing plant where gas was being treated or processed and importing part also.

There may be having a different part in the pipeline system where they can be included through this trunk line system the long distance trunk line system and put it in the main truck line. So if we classify this in a broad way we are having three type of pipeline in the system the gathering system where we are collecting the gases from various sources import gas processing plant supply sources then it is going through the main trunk line and travelling a very long distance.

And at the other side before it goes to consumer we are having another place local distribution service load where these gases are further transported in a small diameter pipeline to consumer ad these lines all the distribution line . Between the gather system and distribution line there is a main trunk line where the natural gas is transporting from one place to other place.

As already discussed in compressor class the flow is happening because of the pressure difference and pressure decline because of the friction losses in the pipeline system that is a several compression stations are required to compress the gas. Two important aspects here LNG plant liken when natural gas is transported from one place to other place in the system from gathering system to distribution line may be the demand and supply is not matching because during the summer time and winter time the demand is different.

In the winter time more natural gas is required to heat the building the heat the residential areas and for other purposes the natural gas that is being produced should be stored that could be stored either in the form of LNG plant or it can be stored underground in the depleted oil gas reservoir.

Where we know the geological formation detail sorted this natural gas and whenever the demand is high compared to supply when use this underground storage or LNG plant processing facilities to match the demand. Altogether pipeline that is having different diameter different specification and similar here and the trunk line that is spread over a long distance pass through several (()) (12:36) like several path it is going to travel.

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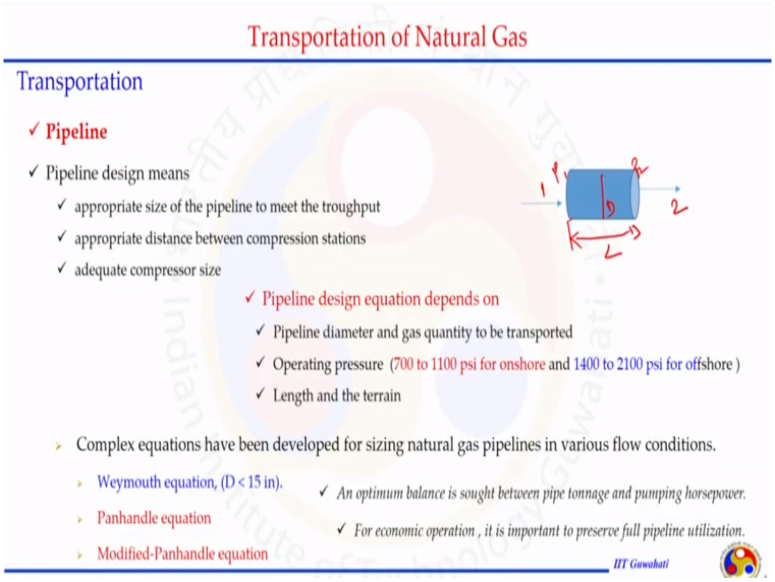

So when it comes to transportation through pipeline, pipeline design is very much important because that says depend on the quantity and the distance how to design the specific diameter pipeline we are going to discuss mechanical aspect we are just on the flow rate pressure and diameter relationship so the pipeline design means appropriate size of the pipeline to meet the through port.

So we want to send specified quantity of natural gas from point 1 to point 2 through pipe line that is having certain diameter and certain length that we need to travel in point 1 and point 2 how much gas we are going to send through this pipeline depend on pressure difference also. When there was not demand of natural gas the calculation involved in pipeline design where good enough to understand the process now the demand is high the pipeline system should be used very efficiently even at higher pressure or the maximum level pressure to meet the through port or the requirement of the natural gas at the other end.

That is why appropriate size of pipeline to meet the throw port should be considered in the design appropriate distance between compression station as already mentioned between this long distance between one and two there might be N number of compression station are required that is compressing the natural gas to meet the demand again. So appropriate location of compressor should also be identified it should be part of the pipeline designs system where the compressor should be installed and at what horse power working power should be provided to a compressor.

So the specified amount of the natural gas can be transported with the already led out pipeline system. Pipeline is an equation when we talk we should do the pipeline design the design equation depends on the diameter and gas quantity to be transported operating pressure and temperature most of the time it is considered the temperature is not changing and the flow is happening under isothermal condition and the length and the terrain.

How long it is going to travel and what type of the path it is going to face like it is having just a horizontal flow it is having some inclination or it should be just a single pipeline should be a combination of single pipeline or just a bigger diameter single pipeline or may be the looping of the pipeline with that we will be discussing the transportation of natural gas to.

So the complex equation that have been developed for sizing natural gas pipeline in barriers flow conditions as already mentioned depend on how much quantity we are supplying what type of terrain it is going to face the equation we take little bit different form. The typical equations those are used in the natural gas industry to design the pipeline or to establish the relationship between the flow rate pressure draw down specification of the pipe line like the diameter and the length as well as fluid properties that equation can be in a different form the mostly used forms are Weymouth equation, Panhandle equation and modified Panhandle equation we will discuss this one by one.

And optimal balance is sought between pipe tonnage and pumping horse power record how much quantity is being transported pipeline and how much energy is required to transport that natural gas that function or that relationship must be optimized. For economic operation it is important to preserve full pipeline utilization whatever the mode the pipelines are designed serial parallel or loop pipeline the entire diameter of the pipeline all this things must be effectively utilized for transporting natural gas economically.

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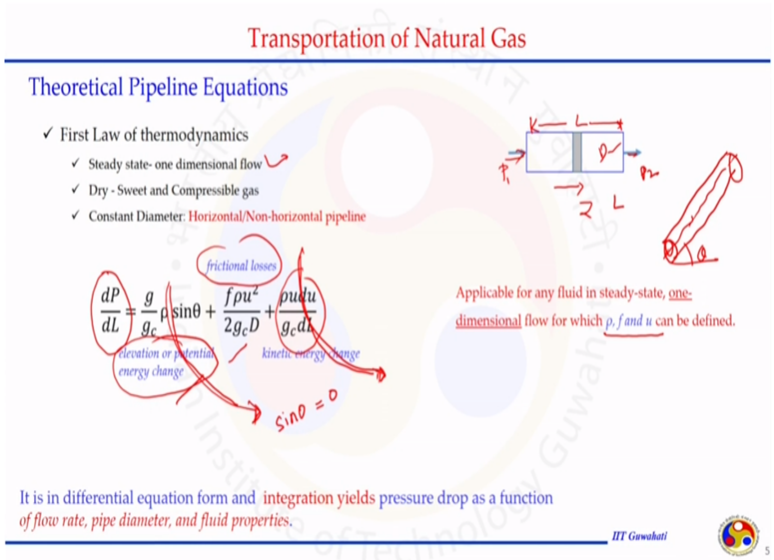

If we go further and see how to set up the mathematical equations for this pipeline transportation mechanism. The theoretical equation can be set up by considering the first law of thermodynamics several assumption need to made we will make the assumption as we go further and solve the problem or solve the equation that is in the desired form is how my flow rate is related to pressure draw down with other important parameter like the fluid properties and diameter and length of the pipeline as well as the inclination if it is travelling through different terrene.

So under steady state condition one dimensional flow we are just assuming the flow is assuming only in one direction that is Z where we are having the pressure difference P1 – P2 the length of this pipeline is L if it is having certain inclination like this we can account that with the help of angle theta that this pipeline is making if the pipeline is inclined at a particular angle we can adjust the gravity forces accordingly.

So for steady state condition one dimensional flow considering only gas phase is flowing we can modify that terminology saying dry means only the methane gas mostly the methane gas sweet means most of the impurities already taken out and compressible that is our natural gas in compressible gas is flowing through this pipeline of diameter D and length L for this constant diameter D we can set up the equation considering it is under the horizontal condition or it is at being certain inclination or the non-horizontal condition the pipeline is layed out.

We can see the balance of the forces of the flow driving force that is allowing the flow happening from P1 to P2 will be balanced by 3 type of the forces the elevation or potential energy changes that is happening so the pressure energy will be equal to the potential emery changes happening in the system because of the friction the pipeline roughness depend on the roughness of the pipeline the friction forces can be applied and there will be rest in the flow.

So the friction losses should also be accounted in the balance equation as well as kinetic energy change we are ignoring any shaft work done on the system we are just considering a section of a pipe where we are saying the pressure is changing from P to P2 flow is happening at that is applying the first law of thermodynamics we can set up the conservation equation that says dP / dL = kinetic energy change frictional losses + potential energy change in the system.

This is one type of differential equation if we can interrogate this equation we can get how the pressure drop is a function of flow rate pipe diameter and fluid properties. If we look more closely on this equation we can say this equation can be applicable or can be apply for our system where rho, f and u.

Rho is the density of the fluid the gas which is flowing through the system through this pipeline F is the friction factor that is offered by the tubing and u is the velocity with means this gas is flowing through this tube if they can be defined we can solve this equation easily considering any analytic solution and we can get the desired relationship depends on the system we are having we can simplified this equation also.

So for example when we are having the horizontal flow this angle should be 0 and we are getting so this angle should be 0 and we are getting sin theta 0 that is equal to 0 means gravity is not contributing into this system and we can ignore it. other cases could be there when we are saying the cross sectional area of tube is not changing the flow is not happening at that high rate where the kinetic energy change is also contributing for this pressure drop we can ignore this kinetic term also.

If it cannot be ignored either one either the gravity or the kinetic we have to include in the equation and more complex equation need to be solved. Let us go step by step in the first case we area assuming the gravity is not playing any role as well as kinetic is also not playing role the pressure drop is happening because of the friction losses only.

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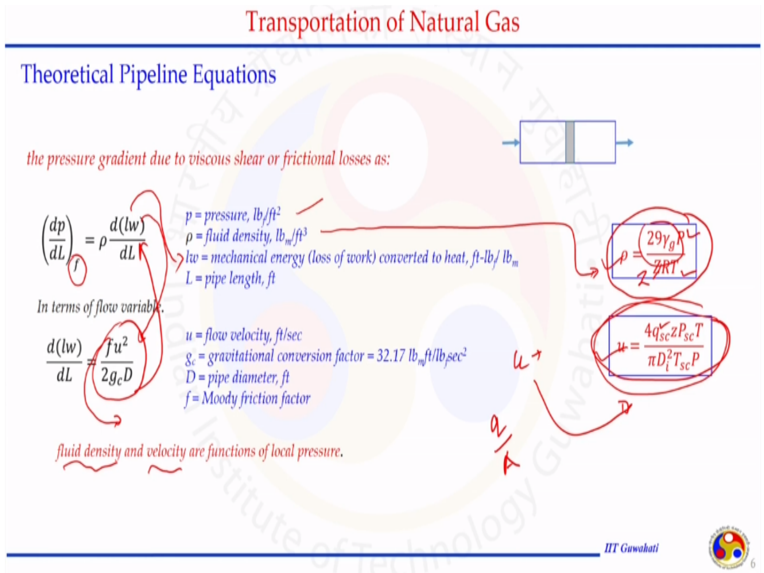

And when we do so we get very simplified equation that says the pressure drop because of the friction can be related with the viscous shear or the frictional losses and that is dP / dL = Rho some mechanical energy losses of work that is getting converted to heat when the fluid is flowing through this tube because of the resistance offered by the two line heat will be releases to the environment and that will be equivalent to the pressure drop happening because of this friction losses.

We can convert this into some flow variable we know how to do it we did two three time we passed also especially when we are dealing with the WPR well bore performance relationship where we can establish this is equal to fu square by 2gcD and this is responsible for accounting the fluid properties in terms of f. So thus if we put all of this here what we are going to get the relationship that says if the flow through pipeline is having is happening in the horizontal tube and no kinetic energy is changing we got this form of the equation just substituting this here we will get it.

And that also be related by the definition of friction factor that says friction factor f = tau / rho u square by 2 if we put that thing we are going to get the similar thing. Here the terms are having their usual meaning like the pressure the unit may be different and depend on the unit system chosen and in numerical coefficient any appear there if all the unit system are matching there wil be any numerical coefficient.

We did this several time in the past so we can ignore this time and rho flow density now a fluid is not incompressible the density will change and we know from our properties of natural gas class how to relate rho with the local condition that is P and temperature this is a compressibility should be small Z. Z compressibility 29 gamma Z is the molecular weight of the natural gas or the apparent molecular weight of that natural gas.

Similarly when we converting this into the flow properties like the velocity of the fluid we know u it is difficult to measure the velocity of u. But you can convert that into some quantity those are locally can be evaluated or can be considered for example we can convert by knowing the flow rate and cross sectional are u q/A again q is a property of temperature and pressure we can convert it to q is the standard condition and we will get the expression we did this few times before also should not be having any problem to understand how we got the expression for rho and u.

When we put in this equation we will see now this function is in terms of pressure and temperature serious it was in terms of fluid density and velocity and they are the function of local condition we converted them both density and velocity to pressure condition.

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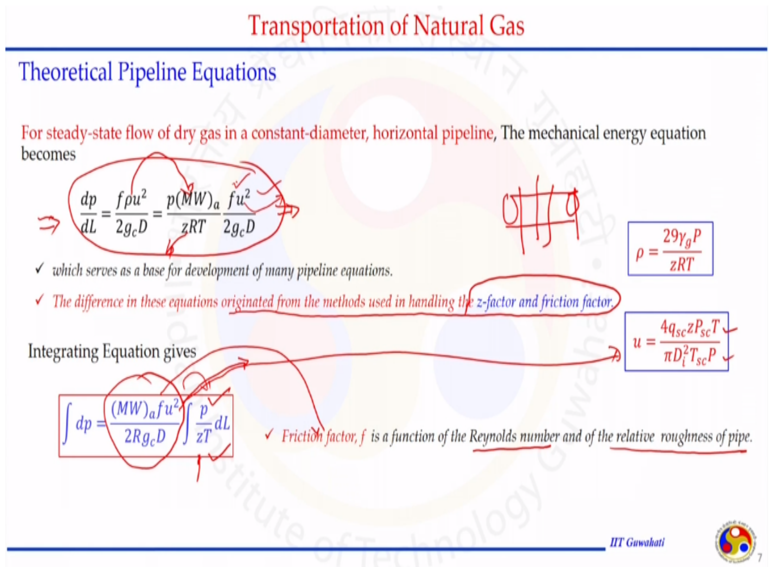

And when we do so we are going to get the expression that is appear like this after substituting the value we can also get this expression. So this is rho value we got the equation how the pressure drop is happening when the fluid is flowing or the gas is flowing through a pipeline of the diameter D at a particular length in this pipeline we can estimate the pressure at the end or at any location after solving this differential equation but again the problem is not solved because we see here when we converted this we are having f and u.

This equation which is a balance equation or energy balance equation under certain condition says how the pressure drop is related to fluid properties and it shows the basic equation for the development of any pipeline equation under certain assumption those assumption may create some problem or some deviation from the result obtained by this equation.

For example gravity, kinetic energy were not considered steady state condition may not be a case when is happening and shaft work is not considered there might be some addition work done on the natural gas form the outside but under certain assumption those we had discussed this mathematical equation is good enough to represent the flow through horizontal pipeline under steady state condition through a pipeline of constant diameter.

The difference in this equation originated by the method using handling the compressibility factor and friction factor so in this equation we will see the compressibility is appearing and

F is spearing and both are having dependency on other parameter. Similarly we will see u also depend because by the definition u is also function of temperature and pressure now.

When we integrate this equation considering all this terms are constant although those are not constant we will see we will get this kind of expression where it says inside the integral we are having the pressure, temperature and compressibility temperature may be assume constant may be taken average similar the pressure either we are evaluating it locally or we are taking it as a constant or the average by any mean once we know the temperature and pressure as well as gamma Z of this system we can calculate the compressibility as we know from our properties of our natural gas class how to calculate the compressibility.

We were discussed one example to understand the processor of performing the pipeline design integrating this equation may result in a simple expression but before we go further we see the friction factor eu is function of Reynolds number and of the relative reference of the pipe we cannot take it out of the derivative term because it is function of Reynolds number. Reynolds number is a function of flow rate, flow rate is a function temperature and pressure.

Similar for u also so let us see what we can do or each term when we go further for velocity we can simply this can be converted in terms of temperature and pressure and we can put it inside the integral side for the F friction factor it depends on which form we are going to calculate the friction factor value.

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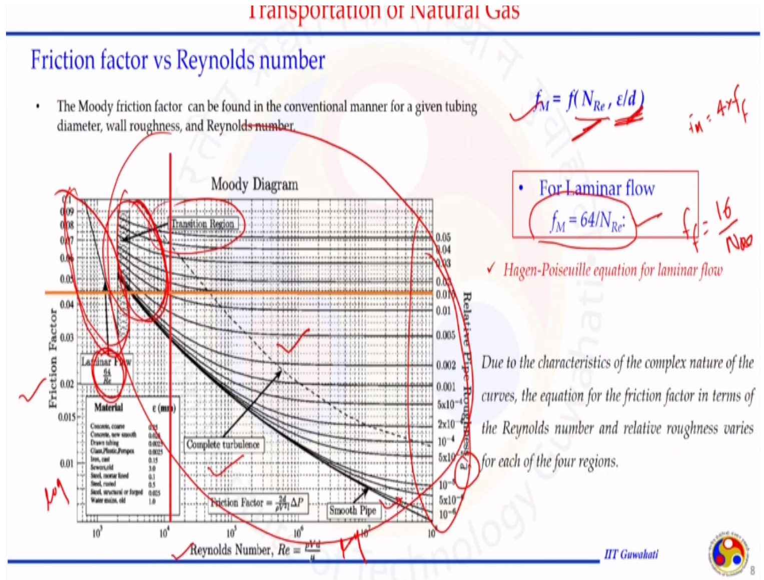

So if we look in the literature we see the friction factor versus Reynolds number relationship that is also called the Moody's chart relationship that account for the changes happening in the value of friction factor when a gas or any fluid is passing through a tube of some roughness and some diameter. So this relationship is log log scale on the Y axis is the friction factor on the X axis it is Reynolds number and there are several lines those represent for different relative roughness of the pipe.

If we classify this chart we can see there are four reason when is laminar flow where the flow is not dependent of the roughness of the pipe it just a Viscos flow or not very high flow rate is present in the system. In most of the cases in pipe line design we are in the turbulent region before we hit the turbulent region there is transient region where the distribution in the value of friction factor is not that high with respect to f salient divided by d then the third reason is complete turbulent region and forth one is smooth pipe region where it is not depending much on the Reynolds number jus tit deepens on the roughness of the pipe.

It is important to understand the chart is in terms of Moody's chart not in the finding friction factor for so value of F we are getting from where is a Moody's friction factor fm that is I mention here fm is a function of Reynolds number and roughness depend on which reason we are it is depending on Reynolds number or not it is depending on the relative roughness of the pipe or not and what value should be chosen depends on under what condition the flow is happening through the pipeline.

For example in the laminar region we can see here form this chart this is the region where the friction factor is just function of Reynolds number and it is having the reciprocal relationship. So the Moody's friction factor is just can be calculated by 64 divided by the Reynolds number you do not need to worry about roughness of the pipe and if it is finding friction factor chart we will see the relationship between fm = 4 times finding friction factor accordingly the adjustment need to be done.

I case of finding friction factor we will get ff = 16 / Nre so we are seeing here the 16 by Nre this point we will see this chart is respect the finding friction factor otherwise it is Moody friction factor. The relationship in laminar region can be established by well-known phenomena of Hagen-Poiseulle flow in the pipeline. Due to the characteristic of the complex nature of the curve several equations have been designed for this region all three region transient region, turbulent region and smooth pipe region.

And accordingly we can choose which region the flow is happening in the pipeline not only the region where the flow is happening in the pipe line but we can see how it is changing with respect to Reynolds number and F salient D several expressions have been reported in the literature in the form of correlation we can choose based on the limit range or condition is specified for each expression and that we can see in the next slide.

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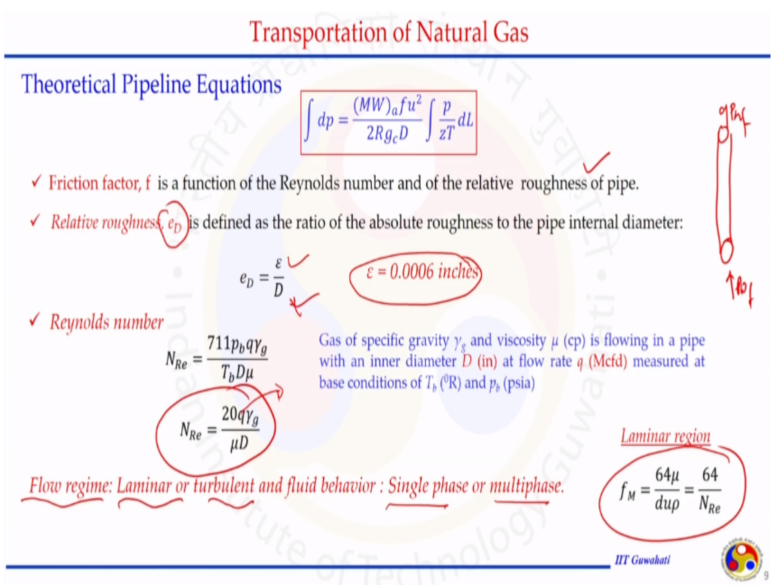

We already discussed similar kind of the things when we were developing the relationship before wpr. In wpr we were having the vertical flow of the gas from pwf to phf we discuss the phenomena with some inclination later on we solve the problem for vertical flow system. Let us come back to our problem where we said the friction factor f is a function of Reynolds number and of relative roughness of pipe.

Yes we know by the definition of f or from the Moody's chart it depends on how to estimate the relative roughness ed. It is defined as relative roughness of the pipe to the pipe internal diameter f salient by d it is the value should be provided by the vendor who design the pipe or who is supplying the pipeline. Incase it is not available we can calculate by performing certain experiment and see comparing the pressure drop is happening in a particular pipeline compared the very smooth pipeline.

We can estimate this value or in other case when we do not have the value we are dependent on somebody we can choose very acceptable value of F salient that is 0.0006 inches and divided by the diameter we can calculate the relative roughness where we know the relative roughness of we need to know the Reynolds number to read the Moody's chart. We know by the definition of Reynolds number rho Reynolds number = rho eD / mu by adjusting the parameter as we did in previous classes we can establish the relationship Reynolds number = 20 q gamma g mu D.

So it depends on q and q depends on temperature and pressure that is why when we are going to read the Moody's chart we should know the flow rate. And if we are going to calculate the flow rate we have to perform the iteration. So depend on the flow regime we are in the laminar region, turbulent region, transient region or later turbulent region we can establish the either we can read the chart and get the value of f for the single phase and multi-phase the system will be different we have to be little bit careful when we are taking about the multiphase system.

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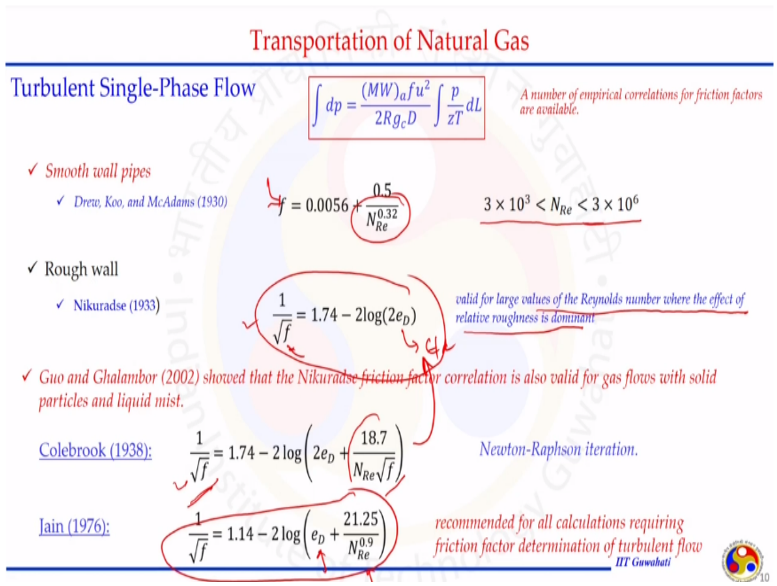

For the laminar flow now we know Moody friction factor is 64/ NRe in case of turbulent single phase flow system for f value there are several expression only few of them are included in this several we discussed already in the class of wpr. So for smooth wall pipe Drew Koo and McAdams in 1930 they had designed or establish the correlation that says when you are in the Reynolds number where 10 to the power 3 to 10 to the power 6 you can use this expression and that says it does not depend on F salient D you can just establish the value of F knowing the Reynolds number value.

And this is for smooth pipe when it is a rough pipe Nikuradse say had developed relationship and that relationship is widely used for the pipe line design because it do not depend on the Reynolds number and you see here this is just eD that is F salient D. So calculate the value of F we need to know only the roughness of the pipe and if roughness of the pipe is known we can get the value of F.

This is valid for large value of Reynolds number where the effect of relative roughness is dominant it is not the value of Reynolds number but the effective roughness that is more contributing towards deviation in the F value depend on the condition. So for F salient D value we can use this expression Guo and Gallambor showed that this expression given by the Nikuradse for friction factor is valid not only for the gas flow but gas flow with some solid and liquid mist this same expression can be used.

Further the expression accounting the range of the flow where both F salient by D as well as Reynolds number are going to dominate the phenomena is developed by Colebrook in 1938 and the relationship says we can also include Reynolds number in Nikuradse expression which accounts for the Reynolds number effect on the calculation of f. This expression can be put back to Nikuresade if we assume the Reynolds number effect is not significant this equation will be similar to what Nikuresade has proposed.

Now in this equation the problem is on the left hand side we are having the friction factor and the right hand side we are having the friction actor also solve this kind of the equation we need to perform the iteration processor either by the (()) (38:55) or Newton- Raphson method or other optimization method we can perform trial and error processor the iteration processor to establish the relationship.

And to avoid this difficulty Jain in 1976 modify this equation and proposed equation that says you can use this equation which is having eD and Reynolds number both but does not need iteration and this equation proposed by Jain is recommended for all calculation requiring friction factor determination to a system where the turbulent flow is happening.

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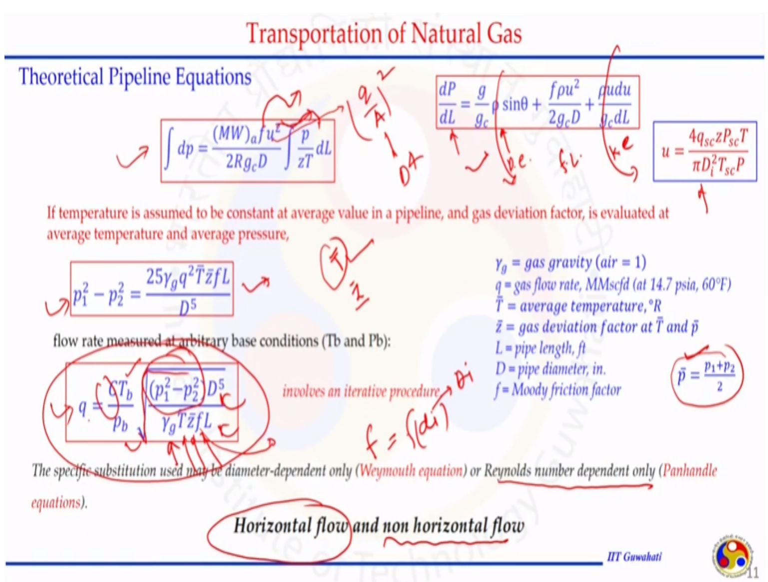

So let us comeback to our theoretical equation where we say this equation which was accounting for change in potential energy change in frictional losses and kinetic energy change for those are continuity to pressure drop with the help of non-parameter like how to convert rho and velocity into temperature and pressure condition we could establish this relationship.

And that relationship says now if we know f how to count it can we take it constant or not similarly for u2 you can solve this expression we know u2 cannot be taken out it has to go inside of the integral sign using this relationship when we integrate this we are going to get this expression. To integrate this equation we have to make certain assumption for the temperature we can assume the isothermal process is happening there is not temperature changes happening or temperature changes happening is represented by the average temperature T bar.

Similarly the compressibility factor Z is measured as average temperature and average pressure condition. So average temperature can be calculated like this compressibility factor z is measured at average temperature an average pressure condition. So average temperature can be calculated d like this like the if any temperature changes happening we can average out and for pressure also we can go by the arithmetic average p1 + p2 / 2 at this temperature and at this pressure we can calculate the compressibility factor and that can be taken out of the internal sign assuming it is constant in the process.

And when we integrate this we will see after during the separation of pressure term on the left hand side and others on the right hand side we got this expression if we can re arrange the things we are going to get in terms of q where inside the root we are having p1 square – p square D to the power 5 then D to the power 5 came because u square we are having this q / A. So when we square it q / A square and from it become D to the power 4 1D was already there we could get D to the power 5 here.

After adjustment seeing this is Tb Pb at a particular tape temperature and pressure we can relate Q with pressure draw down or pressure difference in the square form D to the power 5 means the diameter of the pipeline gamma g specific gravity or property of the natural gas average temperature average compressibility f is still there the F value will be put up there and the L the length of the tubing.

S all are having the usual meaning here depend on the unit system specified for each we will get this C the numerical coefficient here that may get different numerical number. But here again this equation we go after doing the integral after making certain assumption we see the Q on the lift hand side is again depend on f that is friction factor and if f is calculated by Reynolds number iteration are required to come out the accurate solution of this equation.

The specified substitution used may be diameter depended then we already know if we are f that is just depending on diameter of the tube either it is small di or capital Di or it is depends on the Reynolds number only Panhandle equation derived based on certain assumption. So in the Weymouth equation is just a function of the diameter and in Panhandle equation it is a function of just Reynolds number we will see this in the coming slide.

So now the equation that has been developed here is only for horizontal we had considered theta = 0 and we had neglected this term as well as the kinetic term assuming constant diameter tube. Now we can derive the same equation considering the theta is not 0 it is having particular inclination the pipeline is having inclination from the surface we can establish the relationship for non-horizontal flow condition also we will do this later on.

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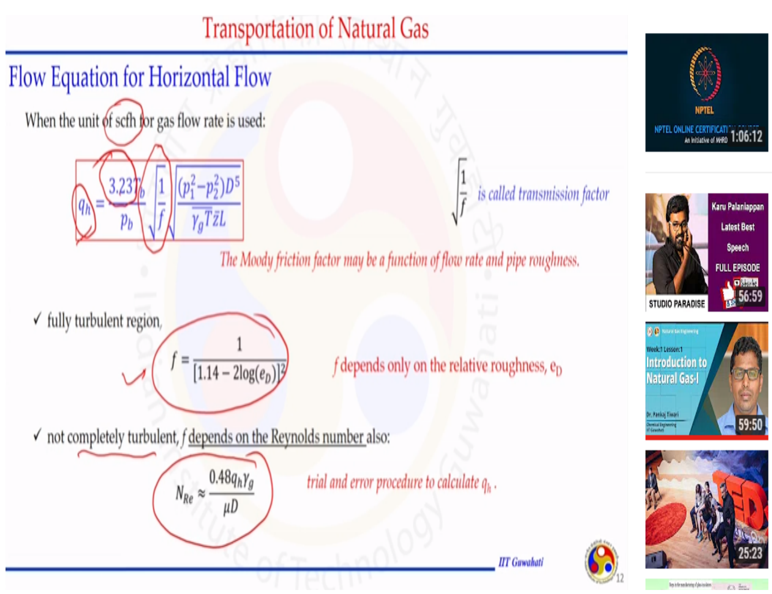

So let us go for the horizontal flow what we got when we convert the unit as mentioned in the last slide the numerical coefficient c that is appearing in the last will get change now the q will also get change here it become qh it means the flow rate is measured per hour standard cubic feet per hour and the numerical coefficient appear here remaining things are same it has been taken out outside and this term is called transmission factor

So when by f and its root is called transmission factor the Moody's friction factor may be a function of flow rate and pipe roughness that we discussed depends on the functionality of f this may take different form for fully turbulent reason for f may be defined like this where it's not a function of Reynolds number just the relative roughness eD or in other term F salient / D we can say using this it is not depending on the Reynolds number if not complete turbulent reason is there F depends on the Reynolds number and we have to calculate the Reynolds number put it in the equation of f which uses the Reynolds and iteration need to be performed to calculate the qh value.

So not depend on the f functionality chosen mathematical equation that is the solution of simple balance equation may take different form.

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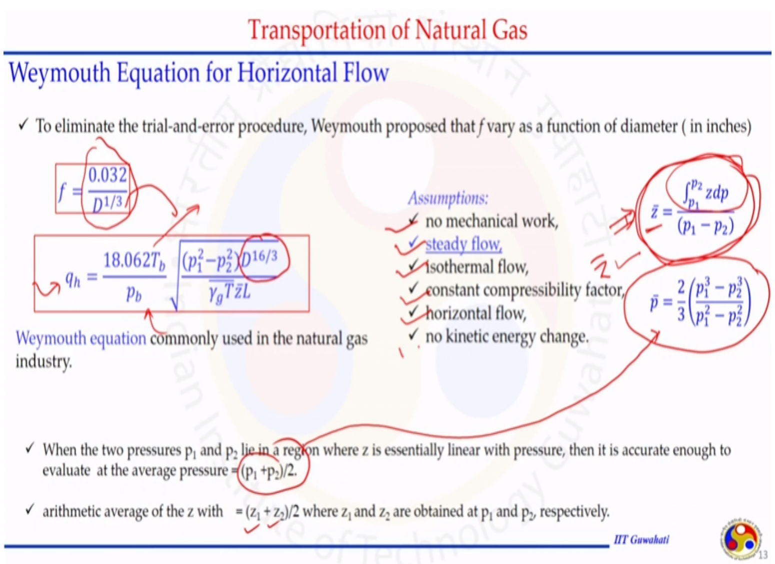

So for example Weymouth equation it is widely used for the horizontal low eliminate the trial and error processor just assuming f is the function of diameter only and if we express f in this form 0.032 divided by D to the power 1 / 3 we will get qh again qh means standard cubic feet per hour the flow rate with respect to some base temperature and pressure will take this form.

Here because of D the D to the power 5 got converted D to the power 16/3 other things are almost same. The Weymouth equation commonly used in the natural gas industries to establish the relationship between q, pressure, temperature diameter of the pipe and other properties. But this equation is under certain assumption what we assume no mechanical work is done steady flow is happening isothermal condition is assume so T either it is isothermal constant temperature or T bar is chosen to represent the flow constant compressibility factor Z bar it is constant.

So it is calculated either at a average pressure that average pressure could be just athematic average P1 / P1 + P2 / P2 or may be the athematic average of compressibility itself. So compressibility is calculated at pressure P1 and then P2 we got Z1 and Z2 take the arithmetic average of both we are going to get the average value of compressibility or it might be defined in other form where how the compressibility is changing with respect to in pressure in this pressure range p1 to p2 integrating the area where that curve in the form of p1 to p2 zDp where integrating from p1 to p2 divided by this range p1 to p2 we can get the average value of the compressibility.

The pressure may be chosen either athematic average or may be other more complex form which provide the accurate value of the average representation of the pressure that depends on the how pressure is changing with respect to p1 and p2 can it be taken as average. Similarly the compressibility factor z how it is changing linearly with respect to pressure may be just average is good enough or if it is not changing linearly with respect to pressure we may use this area under the curve to calculate compressibility value that average condition or it is the average value of the compressibility factor.

We also assume the flow is horizontal theta is 0 and no kinetic energy changes happening in the system. If any of the assumption mentioned here is not applicable we have to modify the equation because the results obtained by setting the mathematical equation by under this assumption will deviate from the real results and that is can be done by including term into the equation like we did in wpr where the flow was happening at a inclination will angle and we assume gravity plus important role in fact in a vertical pipeline system gravity place major role to place the pressure draw down around 75% and that is where we can we could establish the relationship.

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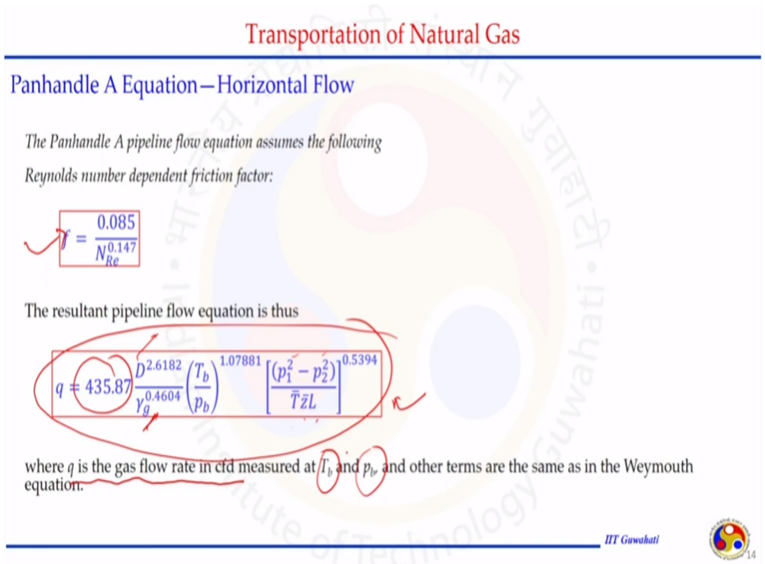

Similar we can do for a transportation of natural gas pipeline also another method that is panhandle A equation panhandle had given two equation pan handle and modify panhandle equation we can say pan handle equation and pan handle equation. In pan handle equation for the horizontal flow it is proposed the f is not just a function of diameter it is a function of Reynolds number only.

In another terms Reynolds number include the diameter so it is including the diameter but including the roughness of the pipe and if it assume in this manner putting the equation that we had we are going to get the resultant pipeline flow equation in this form this is little bit complex because Reynolds number will impose all these parameter this system to be included.

And we will get this expression where all the terms are like P1 P2 are there average temperature average compressibility factor l are there gamma g power got change and d to the power also got change here the numerical coefficient again depend on the unit system and here it is consider as q is the gas flow rate in cfd cubic feet per day measured at based temperature and based pressure other terms are same as we already considered for the Weymouth equation.

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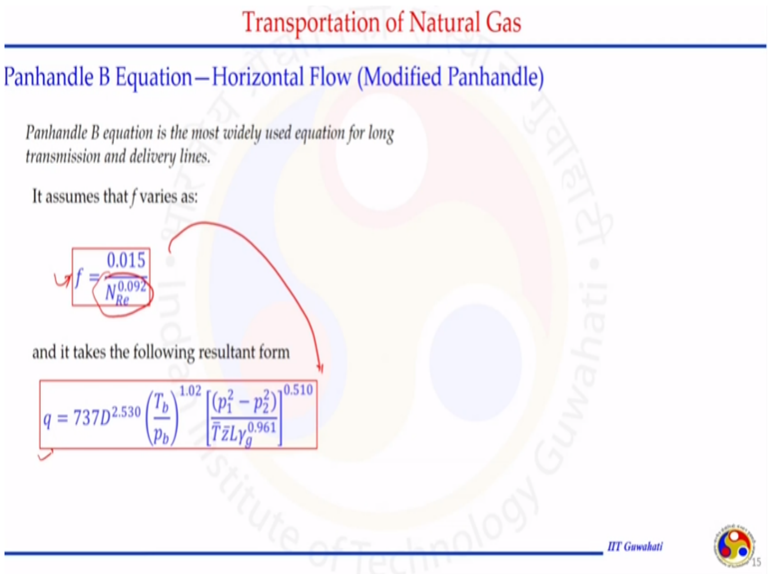

In Panhandle as we already consider for the Weymouth equation in Panhandle B equation this is modified form of Panhandle A equation where it is assumed the modification has been done in terms of so the power of the Reynolds number and the numerator coefficient both are little bit modified to propose more accurate equation to account the relationship between the and the other parameter and the equation will take this form.

We are not going to put this value and reaching this equations it is an exercise you can do and the important is you will get this expression of Q in different for depend on how f is chosen and how f is related to one particular parameter like F salient D and Reynolds number or it is just a diameter or it is just a Reynolds number. And with respective Reynolds number also it is in ex-form and the biform as it is done in Pan handle A and Pan handle B model.

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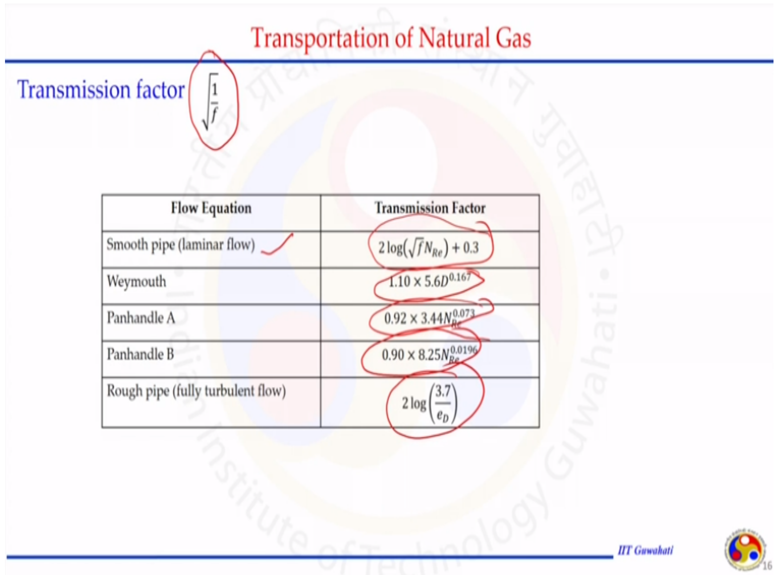

Let us understand what is this transmission factor under root 1 by f that is appear in the mathematical equation that we established for the flow through pipeline and that form dependence on system that we chosen so for the smooth pipeline system we can say jus tit is a function of Reynolds number when Weymouth equation consider on the diameter and handle consider Reynolds number with different numerical coefficient then Pan handle equation.

For the rough pipe we can just ignore Reynolds number and can just include the eD relative roughness of the pipe to have the transmission factor and ultimately that transmission factor we give us value of f friction factor.

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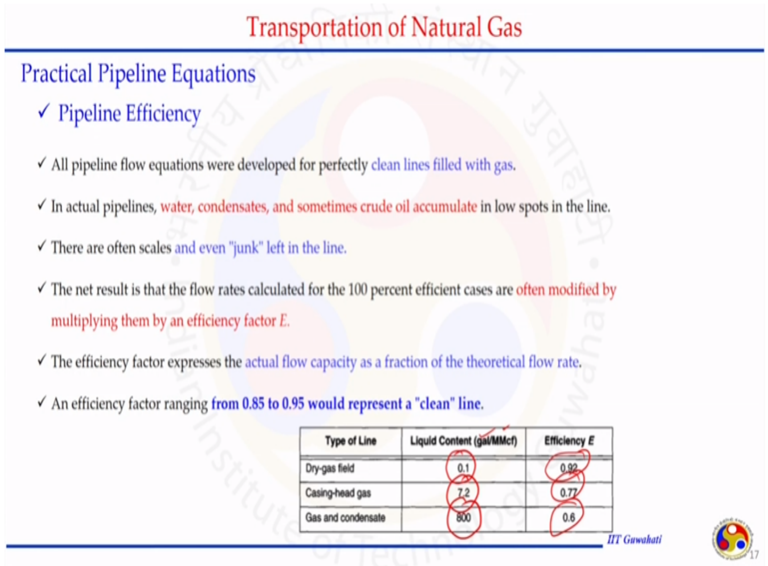

Another thing that did not count in establishing the relationship is pipeline efficiency all pipeline flow equation developed so far are based on the consideration that only gas is flowing through the pipe this is single phase system. But in actual practice water condensate and sometime small amount of the oil or also present if the gag get accumulated in a pipeline and some part of the pipeline miss if they reduce the effective diameter through which can gas can flow.

They create some more problems also we discussed later on but the presence of these liquid in the pipeline reduce the efficiency of pipeline to transport the amount of the gas from one place to other place that it important with respect to the transportation. There are often scale formation or junk left in the line and to account all these terms there should be terms that is should be multiply with the expression obtained that says the correction in the flow rate that is actually transported then the theoretical value.

So the equations based on certain assumption considering ideal gases are giving us the flow rate that theoretical can be transported for calculating the actual value it can be multiplied by the pipeline efficiency that comes in the range of 0.85 to 0.95 compared to clean line and the table source for a type of line it is a dry gas you can use 0.9 to if casing head gas where the a gas is having all sort of the impurities as well as higher carbon number hydrocarbons then the efficiency will reduce 0.77 only and the gas and condensate are present then the efficiency will further go down 0.6.

And depend on the liquid condense this also says how much liquid is content in the system in gallon per MMcf the efficiency factor should be multiplied by theoretical equation should get the actual value of the gas that can be transported through the pipeline which has been designed to transport the gas.

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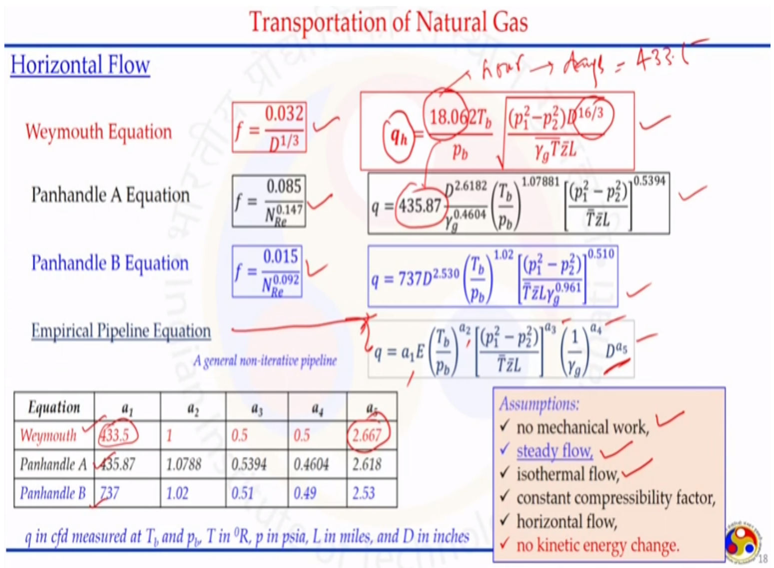

So in summary we can see in a horizontal flow system we are having the Weymouth equation, panhandle equation, Panhandle B equation and only difference is how the F is chosen we are going to get the difference things. Here the Q is mentioned in QH that is why the different numerical coefficient 18.062 is appearing here if it also transport to per day we will see this same value and we are above the same value that is summarizes in this table also.

So if all these three equation can be represented in the empirical formula here this is a more general way of expressing the flow through pipeline or flow through horizontal pipeline we can say the a1, a2, a3, a4, a5 can be written for each equation Weymouth, Panhandle and Panhandle B equation we can summarize from this table like for example Weymouth here it is 433.5 as I said this is in hours if we convert this into days we will get the similar thing 433.5.

And others like here we got 16/3 if we divide this we are going to get this same value with respect to the diameter q5 2.667. So this represent the general where the coefficient value a1, a2, a3, a4, a5 depends on which model equation is chosen and what are the unit area associated with each parameters involved in this expression. These expression are certain under certain assumption no mechanical work under steady state condition isothermal constant value compressibility factors only the flow happening in one direction that is also with the horizontal flow and no kinetic energy change is happening in the system.

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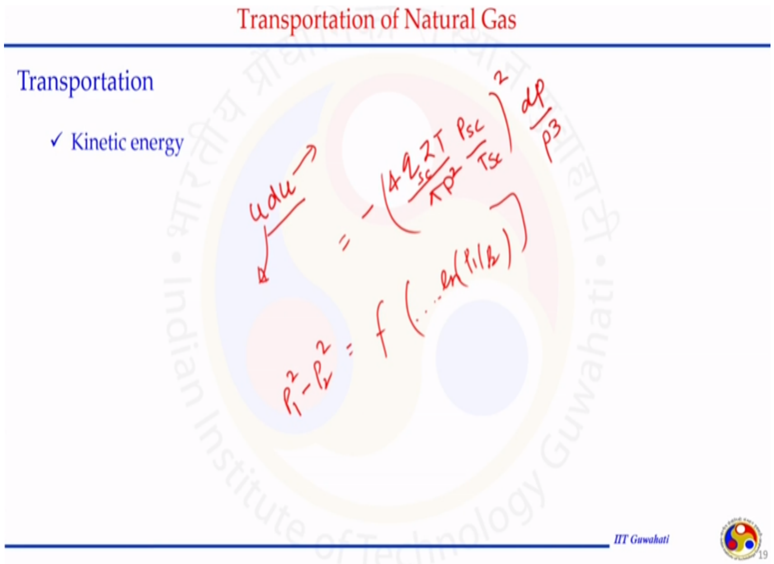

If kinetic energy changes in the system we are having this system u du and if this is there we know how to convert this u similar this u will also get converted and we have to include this in the expression and addition term we will be getting in our system that will like – 4qzT / p square Psc Tsc standard temperature conditions so this will also become Qsc to the power 2 dP / P to the power and when we are including this term in our energy balance equation ultimately we will get in the form of P1 square – p2 square addition term we will get because of the kinetic energy is lnp1/p2 along with that terms here.

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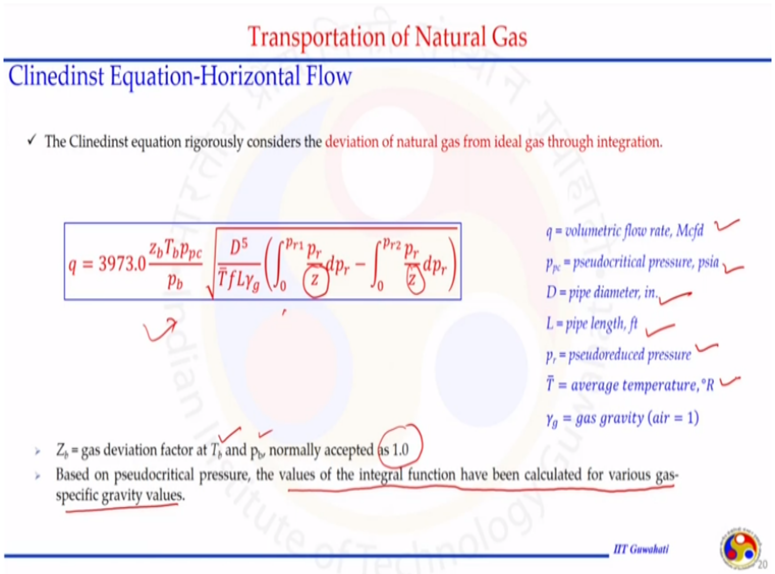

So for the horizontal flow there are some other equations also available in the literature like this Clinedinst equation that is account how the pressure changes happening in the system is going to affect the behavior of the natural gas is the deviation of natural gas from the ideal gas can be represented by this equation. So the compressibility factor is inside the integral sign and it is integrated from 0 to first reduce pressure at condition one and 0 to reduce pressure at condition two here we can get the expression and this expression may give us more accurate result in terms of the deviation of natural gas is more compared to ideal gas.

So the Zb gas deviation factor is calculated at Tb Pb normally accepted as 1.0 based on the pseudo critical pressure the value of integral function have been calculated for various gas in one of the appendix there are several data have been compiled for this method. The expressions are usual here q is Mcf per say pressure is in psia D is in inch length and feet P are pseudo reduce pressure which is having no unit and T bar is in degree ranking and gamma g is gas gravity.

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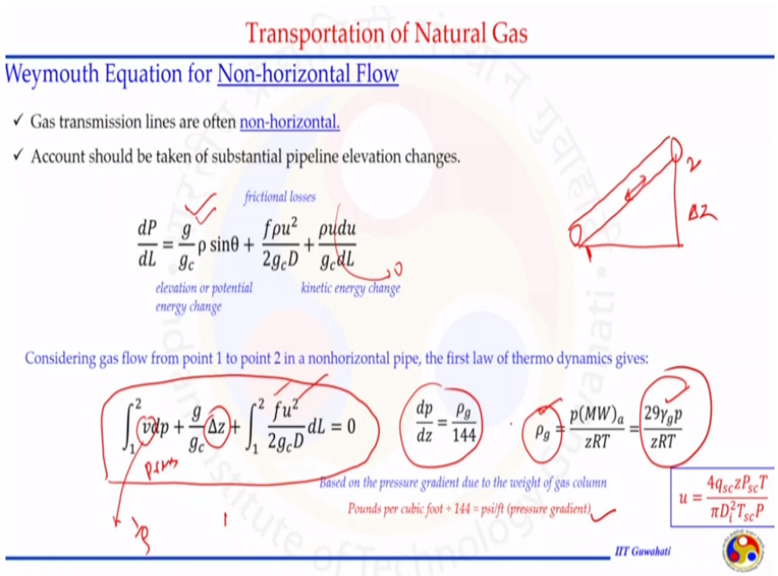

When we talk about Weymouth equation for non-horizontal flow we see the gas transmission line for the non-horizontal flow are often appears when we talk about long distance natural gas flow system and at several places the natural gas is not natural gas pipeline is not horizontal but it is having certain inclination from the surface and depend on the terrain is going to cross this might be appearing very frequently.

For that case we have to account how the gravity term is going to affect the relationship because in this kind of the system the gravity will also be important. Considering that thing we have to establish the relationship again and that says this terms cannot be ignored however kinetic energy can still be ignored if the constant diameter pipe is used. So considering gas flow from one point to another point in a non-horizontal pipe the first law of thermodynamics is for.

Here this is pressure so here this is specific volume that is 1 / rho del Z is just the inclination we can say lz = it is similar to elevation vertical distance from this to this. This is del z and f is having usual meaning u is having usual meaning d and del L again this can be described the pressure drop is happening in this del Z length can be gamma g / 144. 144 is because of the conversion factor like this gamma is ok we know how to convert this density of the gas and the pressure and temperature term.

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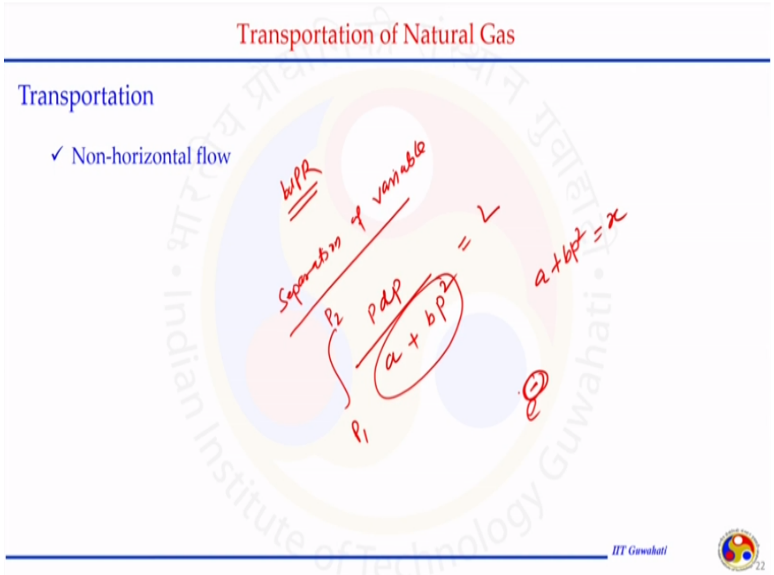

Again the velocity we already did this in our wpr class in wpr class when we understand if we are having the gravity term friction term and pressure term altogether is in the separation of very well after making certain assumption we can convert this in the form of pdp upon some constant + some p constant and interrogate this from p1 to p2 for length L and where we had taken this a + bp square = x and we could integrate this by I have in the very well of separation.

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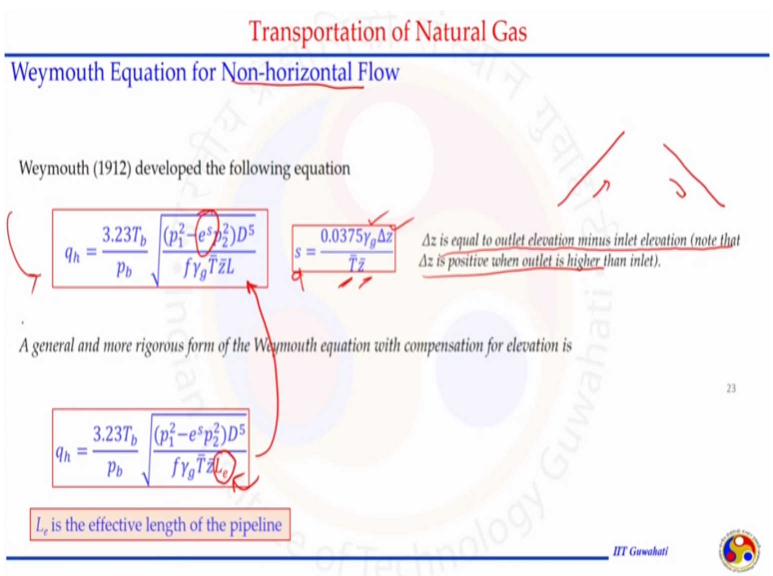

And finally we got the expression in the form of e to the power some value here if we do the same thing we will get the same expression instead of repeating the expression what I can show you the Weymouth equation for non-horizontal flow will be distinguish by this term compared to what we had for the horizontal flow is e to the power s. While s is function of gamma g this elevation del z average temperature average compressibility the del z is equal to outlet elevation – the inlet elevation del z is positive when outlet is higher than inlet.

So the sign will depend on the elevation it is upward or it is downward if the flow is happening at general and rigorous form of Weymouth equation with compensation for elevation cn be represented like this where the difference from this equation to this equation is this Lp L is the effective length of the pipeline that means if the effective length of the pipeline is included here we can get more general and rigorous form of the flow.

So (()) (01:04:04) this expression is return for Weymouth equation similar can be written for the Pan handle A and Panhandle B.

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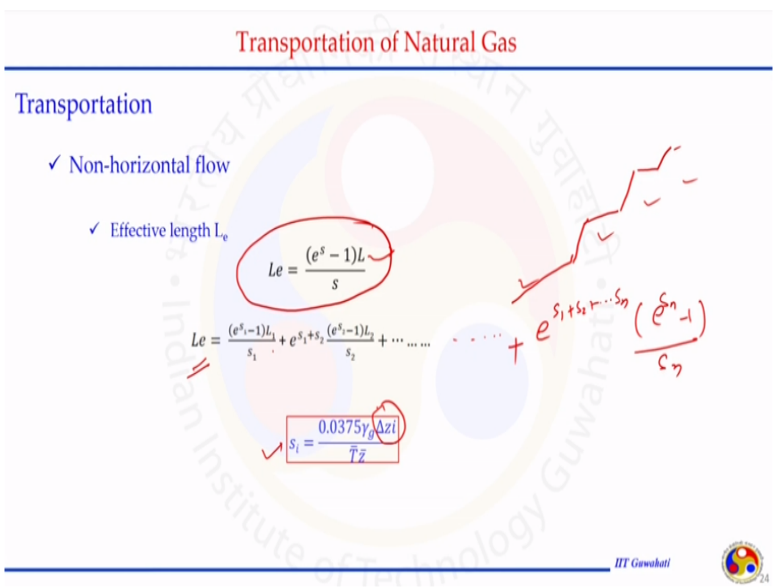

In the effective length is e to the power s – 1 divided by S multiply by actual length and when there is a situation when multiple different elevations are appearing in the path way we can adjust again with the effective length le considering these multiple inclination either upward or downward considering formula e to the power S1 – 1 / S1 multiply by L1 and then in the next term it will be e to the power S1 + S2 e to the power S2 - 1 / S2 L2 and if we write the end term it will be e to the power s1 + s2 + sn e to the power sn – 1 / sn.

So summation of each individual segment or in individual segment we can get the effective length value here. Here S is having the same value only the thing is del zi for each segment the del z will be different. So we can establish our relationship for horizontal as well as for non-horizontal flow condition.

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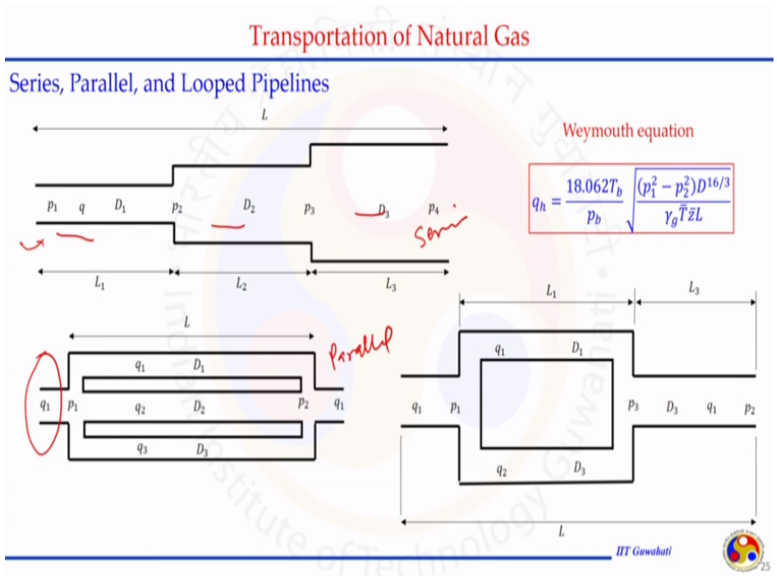

Now in the next class we will understand using the Weymouth equation how to establish the relationship between Q and other parameter we may solve one problem on that and how to layout the pipeline design considering the concept of series pipeline like here where the pipeline diameter change it is in the series and when we are establishing the parallels this is parallel this is series combination and this is looped where some part of the pipeline is series and some part in the parallel mode.

We will consider all this with Weymouth equation the colleague we can do with other form of the equation because the equation differ in terms of how friction factor is included in the balance equation. So with this I would like to end my today's lecture and tomorrow's lecture along with the pipeline we will also discuss about other mode of natural gas transportation thank you very much.