Petroleum Reservoir Engineering

Dr. Pankaj Tiwari

Department of Chemical Engineering

Indian Institute of Technology, Guwahati

Lecture 5: Thermodynamics of Hydrocarbons

Hello everyone., Welcome to this week 2 lecture number 1 of MOOCs course on petroleum reservoir engineering. So far, we had discussed about the origin and composition of the petroleum, geology associated with petroleum and how to find out the location to drill the well and what are the major steps involved in the drilling process. So further in this section 1 we are going to discuss about the reservoir rock and the fluid properties. As we can see in this diagram in the petroleum reserve the fluid those are gas, oil and water are stored in the reservoir rock formation underneath the surface. We need to understand the interaction between this fluid and the rock.

Before going to discuss that let us understanding some of the aspects of this hydrocarbon fluid. So, in this lecture we are going to discuss the thermodynamics of hydrocarbon. Reservoir rock properties will be discussed after discussing the reservoir fluid properties for example gas, oil and water properties. Broadly if we classified the reservoir those are oil reservoir and the gas reservoir.

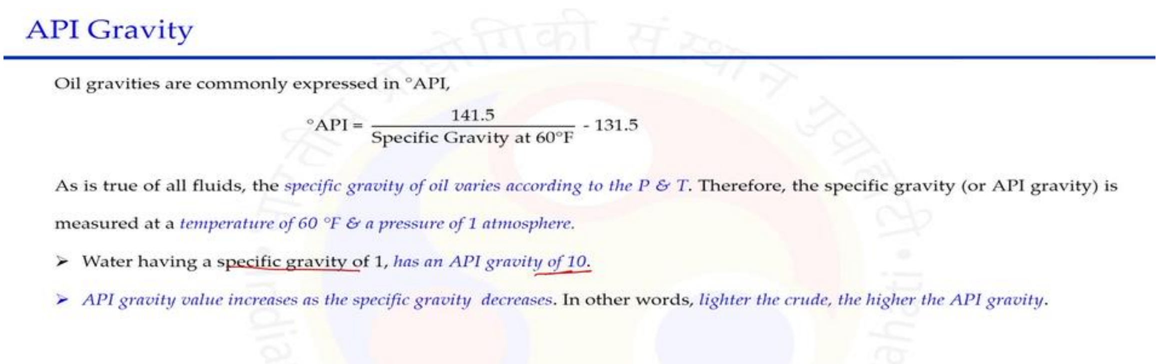
We can classify the reservoir based on the GOR, degree API and the color. So GOR is measuring the amount of the oil and gas produced at the separator. Color and degree API are associated with the liquid production means oil production. So, what exactly happen in this system where we are having very high reservoir pressure underneath the surface fluid travels from reservoir to the surface. It encounters several temperature and pressure zone.

Because of that the phase changes or phase may change depending on the condition it is going to meet. That is why it becomes important to understand the PVT behavior of the fluid that we are dealing in this course and that can be understood with the help of thermodynamics behavior or the phase diagram of the hydrocarbon mixture. That is the discussion of this lecture. The phase behavior depends on the composition of the fluid, reservoir temperature and pressure condition, condition at the surface when this fluid is brought to the surface and types of the drive mechanism those are involved in the reservoir fluid production. We will discuss the drive mechanism in a separate chapter.

So in today's discussion we will see how the reservoir can be classified thermodynamically based on the composition, temperature, pressure at the reservoir condition as well as at the surface condition. Between the reservoir and the surface condition fluid also encountered the different temperature and pressure especially in the case of the natural gas because it is compressible in the nature. The phase change or the properties of the natural gas changes very drastically when the temperature and pressure are changed in the system. This is important because with the help of thermodynamics behavior we can understand the recovery mechanism those are responsible for the hydrocarbon production that helps in taking the further action when the depletion of the reservoir fluid is happening and this also help us in predicting the performance of the reservoir or the production profile. Before going to the thermodynamics aspects let us understand the API gravity.

So the oil API gravity is also one of the majors that is classified the different types of the crude oil. So, the degree API is defined as 141.5 divided by specific gravity of that fluid at 60-degree F minus 131.5. It is one of the ways of defining the quality of the oil or quality of the fluid liquid of course.

So the specific gravity is defined as density of the substance of the fluid divided by the density of the water at the same temperature conditions. So, for example when we know the specific gravity of the water is 1 so its degree API is going to be 10. Specific gravity varies at different temperature and pressure it varies for all the fluid. So, it is going to vary for the crude also that is why it is always measured at a particular temperature and pressure condition. API gravity value increases as the specific gravity decreases or in other words lighter the crude the higher the API gravity value.



So for example the heavy crude that is more dense the API gravity will be in the range of 0 to 20 degree. The medium crude exhibit the API gravity value between 20 to 30 degree and the lighter crude those are very light compared to water the API gravity is always above 30 degree or it may go up to 55, 60 degree also. Let us come back to the phase diagram. So, when we talk about the thermodynamic aspects of any fluid we want to understand when the substance of the fluid is exposed to different temperature, pressure and volume condition how it is going to behave. The phenomena of understanding the thermodynamics is always characterized in terms of PVT diagram.

On the 2D diagram either it is going to be the pressure volume diagram or pressure temperature or temperature volume diagram. So, for a single component when a single type of the fluid is present in the system the pressure and volume relationship could be like this. So, when we are changing the pressure and volume the fluid phase is also going to be changed. So for example here at a very high pressure the fluid is in the liquid phase when we are releasing the pressure the fluid may go to the gas phase. The transition happens through two important points that is bubble point when the first bubble of the gas appear from the liquid phase or the dew point when the last drop of the liquid disappeared from the liquid phase and entire section becomes the gas phase.

So beyond the dew point we are having the gas phase only and before the bubble point we are having the liquid phase only or in reverse we can do when we are having the gas we are compressing the gas means increasing the pressure the gas is going to meet first the dew point means first it is going to produce the liquid droplet and then it will be in the two phase region between this bubble point and the dew point and when the pressure is above the bubble point pressure it will be in the liquid phase. So, this is a typical example of any fluid on the pressure and volume diagram. Here we can see as we are changing the operating conditions let us say pressure and volume the substance or the fluid is becoming either liquid or gas or a mixture of liquid and gas between in this region. So, it becomes important to understand what are the operating conditions this fluid is going to face accordingly the phase properties needs to be calculated or used in the further calculation. On the pressure and temperature diagram when we see this is a typical example you might have seen in thermodynamics work where we see the phase change of any substance from solid to vapor, vapor to liquid, liquid to vapor or the other way we are having this typical diagram on the pressure and the temperature scale.

In this region we are having the solid here we are having the liquid and in this part we are having the vapor. This becomes the triple point kind of the things where all the phases get merged together. We are more interested for the hydrocarbon system in the liquid and vapor system where the temperature and pressure are changing the phase of the liquid either from vapor to liquid or liquid to vapor. Let us look one more time over the pressure and volume relationship at different temperature. So if the temperature is varied in this manner like T1 is lower and T4 is the highest temperature we are increasing the temperature what will happen at temperature T1 for example this was the behavior of the fluid when temperature is increased the pressure required to change the phase conversion also increases.

At the end this becomes a point just one point when only a temperature and pressure condition when both the fluids are having the identical properties or beyond that point or above that temperature and pressure they cannot be adjust together that is we call the critical point and beyond that this is just a single phase substance. So, the critical temperature and pressure can be estimated in this manner for any fluid. The reason which is in the interest for us is the liquid and vapor reason for the hydrocarbon fluid in the reservoir like the crude oil and the gas what happens when the substance of the crude oil or the gas or in general we should say hydrocarbon mixture is subjected for a different temperature and phases. Let us understand when it is just a single component one type of the fluid is present. So this line that separate the liquid and vapor we called it is a vapor pressure line or the dew point curve for the single component system on the one side of this we are having the liquid on the other side we are having the vapor when we are moving from left to right like A liquid is going to convert it into vapor this point called the bubble point.

So when we are moving from left to right like A this line is called the bubble point curve means liquid is going to be into gas phase when we are moving in the other direction B this curve is called the dew point curve when the vapor is going into the liquid phase. So how it happens so for example we are somewhere here in the liquid region when we increase the temperature at a constant pressure the substance is going into the gaseous phase or in the vapor phase or if we are cooling at a constant pressure the gas is going to get condensed and going into the liquid phase. When the same operation is done at the constant temperature means isothermal condition when we are changing the pressure so what happens we are having the gas in the system if we increase the pressure the gas gets converted into liquid or when we are releasing the pressure the liquid gets converted into the gas phase. A typical example is the LPG cylinder we are having at our home so the gas is compressed at a very high pressure to get it into the liquid phase and we are having this LPG and when we are using that LPG we release the pressure bring it to the atmospheric pressure the liquid in the cylinder gets vaporized to the gas phase and we are using the gas at the in the kitchen. So this becomes important how temperature and pressure is going to change the phase In the case of the same single component the vapor pressure line here becomes very important that is actually separated both bubble point curve and the dew point curve for a single component all these three lines are aligned or they are the same.

So some more terms here to be discussed like the C, PC and PC so C is the critical point at this point all the intensive properties like the density becomes identical for both liquid and the gas phase beyond that point either the substance is in the liquid phase or in the gas phase they cannot exist together. Critical temperature the temperature above which the gas and liquid cannot coexist together regardless of the pressure. So, for example here if we are increasing the temperature irrespective of the pressure the substance will be in the gas phase only. Critical pressure, pressure above which the gas and liquid cannot coexist regardless of the temperature so beyond that there is liquid with respect to whatever the temperature we are having in the system. When it comes to two component system the line takes the shape of the envelope and the bubble point curve and dew point curve they get separated from this vapor pressure line curve and we are having a reason where both liquid and vapor can exist together in the envelope.

This called the saturation envelope or the phase envelope and the line in this diagram of different liquid volume called the quality lines. So, we discussed the two-component system on the pressure and temperature scale. Bubble point curve is here on the top beyond that is the liquid dew point curve is there beyond that there is a vapor between the bubble point curve and dew point curve this is a two-phase reason where the liquid and vapor are existing together in different form of a liquid loading those are represented by the quality lines or the tie lines. When it comes to the multi component system the phase envelope will be there as it was in the two-component system as many components are there the tie line will be different that is why the nature of this envelope depends on the composition. So if compositions are varying the shape or the structure of this phase envelope phase envelope means the bubble point curve and the dew point curve those are getting merged at the critical points the shape will be completely different.

One of the examples shown here for the multi component system where we are having the liquid phase here gas phase on the other side and the bubble point curve and the dew point curves are spreading between different percent of the liquid loading tie lines. We can see more clearly on the other side of the diagram where we are having this liquid here gas here there is a shaded reason here we will discuss little bit separately that is called the retrograde reason. So in this hydrocarbon mixture that is the multi component system we are having the line that is we call the 100% liquid line or the bubble point curve. Then we are having the two phase reason here and then we are having the 0% liquid line. So this 100% liquid line is actually the bubble point curve and the 0% liquid line is the dew point curve.

Beyond the dew point curve on the right hand side we are having only the gas phase beyond that bubble point curve on the left hand side we are having only the liquid phase and in between this 100% liquid and 0% liquid two phase reason those are represented by the different loading of liquid values in the form of the tie lines or the quality lines. Two important component comes into the picture that is you can see on this diagram this critical temperature is not the highest temperature the critical pressure is not the highest pressure. Beyond that also on this diagram we are having the pressure that is above than the critical pressure we are having the temperature that is also more than the critical temperature. So, these two components or the two terms Cricandon bar or Cricandon therms comes into the picture. So, what they are? They are actually the highest temperature at which two phase can coexist.

So this is the point that replace in the hydrocarbon multi component mixture for the two-component mixture. In two component mixture it was the critical point but in the multi component system it is the Cricandon therm for the temperature and Cricandon bar for the pressure that is actually represent the highest point at which two phase can coexist or their properties are kind of identical beyond that either you are having the liquid phase or the gas phase on the diagram. The bubble point curve and the dew point curve so they are not like in the case of the single component it was the line they become the curve take the shape of the envelope both point get merge at the critical point. But what happens bubble point curve that separate the pure liquid from the two phase regions here this is bubble point curve beyond that is just only the liquid and here we are having the liquid plus vapor. Below the bubble point curve gas emits from the liquid phase to the two phase region.

So for example we are reducing the pressure from this point at isothermal condition what is happening this liquid is going to the two phase region and some of the gas that was dissolved in the liquid or the component of the liquid those are emitting the gas and we are entering into the two phase region. So at a constant temperature when the pressure is reduced we are having the liquid as well as gas. Depending on how much pressure is reduced the percent of the gas emitting out from the liquid will be changed. Similarly on the dew point curve that separate the pure gas phase from the two phase regions here we are having only the gas and here gas plus liquid. The pressure and temperature at which the first liquid droplets forms out of the gas phase.

So this is the line that separate like when just the liquid begins to form or the vapor or the gas start to condensation process when the first drop of the liquid begins to form that is represented by this dew point curve. And as we enter inside of this envelope the percent of the liquid loading with the percent of the amount of the liquid in the two phase region varies. And when we are going from dew point curves to the bubble point curve the percent of the liquid will keep increasing when we are meeting the conditions of the bubble point curve it is almost every gas component becomes in the liquid component or when we are going beyond point bubble point curve it is only in the liquid phase. So it is clear now the highest temperature and the pressure for a hydrocarbon mixtures are cricondane therm and cricondane bar those actually represent the condition beyond that the phase will be in the single phase. So when it comes to the classification of the petroleum reservoir based on the thermodynamics we can see the same things this is bubble point this is dew point curve this is the critical point.

So beyond this critical point on the left hand sides we are having the oil reservoir on the right hand side we are having the gas reservoir. So broadly we can classify the reservoir into two types oil reservoir when the reservoir temperature is less than the critical temperature Tc so this is our critical temperature side, we are having the oil reservoir and on the other side we are having the gas reservoir when the reservoir temperature is more than the critical temperature of the reservoir fluid. In general, reservoirs are conveniently classified on the basis of the location of the point so we are classifying the reservoir based on the reservoir temperature pressure condition or we are classifying based on the surface temperature pressure condition or somewhere intermediate temperature pressure diagram we can use the PT diagram to classify the reservoir and identifying the reservoir. As already mentioned if the temperature and pressure conditions at which we want to know the reservoir fluid is falling between this two phase envelope it is always going to be a challenging task to understand how much percent of the liquid is there how much percent of the gas there. Tie lines may help us to identify that thing and based on that we can classify the reservoir and the surface facilities or the design of the equipment to handle this fluid can be designed accordingly.

Another component is here in the petroleum reservoir classification is gas condensate reservoir. This is the reservoir when the reservoir temperature is greater than critical temperature here and lesser than the maximum temperature that is the Crickenden-Thirme temperature in this region the reservoir is called the gas condensate reservoir. So this is the broad way we can see when the pressure is above the bubble point pressure the fluid is the black oil when it is near to the critical temperature and pressure condition the crude oil that is getting produces the polyethylene in the nature when it is on the gas side near the critical and temperature this called the gas condensate reservoir. When the temperature and pressure of the reservoir beyond the Crickenden-Thirme temperature the reservoir is the dry gas reservoir when it is in the two phase envelope it could be solution gas drive when the pressure is near to the bubble point pressure or just lesser than bubble point pressure or close to the bubble point curve and when the pressure of the reservoir is close to the dew point curve but lesser than the dew point we call the reservoir as wet gas reservoir. The oil reservoir further classified based on the temperature and pressure location or the condition at the reservoir if the reservoir conditions is beyond the bubble point line the reservoir is called the under saturated oil reservoir.

And when the conditions of temperature and pressure are lying on the bubble point line the reservoir is called the saturated oil reservoir and in between bubble point curve and the dew point curve the reservoir is called the gas cap reservoir means the amount of the gas is there associated with the liquid and both gas and liquid are getting produced. In fact the gas that is emitting out from the liquid is actually pushing the liquid to come to the surface it is kind of a driving force that is why the reservoir are named as gas cap reservoir means the gas is kind of a driving mechanism to push the oil for the production. When we compare the same thing with respect to the GOR gas oil ratio so in the under saturated oil condition the ratio is maintained it constant does not depend on the pressure but in this at the saturated oil conditions the pressure affect the GOR and at lower pressure the GOR will be low when the pressure is increased the GOR will increase and when we reach the under saturated oil condition the GOR becomes constant. Further sub classification of the crude oil can be done based on the thermodynamics nature that is in the black oil low shrinkage volatile oil or the near critical crude oil reservoir. Similarly the classification of the gas reservoir can also be done based on the temperature and pressure conditions the reservoir is so the wet gas reservoir first one when the reservoir is near the dew point curve but in the two phase region dry gas reservoir when the reservoir conditions are beyond the cricandon therm temperature retrograde behavior this is a very unique phenomena in the hydrocarbon system where the reservoir is not exactly near the critical temperature not exactly near the cricandon therm temperature in between critical temperature and the cricondine therm temperature the phase behavior of the hydrocarbon mixture is differently that is defined by the retrograde behavior and then the near critical gas condensate reservoir so this is near the critical point what exactly is happening.

Phase envelope of natural gas can be very differently depending on the compositions even more than liquid the phase behavior of the gas substance is more complex the envelope shape or the two phase region shape may be more complex. Some other terms are there that is the associate gas so this is the gas that is dissolved in the oil at the natural condition or the reservoir condition this is the gas becomes free when the reservoir is brought to the surface so it just emit out from the oil. Non associate gas so the gas is there at the reservoir condition so where the minimum oil is there mostly it is the gas component when we are producing the gas is getting produced to the surface and the condensate gas where the gas with high content of liquid hydrocarbon is present and we are producing the condensate gas at the surface. So we will discuss this unique phenomena of the hydrocarbon mixture the retrograde behavior in more detail in the separate slide. So let us understand classification of hydrocarbon reservoir on the temperature and pressure scale that we said this is the bubble point curve 100% liquid curve this is the dew point curve 0% liquid this is the two phase region several tie lines are there between dew point curve and the bubble point curve of different liquid loading.

These bubble point curve and dew point curve merge at the point called the critical point we are having this criconden war that is above the critical pressure we are having the similar cricandon therm that is more than the critical temperature on the temperature scale these these become the highest point beyond that we are having only the single phase. This region is the retrograde behavior where the fluid is changing retrograde means differently as expected so when we are expecting for example the LPG cylinder example, I gave you so when we are changing the pressure of the gas increasing the pressure it should go to the liquid phase but in this region it becomes differently. So, when we are releasing the pressure, the gas is going to the liquid phase the reverse phenomena that happened and because of that we produce the liquid along with the ga at the surface discuss in more detail later on. Beyond the cricandon therm we are having the dry gas only and the GOR for that dry gas is around 1 lakh or more than 1 lakh SCF per STV. In the region near the dew point curve we are having the wet gas where the reservoir pressure is lesser than the dew point curve but very near to the dew point curve and the GOR varies from 60,000 to 1 lakh and the liquid that is produced because of this phase change behavior is having the degree API of 60.

Near the critical temperature point on the gas side we are having the gas condensate GOR is 8000 or more than 8000 SCF per VBL or STV the liquid that is produced near the gas condensate reservoir so gas condensate or reservoir those are also producing a small amount of the liquid along with the gas the degree API is 50. On the liquid side we are having the volatile oil or near critical so the classification is like volatile and then the near critical sometimes both are merged and said as a volatile oil or the remaining as a crude oil but further classification are there between, we will discuss little bit. On the other side on the liquid broadly we are having the classification as the volatile oil that is in the range near to the critical temperature and pressure or little bit beyond near critical temperature pressure is separately defined as a near critical temperature crude oil beyond that we are having the volatile oil and then we are having the black oil. Black oil is actually that is above the bubble point pressure the GOR is 200 to 700 only and degree API varies from 15 to 40. Based on that we can classify oil reservoir as black oil reservoir, loss increase oil reservoir these are the classification of the crude oil that is getting produced from the reservoir and the volatile oil reservoir near critical crude oil reservoir.

In this region we are producing the crude oil similarly on the gas side we are having the dry wet condensate near critical so this region entire region where we are producing the gas or actually this is the line critical point line here mostly we can classify as the gas reservoir on the other side we are having the oil reservoir. In the oil reservoir we are having the under saturated oil reservoir where the conditions are above the bubble point curve or saturated oil reservoir when the reservoir pressure is similar to the bubble point pressure of the reservoir fluid. So, how this PT diagram will be different for different crude oil. So, for example we are having the ordinary black oil you can see in this diagram on the pressure and temperature diagram the tie lines are almost equally spaced. So, this is the critical point bubble point deep point between bubble point and deep point we are having the tie lines and those tie lines are almost equally spaced.

This is the point E when the reservoir is at the saturated condition and isothermally when we are changing the temperature moving in this direction of these two phases region, we are going to hit different tie lines. So, for example here we are having the 90% liquid 10% gas further reducing the pressure we are going to hit 70% tie line means 70% liquid and the 30% amount of the gas similarly for the others. So, when we compare this PT diagram on the oil shrinkage curve that is the curve between the liquid volume and the pressure. So, when we are changing the pressure isothermally means at a constant temperature similar to this line that is representing isothermal changes in the pressure we are going to get the percent of the liquid change from point E to F in this manner. So, like almost a straight line and when we are getting almost straight line in the liquid volume versus the pressure we can say the reservoir is the ordinary black oil reservoir or the crude oil that is getting produced ordinary black oil crude.

So, in low shrinkage oil from E to F in the similar manner under the isothermal condition we are reducing the pressure to reach the 85% tie line means 85% liquid and 15% is the gas significant pressure reduction is required. Because the tie lines are closer to the dew point curve and oil shrinkage curve shows not very significant reduction in the liquid volume can be achieved when we are changing the pressure means reducing the pressure in the low shrinkage oil case. What happens in the volatile crude oil case? In volatile crude oil case most of the tie lines are towards the bubble point curve as you can see here even the small change in the pressure will let the gas emit out of the liquid and we are going to get significant percent of the gas in the liquid system. So, here the liquid volume will change drastically when we are reducing the pressure residual oil will be having significant percent of the liquid but compared to the low shrinkage oil this oil is having less percent of the liquid more percent of the gas when we are reducing the pressure. What happens near the critical crude oil? So, you can see near the critical crude oil here the tie lines are changed very fast.

So, all the tie lines are originating from the critical points all the points are here 90, 85, 75, 70. So, even a small reduction in the pressure at a constant temperature sudden change in the liquid volume will happen. So, from the bubble point it was 100% a small pressure drop happens suddenly the percent of the liquid decrease and percent of the gas increases and after certain point it also follow the same tie lines and we are not going to get very much change but around 50% liquid volume change may happen in a small pressure reduction because the near critical crude oil is very close to the critical point where all the tie lines are merging. So, even a small change is going to cross multiple tie lines and suddenly it is going to cross 90, 80, 70, 60 tie lines and it is going to give us almost 50 to 60 percent liquid volume reduction in a small change in the pressure. So, this is the way we can compare different types of the crude oil black oil, low shrinkage oil, volatile crude oil or near crude oil based on the thermodynamics behavior how much liquid volume or liquid loading they are going to have in the system.

So, this PT diagram and low shrinkage curve tell us how near the quality lines to the bubble point curve will determine the types of the crude oil. If the tie lines are closer to the bubble point curves we are going to get more volatile crude oil. If they are equally spaced we are going to get the black oil and if they are towards the dew point curves we are going to get the low shrinkage oil means the liquid will be more compared to the gas when we are changing the pressure at the constant temperature. So, similar information is here for all these four categories of the crude oil. So, the GOR for the ordinary crude oil is 200-to-70-degree API is 15 to 40 degree.

The color is brown to dark green in the color for the black oil low shrinkage is having black or deeply colored degree API is 35 around and the GOR is less than 200. When it comes to the volatile the GOR increases because it produces more gas degree API of the remaining crude is 45 to 55 which is lighter near to the critical temperature and when it comes to the very near critical temperature crude oil the high GOR is exceed 300 SCF per STB because it is very close to the critical temperature even a small change in the pressure going to liberated out more amount of the gas and the composition also varies this will be having the heptane plus compound around 35% or more some amount of the methane and ethane will also be liberated out from this crude oil. Similarly for the gas reservoir as we discussed the gas reservoir can be classified as wet gas reservoir or the dry gas reservoir retrograde reservoir near critical temperature gas reservoir. Here in this slide we are having the wet gas reservoir PT diagram and dry gas PT diagram. As we can see the shape of both the curves or the envelopes in both the diagrams are completely different that is because of the composition.

If compositions are different the shape will be different because they will behave differently at different temperature and pressure or the mixture will behave differently. So, for let us take the example of the wet gas similarly we are having here liquid beyond the bubble point curve we are having the gas beyond this dew point curve in between we are having the tie lines those are representing the liquid volume percent near the bubble point we are having the 100% beyond that dew point we are having only the gas. Important point here is this separator point and this is the reservoir point A. So, for example the gaseous phase under reservoir condition is at point A that is beyond the cricandonton temperature hence the gas is adjusting in the gas phase at the reservoir condition that is why it is in the gas reservoir classification. But when we are producing it to the surface isothermally let us say we are reducing the pressure because pressure is the driving force to produce the gas to the surface assuming the operation is happening at isothermal conditions the pressure is declining and we are going to get the gas at the surface also in this manner.

But what happens at this is the compressible in the nature temperature pressure are also different when it is flowing from reservoir condition to the surface condition let us say the separator is here at this condition the separator conditions are falling within the two phase region. So, the path the gas is going to follow is this to get produced. So, when it is entering into two phase region the condensation will happen certain percent of the liquid will also get produced. So, the wet gas liquid drops out once gas reaches the surface the conditions of temperature and pressure fall inside the two-phase region and hence we get the small percent of the liquid and that is why the reservoir is classified as the wet gas reservoir. While what happens on the dry gas reservoir the separator conditions are beyond the dew point conditions it means when we are starting from point A if isothermally we are starting the conditions are okay you change the pressure you are going to get the gas only at the surface.

But when the temperature is also change it is not isothermal about separator condition is here the temperature is here and the pressure is here. Now from point A we are moving to the separator by any mean either this way or this way ultimately, we have to reach to the separator condition or the fluid has to reach to the separator condition. What is happening the separator condition are still beyond the dew point curve and in that case we are going to get only the gas phase produced at the surface. So, at the dry gas primarily methane with little or no heavier compounds are produced surface temperature falling outside the two-phase envelope and no formation of natural gas liquid is happening in case of the dry gas reservoir. Hence with this kind of the understanding the operator or the person who is responsible for the production can tune the operating condition in such a manner they want to produce some percent of the liquid they can set the separator temperature condition in such a manner.

The reservoir fluid or the gas that is getting produced going through the two phase region or if that is not required only the gas need to be produced the separator temperature condition can be adjust in such a manner like only the gas phase is getting produced to the surface. What happens in case of the retrograde system so this is the typical PT diagram or the phase envelope diagram for the retrograde system it is a unique phenomenon that appears only among the hydrocarbon mixture. So, for example this is the condition where the reservoir is having gas in the system. So, this is beyond the dew point curve we are having the gas only when we are moving isothermally 2.2 this is the dew point curve at dew point curve first drop of the liquid will appear means the condensation start some of the gas component will go to the liquid phase.

So, this is still 0% liquid just the process begin and when we enter further. So, let us say this is 0% liquid line this is 5% liquid line this is 10% liquid line. So, this is crossing this line we are reducing the pressure and 5% liquid is getting produced that is actually a very different behavior that I gave the example when we reduce the pressure what exactly happens the liquid goes to the gas but here it is happening reverse way gas is going to the liquid when we are further reducing the pressure it is going to the 10% liquid. So, at this pressure it was 5 further reduction in the pressure it becomes 10. So, this behavior is very unique for the hydrocarbon mixture when we are reaching to a point let us say third point or somewhere we are going to cut this line let us say 15% liquid and when we are further reducing this is going to the 10% means first it was 5% 10% then 15% liquid and then further reduction it goes to the normal operation like the gas or the liquid start getting the vaporize and we are going to get the less percent of the liquid in the operation of further pressure reduction.

So, we are going to get 10% if we are reducing further it might be possibility like the operation is happening in such a manner we are getting the less percent of the liquid. So, depend on the separator condition at what condition separator is designed but before the separator and the reservoir condition this retrograde behavior happens in case of the natural gas that is the hydrocarbons system. So, this is the point 1 where the vapor phase the gas is in the vapor phase only point 2 when liquid begins to condense it retrograde behavior happens because it is reversible point 3 this is the maximum point. So, the liquid volume increases and there is a point when it is going to the normal conditions it means when we are further reducing the pressure liquid is going to vaporize and we are going to get more gas compared to the liquid that is the point 4. We can see that more clearly in this diagram so the amount of the liquid with respect to the pressure so this is the pressure when we are going to get the maximum amount of the liquid drop out from the gas phase.

This kind of the phenomena happens between the dew point and the point where the liquid re-vaporize is the reason of retrograde condensation. So, a shaded reason that I had shown in the previous slide in that reason this is happen more closely tie lines are there the more changes will be there in the liquid vapor condensation and vaporization process. So, this liquid condensation that is happening is favorable or unfavorable depends on the operator needs but what exactly happen because of this retrograde behavior or the liquid condensation it forms a condensate bank around the wellbore. So, the reservoir fluid is producing suddenly it is hitting the pressure region near the wellbore where the pressure is lower the gas is going to convert into liquid and the liquid bank is created around the wellbore region and because of that the gas permeability is reduced and the production may cease because it is not allowing the further gas to produce or if the gas is not having enough energy to carry this liquid to the surface it is going to cease the production. For that purpose what is done the pressure maintained is done we do not want to lose this condensation or the liquid remain in the reservoir because liquid hydrocarbons are more valuable than the gas in terms of the energy content or the market value.

So, what is done to maintain the pressure so this liquid loading that is happening because of the condensation is coming to the surface the pressure is maintained by recycling the gas. So, we are producing the gas re-injecting the gas into the reservoir to maintain the pressure and the liquid that is getting accumulated near the wellbore region is coming to the surface. This happens only in the retrograde behavior or such kind of the reservoir where the pressure is falling in that range or the temperature and pressure falling in such a condition when this is happening near the wellbore. In general the gas and the condensate liquid mixed with it comes to the surface and at the separator conditions suddenly we get that the liquid is getting produced out of the gas and that is happened in the near critical gas condensate reservoir. So, near critical gas condensate reservoir you can see so the gas reservoir 0.

1 means initial condition it is 0% liquid only the gas and suddenly change in the pressure reducing the pressure we reach to the point where suddenly significant amount up to 30-40% liquid get produced and when we are further reducing the pressure the re-vaporization of that liquid happens and the liquid volume decreases and the gas volume increases near the critical gas condensate reservoir. So, the dry gas reservoir hydrocarbon mixture exhibit as a gas both in the reservoir and in the surface facilities only liquid associated with the gas in such kind of the reservoir is the water GR is always greater than 1 lakh SCa per STb no liquid phase is formed no matter how high the pressure is raised the reservoir would produce dry gas without any condensation problem. Wet gas reservoir the gas enters the two phase reason a liquid phase will condense out of the gas GR reduces compared to the dry gas and it goes up to one from 1 lakh to 68000 STb of the produce condensate or the liquid is 60 degree API. The color is in water white the separator conditions lie within the two phase reason that is why this phenomena is happening in the wet gas reservoir. Retrograde gas condensate reservoir they lie between the critical temperature and the quercondient therm temperature.

This is a unique phenomenon of the hydrocarbon mixture GR between 8000 to 70000 SCa per STb the condensate those are getting produced have the API gravity above 50 degree API. So, the near critical gas condensate reservoir the API and GR is similar to what for the retrograde gas condensate reservoir this reservoir is above the critical temperature but near to it and the reservoir is called the near critical gas condensate reservoir. Their phenomena is also like the suddenly change in the pressure they cross the multiple tie lines. In summary what we discussed today about the classification of the reservoir based on GR degree API and the color phase diagram help us to understand the types of the fluid that is getting produced and when the fluid is getting exposed to different temperature and pressure condition how it is going to behave typical diagram is shown here. The shaded region is the retrograde region where the reverse or the retrograde behavior of the hydrocarbon are obtained.

The shape of this envelope or phase envelope will depend on the composition and the reservoir temperature and pressure condition and surface temperature and pressure condition will determine how much percent of the liquid and gas is getting produced from the system. Broadly we could classify the reservoir using this phase diagram into under saturated oil saturated oil gasket reservoir. Similarly for the gas reservoir it is dry gas reservoir wet gas reservoir or the condensate reservoir. GR help us to identify broadly classification so the values are like greater than 1 is the gas well less than 5000 is oil well in between it is a condensate well. The API can classify the grade of the crude oil if it is 0 to 20 it is a heavy grade crude oil 20 to 30 it is a medium crude oil and if it is above 30 degree API then the crude is considered as a light crude oil.

All this understanding becomes very important near wellbore gas condensate flow for the optimization of the gas condensate reservoir. As I said gas condensate reservoir are producing the liquid liquid is more valuable we want to produce those liquid same time we do not want because of that condensation problem the production is getting affected or it is getting seized. So very operating condition need to be designed to produce those condensate in effective manner to the surface. All these phase diagram understanding help us to understand the recovery mechanism those are responsible for this hydrocarbon production we can understand the behavior of the production profile and design the separator and other equipment as per the production profile or what kind of the fluid are getting produced at what quantity they are going to get produced to the surface. So, with this I would like to end today's lecture in the next lecture as we discuss a part of this section 1 we are going to discuss the reservoir fluid.

So in the next lecture we will be discussing about the important properties of the natural gas and further lecture we will discuss about the oil and water properties maybe in the next week we will go to understand the reservoir rock properties. With this I would like to thank you for your attention. Thank you very much. you