Refrigeration and Air conditioning

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Lecture No. # 05

Review of Fundamentals

2. Thermodynamics

Welcome to the fifth lecture on the refrigeration and air conditioning. This is the continuation of the last lecture where in we have reviewed some of the fundamentals of thermodynamics.

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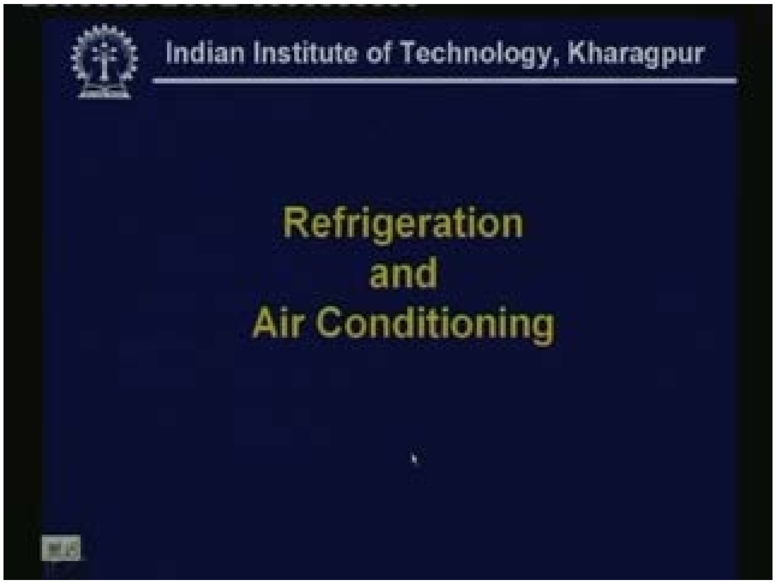

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Refrigeration
and
Air Conditioning

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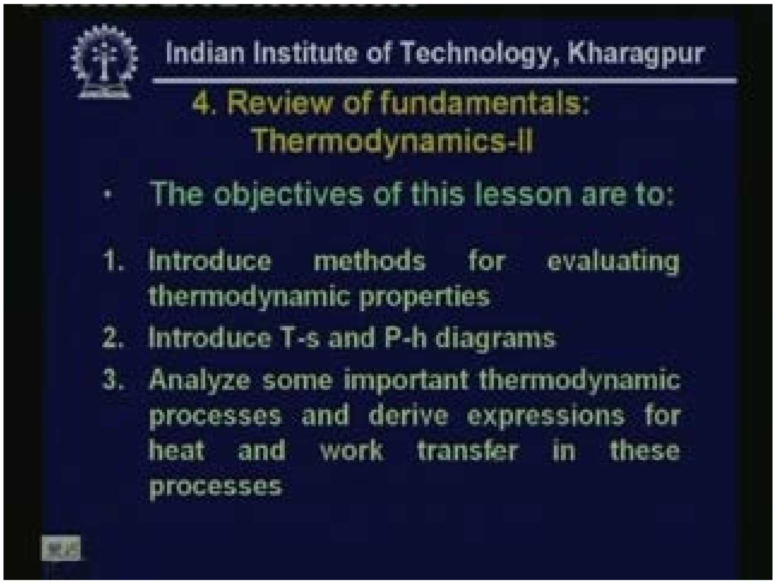

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4. Review of fundamentals: Thermodynamics-II

- The objectives of this lesson are to:

1. Introduce methods for evaluating thermodynamic properties
2. Introduce T-s and P-h diagrams
3. Analyze some important thermodynamic processes and derive expressions for heat and work transfer in these processes

The specific objectives of this particular lesson are to introduce methods for evaluating thermodynamic properties, introduce T s and P h diagrams and analyze some important thermodynamic processes and derive expressions for heat and work transfer in these processes.

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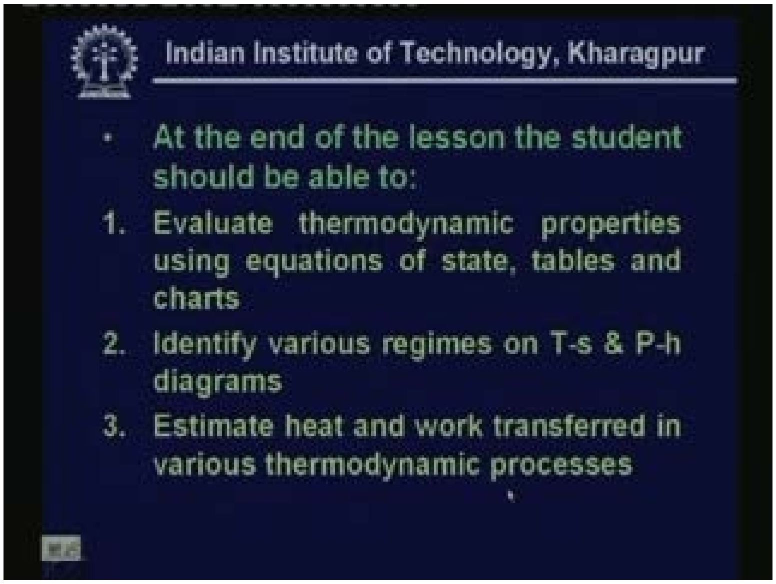

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- At the end of the lesson the student should be able to:

1. Evaluate thermodynamic properties using equations of state, tables and charts
2. Identify various regimes on T-s & P-h diagrams
3. Estimate heat and work transferred in various thermodynamic processes

And at the end of the lesson you should be able to evaluate thermodynamic properties using equations of state tables and charts. Identify various regimes on T s and P h diagrams and estimate heat and work transferred in various thermodynamic processes.

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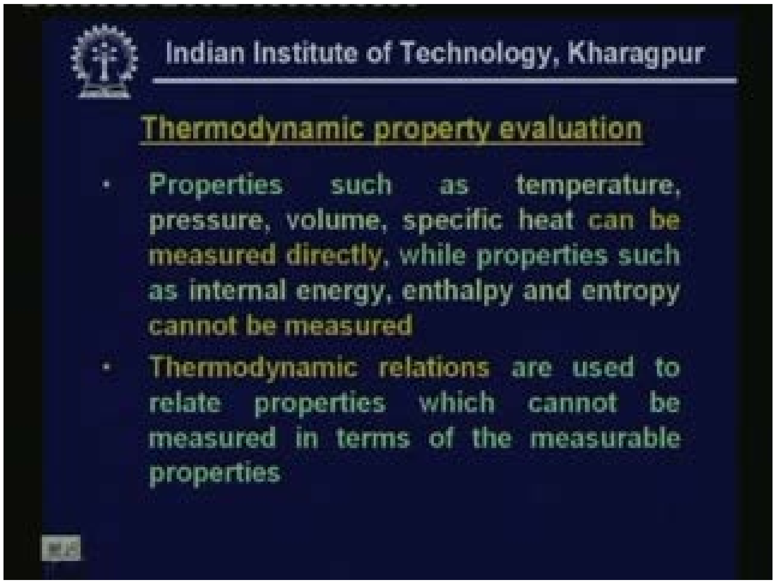

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Thermodynamic property evaluation

- Properties such as temperature, pressure, volume, specific heat can be measured directly, while properties such as internal energy, enthalpy and entropy cannot be measured
- Thermodynamic relations are used to relate properties which cannot be measured in terms of the measurable properties

So let us look at thermodynamic property evaluation in order to carry out calculations in refrigeration are in need thermodynamic calculation on processes or cycles we need to know several properties. Some of the properties are can be measured directly. For example properties like pressure temperature volume specific heat can be measured directly whereas some of the properties such as internal energy enthalpy entropy cannot be measured directly. So thermodynamic relations have been developed to measure properties which cannot be measured directly in terms of properties that can be measured using carrying pout some experiments.

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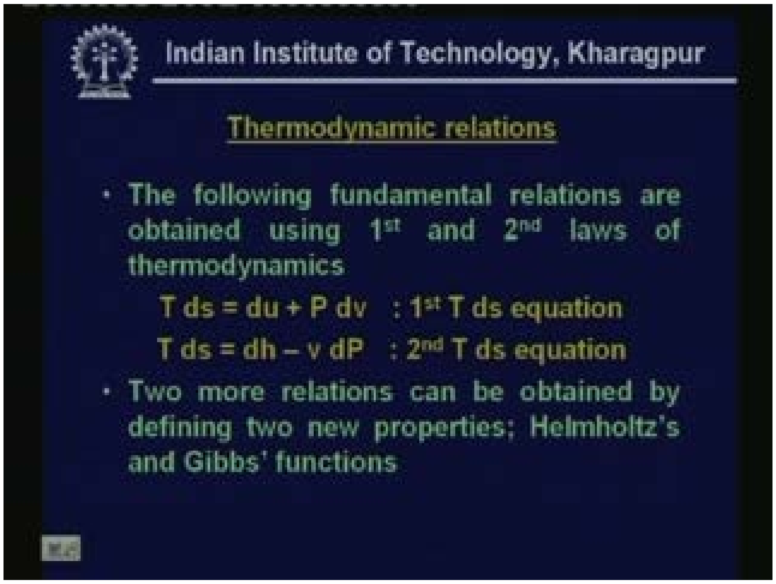

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Thermodynamic relations

- The following fundamental relations are obtained using 1st and 2nd laws of thermodynamics

$T\,ds = du + P\,dv$: 1st T ds equation

$T\,ds = dh - v\,dP$: 2nd T ds equation

- Two more relations can be obtained by defining two new properties; Helmholtz's and Gibbs' functions

Let us look at thermodynamic relations these are what I am going to show here are the fundamental relations which are you obtained using first and second laws of thermodynamics. And the first relation is given by T dS is equal to d u plus P d v. This is now as first T dS equation. And second T dS equation is given by T dS is equal to d h minus v d P and these two relations are very important. We shall see how we use them and since these equations contain only properties they are valid for both reversible as well as irreversible processes and two more thermodynamic relations can be obtained by defining two new properties known as Helmholtz's function and Gibb's function.

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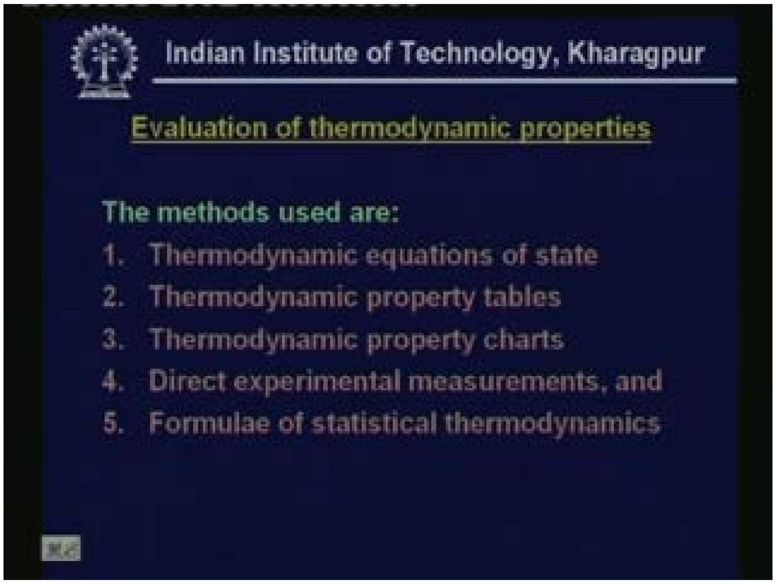

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Evaluation of thermodynamic properties

The methods used are:

1. Thermodynamic equations of state
2. Thermodynamic property tables
3. Thermodynamic property charts
4. Direct experimental measurements, and
5. Formulae of statistical thermodynamics

Now let us look at various methods use for evaluating thermodynamic properties. The methods used are thermodynamic equations of state thermodynamic property tables. Thermodynamic property charts direct experimental measurements and formulae of statistical thermodynamics.

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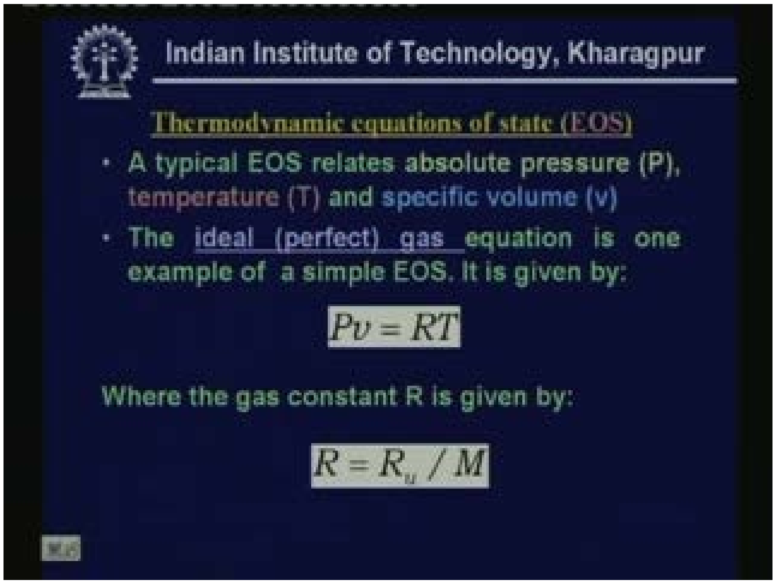

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Thermodynamic equations of state (EOS)

- A typical EOS relates absolute pressure (P), temperature (T) and specific volume (v)
- The ideal (perfect) gas equation is one example of a simple EOS. It is given by:

$$\boxed{Pv = RT}$$

Where the gas constant R is given by:

$$\boxed{R = R_u / M}$$

Now let us look at the first method what is known as thermodynamic equations of state. Now they are also known as EOS and a typical EOS relates absolute pressure P, temperature and specific volume. One of the simplest examples of an EOS is that the specific volume of a solid is a constant. So this is one of the simplest possible equations of state. Next simple equation of state that for an ideal gas that is given here. And as you know very well for an ideal gas the relationship P v is equal to R T holds good where P is the absolute pressure v is specific volume R is the gas constant T is absolute temperature. And the gas constant R as you know is given by the universal gas constant divided by the molecular mass. And let me just repeat what is an ideal gas. I am sure all of you know that a gas is said to be an ideal gas if the inter molecular forces are negligible. And also the volume occupied by the gas molecules is negligible compared to the system volume. Under these two assumptions we can call a gas as an ideal gas and under what are the conditions under which a real gas behave such an ideal gas that is given here.

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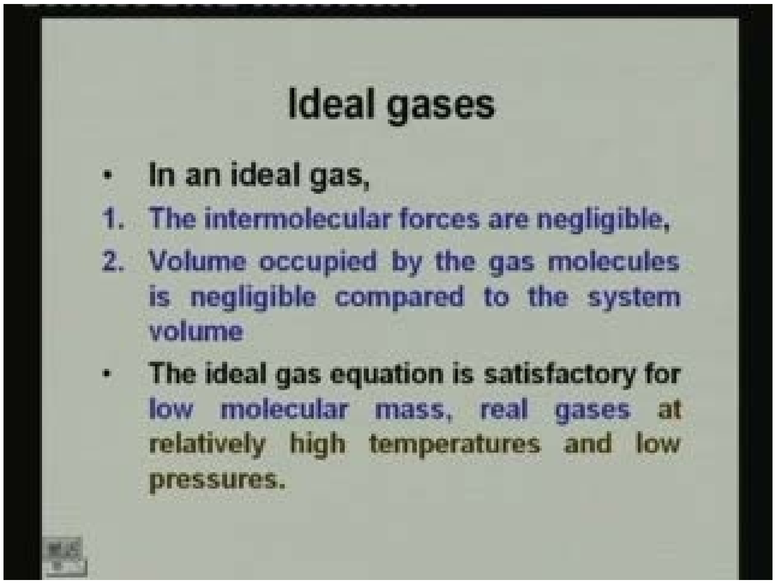

Ideal gases

- In an ideal gas,

1. The intermolecular forces are negligible,
2. Volume occupied by the gas molecules is negligible compared to the system volume

- The ideal gas equation is satisfactory for low molecular mass, real gases at relatively high temperatures and low pressures.

The real gas can be approximated as an ideal gas if it has a low molecular mass and its temperature is relatively high and its pressure is low. That means for relatively low molecular mass gases at high temperatures and low pressures can be approximated as ideal gases and for these ideal gases as you know we can use the ideal gas equation. So ideal gas equation is one of the simplest possible equations of state. Now let us look at how to evaluate the enthalpy change entropy change internal energy change for an ideal gas.

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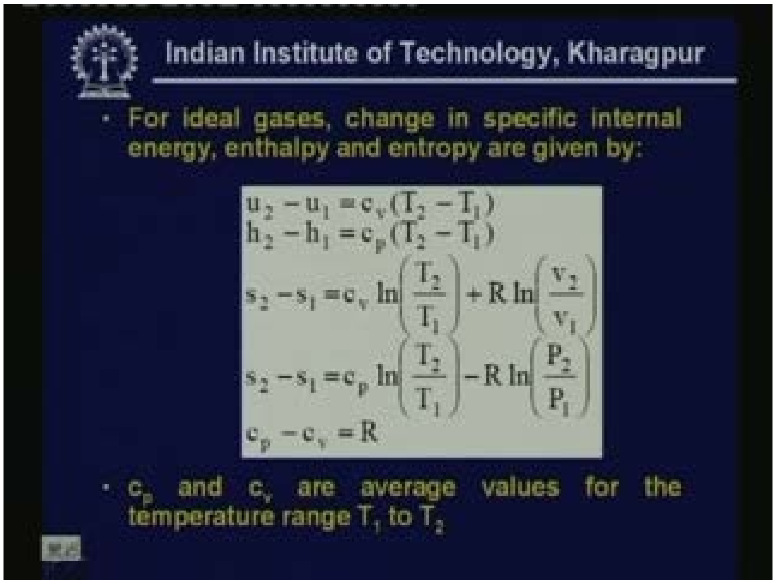

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- For ideal gases, change in specific internal energy, enthalpy and entropy are given by:

$$u_2 - u_1 = c_v(T_2 - T_1)$$
$$h_2 - h_1 = c_p(T_2 - T_1)$$
$$s_2 - s_1 = c_v \ln\left(\frac{T_2}{T_1}\right) + R\ln\left(\frac{v_2}{v_1}\right)$$
$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right)$$
$$c_p - c_v = R$$

- c_p and c_v are average values for the temperature range T_1 to T_2

So these equations are given here for internal energy change, specific internal energy change, specific enthalpy change and specific entropy change of an ideal gas. The first equation u two minus u one gives the specific internal energy change and its given by c v into T two minus T one where c v is an average specific heat at constant volume and its' an average value between T one and T two. And the next equation is h two minus h one that is nothing but specific enthalpy change is the is equal to c p into T two minus T one where c p is the ah specific heat at constant pressure and its assumed that it is either constant or we are taking an average value for the time interval T one to T two.

Next using the first TDS equation we can find out what is the entropy change of an ideal gas that is given by s two minus s one is equal to c v on l n T two by T one plus R l n v two by v one this is obtain using first TDS equation. And then using the second T DS equation we can also find out entropy change in terms of c p and pressures that is given by c s two minus s one is equal to c p l n T two by T one minus R l n P two by P one and as you know very well the different between c p minus c v is equal to gas constant. And one thing is I am sure that you remember that for an ideal gas the internal energy and enthalpy are functions of temperature only and from the equations you can see that the internal energy change is given by c v into delta t and for ideal gases c v is only a function of temperature. So over all the internal energy change is only the function of temperature similarly the enthalpy change is also a function of temperature only.

Now let us look at real gases.

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Ideal gas equation cannot be applied for:

1. Gases with complex molecular structure
2. Gases at high pressure and low temperatures
3. Gases approaching the saturated vapour region

- For the above cases, more complex but more realistic equations of states have to be applied

Ideal gas equation cannot be applied for gases with complex molecular structure. You cannot apply the ideal gas assumption also when the gases are at high pressure and low temperatures and when the gases approach the saturated vapour region. That means under these conditions if you are applying ideal gas equation it will result in significant errors. Then how do we handle these situations. For these situations we have slightly more complex equations of state which are even the more complex are more accurate. Let us look at some of these equations of state typically equation of state.

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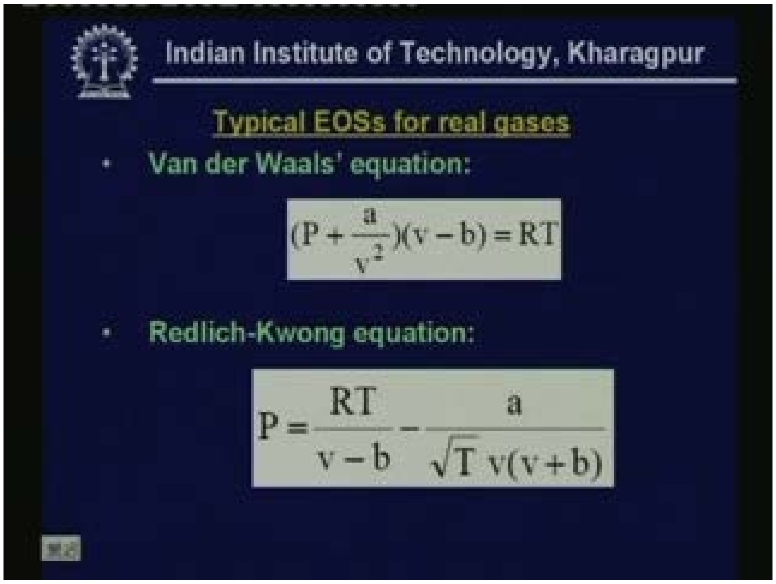

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Typical EOSs for real gases

- Van der Waals' equation:

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

- Redlich-Kwong equation:

$$P = \frac{RT}{v - b} - \frac{a}{\sqrt{T}\, v(v + b)}$$

The first one as you know is what is known as Van der Waals' equation and it is given by P plus a by v square into v minus b is equal to R T. So if you compare these equation with ideal gas equation you find two differences instead of P. We have added the term a by v square to the pressure and this term a by v square accounts for the intermolecular forces between the molecules. And the second difference is the term b we instead of writing v we have written it as v minus b and this b accounts for the volume occupied by the gas molecules. So a by v square term accounts for intermolecular forces and the term b accounts for the volume occupied by the gas molecules and it can be shown that for a particular gas the constants a and b are related to the critical properties.

That means if you can express a and b in terms of the critical temperature critical pressure and critical volume and the next equation of state is what is known as Redlich Kwong equation. This is again if you compare this is slightly different from Van der Waals' equation again you have here P is R T divided by v minus b minus a divided by square root of T into v into v plus b. Again you have the form is slightly different and we have introduced two new constants a and b. And similar to Van der Waals' equation these constants a and b are functions of a critical point and also the nature of the gas. Similar to this we can have many more equations of state people have developed many more equation of state which are suitable for certain conditions and certain working fluids etcetera.

For example we have what is known as a RK's equation which is a modified Redlich Kwong's equation. Then we have another very popular equation known as Martin Hou equation. So these equations we will be discussing again when we discuss refrigerant property evaluations.

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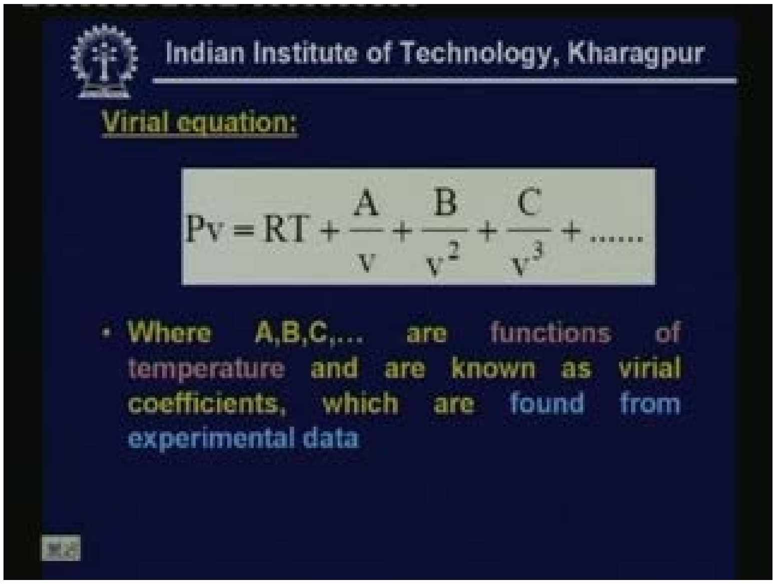

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Virial equation:

$$Pv = RT + \frac{A}{v} + \frac{B}{v^2} + \frac{C}{v^3} + \ldots\ldots$$

- Where A,B,C,... are functions of temperature and are known as virial coefficients, which are found from experimental data

Let us look at one general equation what is known as Virial equation. This Virial equation is given by P v is equal to R T plus A by v plus B by v square plus C by v ah v cube plus etcetera. That I mean, that you can go on adding terms and these constants A B C are known as virial coefficients and they are functions of temperature only. And they have to be evaluated using experimental data. So this is one form of what is known as the Virial equation and as you can see if A and B and C ah become zero then this Virial equation falls down to a simple ideal gas equation of state. So this equation is very useful and the equation of states along with thermodynamic relations are used to obtain relations for properties that cannot be measured directly in terms of properties which can be measured directly. I am sure that you have studied this in your basic thermodynamic courses and for more details you can report to any standard thermodynamics book.

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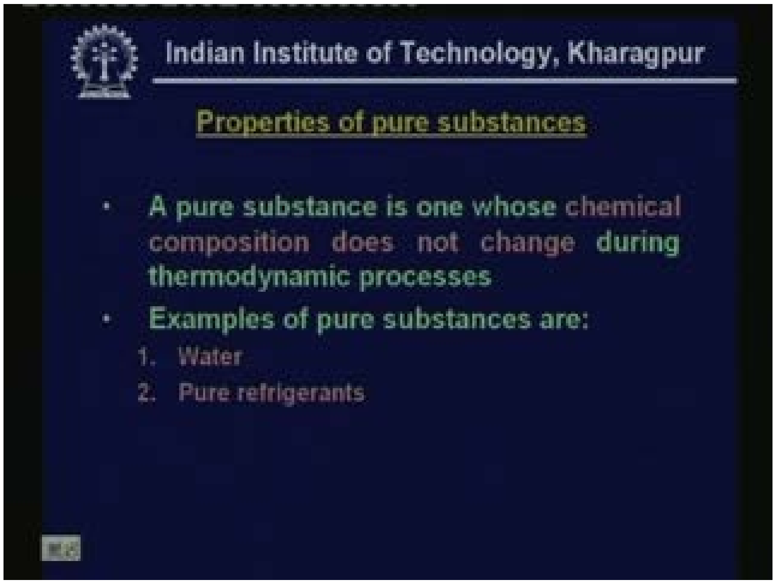

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Properties of pure substances

- A pure substance is one whose chemical composition does not change during thermodynamic processes
- Examples of pure substances are:
  1. Water
  2. Pure refrigerants

Now let us look at properties of pure substances how we define a pure substance? A pure substance is one whose chemical composition does not change during thermodynamic processes that means it does not undergo any Fitch any chemical reaction as it undergoes a thermodynamic process. Such a substance you known as a pure substance. What are the examples of pure substances? The common examples are water and pure refrigerants. And water and pure refrigerants are very important in refrigeration and air conditioning and we will be dealing with these things very frequently again and again.

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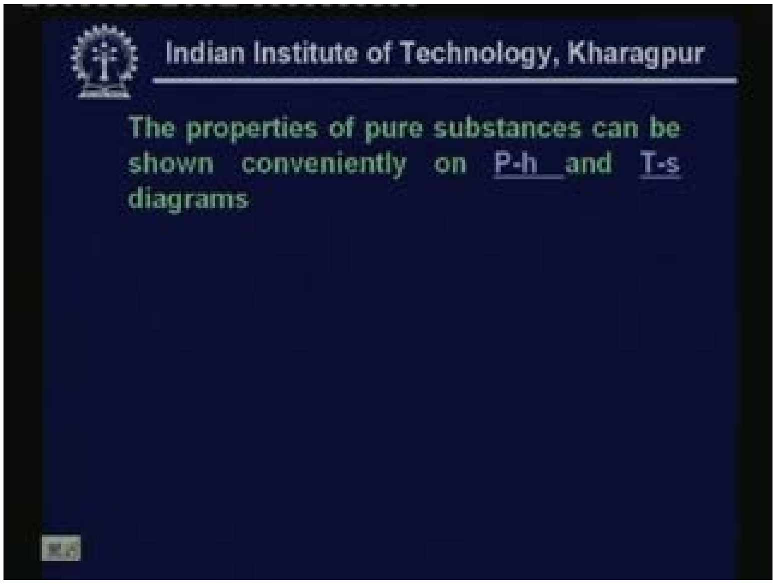

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The properties of pure substances can be shown conveniently on P-h and T-s diagrams

Now let us look at the property evaluation of pure substances. The properties of pure substances can be shown conveniently on P h and T s diagrams. Let me show a typical P h diagram.

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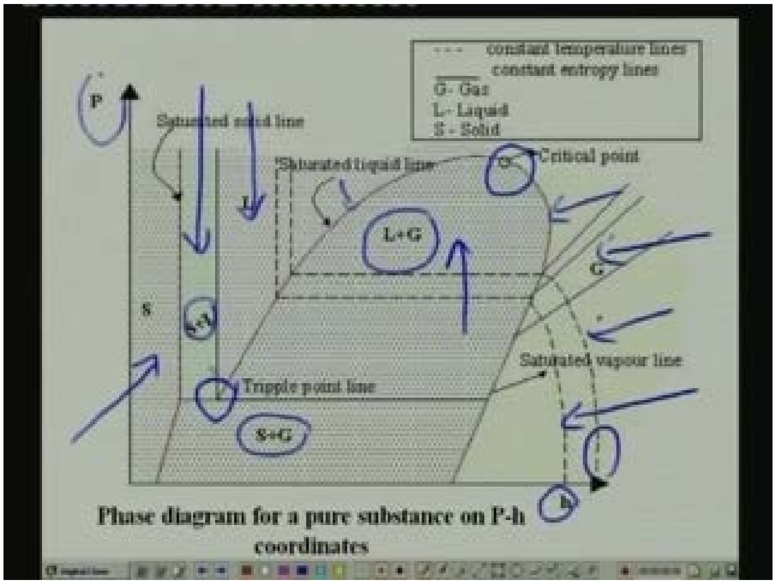

Phase diagram for a pure substance on P-h coordinates

This figure here shows a P h diagram so here you have a solid region and a liquid region and a gaseous region and you also have interfaces. For example this is the region in which solid and liquid exist in equilibrium. This is the region in which liquid and gas exist in equilibrium and this is the region in which solid and liquid exist in equilibrium. So this is the typical phase diagram of a pure substance on P h coordinates. That means we have h on the x axis and p on the y axis and these lines show the isotherms. That means constant temperature lines and the temperature increases in this direction.

That means this temperature is greater than this temperature and you can see that in the liquid region the enthalpy the constant temperature lines almost vertical and it remains horizontal in the liquid plus gas region. That means in the two phase region the constant temperature line is horizontal. Of course this is accordance with this phase rule and when a pure substance boils or condenses at a constant pressure it temperature remains constant that is the reason why it is horizontal here. Again in the two phase region you can see that when the pressure is reduced the constant temperature lines become almost vertical.

That means under these condition they begin to behave as ideal gases that is why they will become vertical and here there are two important points one is what is known as a critical point. As you know critical point is the point where the saturated liquid line that means this line and the saturated vapour line these two lines join. So the critical point is the point at which the saturated liquid line and saturated vapour line join. This is very important and we shall see later how this influence is the selection of refrigerants and ah physically when the working fluids exists below critical point you can distinguish liquid and gas.

That means if you have collected this liquid and gas mixer in a let us say glass beaker then a meniscus forms between the liquid and gas freezes. Whereas if the working fluid is above the critical point you cannot distinct you cannot make any distinction between liquid and gas and that region is known as a super critical region there is another important point known as triple point. So as you know probably the triple point is a point at which all the three phases that means solid liquid and gas exist in equilibrium so that point is shown here so this is the typical phases diagram for a pure substance.

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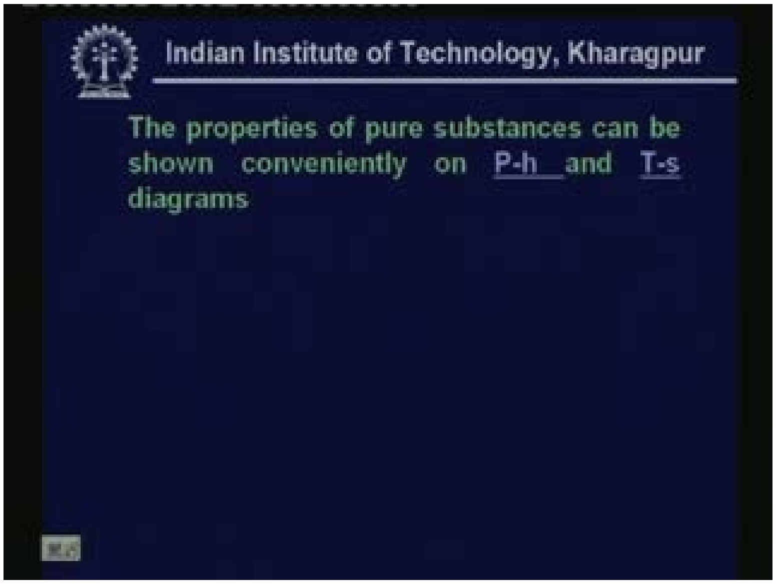

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The properties of pure substances can be shown conveniently on P-h and T-s diagrams

Now let us look at typical T s diagram phase diagram on T s coordinates.

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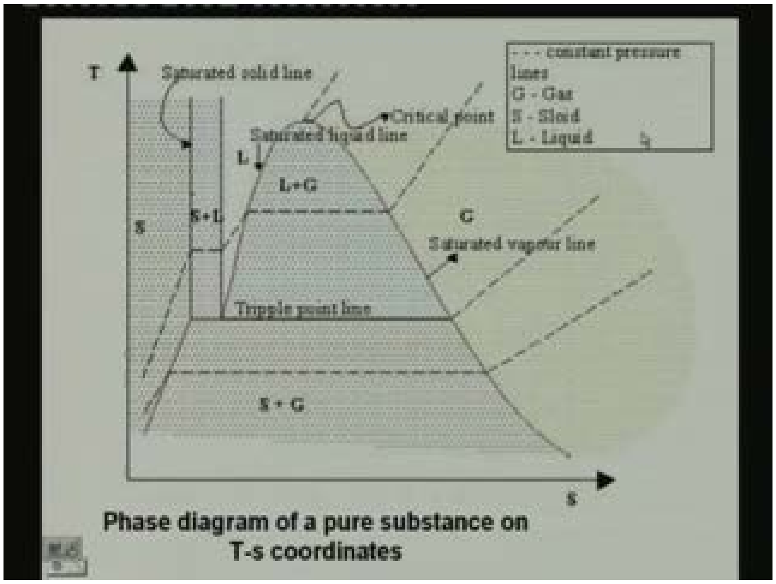

Phase diagram of a pure substance on T-s coordinates

So again this diagram shows a phase diagram on T s coordinates. So you have entropy on the, I am sorry let us come back. You have the entropy on the x axis and temperature on the y axis. Again you can see the solid region gaseous region and liquid region. You can also see the liquid solid plus liquid this as region and liquid plus gas region and solid plus gas region and you can also see the saturated liquid line and saturated vapour line and the critical point and the triple point.

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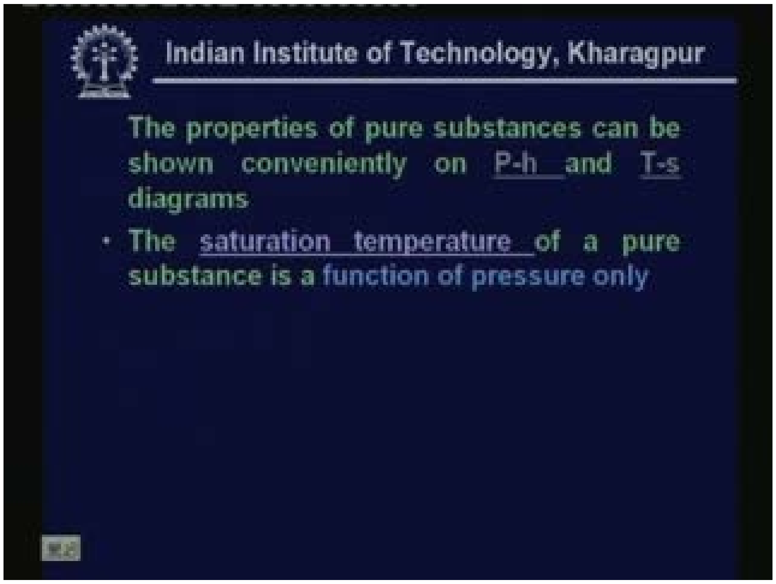

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The properties of pure substances can be shown conveniently on P-h and T-s diagrams

- The saturation temperature of a pure substance is a function of pressure only

The saturation temperature of a pure substance is a function of pressure only. So what do you mean by saturation temperature? Saturation temperature, for example for a liquid vapour mixer can be defined as the temperature at which the liquid and gaseous phases exist in equilibrium.

That means at a given pressure the temperature at which the liquid and gas phases exist in equilibrium is known as a saturation temperature for the liquid gas of phases. Similarly you can also have saturation temperature for solid liquid or solid gas or regime. And the relationship between saturation temperature and pressure is given by an important relation known as Chaperon relation.

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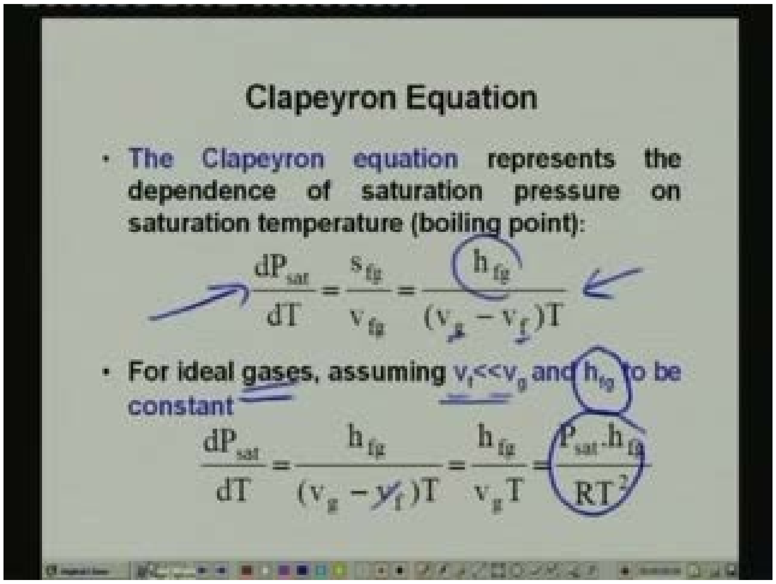

Clapeyron Equation

- The Clapeyron equation represents the dependence of saturation pressure on saturation temperature (boiling point):

$$\frac{dP_{sat}}{dT} = \frac{s_{fg}}{v_{fg}} = \frac{h_{fg}}{(v_g - v_f)T}$$

- For ideal gases, assuming $v_f << v_g$ and h_{fg} to be constant

$$\frac{dP_{sat}}{dT} = \frac{h_{fg}}{(v_g - \cancel{v_f})T} = \frac{h_{fg}}{v_g T} = \frac{P_{sat} . h_{fg}}{RT^2}$$

The Clapeyron equation represents the dependence of saturation pressure on saturation temperature and that equation is given here. This is the equation where d P by d P by d T is nothing but saturated vapour curve fin variation of saturation pressure with temperature and it can be shown that this is equal to latent entropy of vaporization divided by the le divided by the difference between the specific volume of the gas and vapour V f g as it as it is shown here nothing but the difference in the specific volume of the gas and the fluid g stands here for saturated vapour and f stands for saturated liquid.

So d P sat by d T is given by S f g by V f g where S f g is the difference between the entropy of the saturated vapour and the entropy of the saturated liquid and V f g is the difference between the entropy of the saturated, I am sorry, specific volume of the saturated vapour and the specific volume of the saturated liquid and this can be shown to be equal to h f g divided by V g minus V f into T. This equation is derived because for the two phase region the entropy of vaporization is nothing but enthalpy of vaporization divided by the temperature. And as you know for a pure fluid the temperature remains constant. So S f g nothing but h f g divided by T. So we can write this equation in terms of these equations. Even though this equation looks quite simple it is very useful because it relates properties which cannot be measured directly in terms of properties which can be measured directly. And simplification of Clapeyron equation results in if you are assuming ideal gas behavior and if also assumes that the specific volume of the saturated liquid is much smaller than the specific volume of the saturated vapour. And the latent heat of vaporization does not vary much with temperature. If you are making these assumptions you can show that this is nothing but since v f is negligible compare to v g you can drop this term. So this become h f g by v g into T and T can be written as and I am sorry v T can be written as P by R T. So using the ideal gas equation and these assumptions ultimately you get arrive at this relation that means d P sat by dt is equal to P sat into h f g by RT square.

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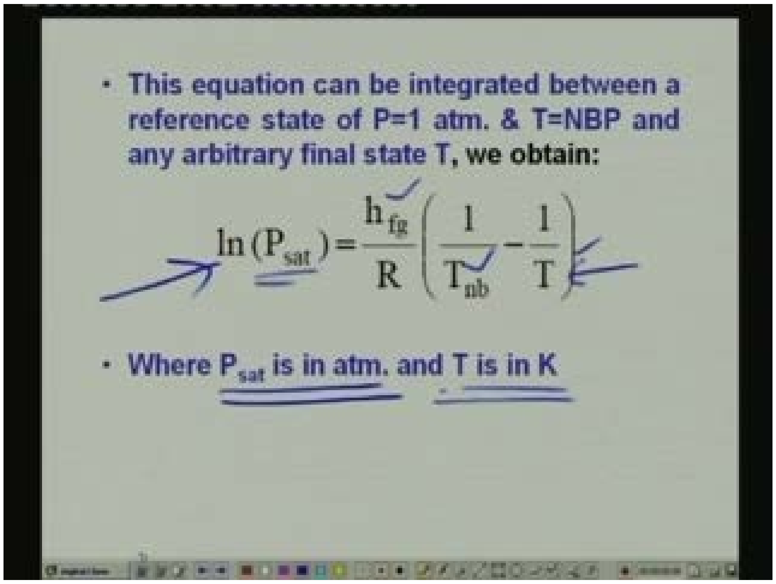

- This equation can be integrated between a reference state of P=1 atm. & T=NBP and any arbitrary final state T, we obtain:

$$\ln(P_{sat}) = \frac{h_{fg}}{R}\left(\frac{1}{T_{nb}} - \frac{1}{T}\right)$$

- Where P_{sat} is in atm. and T is in K

Now you can integrate this equation between two states one and two and if I am taking state one as a reference state. That means pressure is one atmosphere and temperature is normal boiling point that is my reference state one and the state two is any arbitrary temperature at which I would like to find out the saturation temperature. That means I am integrating the Clapeyron equation between reference state of one atmosphere pressure and normal boiling point and any arbitrary state T.

So you get this equation and using this equation this is very useful equation you can see that normally, normal boiling point can be obtained. And this is the temperature at which you want to find out the saturation pressure. So this is known to you and this will be generally known and this can be measured or this will be known. So you can find out using this relation what is the saturation pressure at any temperature T.

So this is the usefulness of Clapeyron equation and this equation also tells you that if you are plotting a l n P sat versus one by T you get a straight line in the slope of which will give you the latent heat of molecule latent heat of vaporization divided by the gas constant. And one thing you must remember here is here the pressure is expressed in terms of atmosphere and temperature T should be in absolute that means in Kelvin degrees Kelvin.

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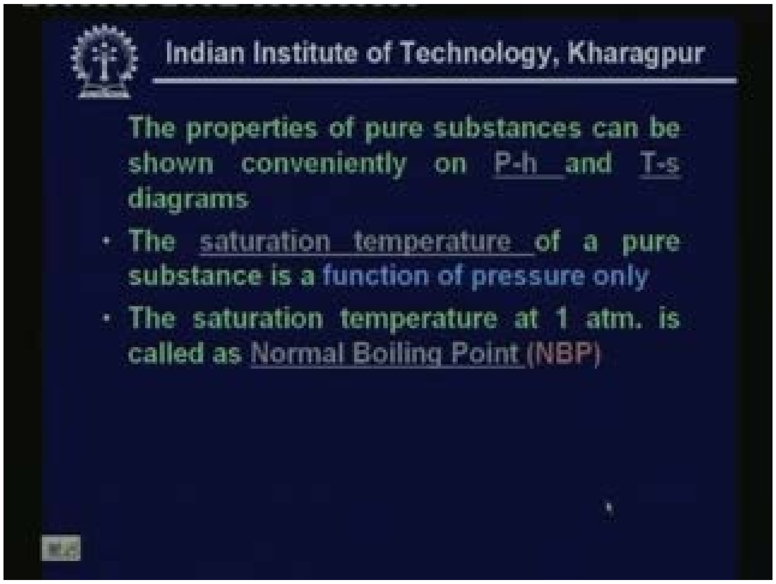

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The properties of pure substances can be shown conveniently on P-h and T-s diagrams

- The saturation temperature of a pure substance is a function of pressure only
- The saturation temperature at 1 atm. is called as Normal Boiling Point (NBP)

So for pure substance just now as I said the saturation temperature is only function of pressure and the saturation temperature at one atmosphere is called as normal boiling point or NBP you know this very well now the definition of normal boiling point.

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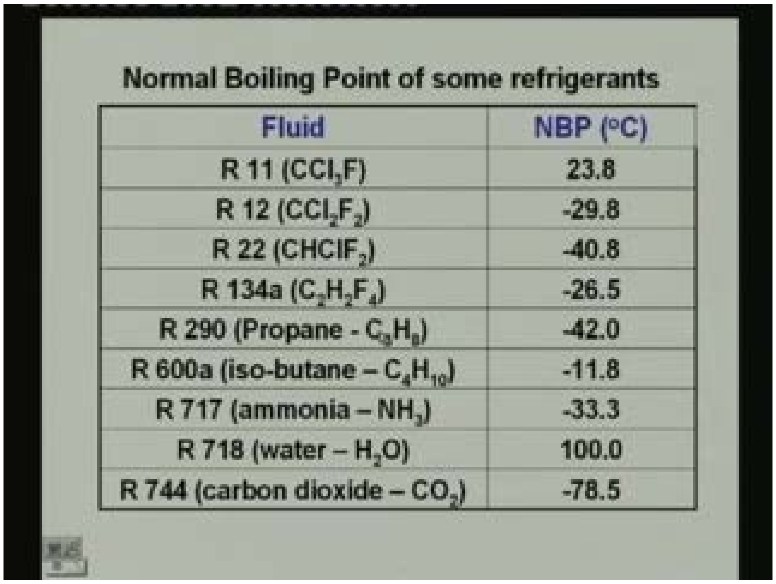

Normal Boiling Point of some refrigerants

Fluid	NBP (°C)
R 11 (CCl_3F)	23.8
R 12 (CCl_2F_2)	-29.8
R 22 ($CHClF_2$)	-40.8
R 134a ($C_2H_2F_4$)	-26.5
R 290 (Propane - C_3H_8)	-42.0
R 600a (iso-butane – C_4H_{10})	-11.8
R 717 (ammonia – NH_3)	-33.3
R 718 (water – H_2O)	100.0
R 744 (carbon dioxide – CO_2)	-78.5

Now let us look at typical normal boiling points of some refrigerants. So what is given here is that a fluid and its normal boiling point. For example for the refrigerant R eleven the chemical formulae is CCl three F and it has a normal boiling point of twenty-three point eight degree centigrade and R twelve which as you know is a very popular refrigerant. And its chemical formula is CCl two F two and it has a normal boiling point of minus twenty-nine point eight. Similarly R twenty-two has normal boiling point of minus forty point eight R one thirty-four has a normal boiling point of minus twenty-six point five. Likewise you can find out the normal boiling points of various refrigerants and this data is very much available in literature.

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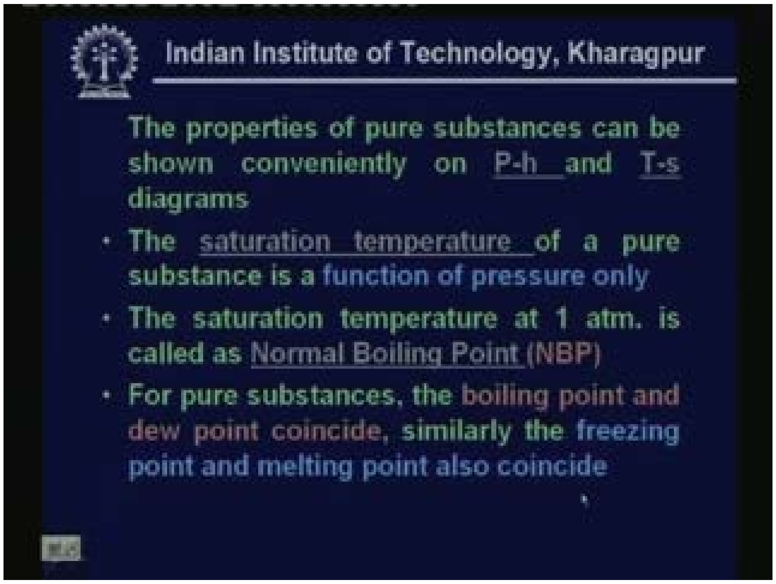

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The properties of pure substances can be shown conveniently on P-h and T-s diagrams

- The saturation temperature of a pure substance is a function of pressure only
- The saturation temperature at 1 atm. is called as Normal Boiling Point (NBP)
- For pure substances, the boiling point and dew point coincide, similarly the freezing point and melting point also coincide

Now for pure substances this is one peculiarity the boiling point and dew points coincide similarly the freezing point and melting point also coincide. That means if you are boiling if you are keeping the pressure constant and if you are boiling, the boiling a liquid then the temperature at which you find the first droplet of some temperature T and now you come in the reverse direction. That means you have a vapour and you are cooling it isobarically at the same pressure.

And the temperature at which you find the first droplet of liquid that is what is known as dew point temperature. And the temperature at which you find the first vapour bubble is known as boiling point and for the pure fluids the boiling point and dew point coincide. Similarly the freezing point and the melting point coincide. For example at one atmospheric pressure the boil boiling point of water is hundred degrees centigrade similarly the dew point of water is also at is also hundred degree centigrade.

Why I am stressing this is for mixture that means a mixture of two refrigerants the boiling point and dew point may not coincide similarly the freezing point and melting point may not coincide. Okay.

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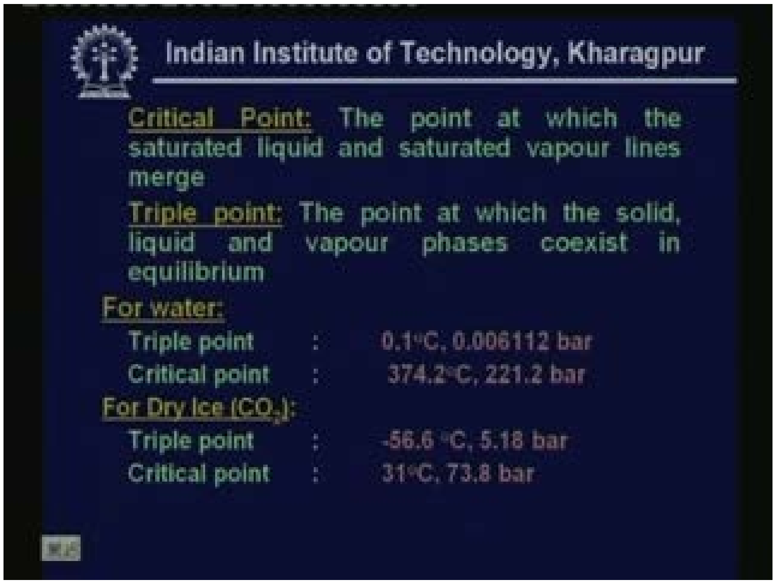

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Critical Point: The point at which the saturated liquid and saturated vapour lines merge

Triple point: The point at which the solid, liquid and vapour phases coexist in equilibrium

For water:

Triple point : 0.1°C, 0.006112 bar
Critical point : 374.2°C, 221.2 bar

For Dry Ice (CO_2):

Triple point : -56.6 °C, 5.18 bar
Critical point : 31°C, 73.8 bar

Now this is the repetition of whatever I have stated earlier. The critical point the definition of critical point is a point at which the saturated liquid and saturated vapour lines merge and the triple point is a point at which the solid liquid and vapour phases coexist in equilibrium. Let me give some typical values of triple critical point and triple point for water.

For example for water the triple point is zero point one degree centigrade and the pressure at triple point is zero point zero zero six one one two bar. And the, its critical point is three seventy-four point two degree centigrade and the pressure it critical point is two twenty-one point two bar. And for carbon dioxide or for dry ice the triple point is minus fifty-six point six degree centigrade and the pressure at triple point is five point one eight bar and the critical point is thirty-one degree centigrade and seventy-three point eight bar. As I mentioned earlier all these things are very important and they play a major role while selecting the suitable refrigerants for a given application. So we will be discussing the importance of triple point critical point etcetera when we discuss selection of refrigerants now.

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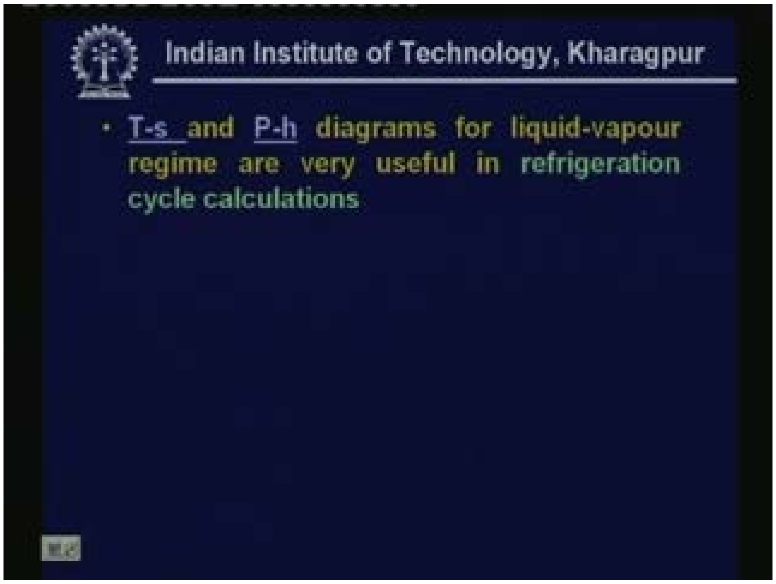

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- T-s and P-h diagrams for liquid-vapour regime are very useful in refrigeration cycle calculations

In most of the refrigeration applications we really will not be dealing with the solid phase that means we will not be dealing with solid and liquid phases or solid and gases phases. Of course there are some applications. For example if you are using ice for refrigeration purpose then obviously you will be dealing with solid liquid equilibria. Similarly if you are using let us say dry ice then you will be dealing with solid gas equilibria but in most of the thermodynamic cycles which we are mostly interested in we will be dealing with liquid gas interface. So we will be concentrating most of the time on phase diagrams for liquid gas phases. So let us look at T s and P h diagrams for liquid vapour regimes there as I said they are very useful in refrigeration calculations.

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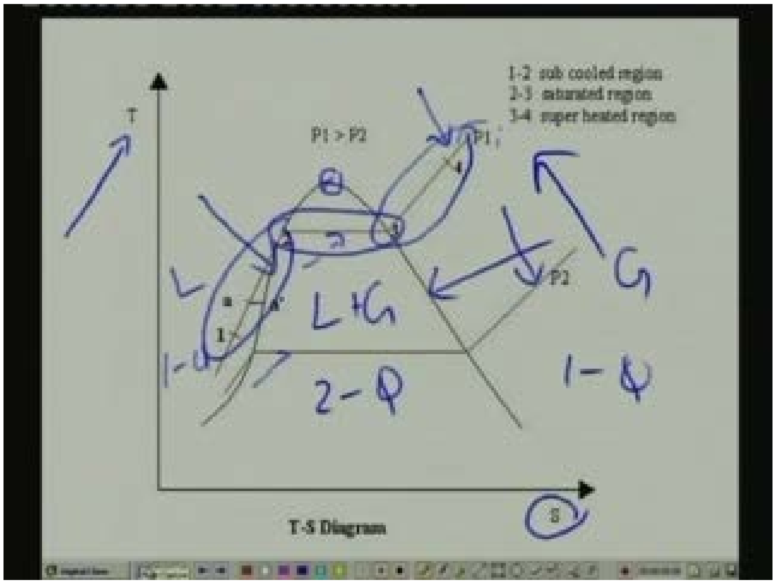

So let me show a typical T s diagram. So here we have entropy S on x axis and temperature on the y axis and this is a typical curve and this is your saturated liquid curve and this is your saturated vapour curve and this is the point at which both of them joined. That is known as your critical point. And on this diagram you have this sub cool liquid region and this is super heated gas region and this is liquid plus gas two phase region. That means you have a single phase region here two phase region here and again single phase region here. And on this figure I have shown two isobars. That means two constant pressure lines P one and P two. So you can see the shape of the constant pressure lines. It has slopes in the single phase region where as it becomes horizontal in the two phase region.

This is again in accordance with your Gibbs' phase rules or based on the fact that when a liquid boils at a constant temperature, pressure also remains constant that is the reason why you have a horizontal isobaric line in two phase region and here the pressure P one is greater than P two. That means pressure increases in this direction. And let us look at one isobar one two three four and here the region one to two that means this region this region is in the sub cooled condition and this region is in the two phase zone and this region is in the single phase super heated condition.

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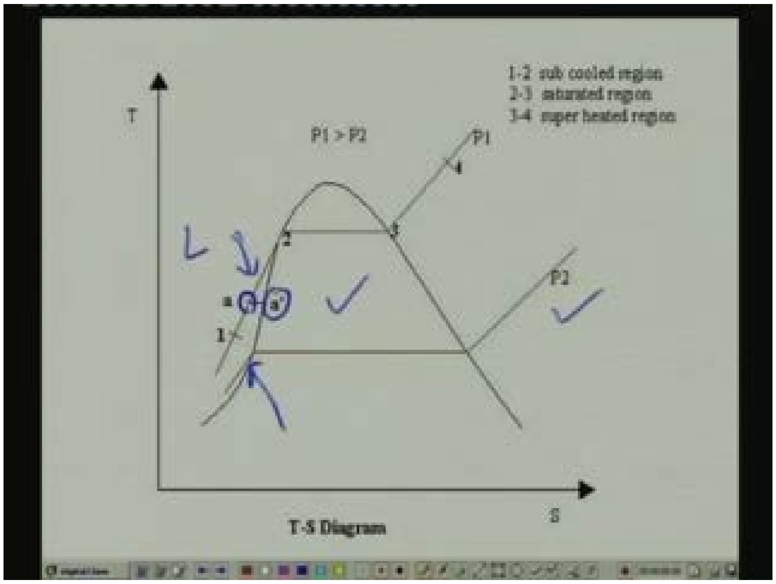

1-2 sub cooled region
2-3 saturated region
3-4 super heated region

T-S Diagram

One thing I would like to point out here is that normally the data for the sub cool liquid region is generally not available. We have the data for this region and data for this region. So most of the times we do not have the data for sub cool regions and sub cool data is also required for refrigeration calculations. In such cases we make certain assumptions and certain idealizations. Here as I mentioned this line is a constant pressure line and this line is a saturated liquid line. Even though they seem to be distinct here in actual case they are very close to each other. So one approximation we can make is they almost merge. That means the isobaric line coincides with the saturated liquid line. So that is one of the assumptions. It is a very useful assumption. And another assumption is that and it can be shown using your thermodynamic relations that if you want let us say the properties at this point which is in sub cooled region. So they can be approximated with saturated liquid properties at point a dash. Okay. This is one very useful assumption and most of the times we will be using this assumption. That means if you want let us say a liquid exists in sub cooled condition and let us say its temperature is thirty degree centigrade and it is at some pressure and it is in at sub cooled condition. So we would like to find out what is the internal energy and enthalpy at these conditions.

So what we can do is instead of finding the sub cooled conditions we can assume them to be equal to the saturated liquid properties at thirty degree centigrade. So this is one very useful idealization and we will discuss this when we do or perform refrigeration calculations.

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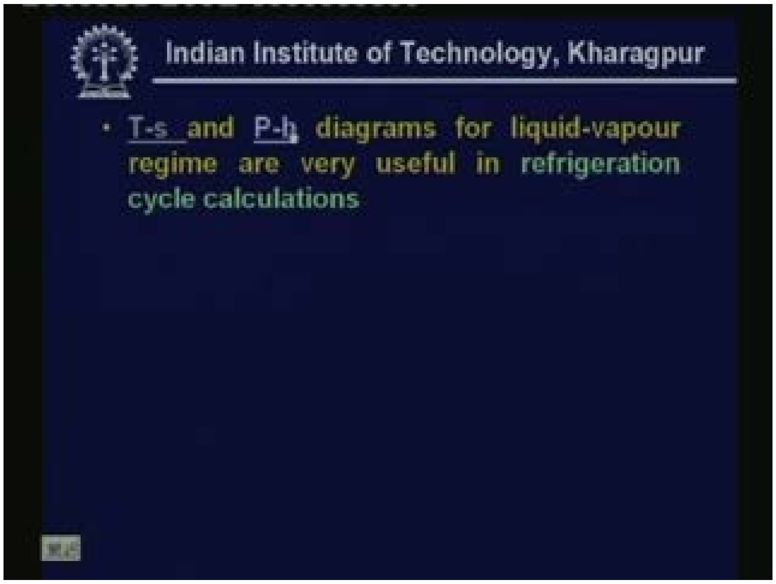

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- T-s and P-h diagrams for liquid-vapour regime are very useful in refrigeration cycle calculations

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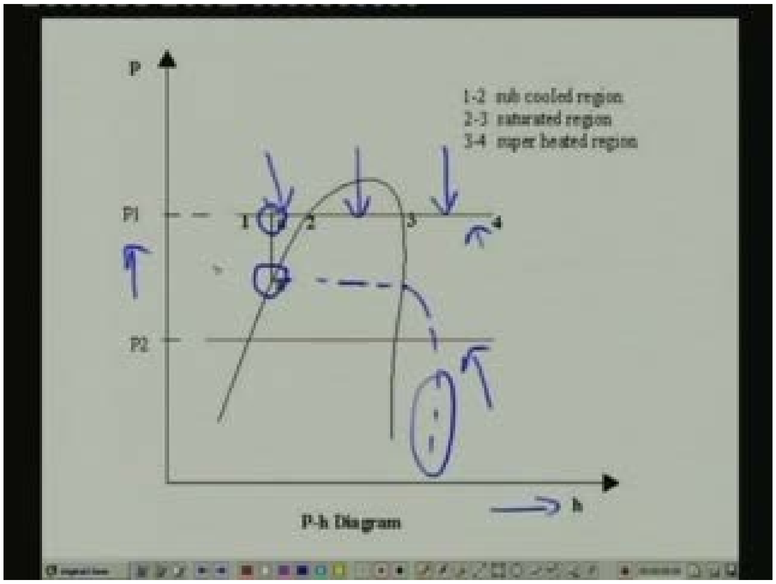

P-h Diagram

Now similar to T s diagram we can also have P h diagram. This figure shows the P h diagram here and these are the isobaric lines. Since we have pressure in the y axis obviously isobaric lines become horizontal and pressure increases in this direction. And on x axis you have enthalpy and I have not shown here. But the isothermal line that means constant temperature lines will be typically something like this. Okay. That means again there will be horizontal in the two phase region and they become sloped in the single phase super heated region and they become almost vertical in the low pressure zone.

And here again I have shown the process for the pressure P one the process one two three four where one two is in the sub cooled liquid region process two three in the two phase region and process three four in the super heated region. And again you can see that as I mentioned the properties at this point a can be approximated and they can be taken as equal to the saturated liquid properties at this condition. Okay. And this P h diagram and T s diagrams are very useful for performing refrigeration calculations and we shall see most of the times we will be showing the cycle diagrams on the T s and P h diagrams.

So one use of these T s and P h diagrams is that you can ever find out the required properties using these charts or diagrams and second use of these charts you can also represent the thermodynamic cycles on the chart so that you can directly perform various calculations using these charts. Okay.

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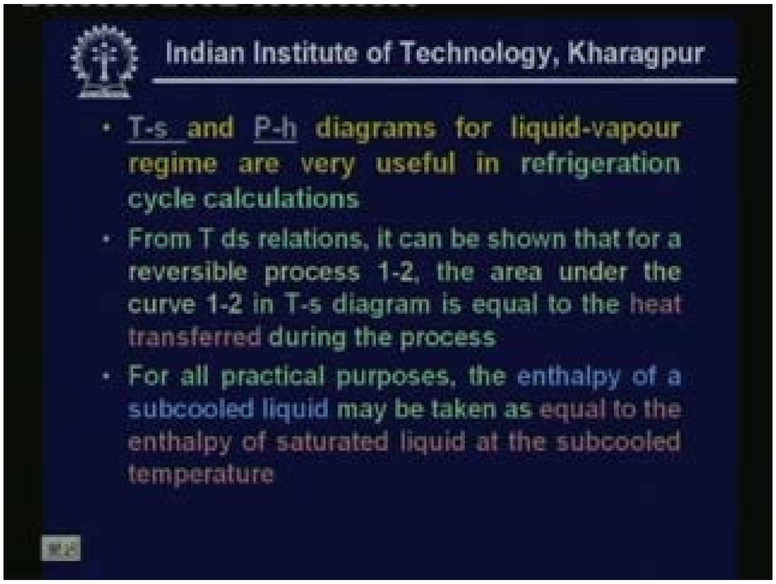

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- T-s and P-h diagrams for liquid-vapour regime are very useful in refrigeration cycle calculations
- From T ds relations, it can be shown that for a reversible process 1-2, the area under the curve 1-2 in T-s diagram is equal to the heat transferred during the process
- For all practical purposes, the enthalpy of a subcooled liquid may be taken as equal to the enthalpy of saturated liquid at the subcooled temperature

so as i mentioned and from your ah from the last class using the second law of thermodynamics and from T dS relation it can be shown that for a reversible process one two let us say that a process the reversible process one two the area under the curve one two in T s diagram is equal to the heat transfer during the process.

This is from your Clausius inequality where entropic change in a reversible process is given by the heat transfer rate. In the, during that process divided by the temperature at the boundary and using that statement we can easily show that the area under any curve one two on T s coordinates or on T s diagram is nothing but the heat transfer during the process.

So if you can plot the process on the T s diagram and if you can measure what is the area under the curve one two then you have the heat transfer during the process. It is very useful and for all practical purposes as I mentioned just now the enthalpy of it may be taken as equal to the enthalpy of saturated liquid at the sub cooled temperature.

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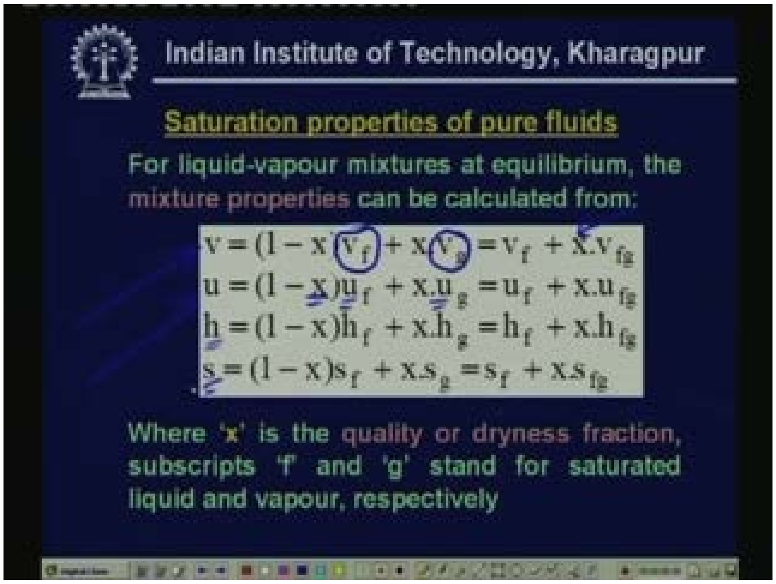

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Saturation properties of pure fluids

For liquid-vapour mixtures at equilibrium, the mixture properties can be calculated from:

$$v = (1-x)v_f + x.v_g = v_f + x.v_{fg}$$
$$u = (1-x)u_f + x.u_g = u_f + x.u_{fg}$$
$$h = (1-x)h_f + x.h_g = h_f + x.h_{fg}$$
$$s = (1-x)s_f + x.s_g = s_f + x.s_{fg}$$

Where 'x' is the quality or dryness fraction, subscripts 'f' and 'g' stand for saturated liquid and vapour, respectively

Now let us look at saturation properties of pure fluids. So what do you mean by saturation properties. Let us say that again I would like to repeat here that most of the times we will be dealing with liquid gas either in single phase or two phases or in super heated regions. So how do we evaluate the properties of liquid gas mixtures in two phase regions? So the equation shown here are for finding out the two phase properties. That means liquid gas equilibrium properties.

For example this equation this equation gives the specific volume of a two phase mixture in terms of saturated liquid specific volume and saturated vapour specific volume and x here is nothing but your dryness fraction or quality. I am sure that you have, we have used these correlations or you have these relations while performing calculations in basic thermodynamics.

Similarly you can express the specific internal energy u of a two phase mixture in terms of the dryness fraction x and the saturated liquid internal energy and saturated gas saturated vapour internal energy. Similarly the properties of properties enthalpy and entropy of the two phase mixture can be expressed in terms of saturated property and the quality. That means we want to find out the mixture properties. You need to know what are the saturated properties first and you also need to know what is the dryness fraction or quality and you probably remember that the quality or dryness fraction if defined as the mass of the map vapour in the mixture divided by the total mass of the mixture. So that is the definition of dryness fraction.

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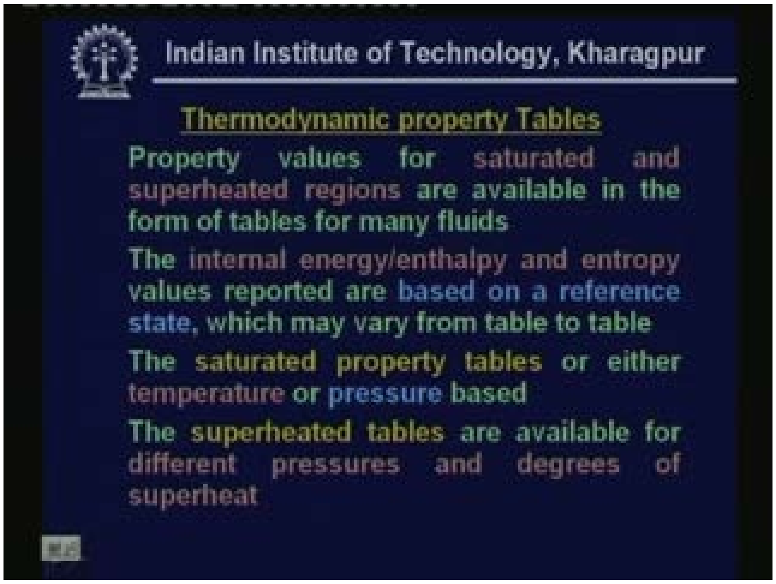

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Thermodynamic property Tables

Property values for saturated and superheated regions are available in the form of tables for many fluids

The internal energy/enthalpy and entropy values reported are based on a reference state, which may vary from table to table

The saturated property tables or either temperature or pressure based

The superheated tables are available for different pressures and degrees of superheat

Now let us look at the second method for evaluating thermodynamic properties. So we have seen thermodynamic equations of state at the and some thermodynamic diagrams are thermodynamic property charts. So now look at thermodynamic property tables. Normally the property tables are available for saturated region. That means for the two phase region and also for the super heated region. And the saturated and super heated property tables for steam are used for calculating power plant calculation and I am sure that you must have used them when you were in basic thermodynamics and the internal energy enthalpy and entropy values reported are based on a reference state which may vary from table to table.

This is a very important point that means when you are using a thermodynamic property table as I mentioned earlier you do not have any absolute values for internal energy or enthalpy or for that matter entropy provided you are not using the third law of thermodynamics. So normally the internal energy enthalpy and entropy values are values with difference state particular datum state. That means all tables they first define a reference state and at that differ reference state they give arbitrary values for internal energy enthalpy and entropy and the internal energy enthalpy and entropy at any other state are given with reference to the reference state. So basically what the value of enthalpy for example enthalpy of h that you seen in the table is nothing but h minus h corresponding to the reference state. Okay.

Similarly for the internal energy and entropy. So as long as you are using the same table then it does not make any difference and what reference values are chosen do not, they do not come into picture. Because normally we will be dealing with enthalpy changes and entropy changes, internal entropy changes et internal energy changes etcetera. So the reference state does not come into picture. So you are safe as well as we are using the same thermodynamic property table. But if you are using a table from different sources then you have to know what the reference states are. You must make sure that the reference states are not different if they are different then you have to make suitable corrections and then only you use the enthalpy and entropy properties.

Normally the saturation property tables are either temperature or pressure based for example a saturated temperature based property table. They give temperature as an independent variable and they give all other properties as functions of temperature that means you have. For example let us say take water they felt that a typical table for water looks like this. Let us say the temperature of water is a ten degree centigrade then the table gives you the saturated table gives you what is the saturation pressure at ten degree centigrade. Then it also gives you what are the saturated liquid properties at ten degree centigrade and what are the saturated vapour properties at ten degree centigrade. So this is the typical table based on temperatures. Similarly you can have saturation table based on pressure that means the pressure is independent in variable let us say that one bar pressure. Then at one bar pressure they give what is the saturation temperature and what are the saturated liquids and vapour properties.

So you can have either saturated either temperature based saturation tables or pressure based saturation tables and normally the super heated tables are available for different pressures and degrees of super heat. We shall discuss these tables when we actually perform the refrigerant calculations and if you look at any of the text books on thermodynamics or refrigeration at the end of the text books all the property tables are available for a wide variety of refrigerants and I am sure you must used this table in your basic thermodynamics. Okay. Now let us look at some common thermodynamic processes

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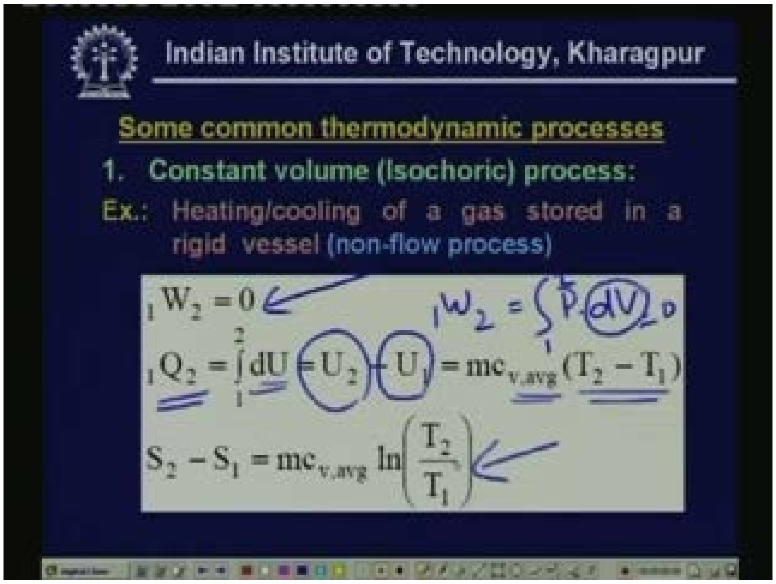

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Some common thermodynamic processes

1. Constant volume (Isochoric) process:

Ex.: Heating/cooling of a gas stored in a rigid vessel (non-flow process)

$${}_1W_2 = 0 \qquad {}_1W_2 = \int_1^2 P\,\boxed{dV} = 0$$

$${}_1Q_2 = \int_1^2 dU = U_2 - U_1 = mc_{v,avg}(T_2 - T_1)$$

$$S_2 - S_1 = mc_{v,avg} \ln\left(\frac{T_2}{T_1}\right)$$

In refrigeration and air conditioning we come across a wide variety of processes and if you want to find out what is the performance of a particular process or a performance for a particular cycle we need to know or we need to understand that particular process. And we have to estimate what is the heat transfer during that particular process or what is the mass transfer during that particular process, what is the entropy transferred during that particular process. All these terms are required in order to evaluate the performance.

So in the, let us look at some of the very basic processes. I will give the basic process and a typical example and the suitable equations for work transfer, heat transfer, energy transfer or energy change etcetera. Okay. So the first process a simple process is a constant volume or isochoric process. So isochoric process means volume does not change and a typical example is the heating and cooling of a gas stored in a rigid vessel. So that means we have a rigid vessel and it consists of gas and which is the system here and we are heating the gas and this process, this example is typically a non flow process that means either the gas is leaving nor entering into the rigid vessel. For this kind of a system if you are heating or cooling the gas what are the typical equations for work transfer heat transfer and entropy change so those equations are given here how did we get these equations. For example this equation how did we get this for a non flow process if you remember the work transfer one W two is given by integral P d V ah integrated between one to two and here d V is the volume change since it is a rigid vessel d V is equal to zero. So work transfer rate is equal to zero so that is how you get this equation.

So the work transferred in a simple heating and cooling of a gas stored in rigid vessel is zero provided we do not have any other modes of work transfer. For example we do not have any electrical heat or any other magnitude or chemical modes of work transfer. Okay. Then we can find out this expression for heat transfer during this process using the first law of thermodynamic process for a non flow process. As you know work law first law of thermodynamics for a non flow process is given by one Q two is nothing but one W two plus integral d U. Since one W two is zero you simply have here have here one Q two is equal to integral d U. Since this is the property the integral d U can be written as U two minus U one where U two is the total internal energy at state two and U one is the total internal energy at state one. Of course this is based on the assumption that other changes like kinetic and potential changes are negligible. And this equation can also be written in terms of first T dS equation. If you remember the first T dS equation is given by ah T dS is d U plus P d V. Okay. And P d V is zero because there is no volume change.

So T dS are simply equal to d U. So d S is d U by T so if you are integrating this between state one and two you get that S two minus S one S one is nothing but mc v into l n T two by T one. Okay. You can also think of other non flow processes for example another very simple example of a constant volume process is that approaches, is that of a heating or cooling of a solid. So for example when you are heating or cooling a solid over a temperature difference which is not too large then its value remains constant and the heat transfer rate during that process is simply equal to mc into delta T and for a solid specific heat at constant volume and constant pressure will be all will be same. So simply mc p into delta T and the entropic change S two minus S one is nothing but mc v l n T two by T one. Okay.

Now let us look at another simple process that is known as constant pressure or isobaric process.

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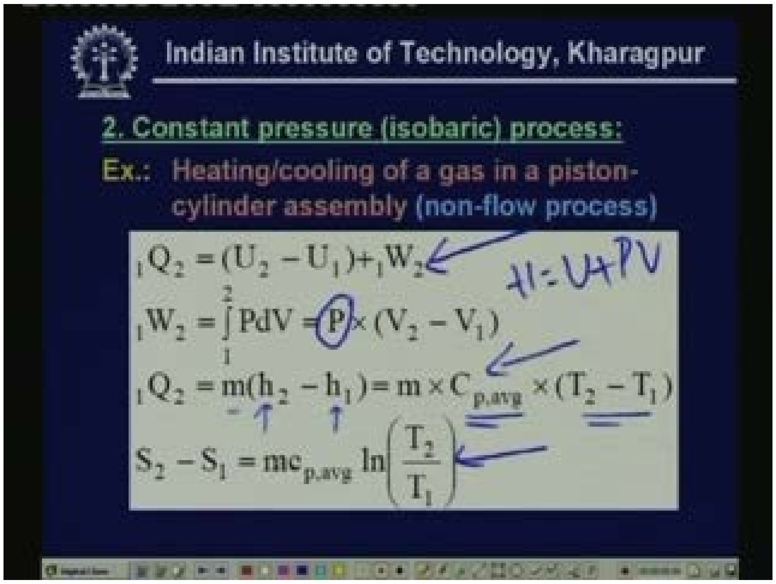

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2. Constant pressure (isobaric) process:

Ex.: Heating/cooling of a gas in a piston-cylinder assembly (non-flow process)

$${}_1Q_2 = (U_2 - U_1) + {}_1W_2 \leftarrow$$

H = U+PV

$${}_1W_2 = \int_1^2 PdV = \boxed{P} \times (V_2 - V_1)$$

$${}_1Q_2 = m(\underset{\uparrow}{h_2} - \underset{\uparrow}{h_1}) = m \times \underline{\underline{C_{p,avg}}} \times (\underline{\underline{T_2 - T_1}}) \leftarrow$$

$$S_2 - S_1 = mc_{p,avg} \ln\left(\frac{T_2}{T_1}\right) \leftarrow$$

So the iso here stands for a constant that means whenever we say iso some thing that means some properties remaining constant. So in a isobaric pro process the pressure remains constant and here let us take the example of again a non flow process we are heating or cooling a gas which is contain in a piston cylinder assembly and let us say that piston is not spring loaded or anything. That means it has an, it is acting against its constant external force. If that is the case pressure remains constant that means the pressure exerted by the piston remains constant. And if you are assume if you are assume that the piston is frictionless that means the movement takes place without any friction. Then we can have an ideal isobaric process.

And for this isobaric process the equations are like this. For example this first equation is nothing but the first law of thermodynamics for an isobaric process in a non flow process. Okay. And as you know very well this is nothing but the statement of first law. Okay. One Q two is nothing but U two minus U one plus one W two. And how do we find one W two one W two for a non flow process is a integral P d V and if you assume that this process is quasi static. Then you can perform the integration and since pressure is constant. This is simply equal to P into V two minus V one where V two is the final pressure and V one is initial pressure. So work done during the constant flow process is nothing, put P into delta V or P into V two minus V one and the heat transfer rate can also be written in terms of enthalpy difference. For example if you are substituting this here and if you are using the definition of enthalpy H is U plus P V and P is constant here you can get this equation. Okay.

That means you can write one Q two as m into h two minus h one where m is the mass of the system and h two is the specific enthalpy at the final state and h one is the specific enthalpy at the initial state. And h two minus h one can be written in terms of specific heat at constant pressure and temperature, difference that means one Q two is mc p into delta T R mc p into T two minus T one and using the second T dS equation you can obtain this relationships for change in entropy. Okay. If you remember second T dS equation is given as T dS is d h minus V d P so V d P is zero because pressure is remaining constant. So d S is integral d h by T and if you are performing the integration between states one to two you get the expression for entropic change during the isobaric process. Okay.

So let us look at another process.

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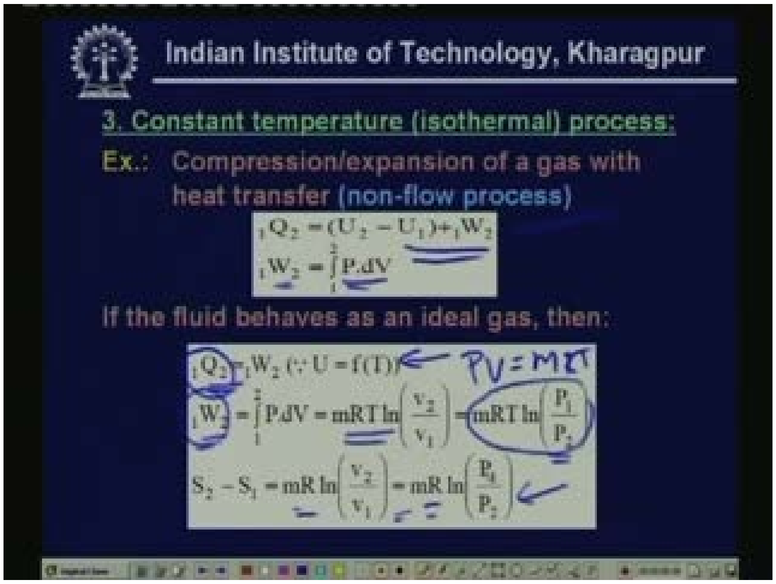

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3. Constant temperature (isothermal) process:

Ex.: Compression/expansion of a gas with heat transfer (non-flow process)

$${}_1Q_2 = (U_2 - U_1) + {}_1W_2$$

$${}_1W_2 = \int_1^2 P.dV$$

If the fluid behaves as an ideal gas, then:

$${}_1Q_2 = {}_1W_2 \; (\because U = f(T)) \leftarrow \quad PV = MRT$$

$${}_1W_2 = \int_1^2 P.dV = mRT\ln\left(\frac{v_2}{v_1}\right) = mRT\ln\left(\frac{P_1}{P_2}\right)$$

$$S_2 - S_1 = mR\ln\left(\frac{v_2}{v_1}\right) = mR\ln\left(\frac{P_1}{P_2}\right) \leftarrow$$

This is known as the constant temperature or isothermal process a typical example of this is compression expansion of a gas with heat transfer that means again we are taking a non flow process. A gas is undergoing compression or expansion in a piston cylinder assembly and at the same time the heat transfer is taking place between the system and surroundings. The heat transfer is taking place in such a way that the temperature of the system remains constant. So this is a, then the process becomes isothermal non flow process and for this process the governing equations for energy for work transfer and heat transfer and there is a entropy transfer are given here. Okay.

For example this equation again, this equation is nothing but your first law of thermodynamic for a non flow process, a general first law of thermodynamics for non flow process and the since you have volume change here and the pressure also can change the work done during this process has to be obtained by integrating this process one to two. And so you must know the differ, the relationship between P and V in order to perform this integration and in order to find out the work done. Of course the process has got to be quasi static otherwise you cannot or pass equilibrium process otherwise you cannot perform the integration and if you assume that this fluid behaves as an ideal gas then U two remains. U two will be same as U one because for ideal gas if you remember the enthalpy and entropy changes or functions of temperatures only. So for an isothermal process temperature remains constant. That means internal energy has to remain constant and enthalpy also has to remain constant because both are functions of temperature only.

If that is the case and if you are applying this conclusion to the first law of thermodynamics you will find that U two is equal to U one. So you end up with this equation that means heat transfer is equal to work transfer okay for this process. And if you are assuming the gas to be ideal you can replace P ah using this equation P B P V is MRT replace P by MRT by V and perform the integration. So you get this equation. Okay. You can also write the work transfer rate in terms of the pressures. Okay. So this is the, these equations are for the work transfer and heat transfer of an ideal fluid undergoing an isothermal non flow process, okay, and how do you find the entropy change.

Again you can use the T dS equation either the first T dS equation or second T dS equation. Since temperature remains constant you do not have the D U or D H terms. So you just have these terms only. That means the second terms of the T dS equations and where if you perform integration you get this equation. Of course you can get some conclusions out of this for example look at the work transfer equation. If the system is undergoing expansion that means P one is greater than P two then this will be positive. Okay. And if it is expanding system is doing work so one W two is positive. Okay. So that is in accordance with our sign change. And if the system is undergoing compression P one will be less that P two. That means this will be negative and one W two will be negative. That means you are, you have to supply work to the system. Okay. And same similar conclusion for entropy change can be obtained by looking at this equation. For example if when it is expanding that means when it is doing work when it is doing work and if its temperature has to remain constant that means there must be some heat transfer from the surroundings only then the temperature can remain constant. Okay.

That means heat transfer is positive. Okay. Because work transfer is positive heat transfer is positive. When heat transfer is positive you are adding heat to the system. That means its entropy has to change. So that is the case here because S two minus S one has to be positive because entropy is increasing this holds good here because P one is greater than P two. So this is positive this is also positive. Okay.

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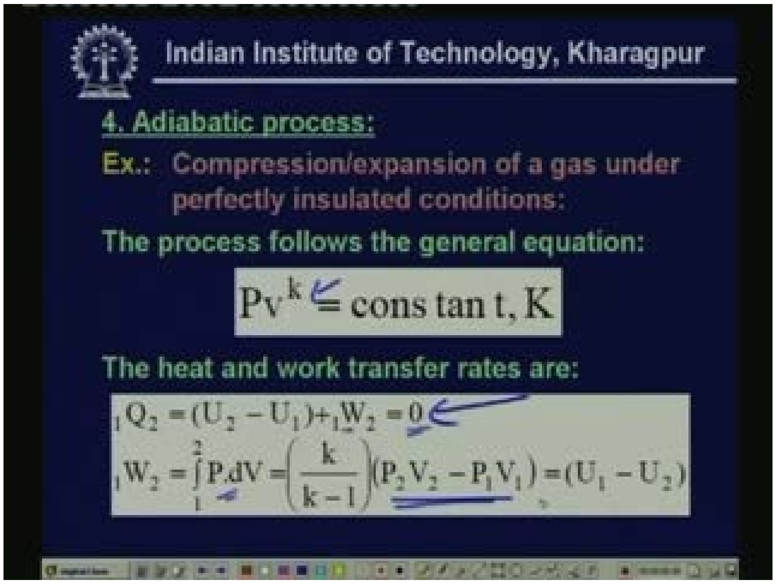

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4. Adiabatic process:

Ex.: Compression/expansion of a gas under perfectly insulated conditions:

The process follows the general equation:

$$\boxed{Pv^k = \text{constant}, K}$$

The heat and work transfer rates are:

$$_1Q_2 = (U_2 - U_1) + {_1W_2} = 0$$

$$_1W_2 = \int_1^2 P.dV = \left(\frac{k}{k-1}\right)(P_2V_2 - P_1V_1) = (U_1 - U_2)$$

Now let us look at another simple process known as adiabatic process. Generally adiabatic process means the process in which there is no heat transfer either to the system or from the system. Okay, such a process is known as an adiabatic process. You can have an adiabatic non flow process or an adiabatic flow process. Let me give an example of an adiabatic non flow process. The example given here is compression and expansion of a gas under perfectly insulated conditions. So you have let us say that the piston cylinder arrangement the gas is contained within the piston cylinder and you are compressing or expanding the gas and at the same time all the walls of the systems are perfectly insulated. Okay. So such a case is the example of an adiabatic process all general all adiabatic process follows the general equation P v to the power of k is constant capital K. Okay. And here P is absolute pressure and v is the volume and k is known as co coefficient of adiabatic compression or adiabatic expansion. Okay. And for such a process and the heat and work transfer rates can be conditions.

So you have, let us say that the piston cylinder arrangement a gas is contained within the piston cylinder and you are compressing or expanding the gas and at the same time all the wall walls of the systems are perfectly insulated. Okay. So such a case is an example of an adiabatic process all general. All adiabatic processes follow the general equation P v to the power of k is constant, capital K. Okay. And here P is absolute pressure and v is the volume and k is known as coefficient of adiabatic compression or adiabatic expansion. Okay. And for such a process the heat and work transfer rates can be obtained again using the first law of thermodynamic processes for a non flow situation. Okay.

That is, this it is the general first law of thermodynamic equation. So one Q two is obviously zero right, because it is an adiabatic process. So no heat is transferred to the system or from the system. So this is the first law of thermodynamics for an adiabatic process. Okay. And since this term is equal to zero the work transfer rate must be equal to the change in the internal energy that is what is shown here. And if we are using this equation along with this equation you get this expression for work transfer rate. Okay. That means work transfer during adiabatic expression is given by k divided by k minus one into P two V two minus P one V one which is nothing but U one minus U two. Okay. So this is the typical ah work transfer for an adiabatic process.

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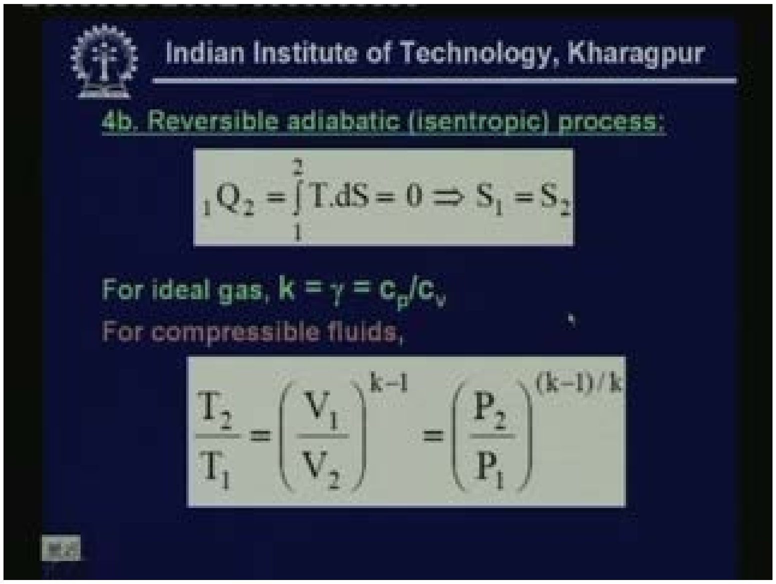

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4b. Reversible adiabatic (isentropic) process:

$${}_1Q_2 = \int_1^2 T.dS = 0 \Rightarrow S_1 = S_2$$

For ideal gas, $k = \gamma = c_p/c_v$

For compressible fluids,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

And if the process happens to be reversible let us say then we have reversible adiabatic process a reversible adiabatic process is also an isentropic process how you prove that. That means a reversible adiabatic process is an isentropic process that means entropy remains constant. It is very easy to prove this if the process is reversible we can use the Clausius inequality that heat transfer rate during in a reversible process is nothing but integral T Ds. Okay. And since one Q two is zero here because its adiabatic integral T dS must be zero since T cannot be zero obviously d S has be zero that means S one is equal to S two. That means a reversible adiabatic process is also an isentropic process. Okay. And if the fluid behaves as an ideal gas then you have an additional relation. This isentropic coefficient k is nothing but isentropic coefficient which is equal to the ratio of C p by C v. Okay.

And for compressible fluids you can get an additional relation this additional relation which relates the temperature with pressure ratios and volume ratios. For example T two by T one is related to the pressure ratio by this relation and it is related to the volume ratio by this relation.

These equations are very useful and we shall see the use of this equation when we perform the actual refrigeration calculations.

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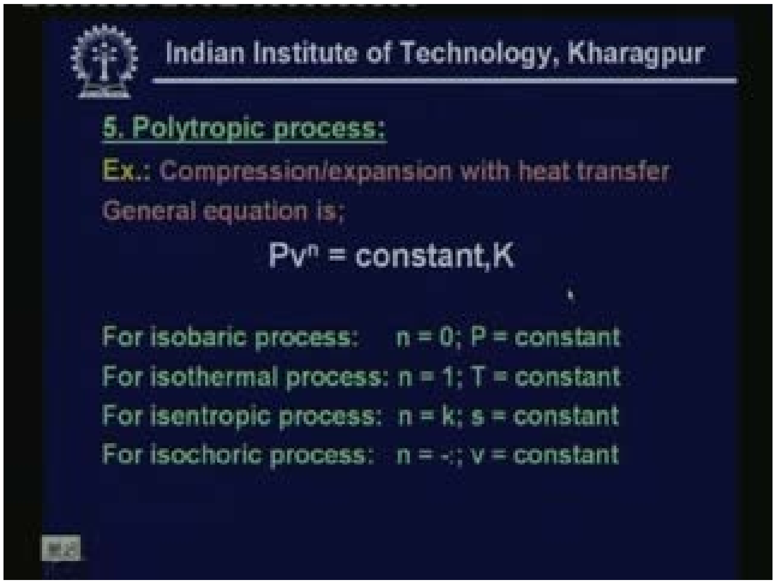

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5. Polytropic process:

Ex.: Compression/expansion with heat transfer

General equation is;

$$Pv^n = \text{constant}, K$$

For isobaric process: n = 0; P = constant

For isothermal process: n = 1; T = constant

For isentropic process: n = k; s = constant

For isochoric process: n = -:; v = constant

Okay. Now let us look at another process called as a polytropic process. A polytropic process is a general process. A typical example of this process is compression or expansion with heat transfer. That means we have the piston cylinder assembly and this assembly consists of a fluid and that fluid is undergoing compression or expansion. And you are not ruling out the possibility of heat transfer that means during compression and expansion there is some heat transfer between the system and the surroundings and here the system means the fluid which is undergoing compression or expansion. Such a process is called as a polytropic process and all the polytropic processes follow general regulation given by P v to the power of n is constant where P is again absolute pressure v is the volume and n is known as polytropic coefficient. And this n can take values anywhere between minus infinity plus infinity that means almost all the processes fall under this polytropic process. For example where for an isobaric process P is constant. So this is example of an isobaric process P is constant that means n has got to be zero. Okay.

So when n becomes zero P where it becomes constant so this polytropic process reduces to an isobaric process. Okay. And when n is equal to one P v is constant and this becomes an isothermal process T is constant. Okay. And for an isentropic process the n simply becomes the polytropic coefficient simply becomes adiabatic coefficients. That means s is constant okay and for isochoric process volume is constant. That means n is equal to minus or it is not printed here n is equal to minus infinity. Okay. So depending upon the value of n the polytropic process encompasses all the processes. Okay. So this is a very general process.

Then how do we find the work transfer and heat transfer?

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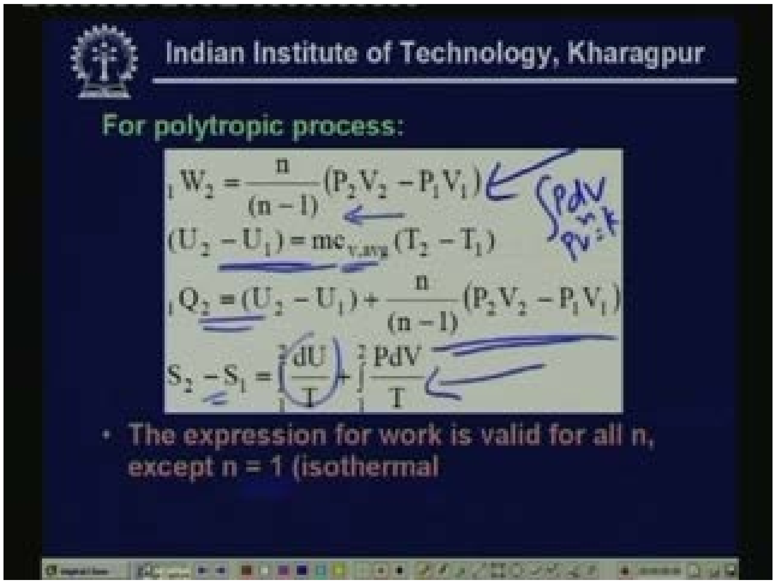

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For polytropic process:

$${}_1W_2 = \frac{n}{(n-1)}(P_2V_2 - P_1V_1)$$

$\int PdV$

$Pv^n = k$

$$(U_2 - U_1) = mc_{v,avg}(T_2 - T_1)$$

$${}_1Q_2 = (U_2 - U_1) + \frac{n}{(n-1)}(P_2V_2 - P_1V_1)$$

$$S_2 - S_1 = \int_1^2 \frac{dU}{T} + \int_1^2 \frac{PdV}{T}$$

- The expression for work is valid for all n, except n = 1 (isothermal

During a polytropic process so that is given here, see again I am taking an example of a flow process. Okay. And the work transfer rate here is obtained by integrating, integral P Dv. Okay. Along with the expression P V to the power of n is constant k. Okay. If i am using these two relations, I can get this equation by integrating P Dv. Okay. And this is the general expression for internal energy change. Internal energy change is given by mc into delta T where c is the average specific heat at constant volume. Okay.

And this is nothing but your statement of first law of thermodynamics for a non flow process what we have done here is one Q two is nothing but U two minus U one and this term is nothing but your work transfer rate. Okay. So this is the simply your heat transfer in a polytropic process and the general entropy equation for entropy change in a polytropic process is given by this. This is nothing but the integration of the T dS equation that means when you perform the integration of the first T dS equation you get this kind of an expression and depending upon the relationship between d U and T and P dV and T you can find out what is the entropy change. Okay. For example if it is let us say an ideal gas then you can write and if you are also assuming that c v is only function c v is constant then you can write this as c v d T. Okay. Similarly P can be expressed in terms of P by T can be expressed in terms of V and you can get expression for S two minus S one.

And this equation is valid for all n except n is equal to one so when n is equal to one obviously here this becomes, you cannot evaluate this. Okay. In such case n is equal to one the process becomes isothermal and as we have seen how to evaluate work transfer for an isothermal process. Okay and the last process is what is known as constant enthalpy or isenthalpic process.

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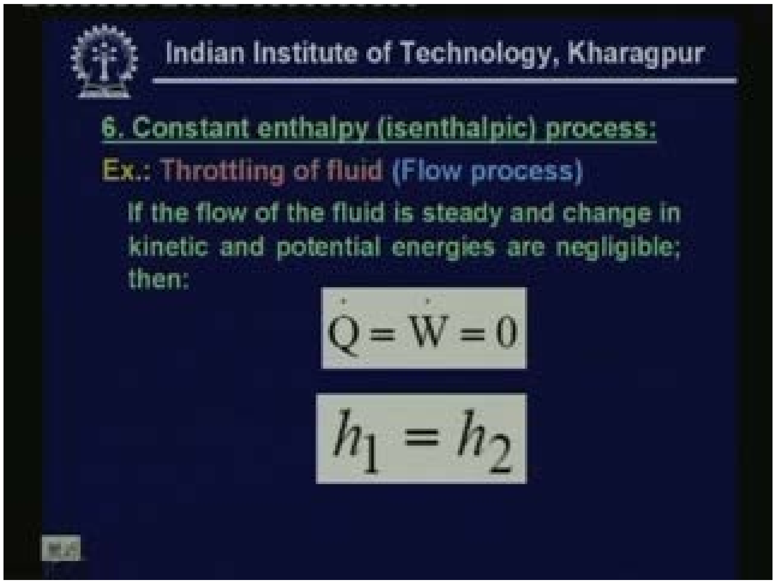

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6. Constant enthalpy (isenthalpic) process:

Ex.: Throttling of fluid (Flow process)

If the flow of the fluid is steady and change in kinetic and potential energies are negligible; then:

$$\boxed{\dot{Q} = \dot{W} = 0}$$

$$\boxed{h_1 = h_2}$$

This is again a very important process as far as refrigeration is concerned and the typical example of this either throttling of a fluid that means a fluid is flowing through a continued and suddenly it encounters a resistance. Okay. For example a fluid is flowing through a tube and suddenly a valve is there in the tube and valve is almost closed. So the fluid has to flow through an almost closed valve. That means a large resistance is suddenly imposed on the fluid flow. Okay. Obviously what happens there will be large amount of friction and because of the friction the pressure drops. That means there will be an expansion. Okay. The pressure drops from the inlet pressure to an exit pressure. Okay.

So this is an example of a throttling process. Throttling process also takes place when you are forcing the fluid, excuse me, through a narrow tube. For example a capillary tube in a vapour compression refrigeration system okay for a typical throttling process. If you are assuming a flow process that means let us say that we are assuming the process to be steady flow. Okay. And if you are if you are also assuming that the kinetic and potential energy changes are negligible during this process. Okay.

Then this is nothing but for such kind of process. If you are assuming that the throttling is taking place in the small area then there is no area available for heat transfer. So Q dot will be zero and no work done during this process so W dot is also zero so Q dot and W dot are zero for the throttling process in a steady flow. Okay. And if you are assume applying the steady flow energy equation which I have discussed in the last class under these assumptions of negligible kinetic and potential energy changes and no heat and work transfer you get this equation. Okay. That means finally the throttling process is an isenthalpic process. So in the fundamentals of heat transfer and fluid flow. Okay.

Thank you.