Natural Gas Engineering
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Module No # 03
Lecture No # 12
Nodal Analysis

Hello in today's lecture we are going to understand a technique to solve the performance relationship that we had developed in last few classes for the IPR, WPR and CPR how to club them to get the operating condition at a particular node that we will run with the help of the nodal analysis. It is (()) (00:54) pattern very simple and you will see that when we going through in today's class.

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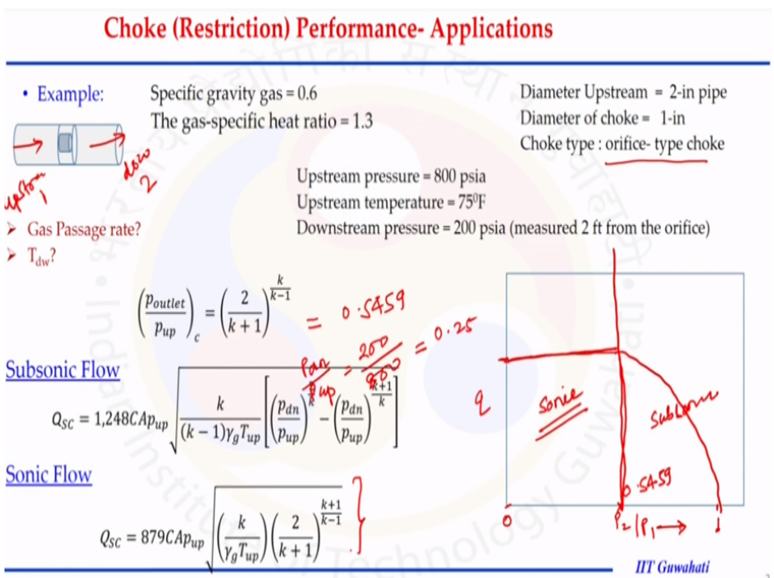

But before going further let us understand what we did so far and even before understanding overall picture of the production system I would like to solve a problem on CPR. So the choke performance it is application we understand in the last class the flow through the choke we can estimate the unknown parameter and that is where the concept of critical the pressure ratio was introduced that decides how to choose a particular flow regime that is happening in the choke and what type of the mathematical expression should be used to estimate the unknown parameter.

So in this example as it is mentioned here we are having a restriction in the pipe line and that restriction is actually let us consider it is a choke with lesser diameter. So the diameter of this choke is very less than the diameter of the pipeline and that is where the isentropic process is happening. So let us see what is given to us to solve a particular problem so the gas information is given to us that is say that specific gravity of the gas is 0.6 and that depends on the composition of the gas is and the specific heat ratio and that is K in sometimes it is referred as gamma is given as 1.3.

So the information of the gas is compositions are given to us the diameter of the upstream choke are given to us and it is specified what type of choke device it is Orifice type choke. Further if we see what other information is required and given to us it is upstream pressure, upstream temperature given to us so in this upstream is here upstream and this is downstream flow is happening in this direction.

So upstream temperature upstream pressure given to us downstream pressure is given to us and let us see what is ask to solve what information we can get? So we can calculate the gas passes rate the production rate of the gas per unit time that time could be day, month or whatever standard condition is per unit days.

We can say daily passes rate is ask to solve and the downstream temperature as we understand under the isentropic process condition because of the joule Thomson effect the pressure may go up down and the temperature should be recorded should be monitored just to make sure we do need to imply the heating or not to prevent the ice plugging or hydrate formation.

So let us this is the problem we have defined to us now if we go further what the first we do if we calculate the critical pressure ratio because the flow through the choke is determined by the critical pressure ratio or by the mac number in other terms. But in terms of pressure it is a critical pressure ratio that depends on the specific heat ratio value of gas that is being passed through this restriction so as given to us the gas specific heat ratio as 1.3 we calculate the pressure critical pressure ratio and we put the numerical value we will get 0.5459.

What is the pressure ratio given to us in case of upstream, downstream value given to us we can calculate the actual pressure ratio or downstream to upstream pressure it is 200 is downstream pressure and it 800 psi upstream pressure it comes out as 0.25.So let us see what this ratio tells us when we compare it with the critical pressure ratio. The flow could be sub sonic flow we are having the mathematical equation for that and the flow can be sonic flow.

We are also having the mathematical equation for that but which one should be used to determine when we compare the pressure ratio with the critical pressure ratio. So let us see what we do we say this is my pressure ratio upstream to sorry downstream to upstream this is 2 this is 1 or we can write it P down by P up and pressure is in this direction. So if we say this is Q versus either capital Q or small Q versus pressure ratio what type of the flow regime we can get.

So if I compare this when I say my upstream pressure is much higher than downstream pressure it means I am having almost the ratio close to 10 to 0 I am having the maximum production of the gas that is happening here and when the pressure ratio downstream to upstream are same. For example the p2 / p1 is 1 we are having no flow from this and everything is happening in between. There is a point that we called the critical pressure ratio that is the value we got for this particular case is 0.5459 the value depends on gas composition.

At this particular point what we understand from understanding of the isentropic process we say at this point if we draw the relationship between the process ratio and Q we see the curve is like this it means when the pressure ratio is lesser than critical pressure ratio we are having a constant flow rate that is a sonic condition or the critical condition we say and on the other side we are having this draw down with respect to the pressure ratio and we called it subsonic condition.

So in our case in a numerical problem given to us we see our 0.25 the pressure ratio is lesser than the critical pressure ratio it means we are in the sonic region our restriction is being operated in sonic region. We should choose sonic flow equation to characterize to represents the flow through the restriction.

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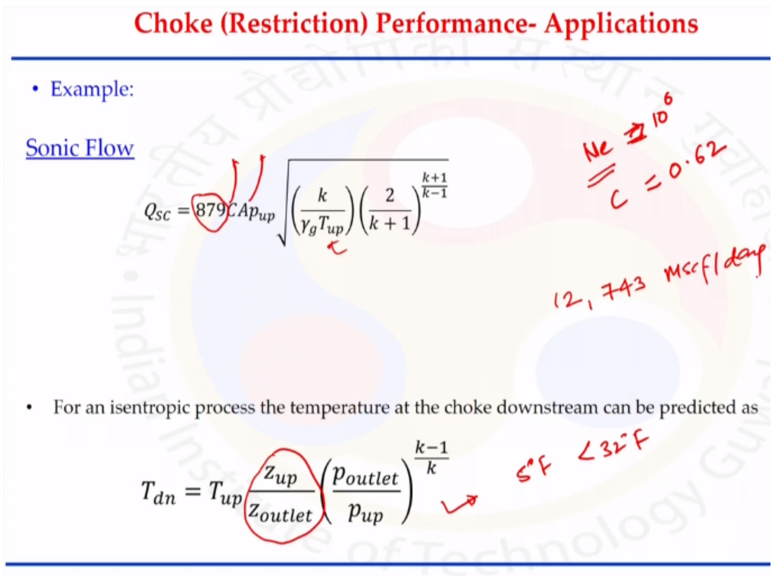

So this is the equation that is going to be used and in this equation we can see what exactly we are having we can calculate the flow rate Q at standard condition the numerical value again depends on the parameter or defined in a particular unit let us say understand what is the numerical value going to be here. The important part is C and A is the area C is the discharge coefficient that should be known and that needs to be calculated if it is not given to us that depends on the type of the orifice and then rest other things.

We understand we know the gamma g is the specific gravity of gas k specific heat ratio T up is the upstream temperature. So what we can do the next we can calculate the value of C the value of C discharge coefficient calculated with the help of the formation given to us and that is simply says the discharge coefficient depends on the Reynolds number and if Reynolds number is not known we cannot calculate this C value.

So for that what that purpose we can assume the Reynolds number value why we need to assume it because Reynolds number depends on the flow rate and we are supposed to calculate flow rate. So what we are going to do we will assume some Reynolds number let us say the Reynolds number vary high where the value of discharge coefficient almost becomes constant. So we take the Reynolds number value is greater than 10 to the power 6 or let us say we are assuming is 10 to the power 6.

So what we will do we can go to the chart or particular equation to calculate the discharge coefficient as discuss in the CPR class we will get the value of discharge coefficient 0.62. After putting all this information given to us we can get the value of Q but that value of Q is correct or not for that what we need to do we need to recalculate the Reynolds number using this flow rate and if the Reynolds number is in the range or in the tolerance range we can say the assumption made was correct otherwise we have to assume.

We have to the recalculate the Reynolds number we have to calculate the discharge coefficient based on that we have to calculate the Q again and that is the way we can calculate the discharge rate. Next point is temperature downstream temperature we understand how to relate the upstream and downstream temperature for an isentropic process it is a very simple case when we are having the real gas we have to calculate the compressibility factor on both condition upstream condition and downstream condition.

If we put all those non-information in this we will get the value of downstream temperature and downstream temperature is very low yes we need to apply the heat for this case we are getting the value of downstream temperature is 5 degree Fahrenheit that is lesser than 32 degree F yes we need to apply the heat across the restriction. Similar here the Q what we are going to get is as a numerical value I can provide you 12743 mscf per day.

So I think that is clear the picture how to choose particular model equation to represent the flow through the restrictions.

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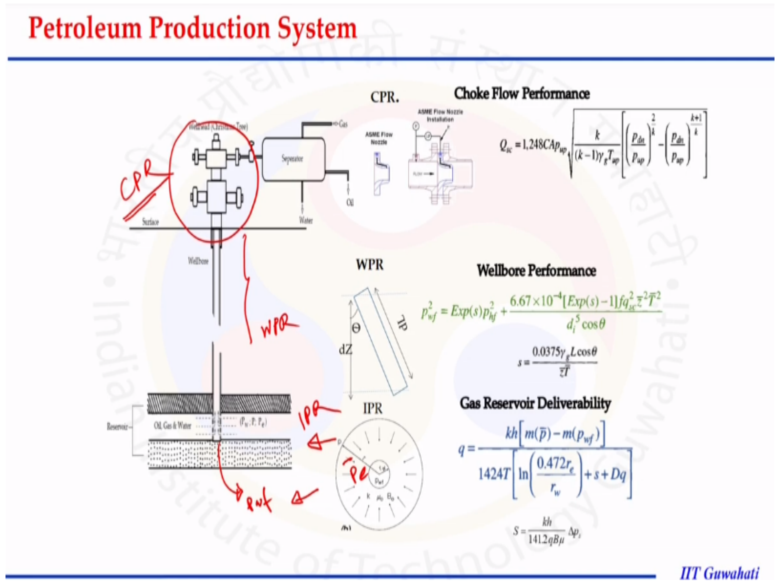

Now if we move further let us see what we understand so far about our production system we see that production of the natural gas happens in this manner when we are having the radial flow under certain assumption what we discuss so far under the radial flow we are having fluid or the gas is being passed from this or being flowed from this porous media by the pressure gradient and the pressure at the sand phase is pwf we also called it is a bottom hole pressure and that is pwf the flow is happening from pe to pwf that is also depend on several factor we discussed in detail in the IPR relation.

From here it is going to this part where we are having the WPR value wellbore performance relationship again because of the gravity will play a major role it is a several thousand feet the pipe line and because of the mechanical energy balance equation we could set up the WPR relationship here for this case WPR this is we called as IPR and this is top part where we just solve an example and we call it has CPR.

So the mathematical we can say how several parameters are going to affect the Q similar for the WPR and choke flow performance. So now we understand each segment or the three segment of the our production system and how they aregoing to relate what the common factor they are having at how to use one type of relationship to assist the other relationship or find out the parameter those are not known will be discussed in today's lecture.

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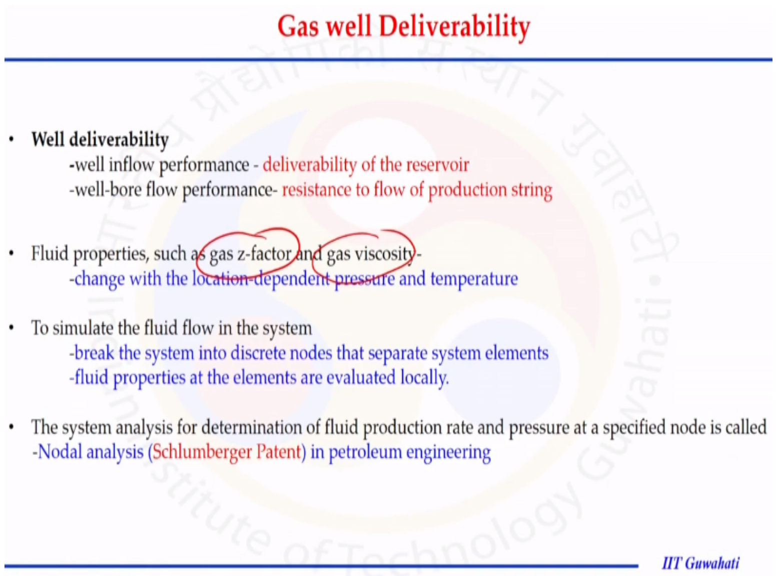

So in today's lecture if I go further this is about gas well deliverability using nodal analysis. So the well deliverability is for example the well deliverability at what potential the gas well is having or the reservoir is having what rate the gas can be produced from a gas well is estimated with the help of gas well deliverability analysis. But in this case as if you see in this the overall picture our gas is being flowed from several pressure zone.

From a porous media the high reservoir pressure to well bore pressure from well bore from PHF well head pressure and at the head we are having the choke device that is again reducing the pressure means again pressure change in happening there though out the temperature also changes and because of that as our gas is the compressible gas its properties are changes and those properties are dependent like properties like compressibility factor z and the gas viscosity Mu depend on pressure and temperature.

And they need to be calculated at a particular temperature pressure condition that particular temperature pressure condition could be the average or could be other mean. To simulate the fluid flow in this system so what we can do we can divide this system as we did to understand the mathematically what is happening in a different nodes we can breakdown the system and the fluid properties are calculated at that node by either taking the average of the pressure or temperature or just specifying that particular temperature and pressure known at that condition we can calculate the fluid properties.

The system analysis for determination of fluid production rate and pressure because over all it is pressure versus Q flow rate relationship so we can establish that relationship at a particular node with the help if the nodal analysis and this is Schlumberger patent and widely used in petroleum engineering just to have the understanding of the reservoir or the well exactly and at a particular operating condition if the value is being produced what will be the flow rate or if we want to achieve that particular flow rate what will be the pressure at that condition.

This analysis can be used to forecast the production in terms of the pressure declination what will be the rate the fluid can be produced or the gas can be produced at the same time what will be cumulative production from the system all this will be discussed later on may be in a separate lecture when we can discuss the system performance. In this lecture we are going to understand the nodal analysis.

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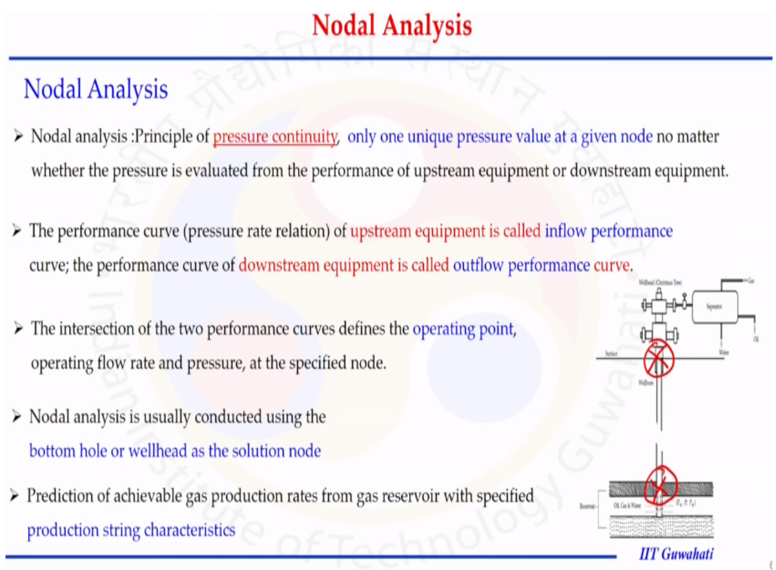

And the nodal analysis works on the principle of pressure continuity is a for example if we choose any particular and we come to this point from the right to left or left to right if the information is continuous. In our case the information is pressure so at a particular point the information or the pressure will be the same does not matter we come from this side or this side this is the concept or core concept of the nodal analysis that is called the continuity of the pressure or pressure continuity.

In this case what we say if we having like 1 one way of the information if going like this direction left to right or in our system we are having the IPR to WPR to CPR. So at a particular point when the information is coming we call it inflow relation and when the and the information when it is moving out of that node we call it outlet outflow information. In our case we will be using two location that is the bottom point and the well head point so bottom hole point and well head point were we will be establish the nodal analysis.

So the nodal analysis can be done with the bottom hole or the well head point considering the nodal point. So the production or achievable gas production rate from gas reservoir which is specified a string characteristics means other information those may affect the flow regime production are considered like constant for example the string conditions or the production string condition the diameter or the parameter we are consider constant and under a particular condition when the flow is happening what will be the operating point at this bottom point or well head point will be estimated with the help of the nodal analysis.

So when I said the inflow curve when information is coming and when the information is going out because of the continuity of the information in our pressure community the intersection of these two points will give us operating condition at that point of our operating conditions are the pressure at that node as well as the flow rate.

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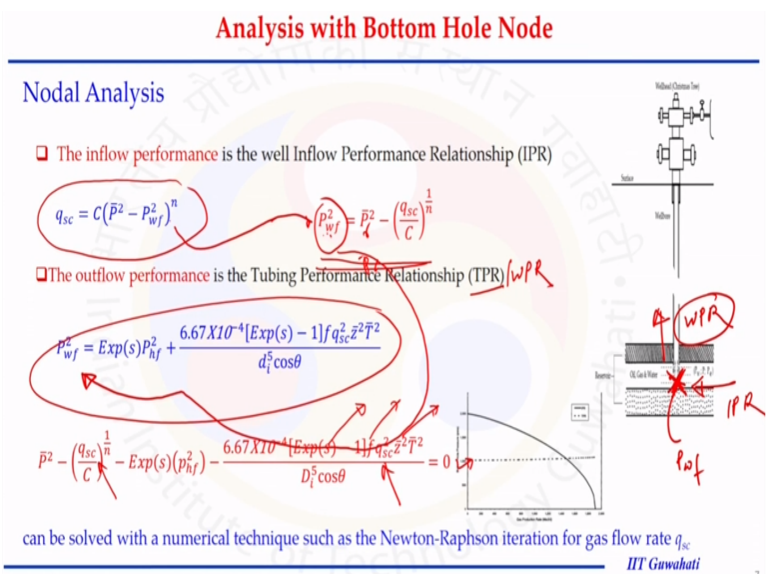

So let us see if we are considering the bottom hole node let us that is here where we are having pwf at this node the inflow relation is the IPR that IPR that is relate the reservoir conditions and the flow through this porous media to well bore so here the inflow performance relation is IPR and we understand IPR could be in different form it could be in quadratic form let we talk about the empirical expression or could be in a back pressure form.

Here what is written is in the form of back pressure we also understand from our IPR correlation class at the cue and pressure relationship can be explain with the several approximation p, p square or a mp for a simplicity we had taken if we are has a p square approach but the similar analysis can be implemented for the p approach and mp approach and what is the out flow performance.

For this node our node is bottom hole the outlook performance relationship is WPR the information going out in the form of WPR the information coming to this point in the form of IPR and the intersectional as per the nodal analysis the intersection of these two points so tell us what are the operating condition at this node bottom node. So let us see when we having this IPR curve for inflow and when we are having this TPR or WPR relationship for outflow what we see the common point between this and this is pwf and we can substitute pwf from one equation to other equation.

Let us see what we can do so from IPR equation what we can do we can adjust this equation in the form of pwf square = p bar square. This P bar is reservoir average pressure sometime it is written as PR also or pe also so this PR bar – Qsc by C to the power 1 / n so now from this expression we can substitute this PWF here pwf can be replaced with the help of this expression and what we will get is p bar square – Qsc to the power 1 / n on the left hand side and the remaining we can also adjust this equation keeping 0 on the right hand side.

So we got the mathematical equation that is relate IPR to WPR and we are not having Pwf in this expression means we could eliminate pwf assuming that was not known to us with the help of two equation we could eliminate the pwf. Now if we can solve this equation we can get the relationship between how my Q is going to be related with a different pwf condition this equation can be solved with a numerical technique such as newton Raphson iteration for gas flow rate Qsc.

So now if I understand if I know what is my reservoir pressure I know what is my phf at the well head conditions other information given this can be estimated with the help of some iteration processors by the iteration processors is recalled you can see the Qsc is here also in both the terms as well as some other properties like for example compressibility is calculated at average pressure that should be known other than that S that represent some term in the WPR equation also account for flow rate as well as gamma g.

This F the friction factor that depends on the Reynolds number or Reynolds number depends on the flow rate. So it is a equation that needs some numerical iteration that can be done with the help of the Newton Raphson method but if we can do that thing yes we can calculate the flow rate and once the flow rate is known either the IPR UPR can be used to calculate the what is the PWF at that particular mode.

Another way could be we can plot this inflow equation on a curve and the outflow equation on occur and when this two curves are intersecting each other we can get the operating condition at that point. So let us see how it can be done with the help of the example.

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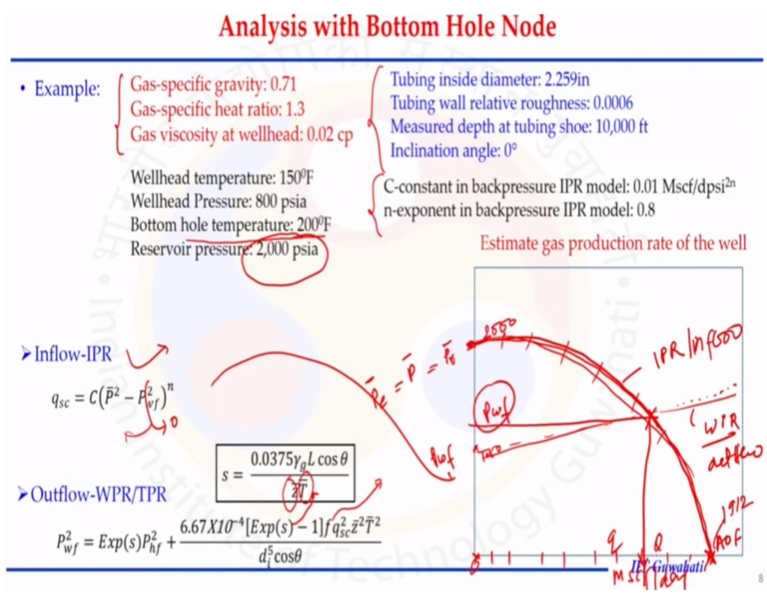

So the example simply identified some of the information that is required to construct this IPR and WPR curve. So for example the gas composition or the properties are related to gas are given to us the tubing through which the fluid is being flown in WPR are given to us. Well head condition are given to us bottom hole temperature are given to us what is the reservoir pressure specified and C and N Constant and backpressure equation C and exponent in back pressure equation are given to us.

That means simply with this information what we can understand the IPR relation use to characterize this flow is in the form of the back pressure CNN are given to us we can choose either the p, p square or mp approach but as we can see here the reservoir pressure is 2000 psi and we understand if the reservoir pressure is around 2000 and below 2000 psi which should go to the p square approach.

So we can choose the IPR in the form of p square and that is like here so the inflow curve is IPR that is in the form of the pressure square approach in a back pressure form. The out flow equation is WPR for this case because the information given to us with the help of that we can construct the WPR curve also. But in WPR curve you see the s is given in that s is gamma ZL cos theta Z bar T bar the bar here is calculated at average condition so we need to calculate the average temperate, average pressure and that average pressure we can calculate the compressibility.

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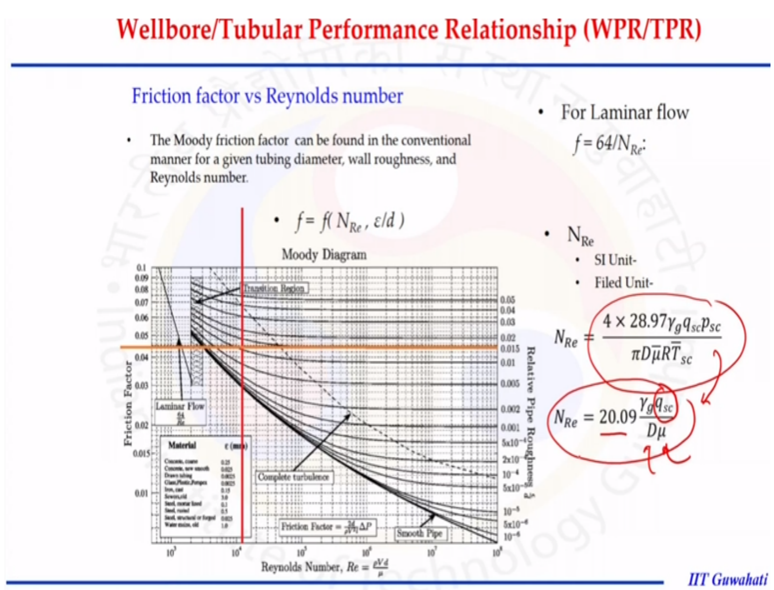

Another important point is this F and this F can be calculated with the help of either the chart or with knowing the Reynolds number we can use some mathematical expression those are given in the literature to calculate value of F and that F remember this F can be either a finding friction factor or Moody friction factor in our case it is a Moody friction factor. So the Reynolds it depends on several parameters here the simplified form of Reynolds number from this equation where we got 20.09 gamma Zg / D Mu Viscosity is given to us diameter is none but we do not know Qsc that we are trying to calculate.

So what we can do we can assume some value of the Qsc calculate the Reynolds number and Reynolds number to put there to calculate this F value here and every time we have to correct the value is correct or not. So with this help assuming we can calculate S we can calculate F we know everything. So what we can do we can construct the inflow curve here and the outflow curve with the help of second equation.

And when we are going to do what we are going to get let see so from this equation what we are having for the IPR we can simply say the Qsc is related to pressure in this form and there will be a situation when my pwf is so this is my pwf so this is my flow rate Q. So when my pwf is 0 here what I am having the maximum flow rate so pwf is 0, I am having the maximum flow rate. So let us say this is 0 this could be the maximum flow rate and we called this AOF.

And when my pwf is reservoir pressure that will be the situation assume here Pr bar I said this is equivalent to p bar or sometime it is denoted as Pe bar we are having this point and we can see here depend on the value of the C and n the curve can take a particular shape and most of the cases this is like this and similarly we can construct the curve with the for the outflow also when we know all these parameter we can say how my pwf is related to Q.

Yes of course the iteration to be done for that case also and in that case if we see this is a reservoir pressure given to us 2000 psi this is the maximum flow rate that I can give you some quantity value that will come out as 1912 unit is mscf per day. So we know when there is no flow is happening when absolute open flow condition is there and the pwf is represented by this. So how to calculate this curve when we are having this relationship so what we can do in the IPR curve we can either divide this flow rate from 0 to AOF in 10 equation parts and calculate pwf with this from this equation and construct from the curve.

Or what we can do we can calculate different assume different value of pwf from reservoir pressure to 0 and accordingly we can calculate the different value of Q. By either mean we can construct this curve in the outflow curve similar we can do when we are having different flow rate between 0 to EOF we can put it here do the iteration and can calculate. So it come out says when this is no flow is happening your pressure is here is somewhere here and the value that coming out at condition is around 1050 or something.

But if we are increasing this very slightly the pressure pwf is increasing when we are having the different flow rate. So this is our IPR or inflow curve at that particular node and this is WPR or the outflow we also called in outflow curve. And the point when this two are intersecting can be used to find out what is going to be pwf the operating condition what is the flow rate at that condition.

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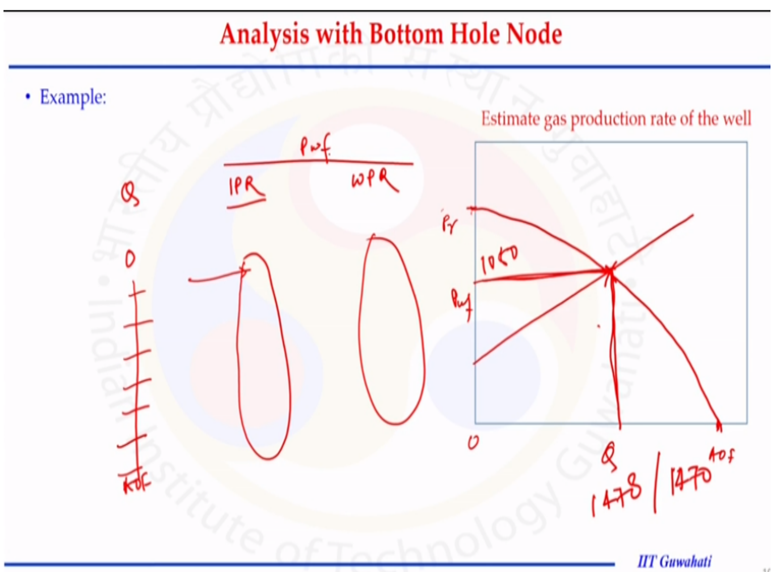

So we can construct the curve to estimate the gas production rate if you want to control the gas production rate we can control with the help of pwf or other way if you want to control the pwf we can control with the help of Q. But important point came out from 0 to AOF this information give us when there is no production is happening if such situation is happening we are having the B curve we can get this and when there is a absolute open flow condition maximum production is happening the curve nature is like this and other curve is like this.

And as I said how to draw this I will just repeat it again so for example Q we can calculate the IPR parameter and WPR. The IPR parameter both are pressure we want to calculate PWR from both the equations the Q which we know will be 0 when there is no production is happening and the maximum AOF situation between this we can calculate the different value we can assume equally divided and accordingly we can calculate the pwf / IPR, pwa by the WPR.

And the value those are going to obtain here and here will be used to construct this thing and with the help of this we can get the operating condition under that situation when we are having another parameter or constant about the IPR and WPR equations this is going to be this situation. For pwf and Q for the numerical case that we discuss the Q is around 1478 or 1470 depend we are using the graphical procedure or we are using the mathematical there is a slight difference depend on the how good optimization we could apply or iteration we could apply for this mathematical equation.

And the pressure is around 1050 psi so I think with this I could explain how to use IPR and WPR to have the bottom hole operating condition.

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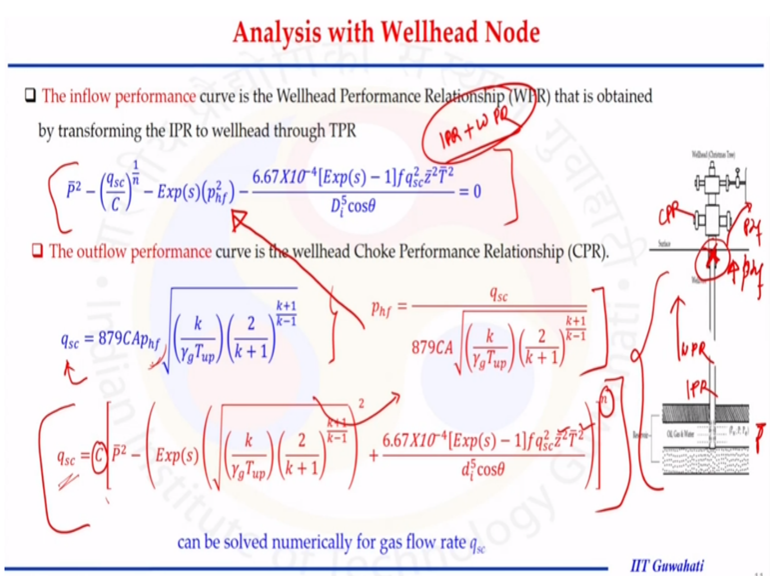

The another is as discuss the node could be chosen as well head and what is the inflow relation for this well head whatever is coming from this side and what is coming from this side is WPR and that WPR can be clubbed with the IPR to get the combined information that is coming to this node and that a well head node the information in our case is pressure and we are saying phf well head pressure and the information going out of the is characterize by the CPR.

So now we understand the inflow relation is IPR + WPR and in the last problem last example we had understood if we club both the equation we are going to get this kind of relationship whenever p reservoir pressure p bar is related to phf. Similar the outflow curve that is here outflow information is CPR and we could have this expression where Q is related to phf the pressure at the well head.

This expression depends again what type of the flow we are having in the ahh choke device that may be sonic and subsonic we are assuming this is a sonic flow. The equation can be replaced with the subsonic flow is adjusting at this particular node. Important is now we understand the inflow relation and outflow relation at this particular node and using these two equation we can calculate the operating condition those are going to be at this particular node.

We understand now we can do it either by the mathematical expression when we are clubbing both the equations making one equation doing certain iteration to calculate the flow rate and then after knowing the flow rate we can out in either of the equation and flow are of equation to calculate the phf the well head or the pressure at that node or another base against simply we can plot the inflow and outflow equation and the internal section point may be the operating condition at that node.

So let us see if we adjust this equation outflow equation take out the phf this can be arrange in this way this phf is back here remaining has been transferred to the left hand slide we are going to get this expression phf. Now this phf can be substituted from here to this equation the inflow equation what we are going to get a very big expression and this expression simply says yes I can be solved numerically we just have to do the iteration that can be done again with the help of Newton Raphson method or some other way to get the Qsc value okay.

And you see here the QSC depends on several this CN those are the IPR parameters reservoir pressure average temperature average compressibility whatever the parameter those characterize flow throw reservoir to well head are included this equation.

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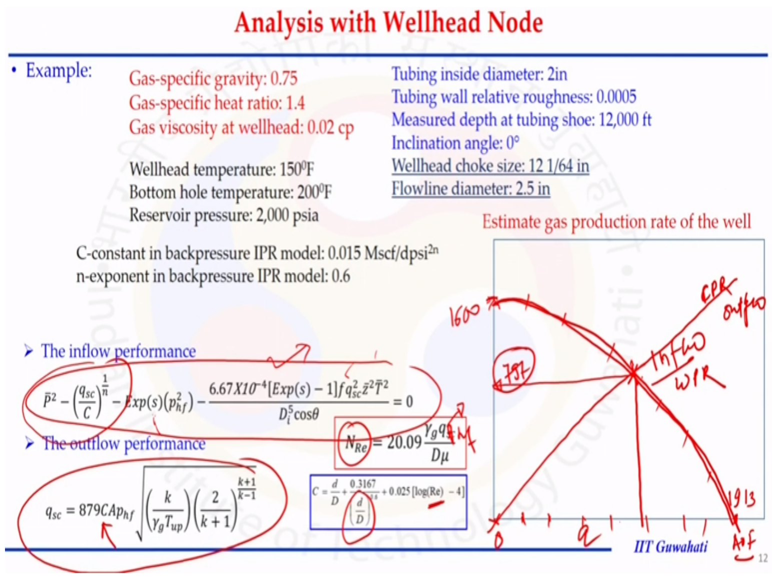

So we can solve it but other procedure is again same we can go with the help of graphical processor where the inflow and outflow are plotted. So let us understand this again with the help of example. The example simple says the gas is specific gravity and other information related to gas composition are given to us means what type of gas is being produced tubing diameter means the wellbore condition are given to us the addition information that is given is choke device diameter.

The size of the choke device and other information that simply says we can use this information at the well head node calculate the operating condition at that particular point. So let us see what we can do similarly we came to the inflow performance relationship that inflow performance relationship is like this we know now how to plot this how to solve it.

We know how to solve it mathematically now we can plot this also and this plot is simply says we are having almost similar relationship as we are having for the IPR because this term will dominate p square reservoir pressure that will dominate the situation and the phf condition will start when this is around 1600 that will be situation when no flow is happening and this is Q versus phf.

For example so around 1600 the value will come out when there is no flow is happening PHF will come out as a 1600 that can be done simply by saying this Q is 0. No flow is happening we can calculate this parameter S and with the help of that we can calculate what is going to be the PHF value and this will come out as 1600 again we can get the AOF and this AOF is what will be the flow rate at AOF is same what we got in the last example is1913 mscf per day.

Now the IPR curve will take almost the same curvature while the equation this is IP inflow equation and I can say this is WPR in our case what about the outflow equation from this expression we can say the Q is related to phf in a direct relationship we are having Y = MX kind of relationship where the intercept ahh is passing through the origin and we will get this kind of expression.

So this is CPR or the outflow equation and when we are having this we will get the same flow rate here Q around 1470 or 1478 as we got in the previous example while phf can be calculated from the Y axis what will be the value of phf that will come out around 797 or something okay. So now we know with the help of plotting this and this phf versus Q relationship we can calculate the phz and Q.

Now the complexity comes when we are solving this equation when we are trying this curve it is not easy because at every point we are going to draw this means we are making this the construction of this outflow and inflow curve we need to calculate the value of phf at particular Q or Q at a particular phf. Now we understand this is 0 this is EOF we can again divide this in ten equal parts and we can calculate the phf from inflow equation similar phf from outflow equation.

But in both the cases if we see this we already discuss the complexity involved in terms of F that depends on Reynolds number. Reynolds number depends on from the Qsc similar here in this case this C is the discharge coefficient that discharge coefficient depends on the type of the orifice we are using and on the Reynolds number as well as the diameter ratio on the orifice to the pipe. So with the help of this kind of calculation we can calculate the C value.

Now Reynolds number again as I already mentioned Reynolds number is defined like this 20.9 gamma g q / DBM and to have this or Reynolds number we need to have the Q value. So the iteration is required is still in the graphical procedure also iteration is required optimization required at each mode points we are going to have and we will construct the we can the this.

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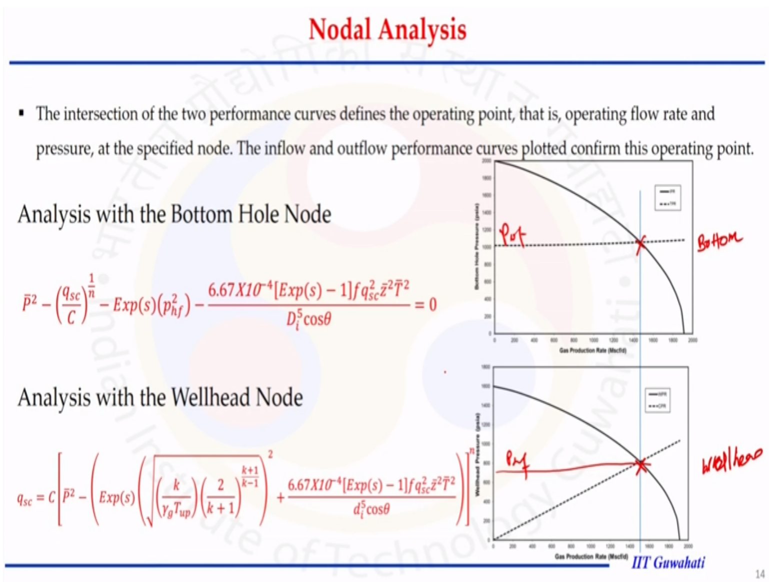

When the obvious question comes if we summarize this when we are having this mathematical equation to be need to go with the graphical procedure or mathematical procedure processor. Because graphical process also need to optimization process so for example we should go through with both the processor and check are the equally good or not. In the analytical we are just solving one equation when we clubbed to equation solving it mathematically while in other case we are having two equations those are going to intersect at one point.

So if any conditions are any change either in the wellbore or in the reservoir or at the choke point the shift should appear and that shift in the curve will tell us the conditions are getting shifted. So is periodically graphical procedure should also be implemented to have the understanding of how this situation is changing if at all in the production system. So this is the summary of the nodal analysis and we can see here either we are having the bottom processor or the well head we are having the bottom as a mode or the well head as a node in both the cases Q will be the same while pressure can be estimated.

So this is ph pwf and this is phf can be estimated with the help of this after understanding this nodal analysis this type of the analysis can be used to forecast the production that could be the cumulative production as well as the production rate and not only that thing this can be used when the operating condition are getting shifted how they are getting shifted for parameters are going to affect them.

For example if the reservoir pressure is declining over the time the shift in the operating condition will be observed and if we are taking the data every month two months making the construct of this nodal analysis at any particular node and the shift will say if any changes happens in the reservoir formation for example the skin factor and non-Darcy effect or any other parameter that is going to effect that will help us.

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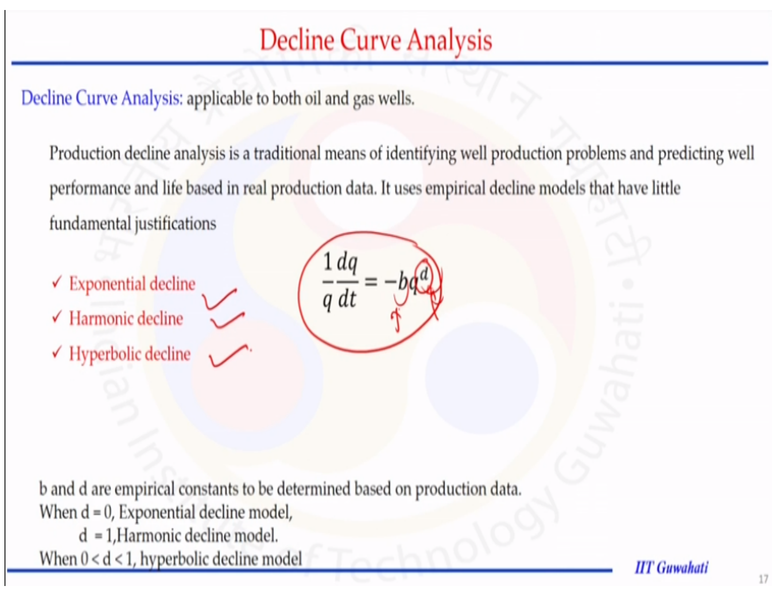

Another concept decline curve analysis so this curve analysis also tells us at what rate the production is declining not only the rate of the production declination but the rate of production rate how it is going to change that can be understood with the help of these equations. This is very standard equation where b and d characterize the nature of this equation and depend on the b and d value specifically value because b is just a proportionality constant the nature of the curve will depend on this d value.

It can be exponential decline it could be harmonic decline model or hyperbolic decline model so we may discuss all these things in detail later on if time permits thank you very much.