Upstream LNG Technology

Prof. Pavitra Sandilya
Department of Cryogenic Engineering Centre
Indian Institute of Technology, Kharagpur

Lecture – 11
Thermophysical Properties of Natural Gas- II

Welcome, today we shall be looking into some estimation methods of some more Thermophysical Properties of Natural Gas.

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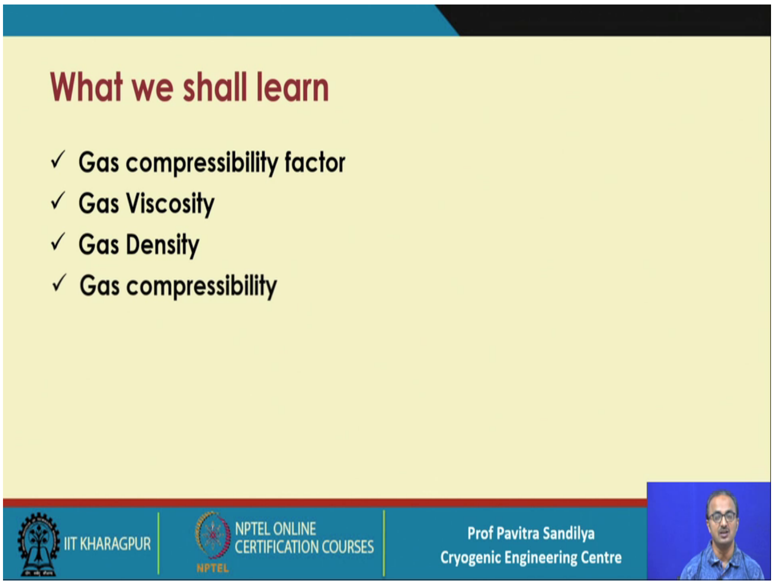

What we shall learn

- ✓ Gas compressibility factor
- ✓ Gas Viscosity
- ✓ Gas Density
- ✓ Gas compressibility

In the last lecture, we learnt about the gas specific gravity and now we shall look into some more. In this case, we are going to look into these properties like compressibility factor, then viscosity density compressibility.

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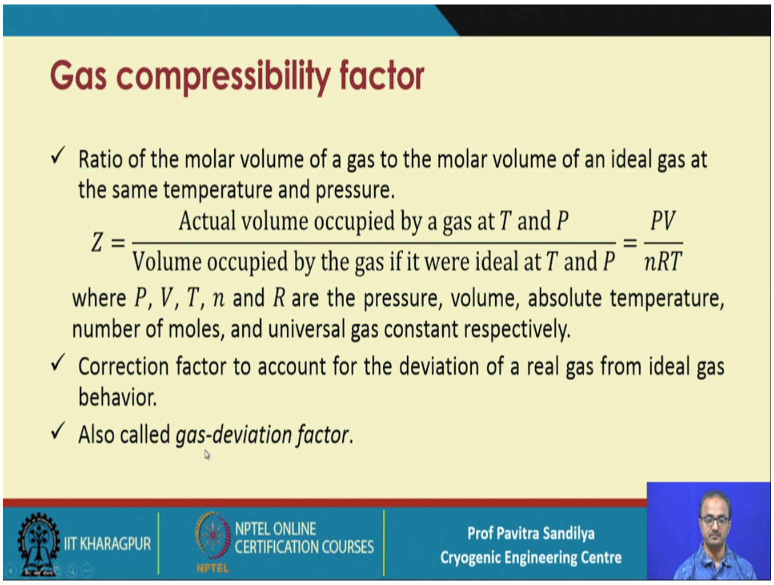

Gas compressibility factor

- ✓ Ratio of the molar volume of a gas to the molar volume of an ideal gas at the same temperature and pressure.

$$Z = \frac{\text{Actual volume occupied by a gas at } T \text{ and } P}{\text{Volume occupied by the gas if it were ideal at } T \text{ and } P} = \frac{PV}{nRT}$$

where P, V, T, n and R are the pressure, volume, absolute temperature, number of moles, and universal gas constant respectively.

- ✓ Correction factor to account for the deviation of a real gas from ideal gas behavior.
- ✓ Also called *gas-deviation factor*.

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First let us come to the compressibility factor; what is this we know that by definition this whenever, we have some real gases they behave differently called ideal gas for a given temperature pressure, we know that ideal gas will be occupying certain volume, but the real gasses will be occupying some other volume.

This is not only true for the volumes, but it also is true for many other properties, we at the same temperature pressure for the same component for ideal behavior and non ideal behavior. So, this compressibility factor is specifically regarding the volume changes. So, this is defined as a ratio of the actual volume occupied by a gas at certain temperature and pressure to the volume occupied by the same gas at the same temperature pressure provided that it were behaving ideally.

So, taking it to the, this in terms of the P, V, T; that is pressure volume temperature relationship we find that it can be easily found out that PV by nRT. In this case, nRT by P is the ideal volume, whereas, V is the actual volume, P is pressure, T is absolute temperature and R is the universal gas constant, perhaps all of you know the difference between the universal gas constant and the gas constant, a gas constant is a function of the type of gas; however, the universal gas constant is a constant which is applicable for all types of gases and n is the number of moles.

Now, if I know the value of the Z, I can know the deviation of the gas behavior from ideality. Now if we if we look at this definition, we find that if both the volumes remain the become the same it means Z will be equal to 1; that means, the if Z is equal to 1, this signifies that the gas is behaving like an ideal gas. So, any deviation from the Z whether it is on the higher side that is more than 1 or on the lower sides that is less than 1 will tell us that the gas is not behaving ideally.

So, that is why this Z is also sometimes called gas deviation factor.

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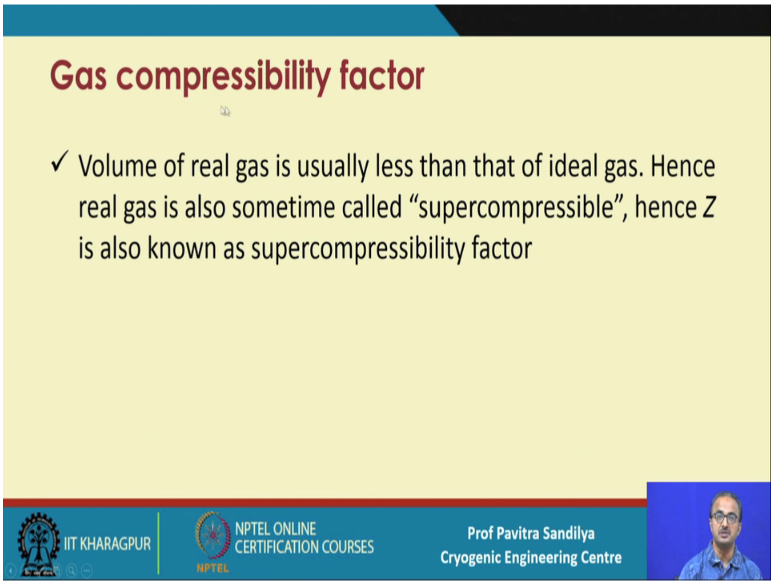

Gas compressibility factor

- ✓ Volume of real gas is usually less than that of ideal gas. Hence real gas is also sometime called "supercompressible", hence *Z* is also known as supercompressibility factor

Generally, it has been found that the volume of the real gas is less than the ideal gas. So, less means as if it is occupying less space. So, less space means as if we are compressing it extra, it is under a more compression. So, that is why it is a you having less space. So, if it is an less space, it is called it is called as a super-compressible; real gases sometimes called super-compressible and hence, this Z is also sometimes called the super compressibility factor.

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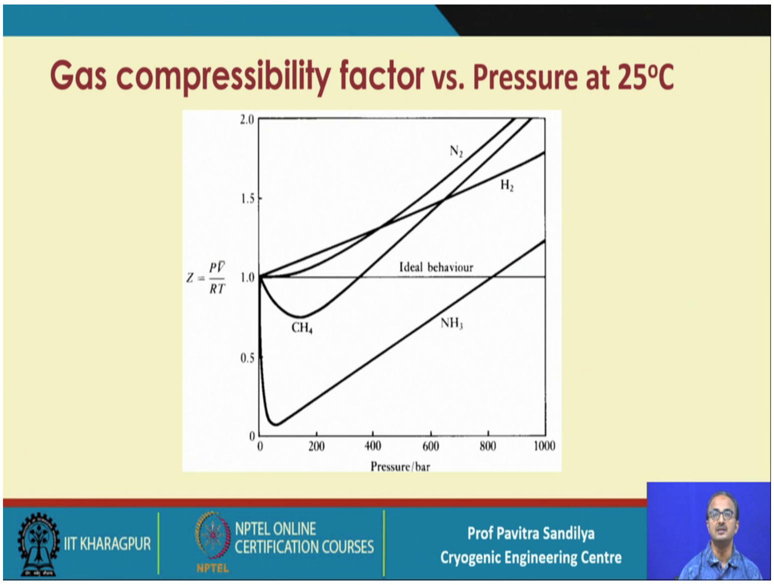

Gas compressibility factor vs. Pressure at 25°C

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But more common is the compressibility factor here in this figure I have shown some typical values of the Z for some few gases and how with respect to the pressure here you see that the value of the Z is changing for example, let us take methane; methane is the primary component of the natural gas and we see that initially as we increase the pressure, it is deviating from 1, it is starting with one unity that is it is ideal gas.

And as I increase the pressure, I find it is deviating, it is coming down and then again it is rising, it is crossing the Z equal to 1 and again for further increase in the pressure, it becomes more than 1; that means, for this only for at some point, it is ideal behavior is maintained and rest of the part it is behaving like a non ideal gas.

Similarly, another important component is nitrogen, we find its behavior, it is different, it is the value of Z in case of nitrogen never comes down below 1, it almost remain 1 for some time for still some higher pressure and then slowly and slowly, it goes above the value of 1, if you look at hydrogen, we find that it is starting with 1 and its value quickly rises to a value which is more than 1 unlike the nitrogen then we have ammonia for ammonium we find that value goes much much below unity and then after some after increase in the pressure it starts slowly rising and at some high very high pressure, it goes above 1.

So, these particular figure shows that at a given temperature 25 degree centigrade, how the various gases are behaving with change in the or increase in the pressure. So, we find that a gas would behave ideally at higher temperature and lower pressure. So, as we increase the pressure at a given temperature, it will go to towards non ideality, similarly, if you reduce the temperature at a given pressure, again, it will go towards non ideality.

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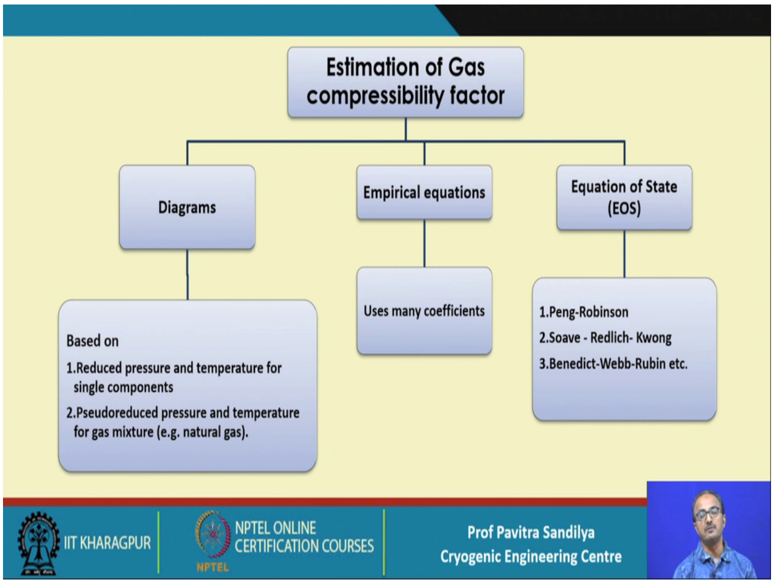

Estimation of Gas compressibility factor

Diagrams

Based on

1. Reduced pressure and temperature for single components
2. Pseudoreduced pressure and temperature for gas mixture (e.g. natural gas).

Empirical equations

Uses many coefficients

Equation of State (EOS)

1. Peng-Robinson
2. Soave - Redlich- Kwong
3. Benedict-Webb-Rubin etc.

Here, we have several types of methods which are used to estimate the compressibility factor.

They may be given in terms of some diagrams and these diagrams are generally represented in terms of reduced pressure and reduced temperature for single components or pure components, whereas, in with respect to pseudo reduce pressure and pseudo reduced temperature for gas mixtures like natural gas, we may have some empirical correlations based on some experimental data and these correlations generally contain many coefficient values and are applicable for certain range of pressure temperature and composition.

And lastly, we have many equations of state and some of them are like we perhaps know Van Der Waals of equation of state which was proposal; proposal, first time to account for non ideality later on many other non ideal or real gas equation of state were proposed and some of them have been given here like Peng Robinson, Soave Redlich Kwong, Benedict Webb Rubin, they are just a few there are several equation of state is reported in literature which you can easily find out from a standard thermodynamics book.

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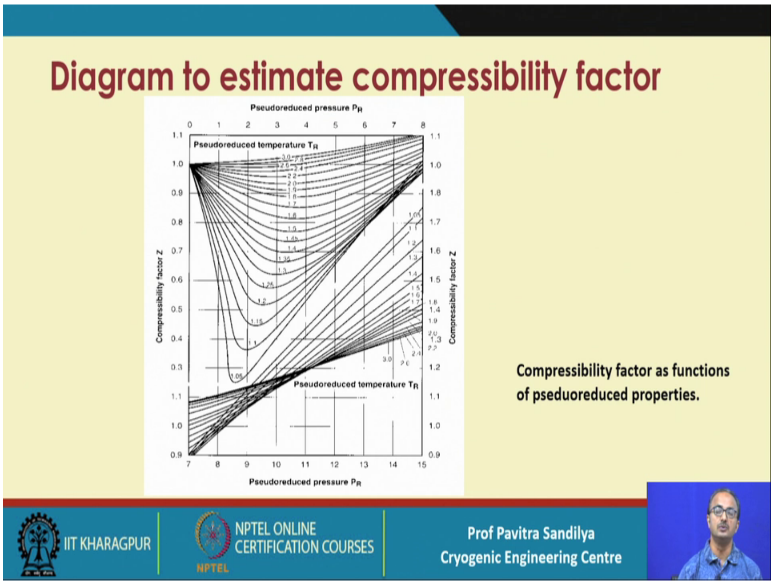

Diagram to estimate compressibility factor

Compressibility factor as functions of pseduoreduced properties.

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Here, we come to a typical representation through a diagram of the compressibility factor in terms of the reduced pressure which is given on the x axis and reduced temperatures which are there for various types of curves shown here and on the y axis we have the compressibility factor now, for example, you can see that this set of curves are applicable from about 1.05 to 3 reduced temperature; that means, the reduced temperature is 3 and 1.05 this range when I am saying reduced temperature pressure please understand, this may also applicable for whether its single component or whether it is a mixture.

So, I will not be always saying pseudo reduced when reduced means either single component or pseudo reduced and here we find the set of curves which are again absolute for a gives a more what you call resolution in terms of this Tr here, it is 1.05, 1.5, etcetera, here we find 1.05, 1 point from 1.15, etcetera ok. So, this gives you more resolution for the values of the Tr.

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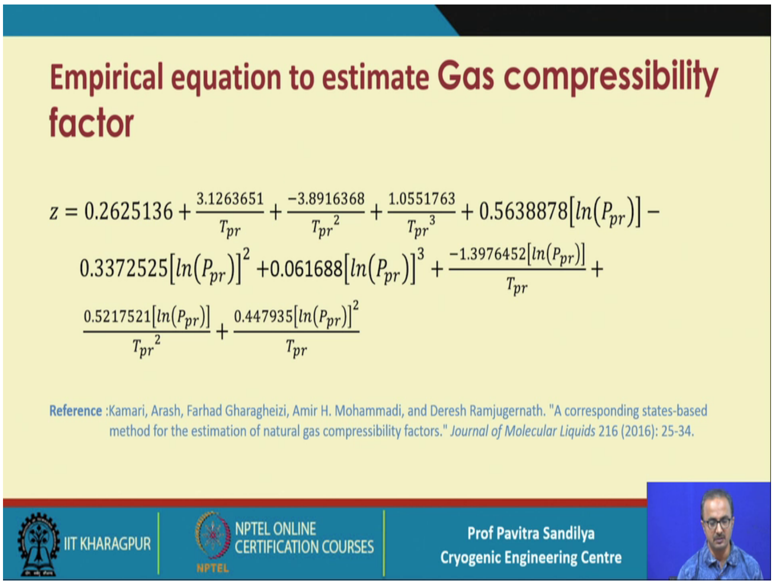

Empirical equation to estimate Gas compressibility factor

$$z = 0.2625136 + \frac{3.1263651}{T_{pr}} + \frac{-3.8916368}{{T_{pr}}^2} + \frac{1.0551763}{{T_{pr}}^3} + 0.5638878[ln(P_{pr})] - 0.3372525[ln(P_{pr})]^2 + 0.061688[ln(P_{pr})]^3 + \frac{-1.3976452[ln(P_{pr})]}{T_{pr}} + \frac{0.5217521[ln(P_{pr})]}{{T_{pr}}^2} + \frac{0.447935[ln(P_{pr})]^2}{T_{pr}}$$

Reference :Kamari, Arash, Farhad Gharagheizi, Amir H. Mohammadi, and Deresh Ramjugernath. "A corresponding states-based method for the estimation of natural gas compressibility factors." *Journal of Molecular Liquids* 216 (2016): 25-34.

Now, here we show a typical expression this is an expression from this experimental data, it is the empirical correlation which you can see the complexity of the equation it is so very complex. So, here we find that it is given in terms of the pseudo reduced temperature pseudo reduced pressure and the logarithm and there are so many coefficients involved in these equations, these all these are coefficients involved and these particular this particular equation has been obtained by considering the experimental data and this is a very recent publication this the; we are here is the publication from which this correlations been taken.

And if you look into the books on referred books which I have put at the end of the lecture, you will find different types of correlations have been given in those books, this is the one, the one, I am showing here is one which is very recent one.

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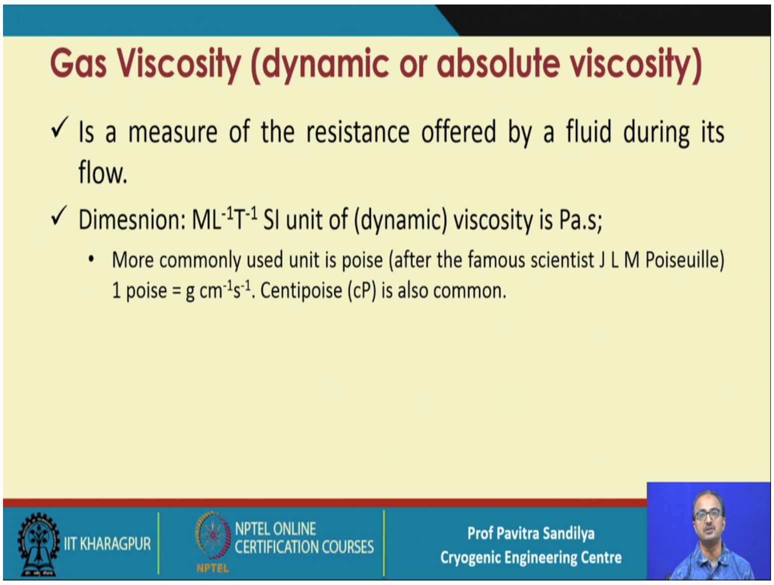

Gas Viscosity (dynamic or absolute viscosity)

- ✓ Is a measure of the resistance offered by a fluid during its flow.
- ✓ Dimesnion: $ML^{-1}T^{-1}$ SI unit of (dynamic) viscosity is Pa.s;
  - More commonly used unit is poise (after the famous scientist J L M Poiseuille) 1 poise = g $cm^{-1}s^{-1}$. Centipoise (cP) is also common.

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Next, we come to another important property that is the gas viscosity when we say gas viscosity, we mean the dynamic viscosity or absolute viscosity perhaps, you know, there is another viscosity, which we call the kinematic or kinetic viscosity that is the ratio of the dynamic viscosity to the density that is the kinetic viscosity.

So, when I say viscosity, it means dynamic viscosity and viscosity is what it is a measure of the resistance to the flow of a fluid over a surface the surface may be a closed circus like pipeline or it may be a open channel like in a river. So, here the viscosity is having this dimension of viscosity is that mass per unit length per unit time and in S I unit its unit is Pascal second, but a very more common unit of viscosity is poise or centipoise 1 poise is equal to gram 1 gram per centimeter per second and centipoise is 10 to the power minus 2 poise.

So, poise comes from the name of the famous scientist Poiseuille, perhaps, you know in fluid mechanics we learn about Poiseuille flow; Hagen Poiseuille flow in a tube ok. So, from the name Poiseuille, we have reduced this to poise.

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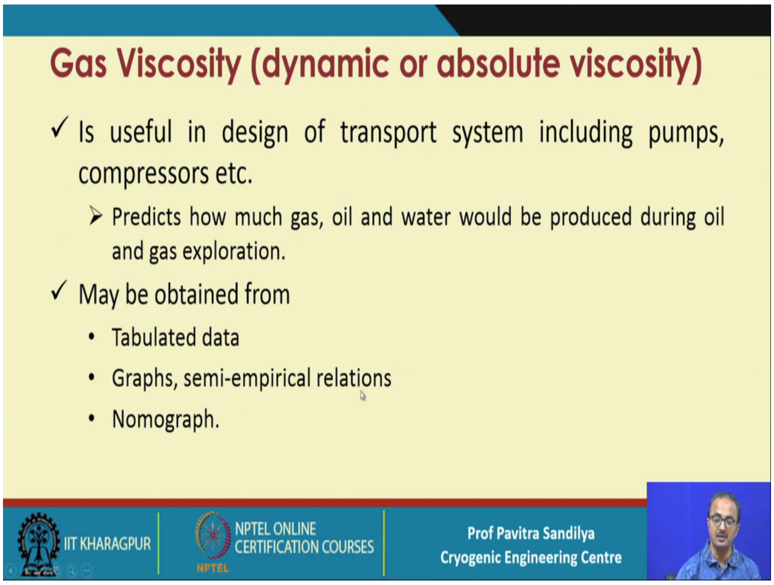

Gas Viscosity (dynamic or absolute viscosity)

- ✓ Is useful in design of transport system including pumps, compressors etc.
  - ➢ Predicts how much gas, oil and water would be produced during oil and gas exploration.
- ✓ May be obtained from
  - Tabulated data
  - Graphs, semi-empirical relations
  - Nomograph.

Now, this by knowing the viscosity, we can estimate the pumping power because the resist the more resistance, the more will be the pumping power and in case of natural gas and oil that it predicts that how much oil gas or water would be produced when we are drilling any reservoir because the how much gas or the oil will be coming out through the pipeline will be determined by the viscosity.

And again this value can be obtained or it has been reported in various manners like tabulated data for several types of compositions and different temperatures pressures, then we have graphical form or semi empirical relations and from some nomographs.

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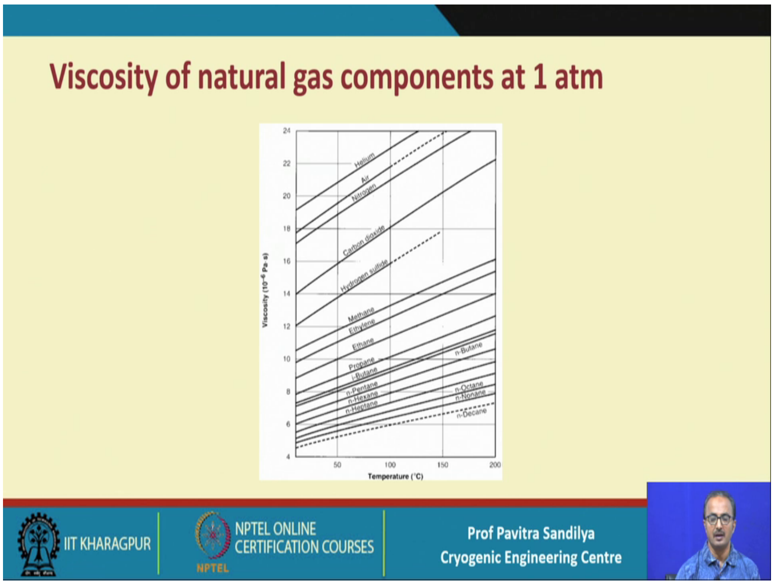

Viscosity of natural gas components at 1 atm

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Here I have shown a typical viscosity representation through a diagram of is few components like here on the x axis, we have temperature and on the y axis, we have the viscosity and this viscosity is in terms of 10 to the power minus 6 Pascal second and the pressure is one atmosphere that is at lower pressure.

And here we have shown several components starting from methane ethane ethylene propane so on and so forth, here, we have hydrogen sulfide here, we have carbon dioxide nitrogen air helium and on this side, we have the higher hydrocarbons what we find here that at a given pressure as the increase the temperature the viscosity increases and also what we find for a given temperature as the molecule becomes heavier and heavier the viscosity is decreasing; so, ok. So, helium is having a very um high viscosity effect whereas, this Dickin or something is having low viscosity effect.

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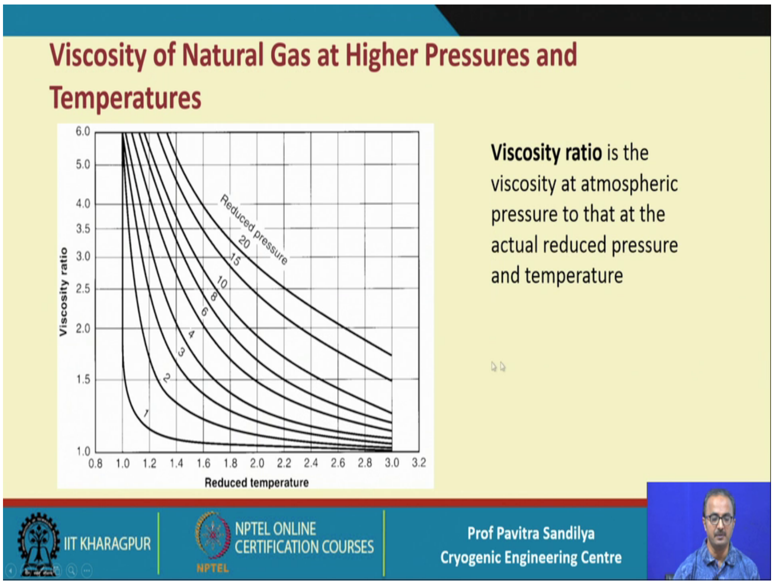

Viscosity of Natural Gas at Higher Pressures and Temperatures

Viscosity ratio is the viscosity at atmospheric pressure to that at the actual reduced pressure and temperature

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And next, we represent the viscosity in terms of the reduced temperature and reduced pressure and this is more handy because here, we do not need to bother about the component here, we have the viscosity ratio this is applicable to estimate the viscosity at a higher pressure the first one, if I know the viscosity at lower pressure then by knowing the viscosity ratio which is defined as the viscosity at the atmospheric pressure to the viscosity at the reduced pressure and reduced temperature.

So, if I know from the previous graph, we know the viscosity at the one atmosphere and this value along with the value of the viscosity ratio, we can find out the viscosity at any given pressure temperature. So, here on this x axis, we have the reduced temperature and on the parameter wise the different curves are representing the different reduced pressures.

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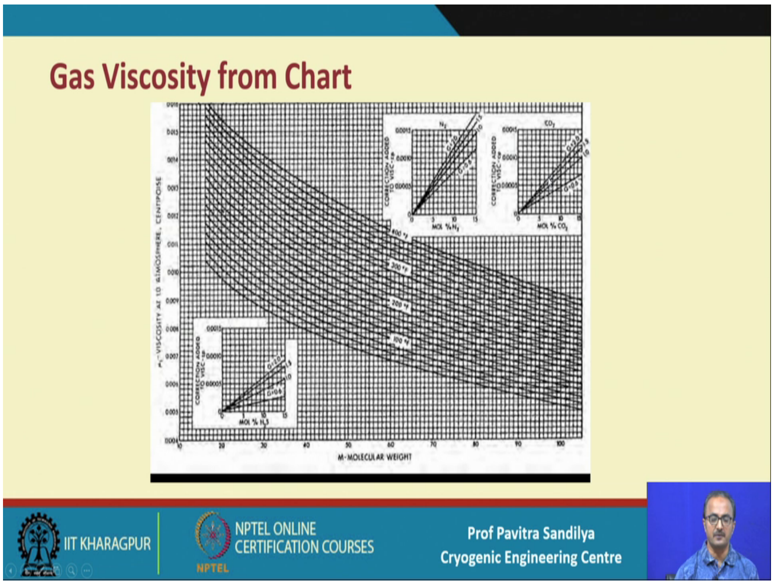

Gas Viscosity from Chart

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Here we have shown another curve this is a very peculiar about the hydrocarbons, especially natural gas and oil in this case, we find there are 3 sub curves here which are accounting for the presence of H 2 S, this is nitrogen and this is for carbon dioxide.

That means once from the previous curves we know the viscosity of the natural gas then we should use this curve to give a correction due to the presence of the H 2 S n 2 and Co2.

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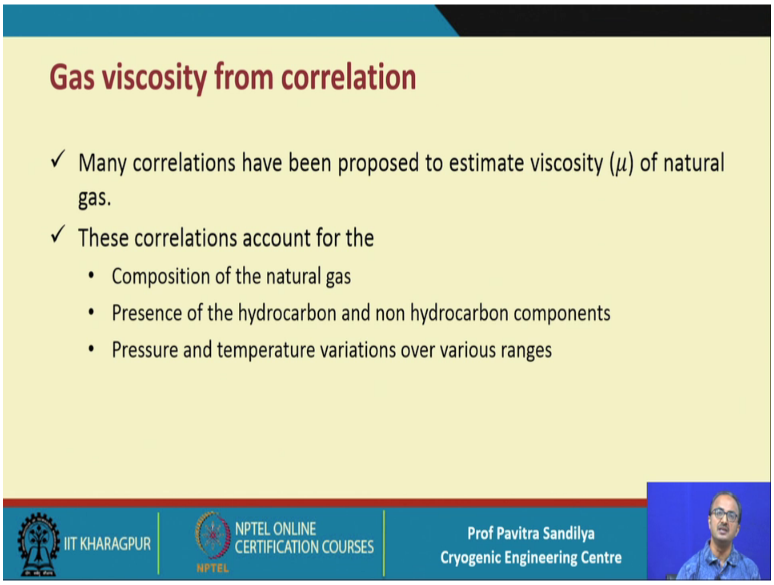

Gas viscosity from correlation

- ✓ Many correlations have been proposed to estimate viscosity (μ) of natural gas.
- ✓ These correlations account for the
  - Composition of the natural gas
  - Presence of the hydrocarbon and non hydrocarbon components
  - Pressure and temperature variations over various ranges

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Coming to another representation of viscosity, we have several correlations in the literature, the various books on the natural gas will be giving of various types of correlations and whatever the correlations may be there are some common points among the correlations and these are that all the correlations have composition of natural gas in them.

And they account for the presence of both the hydrocarbons and the non hydrocarbon components in the natural gas and naturally all the correlations must be giving us or taking into account the pressure and temperature variations for different ranges.

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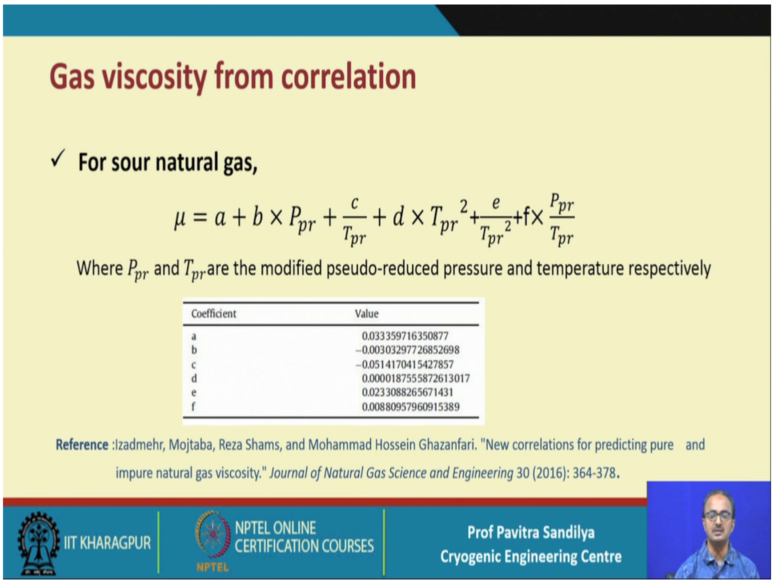

Gas viscosity from correlation

- ✓ **For sour natural gas,**

$$\mu = a + b \times P_{pr} + \frac{c}{T_{pr}} + d \times {T_{pr}}^{2} + \frac{e}{{T_{pr}}^{2}} + f \times \frac{P_{pr}}{T_{pr}}$$

Where P_{pr} and T_{pr} are the modified pseudo-reduced pressure and temperature respectively

Coefficient	Value
a	0.033359716350877
b	−0.00303297726852698
c	−0.0514170415427857
d	0.0000187555872613017
e	0.0233088265671431
f	0.00880957960915389

Reference :Izadmehr, Mojtaba, Reza Shams, and Mohammad Hossein Ghazanfari. "New correlations for predicting pure and impure natural gas viscosity." *Journal of Natural Gas Science and Engineering* 30 (2016): 364-378.

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So, with this, I have put here one correlation that has been published recently. This correlation has been proposed for both the sour natural gas and sweet natural gas.

When I just sour natural gas, it means the natural gas that contains the acid gases like carbon dioxide and H 2 S, whereas, sweet natural gas is the one which does not contain these acid gases. So, these authors gave this particular correlation for the sour natural gas and here we find again there have coefficients a, b, c, d, e and f and these happens the state in this particular table.

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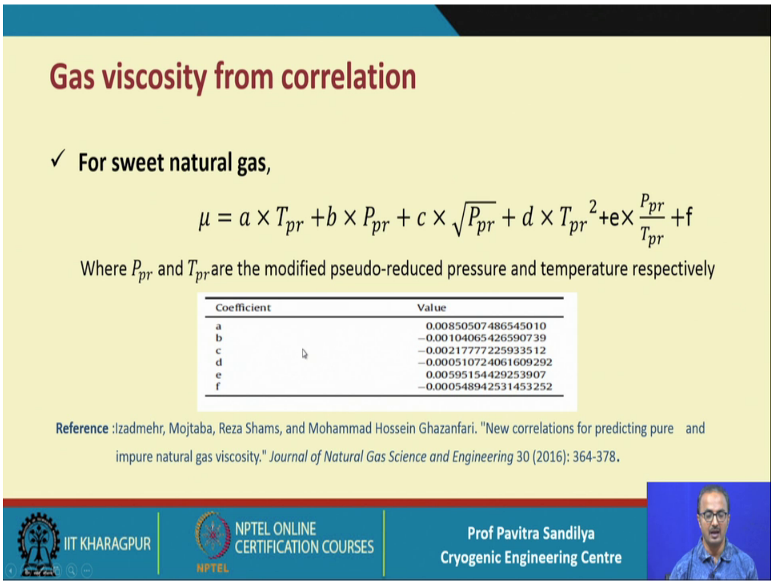

Gas viscosity from correlation

✓ For sweet natural gas,

$$\mu = a \times T_{pr} + b \times P_{pr} + c \times \sqrt{P_{pr}} + d \times T_{pr}{}^{2} + e \times \frac{P_{pr}}{T_{pr}} + f$$

Where P_{pr} and T_{pr} are the modified pseudo-reduced pressure and temperature respectively

Coefficient	Value
a	0.00850507486545010
b	−0.00104065426590739
c	−0.00217777225933512
d	−0.000510724061609292
e	0.00595154429253907
f	−0.000548942531453252

Reference :Izadmehr, Mojtaba, Reza Shams, and Mohammad Hossein Ghazanfari. "New correlations for predicting pure and impure natural gas viscosity." *Journal of Natural Gas Science and Engineering* 30 (2016): 364-378.

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And this is for the sweet gases; again, we have a, b, c, d, e, f. Now you can see the there is a difference in the type of the correlation and there the coefficient values.

And here we have the listed this, this I am listed and these correlations have been given in terms of the read pseudo reduced pressure and pseudo reduced temperature.

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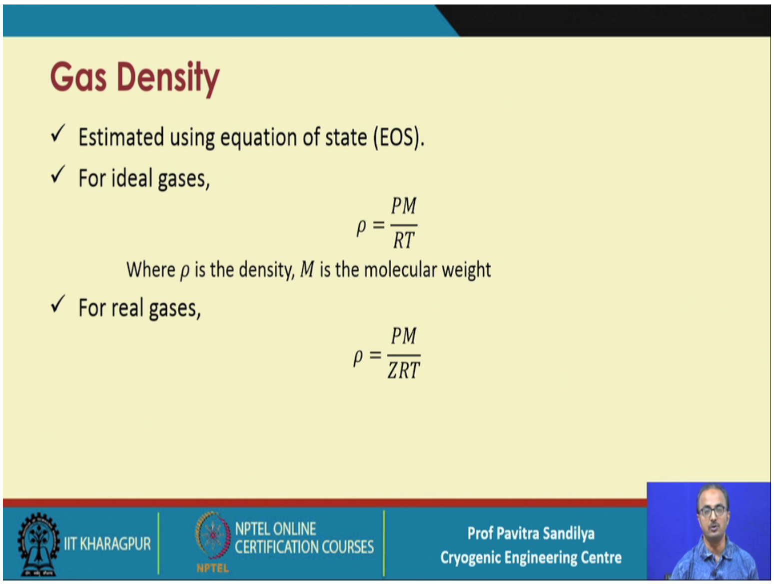

Gas Density

✓ Estimated using equation of state (EOS).

✓ For ideal gases,

$$\rho = \frac{PM}{RT}$$

Where ρ is the density, M is the molecular weight

✓ For real gases,

$$\rho = \frac{PM}{ZRT}$$

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Next we come to gas density and generally gas density is estimated from a suitable equation of state, we know that for an ideal gas the gas density is given by the this expression PM by RT pressure into molecular weight divided by the universal gas constant and the absolute temperature.

Whereas for real gases, we include the value of Z the value of Z about which we have talked earlier.

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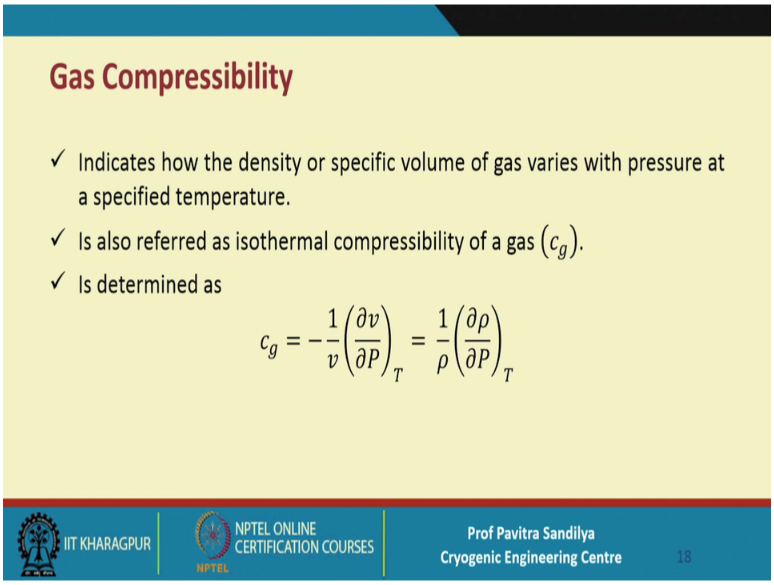

Gas Compressibility

- ✓ Indicates how the density or specific volume of gas varies with pressure at a specified temperature.
- ✓ Is also referred as isothermal compressibility of a gas (c_g).
- ✓ Is determined as

$$c_g = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T$$

Now, with this knowledge, we go to the last property, in this lecture that is the gas compressibility please mind it, this is not same as the compressibility factor, this compressibility factor is talking about the deviation from the ideal behavior, whereas, the gas compressibility indicates that how the density or the specific volume of the gas would change with pressure at a given temperature ok.

The rate of change how the density would change with pressure at a given temperature is given by the gas compressibility. So, that it is given by if notation called cg c for compressibility and g for gas and it is defined like this it is minus 1 by v dou v by dou P at a constant temperature and this v is the specific volume which is nothing, but the reciprocal of the density now why the negative sign has been given. So, that to account for the fact; that with the increase in the pressure the volume reduces at a given temperature that we know from Boles law.

So, dou v by dou P will always be negative and that negative and this negative will keep the value of the cg positive. So, that is why this negative sign has been put, but contrast it with in terms of the density now because density is reciprocal of the specific volume. So, density will increase with increase in pressure at a given temperature. So, there is no need of putting in a negative sign. So, we find that in this expression there is no negative sign. So, this is the way we can get the value of the gas compressibility and to further estimate this value we simply need to know the equation of state.

That equation of state will give us an expression for the v as a function of temperature pressure. So, if I know that we differentiate that with the pressure keeping the temperature constant and we use this expression to get the value of the compressibility gas compressibility.

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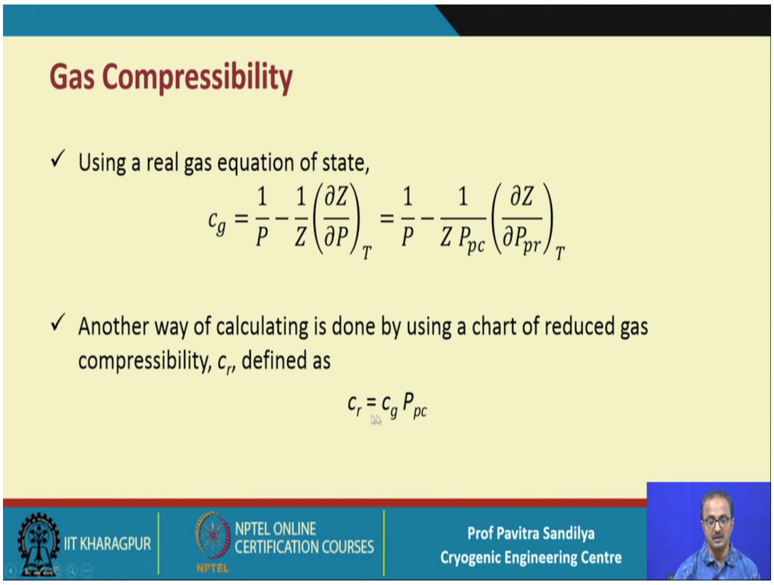

Gas Compressibility

- ✓ Using a real gas equation of state,

$$c_g = \frac{1}{P} - \frac{1}{Z}\left(\frac{\partial Z}{\partial P}\right)_T = \frac{1}{P} - \frac{1}{Z\,P_{pc}}\left(\frac{\partial Z}{\partial P_{pr}}\right)_T$$

- ✓ Another way of calculating is done by using a chart of reduced gas compressibility, c_r, defined as

$$c_r = c_g\,P_{pc}$$

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We will do here, now shown that for a real gas how we can rearrange that expression that Z equal to PV by nRT from that how we can differentiate that expression and we can get this particular, this you can also derive here I have shown that how the gas compressibility is getting from the real gas equation of state.

Here we have represented this in terms of the pseudo critical pressure and pseudo reduced pressure at a given temperature this is because that we have earlier seen that how we can get obtain these values from the diagrams also, here you see as we are talking about reduced values similarly we can also talk in terms of the reduced compressibility that is given by cr and cr is given as cr equal to cg into the pseudo critical pressure.

So, this is the way we can get the value of the reduced gas compressibility. So, this is the definition. So, the we have to accept it at its face value.

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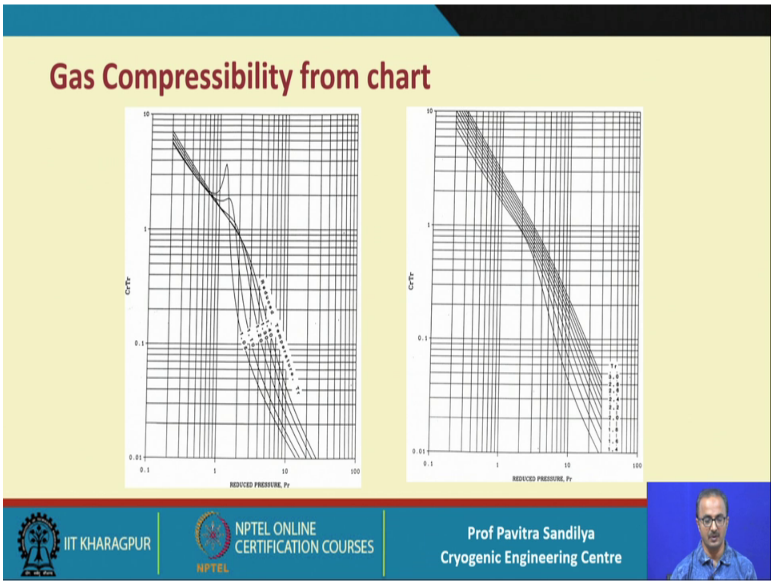

Gas Compressibility from chart

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And here we show the chart for the cr into tr and here from this I am basically the charts are nothing, but showing the pseudo or this sorry reduced compressibility from which we can find out the actual compressibility and here we shall we shall what seeing that this is containing this from this is the x axis is representing a reduced pressure whereas, the y these various curves are made for the reduced temperature.

The difference is this that here the range is smaller and in this thing the range is larger it is going from 1.05 to 1.40, whereas, in this case, it is going from 1.40 to 3. So, this is these two curves together may be used to find out the gas compressibility from the knowledge of the reduced gas compressibility.

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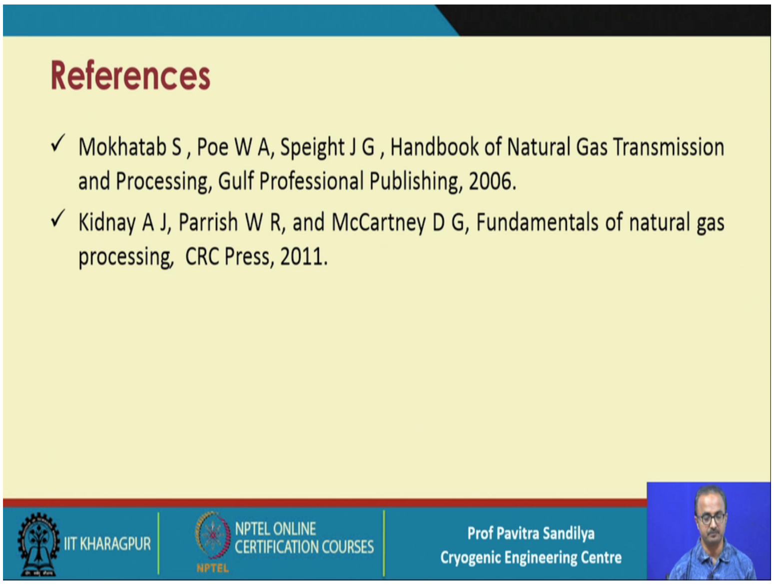

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And these are again a few references, which you may consult to understand these properties further.

Thank you.