

Petroleum Reservoir Engineering

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Lecture 6: Natural Gas Properties

Hello everyone and welcome again to this MOOCs course on petroleum reservoir engineering. So, we are in week 2, lecture number 2. In the last lecture, we discuss about thermodynamics of hydrocarbon. We will continue our discussion to understand the reservoir fluids and the reservoir rock properties. So, in today's lecture, we are going to discuss about natural gas properties. So, what is natural gas? It is a complex mixture of the hydrocarbon and non-hydrocarbon gases.

Hydrocarbon gases ranges from C1 to C7 and sometimes little higher compound also present. But mostly it is dominated by the methane. 70 plus percent is the methane component in the natural gas. Actually after producing the natural gas to the surface and then refining it, taking out the valuable compound, most of the time the end consumer get the natural gas that is methane.

Along with the hydrocarbon gases, natural gas also contain the non-hydrocarbon gases that include the carbon dioxide and water, hydrogen sulphide, nitrogen and helium and some other rare gases are also present with the natural gas production. It is a subcategory of the petroleum system where the organic material on the geological time scale got converted into gas phase. Why it is important? Because when we ignite in the air, the mixture give us the energy, the mixture of hydrocarbon and non-hydrocarbon gases. So, for example, when we ignite the air and gas mixture in the range of 5 to 15 percent, so the lower explosive limit is 5 percent and the higher explosive limit is 15 percent. Between this range, the methane gas or the natural gas get ignites when it is burnt.

For example, when we are burning 1 mole of methane with the oxygen, we get the product CO₂ and H₂O and the amount of the energy is released because of this combustion process. The value of the energy released because of this combustion process vary depending on the composition of the natural gas. Here just one example of methane is given, but natural gas is a mixture of several compound. In fact, inorganic compound those are not combustible. So, if their percent is high, the energy content will get reduced.

That is where the energy content of the natural gas is measured in Btu. That Btu vary from 500 to 1550 Btu. On average, you can say 1031 Btu is the value. Another unit of measurement of the energy content is mm Btu that is 1 million Btu or that is equivalent to 10 therms. This natural gas is colorless.

It has no smell, odorless. That is why in our LPG cylinder somewhere the component is added that smells. It is combustible by nature. It provides the energy and this combustible process is clean by the nature. So, the natural gas combustion is considered the clean fuel system.

So, this slide is showing the typical composition. Again, these are the example. Methane is 70 to 90 percent. Then ethane, propane, butane they account 0 to 20 percent and then the remaining is the non-hydrocarbon gases and some amount in the trace quantity is present for the rare gases. Lean gas and rich gas are the classification of the gases or the natural gas that we are producing.

So, lean gas which is having the less energy content, rich gas which is high energy content, dry gas where the moisture content or the water content is very less, less than 0.1 gallon per 1000 feet cube of the gas, wet gas when the quantity of the moisture or the liquid component is high. Sour gas and the sweet gas. So, the natural gas contain the sulfur compound. They made the smell very bad or they are very poisonous to end users.

So, the gas which is containing the sulfur compound called the sour gas, sweetening processes are performed to make this gas free of the sulfur compound and the gas that comes out after the sweetening process is called the sweet gas. Associate gas and non-associate gas we already discussed. Several form of unconventional gas are also in the discussion nowadays like coal bed methane, sand gas, shell gas, gas hydrate. They are the source of the natural gas where the natural gas is either trapped in one form or it is adsorbed on the surface in the case of the coal bed methane. Some more classification of the natural gas that we heard about, biogas, Mars gas, swamp gas, landfill gas.

Another important aspect is gasoline. So, when we are going to gas station in the United States, we are going to get the gasoline but that gasoline is not the gas. It is at all but in United States they call it gas. A domestic gas LPG that we get that is propane and butane that is again not the natural gas but the fraction of the natural gas propane and butane that is more valuable than the natural gas itself or methane that is we call the LPG that is used in the domestic gas. So, it should not get confused with the gasoline and the domestic gas.

Tight gas, shell gas, coal bed methane and gas hydrate they are the unconventional

source of the natural gas production that we will discuss at the end of this course in more detail. So, let us move further about the properties of the natural gas that we are having the composition of hydrocarbon and non-hydrocarbon gases. Several properties are important to evaluate. What are those important factors need to be considered or the properties those need to be considered is the gas specific gravity, pseudo critical temperature and pressure of the gas mixture, viscosity, density, compressibility factor, formation factor and expansion factor. So, these are some of the properties not listing all the properties like the thermodynamics properties of the natural gas but these are the properties those are required when we are evaluating the gas reservoir or the gas well.

When we are predicting the production and the prediction profile of the production system. When we are designing the separator and the other processing unit to handle the natural gas. So, when the natural gas is produced during the production controlling the production processing the natural gas storing it transporting it to the end consumer even the end consumer is using everywhere we need to know the properties of the material that we are dealing in this case the natural gas. So, that is what we need to discuss some of the properties and these properties will be utilized when we are designing or handling the natural gas. For example, density is simple while the definition is mass per unit volume but when we are dealing natural gas the density needs the compressibility factor and the molecular weight of the mixture.

So, we need to understand how to calculate the compressibility factor and the molecular weight. Similarly, molecular weight needs relative density when we are flowing the gas in the well jet factor and viscosity are important pressure drop in pipelines the setting up of the mathematical equation again needs density and the viscosity even when we are calculating the Reynolds number at what Reynolds number the flow is happening in the pipeline or in any system that is again need the density and the viscosity. So, it becomes important to understand how to calculate the mixture properties of natural gas that is hydrocarbon and non-hydrocarbon gases in different proportionalities are present. So, this is the list of the compound of the pure compound present in the natural gas C1 is the methane C2 is the ethane and the similar classification for the other hydrocarbon gases nitrogen CO₂ and H₂S are taken as the example for the non-hydrocarbon gases. The molecular weight of these pure compound are well documented in the literature we can get from there.

Similarly, the critical temperature of the individual pure compounds are documented in any thermodynamics book by N.S.S. Smith or others you can find out similar for the critical pressure. So, if we know the composition of the gas what are the component are present in what proportionality they are present we can use the documented values for the molecular weight critical temperature and critical pressure for the individual

compound.

So, let us take the example the mole fraction of these compounds are given this is for the example again. So, let us say 77.5 mole percent is the methane and subsequently other gases are present including the non-hydrocarbon gases. And we want to know the properties of the gas. So, the gas law should be applied to understand the behavior of this gas ideal gas law simply said PV is equal to nRT .

But our natural gas is not the ideal gas a natural gas mixture under reservoir condition is very non-ideal. So, the real gas law need to be implemented and that is where the compressibility factor Z appears in the gas law. And we need to understand how much deviation from the ideal behavior the natural gas is having that is can be accounted by the value of Z . Now the value of the Z depends on the composition itself. So, if compositions are varying the temperature pressure conditions are varying the value of the Z will get change.

In this expression we need to substitute the value of R that is the real gas constant 10.73 in this unit system where PSIA fit cube per mole degree ranking if you are going to SI unit system will become 8.31. Other two important parameter those need to be remember is the standard conditions those standard condition for the pressure is 14.7 PSI and for the temperature it is 520 degree ranking.

You can use in the other unit system but the temperature should be in the absolute unit system as we are discussing the reservoir course the field unit system or the US field unit system must be implemented or thoroughly practiced that is where the pressure is in the PSI and the temperature in degree ranking should be implemented and accordingly the R value should be used 10.73 whenever we are using the real gas law. So, how to find out these compositions you collect the sample from the source that could be just at the production well or could be anywhere subject that collected gas sample to gas chromatography. That gas chromatography is having three components inlet, column and then detector. So, here very small quantity in fact like microgram or micro liter something is injected to this column.

Column is kind of a spiral system where the coating of certain material is there inside the column that is provide the retention time for different component and this section is heated with a specific temperature program and then the gas is injected through this inlet. Inlet could be coolant column or split or any other type of the inlet system there could be variety of the column you need to choose particular column depending on the analysis you are doing like for the hydrocarbon gases pona column is good enough and once we are heating the system the gases those are injected in the column they will be having

separate retention time based on the column coating and those gases are reaching to the detector at different time. Now detector could be used TCD thermal conductivity detector for lighter hydrocarbon gases and the non-hydrocarbon gases and another is FID flame ionization detector that is used for the hydrocarbon gases. So, with the help of TCD and FID you can quantify how much percent of the individual component those could be hydrocarbon gases or could be non-hydrocarbon gases are present in the sample based on that the mole fraction could be listed out like shown here. Let us move further the properties like the compressibility factor.

So, if we see standing and Katz had given a chart for estimating the compressibility factor value that compressibility factor value depends on the composition specifically impurities correction like the inorganic gases are there because standing and Katz they had given the chart for the hydrocarbon gases. Specific gravity that we will discuss after few slides is the property of the gas and pseudo reduced temperature and pseudo reduced pressure this should be pseudo reduced temperature. So, we will discuss all these three later on. What I am going to show here the chart that is looking very complex can be used to calculate the value of the compressibility factor. But to use this chart we need to know the reduced pressure value and the reduced temperature value of the mixture when we talk about the mixture pseudo comes front to the properties.

So, these are the pseudo reduced pressure and pseudo reduced temperature for the gas mixture that we are dealing with using this chart we can get the compressibility factor. But reading this chart every time becomes complex in fact it becomes more complex because the value of the compressibility factor from the chart is for the hydrocarbon gases only when it was assumed like no hydrocarbon gases are present. But if the non hydrocarbon gases like nitrogen S2S CO2 are present the correction factor needs to be calculated from this chart Brown et al that was given in 1948 to calculate the actual value of the compressibility factor. Another chart is given where the ratio of CO2 and S2S is varying in the composition of the natural gas so the correction factor can be calculated using this chart. Similarly for the viscosity of the natural gas two-step procedure was suggested by Carr et al using this chart we can calculate the viscosity of the gas at atmospheric pressure.

What we need to know to calculate the viscosity using this chart we need to know the apparent molecular weight apparent means the molecular weight of the mixture and the gas gravity. And this needs to be corrected again for the inorganic gases those are present in the natural gas. So, at different temperature the value of the viscosity at atmospheric pressure can be calculated knowing the molecular weight and the gas gravity and the correction for the inorganic gases can be implemented. But this viscosity is at one atmosphere we want to know at the elevated pressure to calculate the viscosity

at elevated pressure another chart needs to be used that is again given in the form of pseudo reduced temperature and pseudo reduced pressure. Using the value of pseudo reduced temperature and pseudo reduced pressure those can be calculated for the natural gas mixture viscosity ratio can be calculated and that viscosity ratio can be used to calculate the viscosity at the elevated pressure.

So, this is a two step process one calculate the viscosity at one atmospheric pressure and then the second by using the ratio we can calculate the viscosity at the elevated pressure. When we discuss the viscosity of the individual compound we see the viscosity of individual compound like the this is for methane and some other are not visible clearly but for single component like methane, ethane, propane and non hydrocarbon gases the value of the viscosity varies with temperature and pressure. In general the viscosity of the gas increases with increasing the temperature. So, what we can ascertain from this slide calculating the viscosity of the natural gas or the compressibility factor we need to know certain properties to read this chart. And these chart are complex they cannot be utilized for the modeling purpose or in the computer program or in a quick calculation it is better to convert this chart into some mathematical equation that is done later on by other scientists to calculate the compressibility factor viscosity or any other complex property of the natural gas that is depending on the basic property of the natural gas mixture like the pseudo reduced temperature, pseudo reduced pressure, gas gravity, molecular weight.

So, with this background let us start discussing about the basic properties of natural gas. So, first one is specific gravity. Gas specific gravity is the ratio of the apparent molecular weight of the natural gas mixture to that of air. So, by mathematically it is denoted by gamma g that is the ratio of apparent weight of gas mixture divided by the apparent molecular weight of air that is 28.97 when we consider approximately 79% nitrogen is there and 21% oxygen.

Properties of Natural Gas

Specific Gravity

□ **Gas-specific gravity (γ_g):** The ratio of the apparent molecular weight of a natural gas to that of air.

The molecular weight of air is usually taken as equal to 28.97 (approximately 79% nitrogen and 21% oxygen)

$$\gamma_g = \frac{MW_a}{28.97}$$

▪ **Apparent molecular weight (MW_a):**

$$MW_a = \sum_{i=1}^{N_c} y_i MW_i$$

Now question is how to calculate this apparent molecular weight of the mixture simple chain rules or mixing rule can be implemented to calculate the apparent molecular

weight of the mixture. What we need to know? We need to know the y_i individual mole fraction of the component we can calculate y_i or estimate y_i value using the gas chromatography. Molecular weight of individual compound those are already listed like for methane it is 16.04 something. So, y_i is the mole fraction of component i , MW_i is the molecular weight of component i , n_c is the total number of the component present.

So, using this chain rule we can calculate the molecular weight of the mixture y_i is the ratio of n_i by n and then we can use the Dalton's law also to calculate the y_i if we know the partial pressure value and the total pressure value. If the natural gas is just having the pure methane γ_g will come out as 0.55 it means like molecular weight is just 16.04 something divided by 28.

97 you will get the pure methane. If the rich or heavy gas are present like higher hydrocarbon compound are present the apparent molecular weight will be more and the value of the γ_g will also increase up to 0.9. Once we apply the chain rules to calculate the apparent molecular weight similar rules can be applied to calculate the critical properties of the mixture. So, gas pseudo critical properties like the pressure and the temperature can also be calculated by applying the mixing rule. We already knowing the y_i we already knowing the PCI or TCI for individual component.

Properties of Natural Gas

Specific Gravity

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$$\gamma_g = \frac{MW_a}{28.97}$$

▪ **Apparent molecular weight (MW_a):**

$$MW_a = \sum_{i=1}^{N_c} y_i MW_i$$

$$y_i = \frac{n_i}{n}$$

$$p_i = y_i P$$

✓ For pure methane = 0.55

- y_i is the mole fraction of component i ,
- MW_i is the molecular weight of component i ,
- N_c is the number of components

□ **Gas pseudo-critical pressure**

$$P_{pc} = \sum_{i=1}^{N_c} y_i P_{ci}$$

□ **Gas pseudo-critical temperature**

$$T_{pc} = \sum_{i=1}^{N_c} y_i T_{ci}$$

PCI is the critical pressure of component i , TCI is the critical temperature of component i . So, let us take the example quickly to understand how to calculate or apply the mixing rule. So, by using the mixing rule let us determine the apparent molecular weight, pseudo critical pressure and pseudo critical temperature of the gas. So, what are the gas compositions are given same example these are the component of C1 to C7 and then on hydrocarbon gases mole fraction of individual compounds are calculated using the gas chromatography. We already can extract the value of molecular weight of individual compound critical temperature and critical pressure of the individual compound.

Now we multiply individual mole fraction with the molecular weight similar we can do

for the critical temperature and critical pressure and then we can do the summation of this that will give us the apparent molecular weight of the gas that is coming out 20.71 similar for the critical pressure and critical temperature the values are here same unit degree ranking for the temperature psi for the pressure. Now we know the apparent molecular weight of the gas we can use the same formula we are going to get the value as 0.71 for gamma g. So, why I am showing this example you can write your own excel program or MATLAB program or any platform where you are able to calculate quickly the required value like apparent molecular weight gamma g or critical temperature and critical pressure for the mixture and whenever the compositions values are changing you can quickly just change those value and get the result instead of writing every time or performing the calculation every time.

So, it is advisable when you are solving the assignment you make your own program start from here and as we are moving further to calculate the other properties for the oil gas and rock you are working with your own excel program or the MATLAB program to calculate the properties. So, in the previous slide we said gamma g can be calculated by knowing the apparent molecular weight but critical temperature and critical pressure be calculated using the mixing rule and sometimes the critical temperature and critical pressure of course these are pseudo values because these are for the mixture are not very accurate. We had seen for estimating the viscosity and the compressibility factor we need to use the chart those chart needs the pseudo critical temperature and pseudo critical pressure or the next version of pseudo reduced temperature or pseudo reduced pressure. So, the accuracy of the pseudo critical temperature and pseudo critical pressure becomes more important. So, Goa and Galambore in 2005 they had given very simple expression to calculate the value of these critical properties using gamma g.

Properties of Natural Gas

Compressibility Factor

(Standing and Katz)

Brill and Beggs (1974)

Mathematical expressions

$$z = A + \frac{1-A}{e^B} + Cp_{pr}^D$$

Where,

$$A = 1.39(T_{pr} - 0.92)^2 - 0.36T_{pr} - 0.10$$

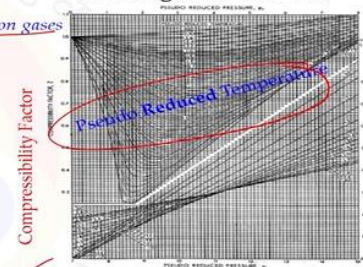
$$B = (0.62 - 0.23T_{pr})p_{pr} + \left(\frac{0.066}{T_{pr} - 0.86}\right)p_{pr}^2 + \frac{0.32p_{pr}^6}{10^E}$$

$$C = 0.132 - 0.321 \log(T_{pr})$$

$$D = 10^F$$

Hydrocarbon gases

Standing and Katz (1942)



So, instead of knowing the composition sometimes the compositions are not known just the value of the gamma g was given to you to calculate the remaining properties gamma g indirectly accounting what is the composition of the gases or what is the apparent molecular weight of the gas you are dealing with. Using gamma g we can calculate the

critical pressure and critical temperature with just simple this linear equation where the gamma g is related to these critical properties. But this is valid only when the H₂S percent is less than 3 and nitrogen percent is less than 5 and total inorganic content is less than 7 percent. So, whenever a model equation or the correlation is given it is having its boundary under what condition it is implemented and for what cases it has been extracted from the experimental data or from the graph. So, the Goa and Galambore equation is having these conditions to be used the equation for critical pressure and critical temperature.

Properties of Natural Gas

Pseudo critical properties of Natural Gas

- If the gas composition is not known but gas-specific gravity is given by **Guo and Ghalambay (2005)**
 - Gas pseudo-critical pressure $p_{pc} = 709.604 - 58.718\gamma_g$ *valid for H₂S < 3%, N₂ < 5%, and total content of inorganic compounds less than 7%*
 - Gas pseudo-critical temperature $T_{pc} = 170.491 - 307.344\gamma_g$
- Correlations with impurity corrections for mixture pseudo-critical properties: **Ahmed 1989**

$$p_{pc} = 678 - 50(\gamma_g - 0.5) - 206.7y_{N_2} + 440y_{CO_2} + 606.7y_{H_2S}$$

$$T_{pc} = 326 + 315.7(\gamma_g - 0.5) - 240y_{N_2} - 83.3y_{CO_2} + 133.3y_{H_2S}$$

Applicable for mixture with impurities such as N₂, CO₂, H₂S
- Standing (1981)**

$$p_{pc} = 706 - 51.7\gamma_g - 11.1\gamma_g^2$$

$$T_{pc} = 187 - 330\gamma_g - 71.5\gamma_g^2$$

Natural gas without nonhydrocarbon gases
Gas- Condensate System

Correlation with impurities correction for mixture are modified by Ahmad in 1989 and Ahmad had given the expression where the percent of inorganic gases like N₂, CO₂ and H₂S are also accounted along with the gamma g for the calculation of the pseudo critical pressure and pseudo critical temperature. This model is applicable for mixture where the impurities such as N₂, CO₂ and H₂S are present. Standing in 1981 he proposed the expression for the natural gas without non-hydro carbon gases. It is good for the gas condensate system also where the gamma g is related in the quadratic form. So, if you see this first set of the equation where it is just gamma g but in this set of the equations, we are having gamma g square.

So, the quadratic equation is proposed by standing to calculate the critical properties. Other like Soton 1985 they had given the similar expression quadratic equation for calculating these properties in the form of gamma g. Gases rich in heptane plus with minor amount of the inorganic hydrocarbon gases are the condition to use this set of the equations and gamma g value should also be in this range when we want to use this Soton 1985 expression. Another expression is also given in the quadratic form and that is suitable for gas condensate. There are some more correlation but I think these number of the correlation are good enough depending on the conditions we are having in hand like what are the percent of the inorganic compounds present, what is the gamma g value, one of the equations we can use to calculate the value of the critical pressure and critical temperature.

Properties of Natural Gas

Gas Density

- Natural gas is compressible, its density depends upon pressure and temperature.

$$\rho = \frac{m}{V} = \frac{MW_a p}{zRT}$$

where m is mass of gas and ρ is gas density.

- Taking air molecular weight 29

$$\rho = \frac{2.7 \times 10^{-6} p}{zT} \quad \text{lbm/ft}^3$$

Although some of the values those are given for the inorganic compound also are not that much accurate. If we want more accurate information Wichard and Aziz in 1972 they proposed the correction factor based on the percent of CO₂ and H₂S to get more accurate value of these critical properties. So, correction factor epsilon 3 is calculated based on this chart. So, this chart can mathematically be expressed like this where the A is accounting for the combined mole fraction of H₂S and CO₂ and B is for the H₂S only. Knowing the value of mole fraction of the inorganic compound we can calculate A and B putting A and B in this expression we can get epsilon and that epsilon is put up here to get the correction in the critical temperature and here in pressure we are having again the corrected value of the pseudo critical temperature percent of the H₂S and this epsilon 3 correction factor.

So, using this chart or this mathematical equation those are derived from this chart we can get the more accurate value of the pseudo critical temperature and pseudo critical pressure. Now the other two important properties pseudo reduce pressure and pseudo reduce temperature most of the charts for the viscosity incompressibility are in this form. This is simply by the definition reduced pressure is pressure divided by the critical pressure of the mixture that is pseudo critical pressure. Similar definition goes for the temperature, temperature at which the gas is present divided by the mixture property that is the pseudo critical temperature of the gas mixture. So, by these two expressions we can calculate the pseudo properties of the gas mixture.

Let us come to another important aspects of the natural gas that is gas density. Natural gas is compressible by nature its density depend upon pressure and temperature. So, natural gas when it is underneath the surface it is very high pressure the compressibility of the natural gas let it be stored in a small volume when the pressure is released it coming to the surface the natural gas density will change. By the definition of the density it is mass per unit volume. Now we can put the value of volume from the real gas law that is $nzRT$ divided by P .

So, the mass can be transferred in the form of the molecular weight. So, we will get the expression for density in this form where m is the mass of the gas and ρ is the gas density. Taking air molecular weight 29 we can convert this apparent molecular weight into the form of γ_g by using this 29 value or 28.97 value for the air.

So, the final expression that is coming for the gas density is $2.7 \gamma_g P$ by ZT where we also put the value of r 10.37 and the unit for ρ is lbm per foot cube . So, the unit is important if you are expressing the property those are associated here in other unit the unit of the density will get changed and accordingly the coefficient will also get changed. So, when we are having pressure in PSIA temperature in degree ranking the value of density is 2.

$7 \gamma_g P$ by ZT . Viscosity of the natural gas is a measure of the resistance of flow exerted by the gas. So, the simple definition as for the other fluid for the viscosity. Two types of the viscosity we generally deal with dynamic viscosity that is measured in centipoise.

Properties of Natural Gas

Viscosity of Natural Gas

- Gas viscosity is a measure of the resistance to flow exerted by the gas.
- Dynamic viscosity (μ_g) in centipoises (cp) $1 \text{ cp} = 6.72 \times 10^{-4} \text{ lbm/ft-sec}$
- Kinematic viscosity (ν_g) is related to the dynamic viscosity through density (ρ_g)

$$\nu_g = \frac{\mu_g}{\rho_g}$$

$1 \text{ cm}^2/\text{s}$ is equivalent to 100 cSt

1 centipoise is equal to 6.72×10^{-4} lbm feet second. Another unit of this is Pascal second. Kinematic viscosity is related to the dynamic viscosity through the density. So, we already know this definition dynamic viscosity divided by the density will give us the kinematic viscosity value and the unit for the kinematic viscosity is 1 centimeter square per second or we can measure in meter square per second or in general it is measured in terms of stock. So, 1 centimeter square per second is equivalent to 100 centistocks. So, the viscosity of gases are in general considerably lower than those for the liquid.

For a perfect gas the viscosity increases with temperature we can explain this with the kinetic theory of the gases. In this regard the behavior of gas is just reverse of the liquid. So, liquid viscosity decreases with increasing the temperature while for the perfect gases it increases. Viscosity of a perfect gas is independent of pressure at constant temperature but that is not the case for the natural gas because it is not the perfect gas.

Although this perfect gas behavior is unexpected for the gases that can be explained based on the kinetic theory of the gases.

As the pressure on a perfect gas is increased it becomes imperfect and its behavior approaches that of a liquid. So, at a high pressure this behaves like a liquid. Consequently at high pressure usually encountered in the petroleum reservoir that is our system the viscosity of gases may increase with pressure and decrease with temperature as in the case of the liquid. So, at very high temperature pressure conditions the gas is behaving as a liquid and the properties of the viscosity may also following the same path as it is for the liquid. However, in general not at very high pressure conditions the viscosity of the gas increases with temperature and also increases with pressure.

Properties of Natural Gas

Viscosity of Natural Gas

- Mixing rule can be used for determining the viscosity of the gas mixture:

$$\mu_g = \frac{\sum (\mu_{gi} y_i \sqrt{Mw_i})}{\sum y_i \sqrt{Mw_i}}$$

We will see here. So, the viscosity of the natural gas how to estimate it? Simple we can apply the mixing rule and this mixing rule simply says if we know the viscosity of the individual compound what are the compound present. If we know the mole fraction of those compound and molecular weight of the individual compound. So, this is the weighing factor to calculate the viscosity similar factor needs to be in the denominator to cancel out. So, the viscosity of the mixture can be calculated but to calculate that we need to know individual compound viscosity mole fraction and molecular weight is easy to get from the literature. But it is again did not show any effect of the temperature and pressure on viscosity.

Properties of Natural Gas

Viscosity of Natural Gas

➤ Example

A 0.65 specific gravity natural gas contains 10% nitrogen, 8% carbon dioxide, and 2% hydrogen sulfide. Estimate viscosity of the gas at 10,000 psia and 180°F from Carr-Kobayashi-Burrows Viscosity correlation

- Gas viscosity at elevated pressure

$$\mu_g = \frac{\mu_1}{T_{pr}} e^{\mu_r}$$

So, Lee et al has given the expression that expression calculating the μ_g value the viscosity of the gas using a factor k and density of the gas along with two more factor x and y . So, what is k ? k is a factor that is relating the temperature. So, the Lee et al given the expression that is actually at a constant pressure only the effect of the temperature is included in the variation of the viscosity how the viscosity is varying with the temperature. And we can calculate this x value knowing the molecular weight of the gas this m_w is equivalent to m_w molecular weight of the gas or apparent molecular weight. And then putting this value x here we can get y both x and y are put up in this equation along with k to calculate the viscosity of the gas.

Again this Lee et al is having just the expression that is accounting for the temperature effect on the viscosity not for the pressure. So, more complex expressions are there as we already discussed these two chart. So, a two step process where the viscosity is calculated at the atmospheric pressure and then elevated pressure value is calculated using the viscosity ratio. So, this method is given by Kaur, Kovayasi and Boros. In short it is known as CKB method that is involved two step process using this chart we can get the value of viscosity.

But we need to know the molecular weight and the gas gravity pseudo reduce temperature pseudo reduce pressure. So, if either the compositions are given or γ_g value is given we can calculate all these x and y values for reading this chart and calculate the viscosity. But again in this case also we need to account for the inorganic compound present in the gas or in this case also we need to read this chart and the inorganic compound contents are also need to be corrected using this correction factor. So, the gas viscosity at temperature and atmospheric pressure is determined using this chart one and then it is adjusted to the pressure by using the second chart that give us the viscosity ratio. So, this chart later on has been converted into mathematical expression two step procedure estimating viscosity at atmospheric pressure adjusting for the pressure condition.

Properties of Natural Gas

Viscosity of Natural Gas

Carr, Kobayashi and Burrows (CKB), 1954

The atmospheric pressure viscosity (μ_1) can be expressed as:

$$\mu_1 = \mu_{1HC} + \mu_{1N_2} + \mu_{1CO_2} + \mu_{1H_2S}$$

Where, $\mu_{1HC} = 8.188 \times 10^{-3} - 6.15 \times 10^{-3} \log(\gamma_g) + (1.709 \times 10^{-5} - 2.062 \times 10^{-6})T$

$$\mu_{1N_2} = [9.59 \times 10^{-3} + 8.48 \times 10^{-3} \log(\gamma_g)]\gamma_{N_2}$$

$$\mu_{1CO_2} = [6.24 \times 10^{-3} + 9.08 \times 10^{-3} \log(\gamma_g)]\gamma_{CO_2}$$

$$\mu_{1H_2S} = [3.37 \times 10^{-3} + 8.49 \times 10^{-3} \log(\gamma_g)]\gamma_{H_2S}$$

Two step procedure

- Atmospheric pressure ✓
- Adjusted to pressure condition ✓

So, to calculate the viscosity at the atmospheric pressure μ_1 of the gas mixture it is a

summation of hydrocarbon gases and for the non hydrocarbon gases viscosity. The hydrocarbon viscosity of the hydrocarbon gases that is again the function of gamma g and the temperature. We are calculating at one atmospheric pressure so the pressure effect is also not there and similarly the expression are given to calculate the viscosity of nitrogen, CO2 and H2S when they are present in a mixture. So, these are not the value of the individual compound like individual nitrogen viscosity these are the value of these gases when they are present in a mixture whose gamma g value is known and the mole fraction of these compounds need to be known to calculate the individual viscosity putting up all them in this formula we will get the viscosity of the gas mixture at atmospheric pressure that is step one. To move to the step two we need to calculate this viscosity ratio mu r that is given in this expression and mathematically the second chart that we had seen is a complex function of pseudo reduced pressure and pseudo reduced temperature.

So, you can say this is with respect to no temperature effect parameter here the temperature effect in just T to the power 1 here it is in quadratic here it is in q form and each individual component is having pressure, pressure score and pressure q. So, a total 12 compounds are present there with 15 coefficient 3 are these kind of the coefficient are also there without pressure just the effect of the temperature and the value of a 0 to a 15 are the fitting parameters when the equations are generated by fitting the graph. So, the values are constant from a 0 to a 15 given in the literature you can use them. So, by using this expression you can get the value of mu r this is the ratio knowing the value of mu r here if we adjust this expression taking the exponential of both the sides the viscosity of the gas at elevated pressure can be calculated using this expression when the viscosity of

Properties of Natural Gas

Viscosity of Natural Gas

Carr, Kobayashi and Burrows (CKB), 1954

The atmospheric pressure viscosity (μ_1) can be expressed as:

$$\mu_1 = \mu_{1HC} + \mu_{1N_2} + \mu_{1CO_2} + \mu_{1H_2S}$$

Where, $\mu_{1HC} = 8.188 \times 10^{-3} - 6.15 \times 10^{-3} \log(\gamma_g) + (1.709 \times 10^{-5} - 2.062 \times 10^{-6})T$

$$\mu_{1N_2} = [9.59 \times 10^{-3} + 8.48 \times 10^{-3} \log(\gamma_g)]y_{N_2}$$

$$\mu_{1CO_2} = [6.24 \times 10^{-3} + 9.08 \times 10^{-3} \log(\gamma_g)]y_{CO_2}$$

$$\mu_{1H_2S} = [3.37 \times 10^{-3} + 8.49 \times 10^{-3} \log(\gamma_g)]y_{H_2S}$$

$$\mu_r = \ln\left(\frac{\mu_2}{\mu_1 T_{pr}}\right) = (a_0 + a_1 p_{pr} + a_2 p_{pr}^2 + a_3 p_{pr}^3) + T_{pr}[(a_4 + a_5 p_{pr} + a_6 p_{pr}^2 + a_7 p_{pr}^3) + T_{pr}^2(a_8 + a_9 p_{pr} + a_{10} p_{pr}^2 + a_{11} p_{pr}^3) + T_{pr}^3(a_{12} + a_{13} p_{pr} + a_{14} p_{pr}^2 + a_{15} p_{pr}^3)]$$

Two step procedure

- Atmospheric pressure
- Adjusted to pressure condition

the gas at atmospheric pressure is known by using the step one. Reduce temperature value of the gas mixture and the value of the mu r viscosity ratio are known to us.

Let us take the example of the CKB methods so a gas of specific gravity 0.65 is given to us which is having certain percent of these non-hydrocarbon gases we were asked to estimate the viscosity of the gas at 10,000 psi and 180 degree f using CKB method we

can do. So, this is our expression at elevated pressure that is 10,000 psi. So, let us see how we are going to get it. The temperature effect here will be accounted by this reduced temperature value. So, we are given this is the pressure temperature we want this is the specific gravity these are the composition of that gas mixture for the inorganic gases.

So, again you can write your own program either in MATLAB or Excel to put up all these in the mathematical form and just can get the calculation done whenever the values like for example, specific gravity is changing you just need to change that value and the calculation can be performed in a very quick manner. So, now step by step process we need to calculate the pseudo critical temperature pseudo critical pressure for the gas mixture. So, this is the pressure value this is the value of the temperature we already know if gamma g is given to us we can calculate this and then the uncorrected gas viscosity at atmospheric pressure that is mu 1 hydrocarbon gases. Now you can include this non hydrocarbon viscosity also and then this is going to be the final viscosity of the gas mixture at atmospheric pressure pseudo reduced pressure and pseudo reduced temperature can also be calculated because now we know at what temperature and pressure we are going to calculate this parameter and the pseudo critical temperature and pseudo critical pressure already calculated here. Now using all this expression we can get the value of this mu R and then using this mu R value here putting everything back we can calculate the value of the gas viscosity at elevated pressure that is 10000 psi to calculate the mu R this value the expression is written here to calculate actually the viscosity but this value is calculated from this expression this big expression in terms of the pseudo reduced pressure and pseudo reduced temperature.

Properties of Natural Gas

Compressibility Factor

□ Gas compressibility (deviation factor, or z-factor) reflects how much the real gas deviates from the ideal gas at given P & T.

$$z = \frac{V_{\text{actual}}}{V_{\text{ideal-gas}}}$$

➤ z-factor: the gas law for ideal gas results in the gas law for real gas $pV = nzRT$

➤ z-factor : measurements in laboratories

Similarly for the compressibility factor we need to use more complex formula but before going to complex formula let us understand compressibility factor it actually reflect how much the real gas deviate from the ideal gas at given temperature and pressure condition. So the gas mixture is given to us that is the natural gas if it is not ideal how much deviation it is having and the deviation varies with temperature and pressure condition the gas mixture is exposed to and that is accounted by Z so the actual volume divided by the ideal gas volume if the gas is considered ideal what will be the volume at the bottom.

So the Z factor that is actually account for the gas law for ideal gas result in the gas law for the real gas and that is ideal gas law is modified for the real gas by including this Z factor into it. Z factor can be measured in the laboratory but several correlations are given those can be utilized to calculate the Z value at elevated pressure at constant temperature we can use this correlation by simply this one because the R will cancel out number of mole will remain same. We can calculate the value of the Z considering one condition as the standard condition that is standard pressure at constant temperature temperature will cancel out the compressibility factor can be calculated but we need to know the volume at condition 1 volume at standard condition and then the pressure at which we want to calculate the value of compressibility.

Properties of Natural Gas

Compressibility Factor

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$$z = \frac{V_{\text{actual}}}{V_{\text{ideal-gas}}}$$

➤ z-factor: the gas law for ideal gas results in the gas law for real gas $pV = nzRT$

➤ z-factor : measurements in laboratories

➤ At elevated pressure (constant temperature) $z = \frac{p_1 V_1}{14.7 V_0}$

Standing and Katz (1942)

$R = 10.73 \frac{\text{psia} \cdot \text{ft}^3}{\text{mole} \cdot ^\circ\text{R}}$

$P_{sc} = 14.7 \text{ psi}$
 $T_{sc} = 520^\circ\text{R}$

Again this expression is at constant temperature the temperature effect is not there. So for that more accurate calculation of the compressibility factor standing in CADs has given this chart again this chart is for the hydrocarbon gases where the compressibility factor can be calculated by knowing the reduced pressure and reduced temperature value. Mathematically Brill and Waggs in 1974 derived the expression from this chart and they had given this expression to calculate the value of compressibility factor Z using some coefficient A, B, C, D and the pressure effect is here. A, B, C, D also having the effect of the temperature like you can see in this expression and they also accounting for the pressure. So if we can calculate A, B, C, D, E, F by knowing this pseudo reduced temperature and pseudo reduced pressure we can put up those A, B, C, D value here and we can get the compressibility factor value that is accounting for both temperature and pressure effect. So whenever gas is exposed to different temperature and pressure condition Brill and Waggs method can be utilized to calculate the expression but again this is for the hydrocarbon gases.

Properties of Natural Gas

Compressibility Factor

➤ Example

A 0.65 specific gravity natural gas contains 10% nitrogen, 8% carbon dioxide, and 2% hydrogen sulfide. Estimate z-factor at 5,000 psia and 180 °F.

Brill and Beggs (1974)

$$z = A + \frac{1 - A}{e^B} + C p_{pr}^D$$

Given	
Pressure:	5000 psia
Temperature:	180 F
Gas specific gravity:	0.65 air =1
Mole fraction of N ₂ :	0.1
Mole fraction of CO ₂ :	0.08
Mole fraction of H ₂ S:	0.02

Pseudocritical pressure:	697 psia
Pseudocritical temperature:	345 R
Pseudo-reduced pressure:	7.17
Pseudo-reduced temperature:	1.85

A =	0.5746
B =	2.9057

Example for the Brill and Waggs method same specific gravity gas 0.65 with certain percent of the inorganic compounds is present. We were asked to estimate the value of Z at 5000 psi and 180 degree F. Expression is here you can write similar program in excel where what are the information given to you what are the parameters you need to calculate you can calculate by putting the expression for them. Calculate the value of A, B, C, D put those A, B, C, D along with the reduced pressure value or pseudo reduced pressure value we will get the compressibility factor value at that pressure and the temperature. Another method for compressibility factor calculation is proposed by H-Y method this called the H-Y method given by Hall and Yarborough in 1973.

Properties of Natural Gas

Compressibility Factor

Hall and Yarborough (HY, 1973)

A more accurate correlation

$$t = \frac{1}{T_{pr}}$$

$$A = 0.06125te^{-1.2(1-t)^2}$$

$$B = t(14.76 - 9.76t + 4.58t^2)$$

$$C = t(90.7 - 242.2t + 42.4t^2)$$

$$D = 2.18 + 2.82t$$

It is more accurate expression where a parameter T is defined that is 1 by TPR, TPR is reduced temperature or pseudo reduced temperature value for the gas mixture and by performing certain intermediate steps we can calculate the value of compressibility factor by applying some A reduced pressure or pseudo reduced pressure and value of Y. What is A and Y? A is defined in terms of T here, B is also defined in terms of T, C, D they are defined in terms of this parameter that is 1 by TPR and what is Y is the reduced density and reduced density is the value of Y that satisfy this function and this function is having

Properties of Natural Gas

Compressibility Factor

Hall and Yarborough (HY, 1973)

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$$B = t(14.76 - 9.76t + 4.58t^2)$$

$$C = t(90.7 - 242.2t + 42.4t^2)$$

$$D = 2.18 + 2.82t$$

several form of the Y up to the power 4 and the coefficient A, B, C, D those are calculated from here. So, the optimum value or the root value of this equation is actually the Y using this A reduced pressure value and the Y we can get the value of the compressibility factor Z by this method that is called the H-Y method. For performing this calculation we need to have the Newton Raphson iteration method because we need to calculate the value of that. So, let us see the similar example previous one we were asked to calculate the compressibility factor at this condition.

Properties of Natural Gas

Compressibility Factor

Hall and Yarborough (HY, 1973)

A more accurate correlation

$$t = \frac{1}{T_{pr}}$$

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$$B = t(14.76 - 9.76t + 4.58t^2)$$

$$C = t(90.7 - 242.2t + 42.4t^2)$$

$$D = 2.18 + 2.82t$$

$$f(Y) = \frac{Y + Y^2 + Y^3 - Y^4}{(1 - Y)^3} - Ap_{pr} - BY^2 + CY^D = 0$$

$$Z = \frac{Ap_{pr}}{Y}$$

Y is reduced density

because we need to calculate the value of that. So, let us see the similar example previous one

Given
Pressure: 5000 psia
Temperature: 180 F
Gas specific gravity: 0.71 air = 1

Solution: Newton-Raphson's iteration method

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We can calculate all these parameters in the excel program somewhere like pseudo reduced pressure, pseudo reduced temperature, critical temperature, pressure and the parameter T that is important. And then assume any value of the Y do the iteration using the Newton Raphson method and finally we will get the value of Y that is satisfying this equation putting that value of Y we are able to calculate the compressibility factor Z at the given condition temperature and pressure. This is the property called the volume formation factor that relates the amount of the volume of the gas at reservoir condition to the surface condition. Surface condition we can assume the standard condition. So, the ratio of gas volume at reservoir condition to gas volumat standard condition is called the formation volume factor for the gas.

Properties of Natural Gas

Formation Volume Factor

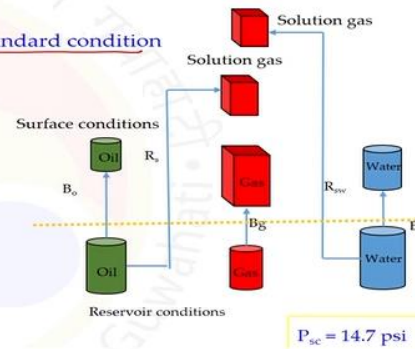
- The ratio of gas volume at reservoir condition to the gas volume at standard condition

$$B_g = B = \frac{V}{V_{sc}} = \frac{p_{sc}}{p} \frac{T}{T_{sc}} \frac{z}{z_{sc}} = 0.0283 \frac{zT}{p}$$

where the unit of formation volume factor is $\text{res ft}^3/\text{scf}$.

- If expressed in rb/scf , it takes the form of

$$B_g = 0.00504 \frac{zT}{p}$$



Mathematically it is volume of the gas at reservoir condition to standard condition. We can use the real gas law and we assume real gas law the gas is having compressibility factor Z at standard condition 1. So, at standard condition the natural gas mixture behave as a ideal gas and compressibility factor value becomes 1. Putting everything here using the standard temperature and pressure condition from here we can get this expression. So, the B_g is in the form of ZT by P where the unit of formation volume factor is reservoir feet cube per standard cubic feet for the gas. If expressed in different unit system like reservoir barrel per standard cubic feet the coefficient will get changed because of the unit system here and we are going to get the B_g expression that is 0.

00504 ZT by P . You will see this expression is getting utilized very effectively when we are setting up the mathematical equation. This diagram shows here under the reservoir conditions the gas, oil and water is present when we are bringing them to the surface their volume changes and that volume changes can be correlated by this volume formation factor for individual phase for the oil, for the gas, for the water. The reverse of this volume formation factor is expansion factor that is 1 by B_g just reverse of it that is actually reversely related the surface condition to the reservoir condition and it is utilized to estimate the gas reserve present underneath the surface at reservoir temperature and pressure conditions. Compressibility factor of the natural gas we are keep talking about our natural gas is very highly compressible in the nature how to account that compressibility value the factor is defined as CG or C but in case of the gas it is CG that is change in volume with respect to pressure at constant temperature divided by the original volume. So, the natural gas compressibility can be calculated by applying the real gas law how the volume is changing when the gas is subjected to different temperature and pressure conditions using this definition of the isothermal compressibility as it is at the constant temperature we call it isothermal compressibility coefficient for gas CG .

Now this B here can be replaced and this also can be replaced here.

Properties of Natural Gas

Compressibility of natural gas

- Gas compressibility is defined as:

$$C_g = C = -\frac{1}{V} \left(\frac{\partial V}{\partial p} \right)_T$$

- The gas law for real gas

$$V = \frac{nZRT}{p}$$

- Substituting the above equation into the definition yields:

$$C_g = \frac{1}{p} - \frac{1}{Z} \frac{\partial Z}{\partial p}$$

1 by P minus 1 by Z derivative of Z with respect to P. So, this expression will allow us to

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So, take the derivative of this with respect to pressure now your compressibility factor Z and pressure both are the function of pressure. So, the derivative can be performed at constant temperature so the temperature is as in constant and the value can be substituted both value of the volume and the value of this derivative and the expression we are going to get for the CG is 1 by P minus 1 by Z derivative of Z with respect to P. So, this expression will allow us to calculate the isothermal compressibility of the natural gas for the ideal gas as the Z value is 1 the CG value becomes just 1 by P so this term will not be appear here or you can do the same derivative and the replacement considering Z is equal to 1 you will get for the ideal gas this value will be equal to 1 by P. So, the unit of CG is just pressure inverse. So, let us summarize what we learned about natural gas gamma g that can be calculated by a print molecular weight of the gas divided by the air molecular weight.

Properties of Natural Gas

- Gas-specific gravity

$$\gamma_g = \frac{MW_a}{28.97}$$

- Apparent molecular weight

$$MW_a = \sum_{i=1}^{N_c} y_i MW_i$$

- Gas pseudo-critical pressure

$$p_{pc} = \sum_{i=1}^{N_c} y_i p_{ci}$$

- Gas pseudo-critical temperature

$$p_{pc} = 709.604 - 58.718\gamma_g$$

$$T_{pc} = 170.491 - 307.344\gamma_g$$

$$T_{pc} = \sum_{i=1}^{N_c} y_i T_{ci}$$

Correlations with impurity corrections

$$p_{pc} = 678 - 50(\gamma_g - 0.5) - 206.7y_{N_2} + 440y_{CO_2} + 606.7y_{H_2S}$$

$$T_{pc} = 326 + 315.7(\gamma_g - 0.5) - 240y_{N_2} - 83.3y_{CO_2} + 133.3y_{H_2S}$$

- Pseudo-reduced pressure can be used to calculate the pseudo reduce pressure and pseudo reduce temperature properties.

$$p_{pr} = \frac{p}{p_{pc}}$$

$$T_{pr} = \frac{T}{T_{pc}}$$

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A print molecular weight can be calculated by chain rule similar pseudo critical pressure and pseudo critical temperature can also be calculated by the chain rule but for more accurate we are having the expression in the form of gamma g also or when the composition are not known gamma g is known we can use directly these kind of the expression for calculating the critical properties. These critical properties can be used to calculate the pseudo reduce pressure and pseudo reduce temperature properties.

Viscosity CKB method is there for gas compressibility Brel and Bex and HY methods are there gas density just by the simple definition we can convert this into the form of the parameter those are commonly given like gamma g and pressure temperature formation volume factor value and reverse of this is the gas expansion factor and important is isothermal gas compressibility the expression for the real gas or for the natural gas mixture would appear like this. So, along with these properties there are certain parameters those also need to be understood when we are setting up the mathematical equation at the later stage.

Properties of Natural Gas

Viscosity	$\mu_g = \frac{\mu_g}{\rho_g}$	Carr, Kobayashi and Burrows (1954)
Gas compressibility, z-factor)	$z = \frac{V_{actual}}{V_{ideal-gas}}$	Brill and Beggs (1974) and Hall and Yarborough (1973)
Gas density	$\rho = \frac{m}{V} = \frac{MW_a p}{zRT}$	
Formation volume factor	$B_g = \frac{V}{V_{sc}} = \frac{p_{sc} T}{p T_{sc} z_{sc}} = 0.0283 \frac{zT}{p}$	
Gas expansion factor	$E = \frac{1}{B_g} = 35.3 \frac{p}{zT}$	
Gas compressibility	$C_g = -\frac{1}{V} \left(\frac{\partial V}{\partial p} \right) = \frac{1}{p} - \frac{1}{z} \frac{\partial z}{\partial p}$	compressibility the expression for the real gas or for the natural gas mixture would appear like

So, the pseudo properties of gas depend on the viscosity and compressibility. We had seen viscosity and compressibility both are the function of the pressure and temperature. So, a factor called the real gas pseudo pressure MP was designed that is a counting the effect of the pressure on viscosity effect of the pressure on compressibility factor and pressure itself in the lumped form that is called the MP. So, it is a lumping the parameter or combining the parameter those are pressure dependent in the form of MP and the unit becomes psi square percent poise and the 10 to the power 6 is the conversion factor when we are dealing with the unit system. It is widely used for mathematical modeling of IPR of gas well. IPR is inflow performance relationship we will set up the mathematical equation for gas reservoir later on then you will see how effectively this MP to make the equation soluble.

Properties of Natural Gas

Parameters

Real gas pseudo-pressure $m(p)$

Al-Hussainy et al. (1966)

➤ widely used for mathematical modeling of IPR of gas wells.

$$m(P) = \int_{p_b}^p \frac{2p}{\mu z} dp \quad (\text{psi}^2/\text{cp}) \times 10^6$$

where p_b is the base pressure (14.7 psia).

➤ "pseudo-property" of gas : depends on gas viscosity and compressibility factor, which are properties of the gas (functions T & P).

in the form of MP and the unit becomes psi square percent poise and the 10 to the power 6 is the

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How to calculate the value of MP? So, we can divide the pressure into different segment

as a smaller segment we are getting similarly we can estimate the viscosity of gas and the compressibility factor at those small small segment of the pressure combinedly we can calculate the value of this and finally we are going to get the MP value by integrating this. So, we discussed the trapezoidal rule in our first lecture for that purpose only when we are going to calculate the integral term we can divide the entire spectrum in small small segment calculate the value of a parameter at each pressure value and then do the sum of all those things. So, by using the integral method you can calculate the value of MP but that MP is a very important property because it is account viscosity and compressibility factor together. Another is Reynolds numbers so we already know Reynolds number is $\rho V d$ by μ so this is kind of the exercise I am going to give you.

Properties of Natural Gas	Parameters
Reynolds Number $N_{Re} = \frac{4 \times 28.97 \gamma_g q p_{sc}}{\pi D \bar{\mu} R T_{sc}}$ $N_{Re} = 20.09 \frac{\gamma_g q}{D \bar{\mu}}$ volume in natural gas properties form and you should be able to get this expression when you	$R = 10.73 \frac{psia - ft^3}{mole - ^\circ R}$ $P_{sc} = 14.7 \text{ psi}$ $T_{sc} = 520^\circ R$

*p is in psia,
q is in Mscf/d,
D is in inches,
μ is in cp,
T is in R.*

$N_{Re} = \frac{\rho V d}{\mu}$

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Convert this Reynolds number that is characterized the flow behavior of any fluid for the natural gas. So, by putting the parameters that we discussed how to express the viscosity, density, volume in natural gas properties form and you should be able to get this expression when you accounting the properties in this unit system and further this should be reduced to a simple expression to calculate the Reynolds number for the natural gas dealing that is $20.09 \gamma_g q$ by $d \mu$ bar. q is actually the volumetric flow rate that is standard cubic feet per day q is equal to area into velocity. So, this is velocity here also $\rho V d$ by μ this velocity. So, you convert this into the expression this is kind of the exercise for you come out to this expression of the Reynolds number based on the properties and the representation of the properties we discussed in today's class.

Properties of Natural Gas

Initial Gas in place

- For a given quantity of gas

$$\frac{p_1 V_1}{Z_1 T_1} = \frac{p_b V_b}{Z_b T_b}$$

$$\frac{p_1 q_1}{Z_1 T_1} = \frac{p_2 q_2}{Z_2 T_2}$$

where:

V_1 = volume of space-holding gas, cu ft

V_b = volume of gas in the reservoir at standard conditions, cu ft

b = standard conditions for gas measurement

- Initial gas in place

$$G_i = 43,560 \frac{A h \phi S_g}{B_g} \text{ (scf)}$$

A = Area (reservoir), acres

h = Reservoir net thickness in ft

ϕ = Reservoir porosity

Another is initial gas in place so the natural gas can be considered as a gas that is changing its properties based on the temperature and pressure but the combinedly when we are applying the real gas law at one condition to the other condition that will be equally applicable and that can be done for the volume or can be done for the volumetric flow rate. So, $P_1 V_1$ by $Z_1 T_1$ at one condition equal to $P_2 V_2$ by $Z_2 T_2$ at another condition similarly for the replacing the volume by volumetric flow rate and another condition can be considered as the standard condition and if you are considering this as the standard condition we are knowing Z_2 is equal to 1 we know what is P_2 value 14.7 T_2 value is equal to 520 degree ranking this is psi. So, that help us to relate the properties of the gas from one condition to the other condition or from one condition to the standard condition. Initial gas in place can be calculated using this expression we will discuss in detail in other lecture but here it is showing like calculating the initial gas in place this is the numerical factor this is the actually volume of the reservoir area into height.

Multiplying this with the porosity you will get the volume of the reservoir that is available to hold the hydrocarbon fluid. Multiplying this with the saturation of the gas that will be accounting the volume of the reservoir occupied by the gas and now here it is appearing the volume formation factor that is relating the reservoir volume to the surface volume and we are going to get the gas in place in terms of standard cubic feet underneath the surface. So, this nomenclature are as usual. So, the solubility of the natural gas in connate water is again the function of the temperature and pressure. So, the solubility of natural gas in connate water, connate water means the residual water that remains in the reservoir is small compared to solubility in the crude oil.

So, the natural gas is less soluble in the water than the crude oil. At constant temperature the solubility of natural gas in connate water increases with pressure. As we can see here when we are increasing the pressure and the temperature at a particular constant temperature when we are increasing the pressure the solubility of the natural gas is

increasing. At constant pressure the solubility of natural gas in connate water decreases with temperature at a low pressure reason. So, when we are increasing the temperature the solubility is decreasing but when we are going to high temperature reason sum of and high pressure reason the solubility of the natural gas in water increases.

So, at high pressure the solubility reaches a minimum so that the further increase in temperature it increases. So, we know the natural gas and water and oil are present in the reservoir together. Some of the natural gas dissolve in the oil and some may be in the connate water. Connate water is the water that is present in the reservoir. Experiments on the solubility of natural gas in connate water has permitted certain guidelines to be made. For example, the solubility of the natural gas in water is less compared to solubility of the natural gas in the liquid or in the crude oil actually.

Crude at the same temperature and pressure conditions. So, the solubility of natural gas in crude oil is more. At constant temperature the solubility of natural gas increases with pressure. As we can see here when we are having a constant temperature the solubility of the natural gas is increasing when the pressure is increased. At constant pressure if we talk on a particular pressure at a low pressure reason increasing the temperature the solubility decreases but at a high pressure and high temperature reason the solubility of the natural gas in water increases. This will be important when we are doing the complete balance for the system where particular amount of the gas is present in the reservoir. How much is the free gas? How much is dissolved in the gas? And how much is dissolved in the water? So, in summary composition and properties of the natural gas are discussed.

We know natural gas is complex mixture of hydrocarbon and non-hydrocarbon gases. Its composition varies even within the reservoir within the field and within one well the composition may vary during the production. Natural gas properties vary significantly with respect to temperature, pressure and the composition and from production to consumer we need to take care about the variation in these properties. Composition of the natural gas can be found using the gas chromatography. Properties can be estimated using the well established correlation or graph or the lab measurement. Designing and analyzing natural gas production and processing and further transporting it to the end consumer the properties changes because of the temperature and pressure changes.

Natural Gas

- Natural gas is a complex mixture of hydrocarbons, with a minor amount of inorganic compounds.

- A subcategory of petroleum : Organic Materials on geological time scale
- Ignites when the air-and-gas mixture is between 5 and 15 percent natural gas.

☐ 5% LEL and 15% UEL



Measured in energy content : Btu

1 standard cubic feet: 1031 btu (500-1550 btu)

Methane ✓	Hydrocarbon
Ethane	
Propane	
i-Butane	
n-Butane	
i-Pentane	
n-Pentane	
Hexane ✓	
Heptanes and Heavier	
Carbon dioxide + H ₂ O ✓	Non-hydrocarbon
Hydrogen sulfide ✓	

So, the values need to be estimated at the particular temperature and pressure to design effectively the handling and processing equipment. At the end the natural gas that goes to the consumer is dominated by the methane. These certain properties we discuss those will be useful when we are going further in this course. Some of the example I listed here again like how to calculate the Reynolds number it needs density and viscosity and we need to know how to calculate density and viscosity. So, in the next lecture we are going to continue our discussion about properties of the crude oil and we will also include briefly the water properties in that lecture.

So, combinedly we will discuss oil properties and water properties in our next lecture and after that in the week 3 we will continue our discussion of the section 1 about the reservoir rock properties. With this I would like to end my today's lecture. Thank you very much for watching the video. Thank you.