Applied Thermodynamics

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Module - 01
Review of Basic Thermodynamics
Lecture - 01
Thermodynamic Systems and Pure Substances

Dear learners, greetings from IIT Guwahati. I welcome you to this course Applied Thermodynamics. It is being offered under MOOCs platform by Centre for Educational Technology IIT Guwahati. So, we are in the 1st module that is module 1 and in this module we will discuss about the basic aspects of thermodynamics and this title of this module I have kept it as a Review of Basic Thermodynamics.

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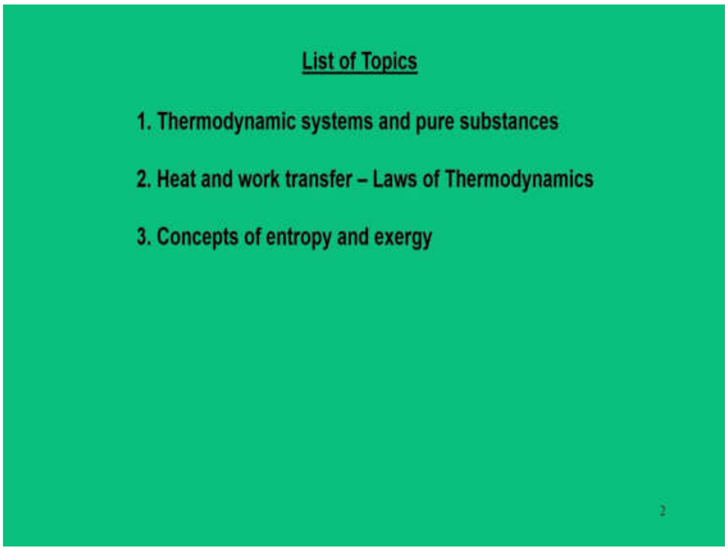

List of Topics

1. Thermodynamic systems and pure substances
2. Heat and work transfer – Laws of Thermodynamics
3. Concepts of entropy and exergy

So, under this topic the following components will be covered. The 1st lecture will be thermodynamic systems and pure substance. 2nd lecture would be heat and work transfer, we will discuss about laws of thermodynamics and 3rd one will be concepts of entropy and exergy. Please remember these are the review concepts. So, we will basically give importance to the basic understanding that has been covered at the UG level.

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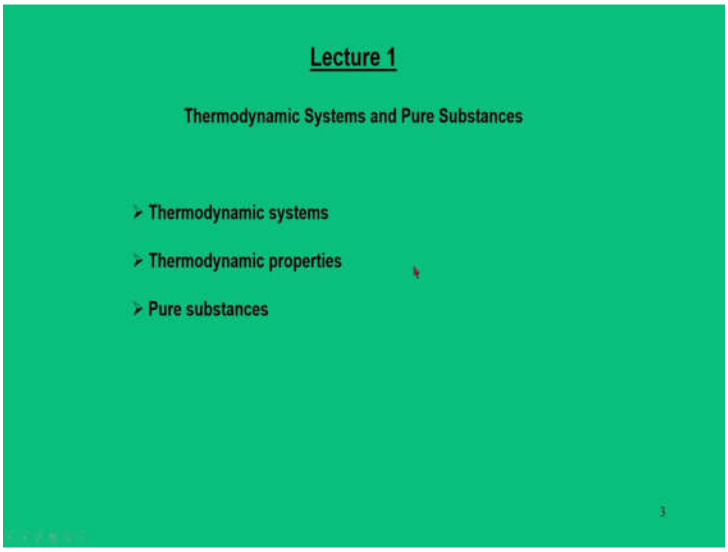

Lecture 1

Thermodynamic Systems and Pure Substances

- Thermodynamic systems
- Thermodynamic properties
- Pure substances

Now, in the first lecture that is thermodynamic systems and pure substances. I will touch upon the thermodynamic systems with its basic terminology, properties then we will discuss something about pure substance.

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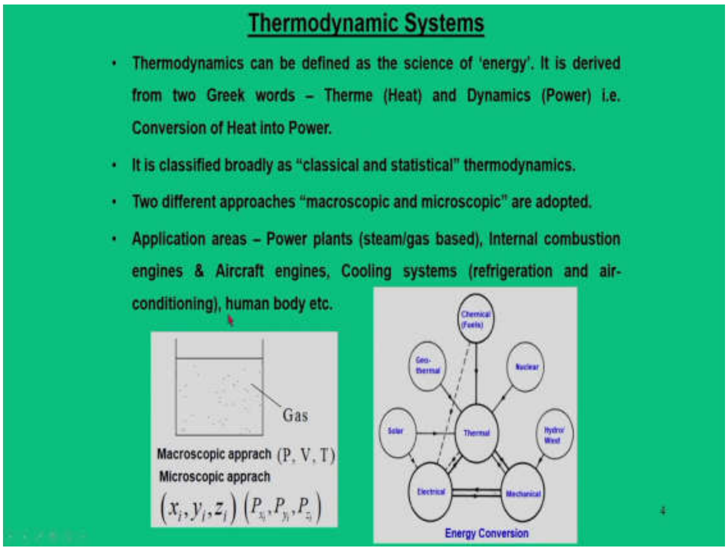

Thermodynamic Systems

- Thermodynamics can be defined as the science of 'energy'. It is derived from two Greek words – Therme (Heat) and Dynamics (Power) i.e. Conversion of Heat into Power.
- It is classified broadly as "classical and statistical" thermodynamics.
- Two different approaches "macroscopic and microscopic" are adopted.
- Application areas – Power plants (steam/gas based), Internal combustion engines & Aircraft engines, Cooling systems (refrigeration and air-conditioning), human body etc.

So, let me start the word thermodynamics how it comes from. So, as I mentioned in my first introduction lecture, thermodynamics is nothing but the conversion of heat and power. So, human mankind has been habituated with different source of energy and its requirements in various forms.

So, they are electrical, thermal and mechanical and for all these things the very basic bottom line is the thermal energy and which is in the abundant form and we also need to know how to convert the thermal energy into various forms and for this conversion, we require some kind of fundamental laws that we get from the basic concepts of thermodynamics.

So, the word thermodynamics has two components and they are from the Greek words that is Therme which is means heat, other is dynamics which means power. So, basically it is a conversion of heat into power. These thermodynamics is mainly classified as a "classical thermodynamics" and "statistical thermodynamics".

Statistical means you do go with a very microscopic approach and classical thermodynamics goes in a macroscopic approach. By macro and microscopic approach I mean, when a gas is contained in a cylinder as shown in this figure. So, in a microscopic approach we will say state it has certain pressure certain P, volume V and temperature T.

But, when you thing this gas in a microscopic approach then we have to divide this entire container into coordinate systems that is x, y, z and we are looking about every molecules minutely and its locations and corresponding its pressures. So, likewise for the molecule i whose coordinate is x_i, y_i and z_i, we say its pressure is P_{xi}, P_{yi} and P_{zi}. So, likewise all other parameters can be defined.

But however, our approach in this course should be a macroscopic approach where we are looking at the global behaviour of a given situation. And as we will show that this course is about applied thermodynamics, so, it has a lot of application areas. And in fact, this particular course is mainly deal with different power plants, internal combustion engines, aircraft engines, cooling systems, which means refrigeration and air conditioning. In fact, human body has lot of thermodynamic systems, which is governed by its principle.

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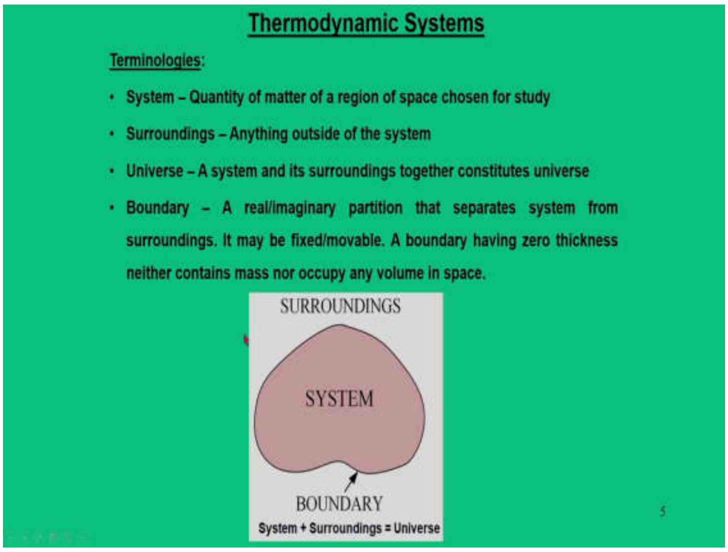

Thermodynamic Systems

Terminologies:

- System – Quantity of matter of a region of space chosen for study
- Surroundings – Anything outside of the system
- Universe – A system and its surroundings together constitutes universe
- Boundary – A real/imaginary partition that separates system from surroundings. It may be fixed/movable. A boundary having zero thickness neither contains mass nor occupy any volume in space.

System + Surroundings = Universe

So, let me give a basic terminology. When you deal with the thermodynamic systems at UG level you must have come cross many such terminology and which are available in many fundamental textbooks. So, I will touch upon some of them. First is system: In thermodynamic sense when we say it is a system, its nothing but a quantity of matter or region in the space chosen for the study.

For example, in this figure if you have a system that means, this particular colored region has been chosen for our user attention. So, if this is our system then apart from the system rest of the things are called surroundings and the system plus surroundings constitutes a universe.

So, this is all about the fundamental definitions of system or surroundings. And in fact, obviously, this system and surrounding must have a boundary. So, we call this as a boundary. So, this boundary could be a flexible boundary or it could be a fixed boundary. So, this is how it is defined in the form of thermodynamics.

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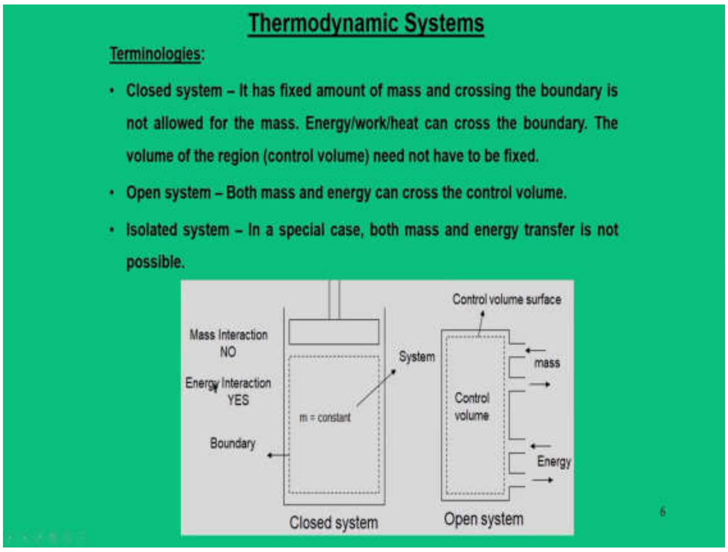

Thermodynamic Systems

Terminologies:

- Closed system – It has fixed amount of mass and crossing the boundary is not allowed for the mass. Energy/work/heat can cross the boundary. The volume of the region (control volume) need not have to be fixed.
- Open system – Both mass and energy can cross the control volume.
- Isolated system – In a special case, both mass and energy transfer is not possible.

Then we have come across different types of systems in thermodynamics. One is closed systems, open system and isolated system. So, what does this mean basically in our terminology is that when you talk about a closed systems; normally when you say the system, the system can have mass interactions, it can have energy interactions or it can have both.

But, when you say it is a closed systems, we have to say there is no mass interactions, but energy interaction is possible. And typical example could be given as a piston cylinder devices where a certain volume or certain quantity of mass is always compressed or expanded in certain region. So that means, there is no mass interactions there is no mass coming into it, but it can do energy interactions. So, while doing so, what happens? The gas is compressed.

So, the gas compressed and in some situations its temperature goes up. So, there could be energy interactions in the form of heat. So, when we do not have mass interaction, but energy interaction is possible, it is a closed system. But when we have both the things possible, like there is as mass interaction as well as energy interactions then we call this as a open system.

Now, in some situations or a special case when there is no mass and energy interaction is possible then we call it as a isolated systems. And in our terminology normally when we say it is a open system we have a control volume approach. So, we call this as a control volume. So, the volume or space under the chosen for the study we call this as a control volume.

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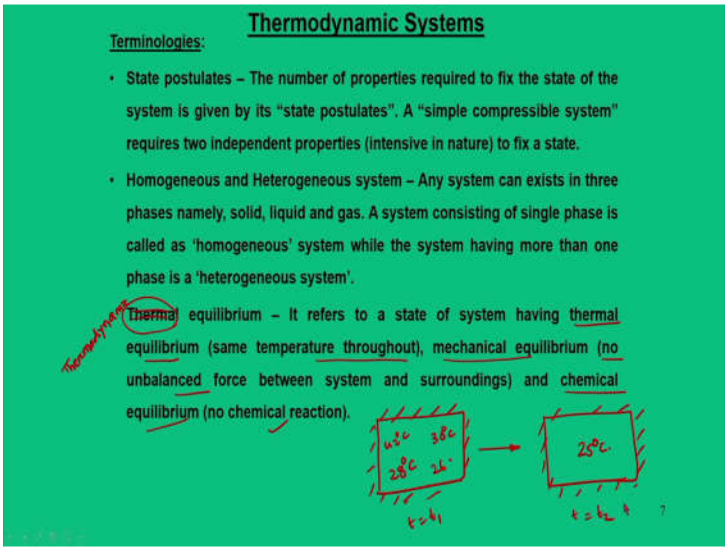

Thermodynamic Systems

Terminologies:

- State postulates – The number of properties required to fix the state of the system is given by its "state postulates". A "simple compressible system" requires two independent properties (intensive in nature) to fix a state.
- Homogeneous and Heterogeneous system – Any system can exists in three phases namely, solid, liquid and gas. A system consisting of single phase is called as 'homogeneous' system while the system having more than one phase is a 'heterogeneous system'.
- ~~Thermal~~ Thermodynamic equilibrium – It refers to a state of system having thermal equilibrium (same temperature throughout), mechanical equilibrium (no unbalanced force between system and surroundings) and chemical equilibrium (no chemical reaction).

The other terminology could be is the state postulates. State postulates means, when a system is at a given situation if you want to define a system we have to give some name to it, here we name I mean coordinates of the system. So, coordinate of the system could be its property.

So, the number of properties that are required to fix the state of a system is known as state postulates. A typical example could be a simple compressible systems, which requires two independent properties; mainly pressure, temperature or volume, specific volume. So, these are required to fix the state. Then we have a homogeneous and heterogeneous systems.

So, any system can exist in three phase. So, it can be solid phase, liquid phase or gas phase. When you say homogeneous system that means, it contains a single phase there is no multiple phase present in it. So, it is a homogeneous system, but when the system has more than one phase then we call as a heterogeneous systems.

The next word that we are going to use frequently is the thermal equilibrium. So, it refers to a state of a system where having a thermal equilibrium, it refers to a state of a system when there is same temperature throughout. It also has mechanical equilibrium and it also has a chemical equilibrium.

So, basically thermal equilibrium has three components. One is its temperature is same throughout. When you have a mechanical equilibrium it has no unbalanced force and when you have chemical equilibrium we have no chemical reactions.

So, the word instead of using thermal you will use this as a thermodynamic equilibrium. So, this thermodynamic equilibrium has three components that is thermal equilibrium, mechanical equilibrium and chemical equilibrium. So, in most of our situation when you will we will talk about thermal equilibrium which means that for a given system if you look at a particular system and it contains may be a gas, but this container has a non uniform temperature at $t = t_1$.

So, let us say at different locations we measure the temperature had different values like 42, 30, 28, 26 but that is at time $t = t_1$. Now, when it goes to a thermal equilibrium we expect that entire container will have uniform temperatures throughout or same temperature throughout. Let us say 25 degree; that means, at $t = t_2$ the system attains thermal equilibrium.

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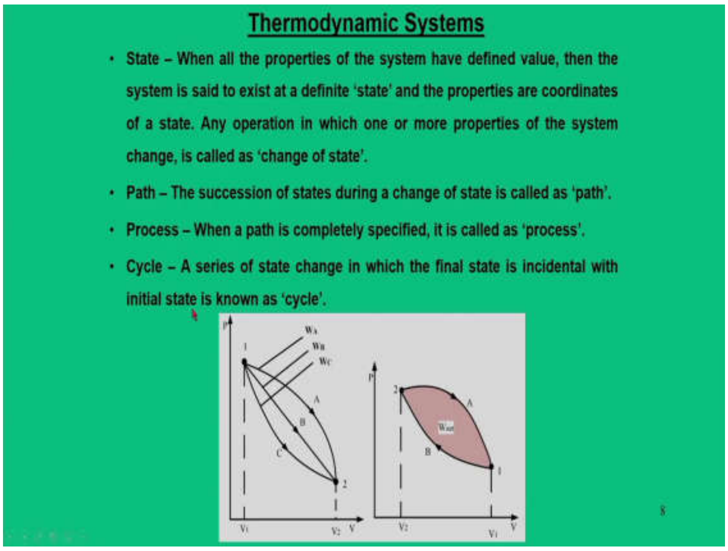

Thermodynamic Systems

- State – When all the properties of the system have defined value, then the system is said to exist at a definite 'state' and the properties are coordinates of a state. Any operation in which one or more properties of the system change, is called as 'change of state'.
- Path – The succession of states during a change of state is called as 'path'.
- Process – When a path is completely specified, it is called as 'process'.
- Cycle – A series of state change in which the final state is incidental with initial state is known as 'cycle'.

Then next terminologies are state, path, process and cycle. So, the state of a system means, it has a definite value and definite value I give in terms of its properties. So, the properties are nothing but the coordinate of the states. So, for example, in this particular PV diagram if I want to define a coordinate, pressure and volume; that is point 1 that is the state. So, that is the state of the systems.

Now, in another situations, the state of the system change to point 2, where the coordinates also change. In this way there is a change in the state. So, that is called change in the state. Now, while changing a state it can follow different path. So, path could be A, B, C and for different path it can spend most of its energy in the form of work or heat. So, the path could be A, B, C.

So, that means, we can have infinite ways we can reach from 1 to 2, this is called as a path. And when a path is completely described; that means, if you can give the path as a form of a equation then we call this as a process. So, you have to say that 1 to 2, I can have a process A, I can have also process B or I can have a process C. So, this is what we call as a process; that means, this path is completely specified.

Then cycle; what do you mean by cycle? That means, when a system from its initial state goes to a final states and then come back to its original state. So, in this process it comes a cycle. So, for example, in this particular figure the system state 1 goes to state 2 in a path B, but on return also it comes to another path A and comes backs to original states. So, in this way we say it is a cycle. So, this is the series of state change in which the final state is identical to the initial state is known as a cycle.

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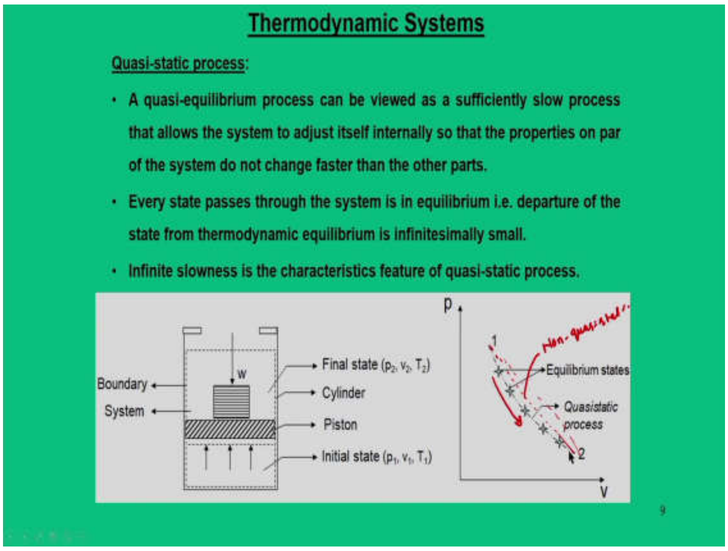

Thermodynamic Systems

Quasi-static process:

- A quasi-equilibrium process can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that the properties on par of the system do not change faster than the other parts.
- Every state passes through the system is in equilibrium i.e. departure of the state from thermodynamic equilibrium is infinitesimally small.
- Infinite slowness is the characteristics feature of quasi-static process.

Now, in the thermodynamic systems many a times we will come across a word which is called as a quasi static. Quasi-static means, it is a infinite slowness of a system. So, it is a very slow process. And what does this mean thermodynamically to us that if you want to explain this, let us consider this particular figure. So, we have a particular piston cylinder system device in which there is a weight which keeps this piston in balance positions.

So, its initial state I can make that it is the point 1, I can give the initial state. So, the system is in equilibrium because the gas which is in the bottom of the piston exerts a force on the bottom of the piston and this is balanced by the weight, which is acting on it. So, in this way we say that this initial state of the system is point 1.

Now, another way I am looking at that if I remove this weight instantly then I can come back to a state 2, but in this process it will not be a quasi static. So, to define a quasi static, what I will say is that I will assume that this particular total weight W can be divided into small segments of weight of very small mass and each time I will remove one-one mass.

So, that there is a very minute change in the system. So, the next equilibrium state which I can achieve is here. So that means, if I remove the first layer of weight the system goes from 1 to the first star. If I remove the second layer of mass the system goes from the state 1 to the second star. So, likewise the process will follow in a particular slow fashion and finally, it is going to land in the point 2.

So, this particular process is a quasi static process, but had I removed this weight instantly then this process would have reached very instantaneous manner and this is not qualified as a quasi static process. So, this dotted line I will refer as a non quasi static and the path that is followed through stars they are given as a quasi static process.

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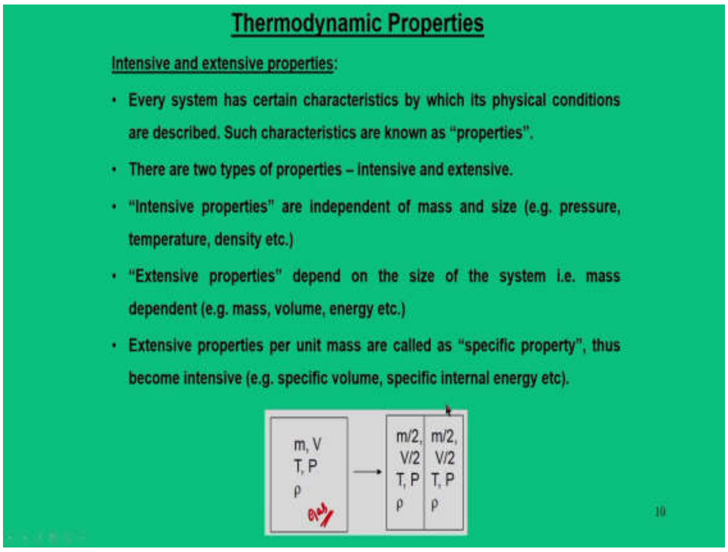

Thermodynamic Properties

Intensive and extensive properties:

- Every system has certain characteristics by which its physical conditions are described. Such characteristics are known as "properties".
- There are two types of properties – intensive and extensive.
- "Intensive properties" are independent of mass and size (e.g. pressure, temperature, density etc.)
- "Extensive properties" depend on the size of the system i.e. mass dependent (e.g. mass, volume, energy etc.)
- Extensive properties per unit mass are called as "specific property", thus become intensive (e.g. specific volume, specific internal energy etc).

Then comes back to thermodynamic properties. So, when you talk about properties, in fact, these are nothing but the coordinates of the state. And in the sense of thermodynamics we define in two categories one is intensive properties other is extensive properties.

So, what do you mean by intensive properties? So, intensive properties are independent of mass and size. So, typical example could be pressure, temperature and density. So, they are not dependent. And extensive properties depend on the size of the system that is mass dependent. And of course, extensive properties per unit mass we call this as a specific properties and also they become intensive.

For example specific volume becomes an intensive properties, whereas, volume is a extensive properties. Similarly, specific internal energy is an intensive properties, but internal energy is only extensive properties.

A typical example could be given in this way that how do you distinguish an intensive and extensive properties. For example, if you look at a container having a certain gas and it has a mass m, volume V, pressure P, temperature T and density ρ. So, what you do is you insert a physical partition into this container. So, in such a way that entire volume becomes half.

So, volume becomes V/2, mass becomes m/ 2, but what remains unchanged that both partitions will have same pressure, same temperature and same density. So that means, these three properties do not change through this partition. So, they are called as intensive properties. Whereas, what changes? Mass and volume. So, they are extensive properties, so that means, they depend on the size of the system.

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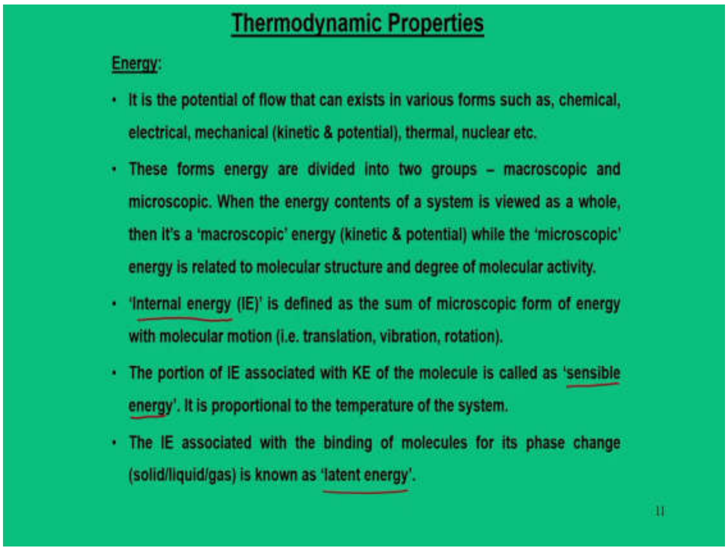

Thermodynamic Properties

Energy:

- It is the potential of flow that can exists in various forms such as, chemical, electrical, mechanical (kinetic & potential), thermal, nuclear etc.
- These forms energy are divided into two groups – macroscopic and microscopic. When the energy contents of a system is viewed as a whole, then it's a 'macroscopic' energy (kinetic & potential) while the 'microscopic' energy is related to molecular structure and degree of molecular activity.
- 'Internal energy (IE)' is defined as the sum of microscopic form of energy with molecular motion (i.e. translation, vibration, rotation).
- The portion of IE associated with KE of the molecule is called as 'sensible energy'. It is proportional to the temperature of the system.
- The IE associated with the binding of molecules for its phase change (solid/liquid/gas) is known as 'latent energy'.

Next important property that we deal with is energy because the thermodynamic is nothing but the energy conversion from one form to other. So, how do you define this energy and in fact, it is also considered as a very important thermodynamic properties. So, it is nothing but the potential of the flow that can exist in various form; chemical, electrical, mechanical, thermal, nuclear etc, but we will be mainly focusing on the thermal part.

So, these energies also can be viewed as a macroscopic energy or microscopic energy. So, macroscopic energy is related to the global behavior in the form of kinetic energy, potential energy, whereas, microscopic nature would depend on the molecular structure and degree of molecular activities. In fact, kinetic theory of gases are the examples in which we deal with microscopic form of energy.

And very important energy that we are going to come across is the internal energy. In fact, this internal energy was introduced when you discuss on first law and it is nothing but the sum of microscopic form of energy with respect to molecular motions. So, it could be translation, vibration and rotation, but we are looking as a whole all this microscopic form of energy has one global form that is ‘internal energy’.

And later on from the first law we will say that this internal energy is nothing but it is a function of temperatures. The portion of internal energy with respect to kinetic energy in molecule is called as sensible energy. That means, the molecular motions have some energy in the form of their motion that means, we say it is a kinetic energy of molecules.

So, they are consider as a sensible energy. So, internal energy has two components. One is sensible part. Other is the binding force of the molecules with respect to phase change. So, this particular component we call as latent energy. So, internal energy have two components. One is sensible energy, one is latent energy. So, these two are very important and when you sum it up will give the total internal energy of the system.

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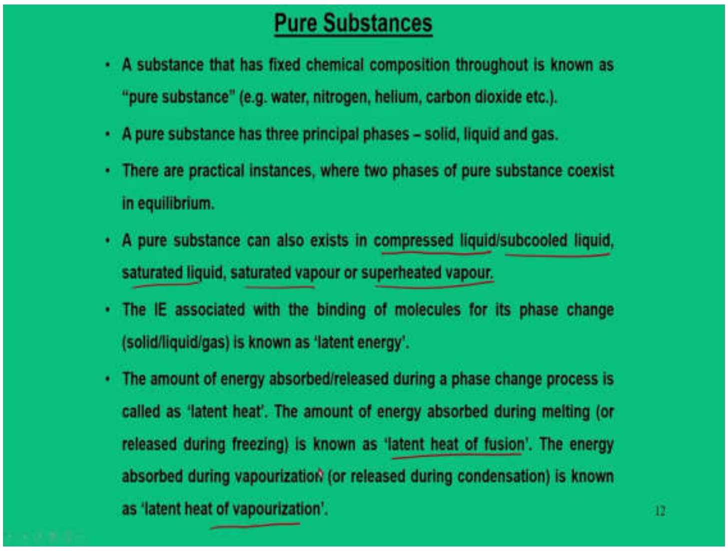

Pure Substances

- A substance that has fixed chemical composition throughout is known as “pure substance” (e.g. water, nitrogen, helium, carbon dioxide etc.).
- A pure substance has three principal phases – solid, liquid and gas.
- There are practical instances, where two phases of pure substance coexist in equilibrium.
- A pure substance can also exists in compressed liquid/subcooled liquid, saturated liquid, saturated vapour or superheated vapour.
- The IE associated with the binding of molecules for its phase change (solid/liquid/gas) is known as ‘latent energy’.
- The amount of energy absorbed/released during a phase change process is called as ‘latent heat’. The amount of energy absorbed during melting (or released during freezing) is known as ‘latent heat of fusion’. The energy absorbed during vapourization (or released during condensation) is known as ‘latent heat of vapourization’.

And more things will be clear when you clear about this internal energy in the form of latent energy or sensible energy, when you deal with the pure substance. So, what do you mean by a pure substance? So, a substance that has a fixed chemical composition throughout is known as a pure substance.

And in our thermodynamic sense we have categorized them as liquids or gases. So, the very common liquid is our water and gases that are available with us is nitrogen, helium, oxygen; all these things are called as a pure substance. And all these pure substances they have three principal phase that is solid, liquid and gas.

Now, when we say it is a pure substance there are some situations where two or more phases can coexist that means, they are in equilibrium. So, that is also possible where two or more substance can be in equilibrium. And typically when you say that what are the different forms in which the substance exist in nature. So, they are in either compressed liquid or subcooled liquid.

So, this is nothing but what we mean as a liquid state, it can be a saturated liquid, it can be a saturated vapour or it can be a super heated vapour. So, these are the fundamental existence of a pure substance in nature. So, this is applicable for all types of substances. Now, here when we have a liquid state or vapour state, so that is what the importance of internal energy comes into picture it can have a latent energy or it can have a sensible energy.

So, as I mentioned earlier, so, sensible energy is associated with the random molecular kinetic energy of the molecules, latent energy is associated with respect to binding force among the molecules. So, basically when you change the state that means solid to liquid, there is a physical phase change then we say it is a latent energy.

But here the word energy we are now going to replace with heat because this energy is nothing but this is in the form of heat. So, the amount of energy absorbed or release during a phase change process is called as a latent heat. So, during melting or the energy release during freezing is known as latent heat of fusion. The other term that we are going to use in the case of vaporization, where the energy could be absorbed or it will be released during condensation is known as latent heat of vapourization.

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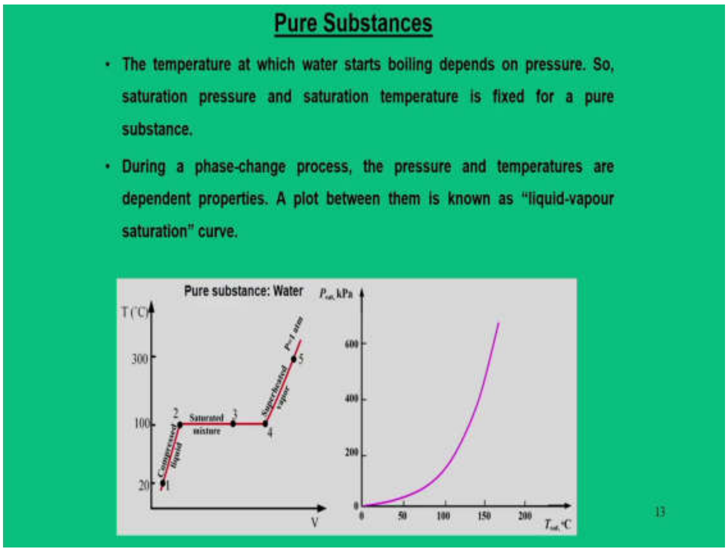

Pure Substances

- The temperature at which water starts boiling depends on pressure. So, saturation pressure and saturation temperature is fixed for a pure substance.
- During a phase-change process, the pressure and temperatures are dependent properties. A plot between them is known as "liquid-vapour saturation" curve.

So, let us explain how different state of a system is possible in thermodynamic coordinate systems. By thermodynamic coordinate system I mean it is pressure, temperature and volume. So, you have to keep one as a constant and plot the other two parameters. So, for example, for a if you take a pure substance of water and we are plotting this different state of water in a temperature volume coordinates.

So, at one atmospheric; that means, at normal atmospheric pressure when we say water at 20°C, we say it is a liquid state. So, it is a liquid state and in our term either we can say it is a compressed liquid or subcooled liquid whatever way we can thermodynamically tell this. So, it is a liquid state.

Now, if you keep on increasing the temperature it goes to a state 2; that means, when you reach 100°C for water, So, it is in the saturated liquid state. So, point 2 is in the saturated liquid state, but still it is about to vapourize, but it has not change its state to vapour. So, you call this as a saturated liquid state.

Now, if you keep on further increasing the temperature, then the liquid has to change its state that means, this binding force has to be broken by adding more and more heat. When you keep on adding more and more heat, the temperature does not change, but its liquid changes its state to vapour. So, this will keep on happening till the state 2 reaches to state 4. So, when we state 4 that means, entire liquid which was at state 2 has now comes to vapour state.

So, this is at the state 4, but what happens in the intermediate between 2 and 4? So, in between 2 and 4 there is another state that is state 3 which is in the liquid vapour mixture state. So, the state 3 is the saturated liquid vapour mixture. It is a liquid vapour mixture state. Now, from 4 again we keep on adding heat then what will happen is we will reach the state 5; where it is a single phase system, it is what we call as a super heated vapour.

So, this is all about the different 5 thermodynamic states that happens on a single line and this is only at 1 atmospheric pressure. Now, if you keep on increasing the pressure this line will go up. So, this is how we define this different state of water that is from 1, 2, 3, 4 and 5 and this has been plotted for 1 atmosphere.

Now, if you change this pressure and we will define some parameter what we call a saturation pressure and saturation temperature. So, saturation pressure and temperature I mean when we are at the saturated state that is at point 2 or 4. So, these are the nothing but the saturation temperature is 100°C.

So, when we say saturation temperature is 100°C and pressure is about 100 kilo Pascal; that means, it is about 1 atmosphere. But when saturation temperature is 150, the saturation pressure also goes up. So, we can have a plot that means, saturation pressure increases with respect to saturation temperatures.

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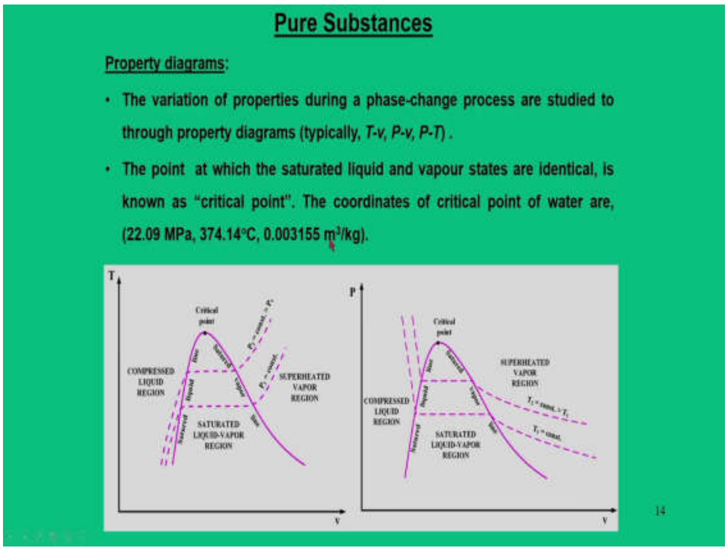

Pure Substances

Property diagrams:

- The variation of properties during a phase-change process are studied to through property diagrams (typically, *T-v, P-v, P-T*) .
- The point at which the saturated liquid and vapour states are identical, is known as "critical point". The coordinates of critical point of water are, (22.09 MPa, 374.14°C, 0.003155 m³/kg).

Now, moving further if you extrapolate all this data for all sorts of pressure and temperature we will have a dome and this dome what we call as a temperature volume diagram and normally we call this as a property diagram. So, the variation of properties during a phase change process are studied through property diagrams.

So, this property diagram when you look at liquid and vapour mixture and all saturated points if you draw them and prepare a locus then it will form as a dome. So, what we have seen here? So, if you look at the first dotted line where pressure is P_1 and the second pressure line P_2 that is P_2 greater than P_1.

So, this length of the straight line which is in between dome is reduces and if you keep on increasing the pressure, entire line becomes a point and what we call as a critical points. So, basically in this saturation line we can have two distinct zones. One is saturated liquid line other is saturated vapour line. They are separated by a point what we call as a critical point.

And beyond this dome we have a compressed liquid region and beyond the saturated vapour line dome we have super heated vapour region. In between the dome we call this as a saturated liquid vapour regions. So, this is all about temperature volume plot and we can replicate the same figure in the pressure specific volume plot.

So, here the lines will be just reverse, so, temperature line T_2 will go up, the temperature line also keeps on increasing. And for water this critical point coordinates would be 22.019 Mpa, 374.14°C and 0.003155 m^3/kg.

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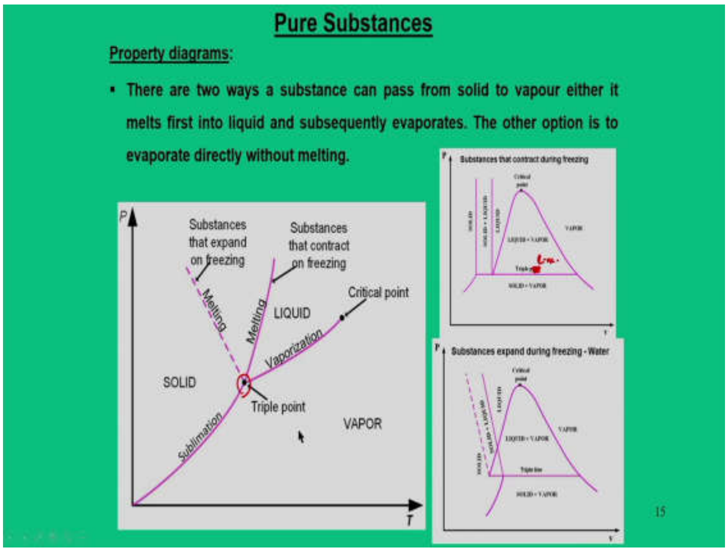

Pure Substances

Property diagrams:

- There are two ways a substance can pass from solid to vapour either it melts first into liquid and subsequently evaporates. The other option is to evaporate directly without melting.

Now, if you extend this particular property diagram with respect to solid phase what is going to happen? The similar pressure volume plot can be plotted. Now, here when you have solid phase after this dome we will have a line which is solid plus liquid and another is purely solid.

And there will be another line which is called as a triple line and this triple line will separate solid with respect to vapour and here there are two plots in the pressure volume coordinates. One is the substances that expand during freezing and the substances that those contract during freezing.

So, the basic philosophy lies here that entire pressure volume diagram now is replicated in a another diagram, which is pressure temperature diagram where this triple line becomes a point. So, the main importance of this diagram is that it can clearly distinguish the different phase of a pure substance that is solid, liquid and vapor.

And all these things like we have discussed about melting, we have discussed about vapourization and we are going to discuss about sublimation that means, a substance can go from solid to vapor through a process that is called a sublimation. And all these three lines they exist at a point in a pressure temperature diagram and we call this as a triple point.

So, at a triple point all the three phases of a pure substance coexist that means, at that point we can have a substance in the solid as well as liquid, as well as gas.

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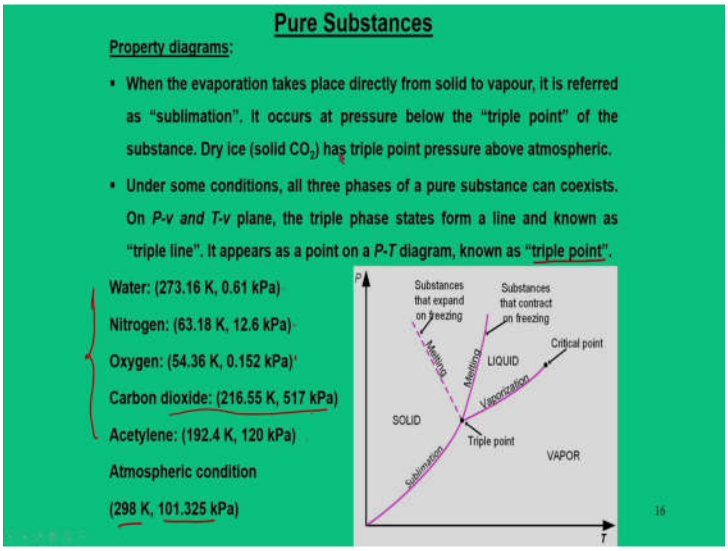

Pure Substances

Property diagrams:

- When the evaporation takes place directly from solid to vapour, it is referred as "sublimation". It occurs at pressure below the "triple point" of the substance. Dry ice (solid CO_2) has triple point pressure above atmospheric.
- Under some conditions, all three phases of a pure substance can coexists. On *P-v and T-v* plane, the triple phase states form a line and known as "triple line". It appears as a point on a *P-T* diagram, known as "triple point".

Water: (273.16 K, 0.61 kPa)

Nitrogen: (63.18 K, 12.6 kPa)

Oxygen: (54.36 K, 0.152 kPa)

Carbon dioxide: (216.55 K, 517 kPa)

Acetylene: (192.4 K, 120 kPa)

Atmospheric condition

(298 K, 101.325 kPa)

So, here the importance of this pressure temperature diagram is because it gives a triple point. So, the main important things that I am going to emphasize here that when you look at actually the pure substance that are available in nature, in some substances they have the triple point pressure temperature coordinates above atmospheric and most of them have below atmospheric.

For example, if you have atmospheric pressure of 101 kPa and 298 K and if you look at water, nitrogen, oxygen, carbon dioxide and acetylene. So, all these four categories if you try to compare we can see that acetylene has a value close to the atmospheric value. But all like water, nitrogen and oxygen they have triple point value much much less than atmospheric. But one significant thing that we can see is the carbon dioxide.

So, it has a peculiar characteristics of triple point value that is 216.55 K and 517 kPa. So, this makes us thinking that if you look at carbon dioxide this carbon dioxide can be thought of existing in two phases. One is solid phase other in gas phase through sublimation process. And in our commercial term we call this as a dry ice and which are being used in many commercial applications. So, this is how I want to emphasize about this pressure temperature diagram.

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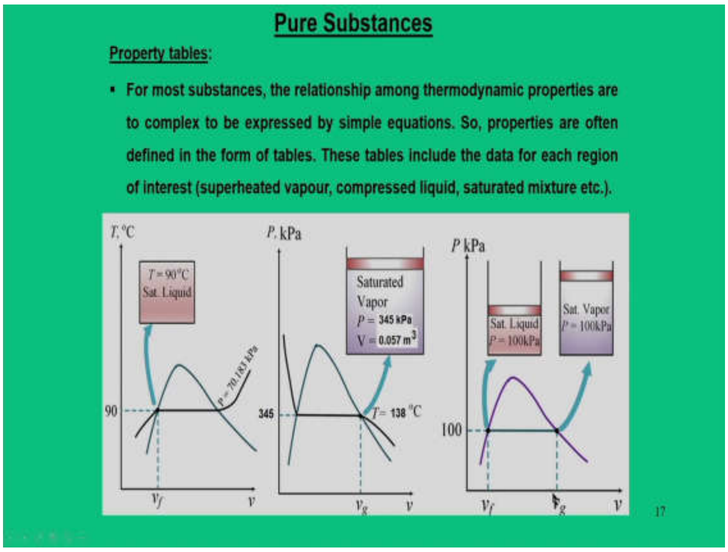

Pure Substances

Property tables:

- For most substances, the relationship among thermodynamic properties are to complex to be expressed by simple equations. So, properties are often defined in the form of tables. These tables include the data for each region of interest (superheated vapour, compressed liquid, saturated mixture etc.).

Now, we will give some introduction about property tables. So, when you deal with the property tables I told that how many coordinates are required to fix the state. So, first thing is that we are in the saturated liquid state. When we are in saturated liquid state we require just one parameter either pressure or temperatures or if you look at saturated vapor also we will require either one temperature.

So, this is how we say that 100 kPa is sufficient to say that whether we can have a saturated liquid or saturated vapor state and it has two specific volume value V_f and V_g.

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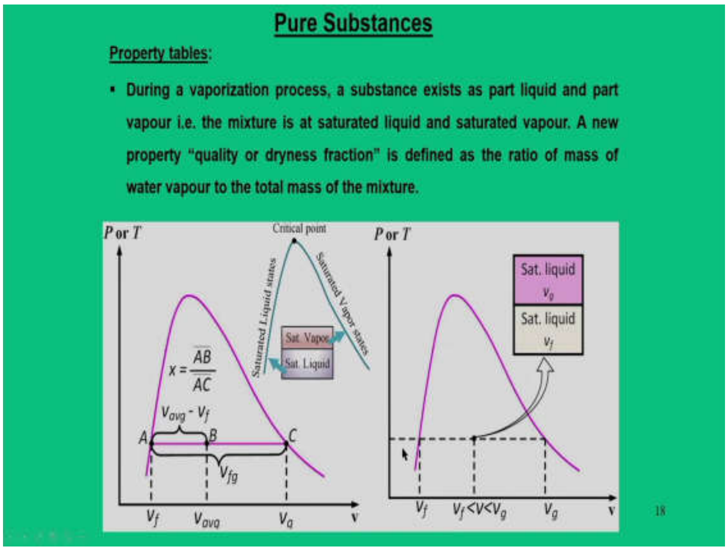

Pure Substances

Property tables:

- During a vaporization process, a substance exists as part liquid and part vapour i.e. the mixture is at saturated liquid and saturated vapour. A new property "quality or dryness fraction" is defined as the ratio of mass of water vapour to the total mass of the mixture.

Now, when we are in intermediate points; that means when we are in the saturated liquid vapor mixture region that is in this dome, then we will have some intermediate points which can be calculated through linear interpolations. So, the average properties values let us say at point B. So point A is the saturated liquid state, point C is the saturated vapor state, its specific values volumes are defined as V_f and V_g.

But average property of point B can be defined as V_{fg} which is nothing but we can define a parameter x that is AB/AC; that means, through linear interpolations from this distance we can calculate this x. And this x we call this as a quality of the substance or dryness fractions and in our steam table term we call as a quality of the steam. And of course, at these state its specific volume value will be higher than the saturated liquid value, but lower than the saturated vapor value.

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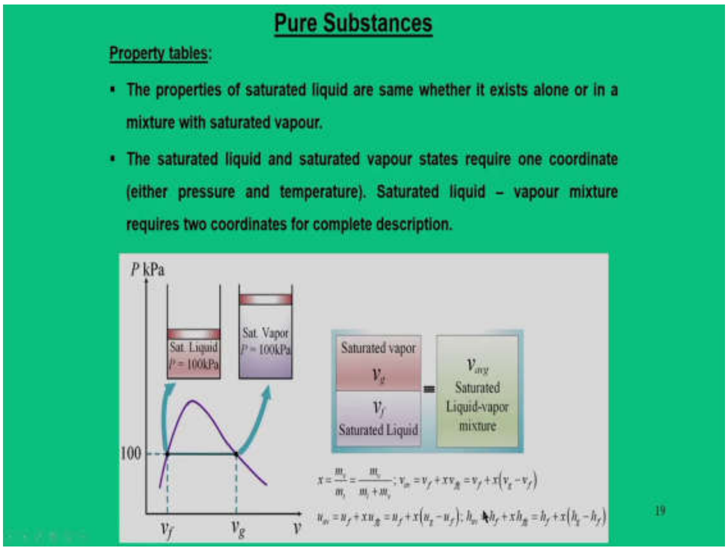

Pure Substances

Property tables:

- The properties of saturated liquid are same whether it exists alone or in a mixture with saturated vapour.
- The saturated liquid and saturated vapour states require one coordinate (either pressure and temperature). Saturated liquid – vapour mixture requires two coordinates for complete description.

$$x=\frac{m_v}{m_t}=\frac{m_v}{m_l+m_v};\ v_{av}=v_f+xv_{fg}=v_f+x\left(v_g-v_f\right)$$

$$u_{av}=u_f+xu_{fg}=u_f+x\left(u_g-u_f\right);\ h_{av}=h_f+xh_{fg}=h_f+x\left(h_g-h_f\right)$$

So, this is the equation that we are going to use when we are going to define the average value of saturated liquid vapor mixer. So, here once you have average value of saturated liquid vapor mixture then we can also have internal energy we can also get the information for average values of enthalpy in the liquid vapor region.

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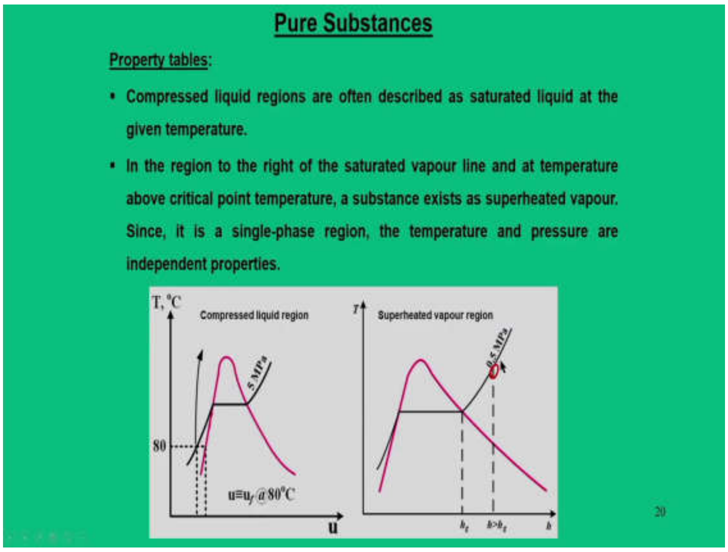

Pure Substances

Property tables:

- Compressed liquid regions are often described as saturated liquid at the given temperature.
- In the region to the right of the saturated vapour line and at temperature above critical point temperature, a substance exists as superheated vapour. Since, it is a single-phase region, the temperature and pressure are independent properties.

Now, let us see when we are in the compressed liquid regions. So, when we are in compressed liquid region typically we are in the beyond this dome that is beyond this line and at this stage we just require the temperature at which it is defined. For example, if you want to calculate the internal energy we can say internal energy at 80°C that is sufficient because you require only one coordinates.

And when we are in the super heated region; that means, when we are going beyond the saturated vapour curve; that means, for example, at this particular location if you want to find a coordinates, its value enthalpy value is much much higher than its saturated vapour value. So, here we require two coordinates. One is the pressure other could be any temperature or any other parameter to define its state. But it is a single phase region.

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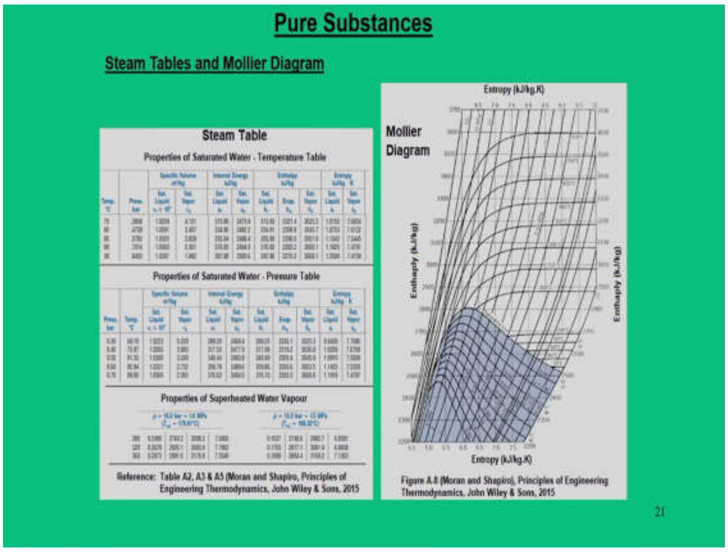

Pure Substances

Steam Tables and Mollier Diagram

Steam Table

Properties of Saturated Water - Temperature Table

Properties of Saturated Water - Pressure Table

Properties of Superheated Water Vapour

Reference: Table A2, A3 & A5 (Moran and Shapiro, Principles of Engineering Thermodynamics, John Wiley & Sons, 2015

Mollier Diagram

Figure A.8 (Moran and Shapiro), Principles of Engineering Thermodynamics, John Wiley & Sons, 2015

Now, whatever things I have explained if I want to summarize I will summarize in the properties of pure substance in two forms. One is in the form of steam table other is in the form of Mollier diagram. So, the first thing is the Mollier diagram. I mean in our thermodynamics course we will be mostly covering this using Mollier diagram, its nothing but the enthalpy vs entropy curve.

So, the enthalpy vs entropy curve when it is plotted, if you can see in this particular plot there are different constant pressure lines, constant volume lines all these things are given. And this is very bottom line philosophy for calculation of properties of steam when you are using this for steam power plants.

So, it is very easy to calculate because it does not require any interpolation. From this coordinate you can fix any two parameter; if it is given to you we can locate that point and when we are locating that point then rest of the parameters can be found out. The other way people look at is in the form of steam tables.

So, when you have steam tables it has three parts. One is saturated water for temperature table, saturated water for pressure table and super heated water vapour table. So, for temperature table if you look the temperatures are given, corresponding saturated pressure also given and all the rest of the properties are noted here.

Similarly, in the saturated pressure table pressure is given first that is followed by, saturated temperature and subsequently all other properties. Now, when you deal with the super heated vapour it has two important coordinates. One is you require a pressure and corresponding temperatures. So, this is what about the pressure and these are the temperatures.

For example, in this case we have a 10 bar pressure and the temperature could be 280, 320 and 360 °C and corresponding value of internal energy, enthalpy and entropy are noted here. So, these two are the extracts from the very fundamental book Moran and Shapiro. So, from these books probably while solving the problems we can use the data from this refer table.

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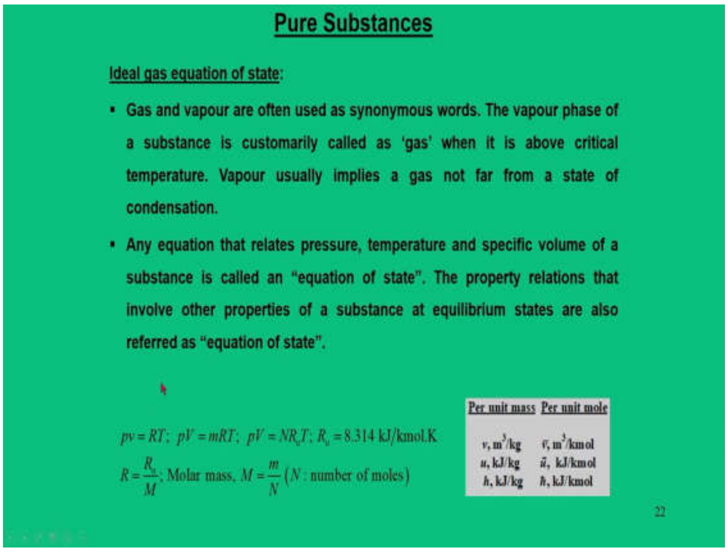

Pure Substances

Ideal gas equation of state:

- Gas and vapour are often used as synonymous words. The vapour phase of a substance is customarily called as 'gas' when it is above critical temperature. Vapour usually implies a gas not far from a state of condensation.
- Any equation that relates pressure, temperature and specific volume of a substance is called an "equation of state". The property relations that involve other properties of a substance at equilibrium states are also referred as "equation of state".

$pv = RT;\ pV = mRT;\ pV = NR_uT;\ R_u = 8.314\ \text{kJ/kmol.K}$

$R = \frac{R_u}{M}$; Molar mass, $M = \frac{m}{N}$ (N : number of moles)

Per unit mass	Per unit mole
v, m^3/kg	$\bar{v}$, m^3/kmol
u, kJ/kg	$\bar{u}$, kJ/kmol
h, kJ/kg	$\bar{h}$, kJ/kmol

And last component of this lecture is the gases. So, when you look at the gases. So, gases normally follow ideal gas equation or equation of states. So, properties of pure substance; if it is a gas it follows a fundamental equations $pv = RT$. So, here p and v are specific volume, R is the characteristics gas constant, T is the temperatures.

Another way we looking at $pV = mRT$ and here also we are going to introduce universal gas constants when we are dealing with kg-mol and mostly this particular notations were used for the chemistry people, where they use the universal gas constant.

But in our routine approach either we will be using air or water vapour or something. So, in that case we are mostly concentrate in the simple form that is equation of state $pv = RT$. So, also we can introduce the universal gas constant R_u and molar mass or molecular mass M.

So, if you look at the per unit mass basis we can define them m^3/kg. If you are defining per mole then you can define as $m^3/kmol$. So, there we have to use the word universal gas constant, but in normal routine practice when you are using per unit mass basis we are ok with the simple mass base systems not molar mass system.

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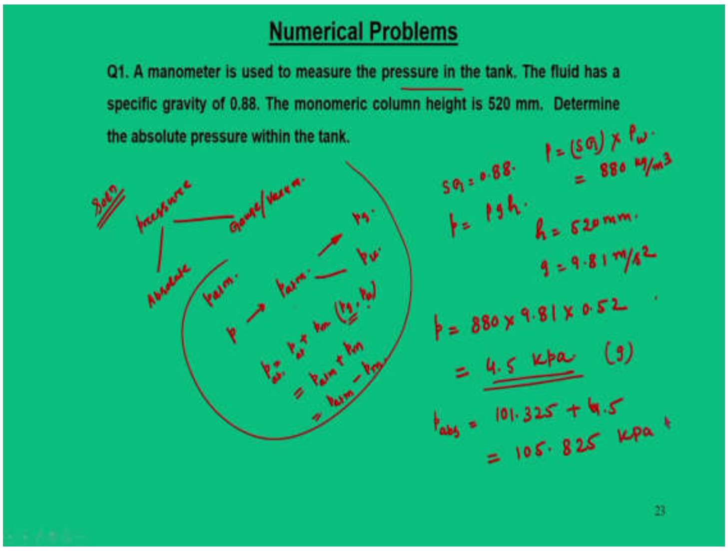

Numerical Problems

Q1. A manometer is used to measure the pressure in the tank. The fluid has a specific gravity of 0.88. The monomeric column height is 520 mm. Determine the absolute pressure within the tank.

Soln

pressure — Gauge/Vacuum.

Absolute

p_{atm}.

$p \rightarrow p_{atm}$. $\nearrow p_g$. — p_v.

$p_{abs} = p_{atm} + p_m \; (p_g, p_v)$

$= p_{atm} + p_m$

$= p_{atm} - p_m$

$SG = 0.88$.

$\rho = (SG) \times \rho_w$.

$= 880 \; kg/m^3$

$p = \rho g h$.

$h = 520 \; mm$.

$g = 9.81 \; m/s^2$

$p = 880 \times 9.81 \times 0.52$

$= \underline{\underline{4.5 \; kPa}} \; (g)$

$p_{abs} = 101.325 + 4.5$

$= 105.825 \; kPa$

So, let me solve some problems, which we have covered in this particular course. So, the 1st problem is based on a property called as pressure. So, when you deal with the pressure this could be in two terms. One is absolute form other may be gauge or vacuum and reference is p atmospheric.

So, when any pressure is measured with respect to atmospheric and its value we can define as p_{gauge} or p_{vacuum}. But, when the actual pressure is calculated $p_{absolute}$ it may be $p_{atm} + p_{measured}$. So, either this measure pressure could be gauge or vacuum.

Now, when we say gauge it is above atmospheric, when we say vacuum it is below atmospheric. So, absolute pressure can be further written as $p_{atm} + p_m$ or $p_{atm} - p_m$. So, this is all about the concept. Now, for this particular problem what has been given to us that we have a manometer and it is used to measure the pressure in the tank.

So, what is given is fluid has a specific gravity as 0.88. So, pressure can be written as $p = \rho g h$. So, $\rho = (SG) \times \rho_w$. So, in this case density of water is 1000. So, specific gravity is 0.88. So, it will be 880 kg/m^3.

So, h is given as 520 mm. So, g is 9.81 m/s^2. So, we can calculate p = 880 x 9.81 x 0.52. So, this turns out to be 4.5 kPa and this 4.5 kPa if I say its gauge because it is positive. So, if you make absolute, so, I have to add atmospheric pressure that is 101.325 + 4.5. So, this turns out to be 105.825 kPa.

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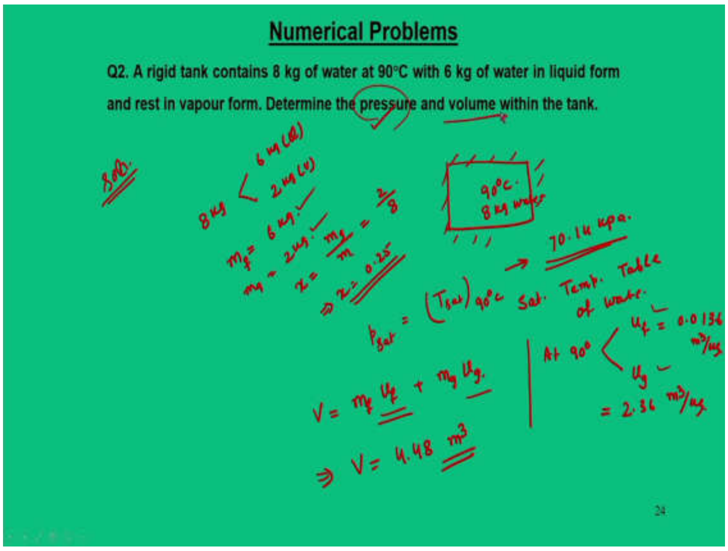

Numerical Problems

Q2. A rigid tank contains 8 kg of water at 90°C with 6 kg of water in liquid form and rest in vapour form. Determine the pressure and volume within the tank.

Soln.

8 kg < 6 kg (l), 2 kg (v)

m_f = 6 kg.

m_g = 2 kg.

$x = \frac{m_g}{m} = \frac{2}{8}$

$\Rightarrow x = 0.25$

90°C. 8 kg water

$p_{sat} = (T_{sat})_{90°C}$ → Sat. Temp. Table of water. → 70.14 kpa.

At 90° < v_f = 0.0136 m^3/kg, v_g = 2.36 m^3/kg

$V = m_f v_f + m_g v_g$

$\Rightarrow V = 4.48$ m^3

So, next problem that we are going to discuss is that we have a rigid tank and it is at 90 °C and it contains 8 kg of water, out of this 8 kg of water we have 6 kg liquid and 2 kg vapour. So, basically we know m_f as 6 kg and m_g as 2 kg. So, from this we can calculate x that is dryness fraction that is m_g / m.

So, that is 2/8. So that means, x is equal to 0.25. So, the dryness fraction is this. Then we require the pressure. So, pressure can be calculated because it is saturated liquid vapour mixture. So, p saturated is nothing but $(T_{sat})_{90°C}$.

So, from the book saturated temperature table we can get the saturated pressure as 70.14 kPa. So, this number we will get from saturated temperature table of water. So, we got this pressure then we are left with the volume. So, volume can be calculated $V = m_f \upsilon_f + m_g \upsilon_g$.

So, this small v_f and v_g can be calculated at 90 °C. We can have two values v_f and v_g from the saturated temperature table and this number is 0.0136 m^3/kg that is for v_f and v_g is 2.36 m^3/kg. So, total V can be calculated because you know m_f 6, m_g 2 and when you put v_f and v_g, the volume would be 4.48 m^3. So, it is a total volume. So, we are able to get the volume of the tank.

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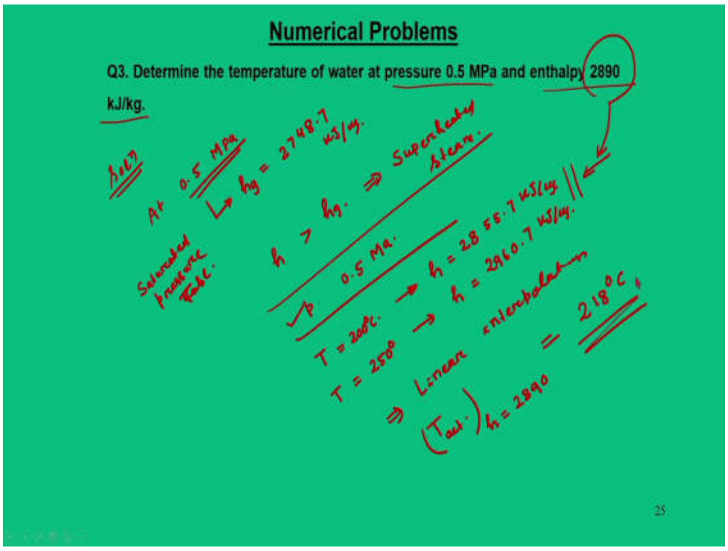

Numerical Problems

Q3. Determine the temperature of water at pressure 0.5 MPa and enthalpy 2890 kJ/kg.

Sol^n

At 0.5 MPa

↳ h_g = 2748.7 kJ/kg.

Saturated pressure Table.

$h > h_g$ ⇒ Superheated steam.

↳ p 0.5 Ma.

T = 200°C. → h = 2855.7 kJ/kg

T = 250° → h = 2960.7 kJ/kg.

⇒ Linear interpolation

$(T_{act})_{h = 2890}$ = 218°C

The next simple problem that is we expect to find out temperature of water at pressure 0.5 MPa and enthalpy 2890 kJ/kg. So, here the first thing that we want to check is that at 0.5 MPa what is its enthalpy h_g. So, this we can get from saturated pressure table.

So, this number if you calculate for 0.5 MPa, this number is 2748.7 kJ/kg. Now, here the enthalpy value is 2890. So, actual enthalpy is much more greater than h_g. So, this will tell you that this data refers to super heated steam. So, for super heated steam then we have to find out the close number for pressure 0.5 MPa corresponding to temperatures at 200 °C.

We will have this enthalpy about 2855.7. Now, for this same pressure and if you look at temperature at 250 °C we will have enthalpy value 2960.7. So, if you look at 2890 number it is somewhere in between. So, this means through linear interpolation we can extract actual temperature which corresponds to h =2890 will have about 218 °C. This is how you are going to refer the super heated table.

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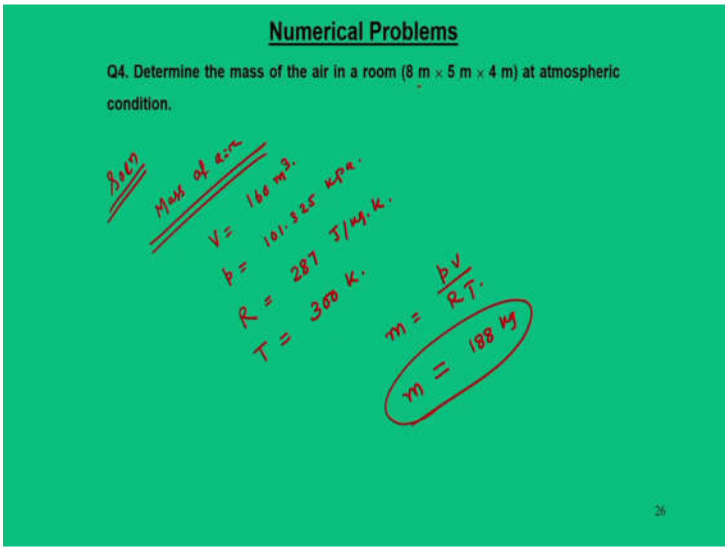

Numerical Problems

Q4. Determine the mass of the air in a room (8 m × 5 m × 4 m) at atmospheric condition.

Soln

Mass of air

$V = 160\ m^3.$

$p = 101.325\ kPa.$

$R = 287\ J/kg.K.$

$T = 300\ K.$

$m = \frac{pV}{RT}.$

$\boxed{m = 188\ kg}$

And the last problem that I am going to use is for mass of air. So, here when you look at mass of air what is given data; V= 8x5x4= 160m^3. Let us say pressure is atmospheric 101.325 kPa, we require R that is characteristics gas constant that is is 287 J/kg-K and temperature it can be assumed as 300 K. So, you have to use simple equation $m = \frac{pv}{RT}$.

So, when we put these numbers we will get about 188 kg. So, this is a very common way that in all our situations we are going to use the typical data value. Even if it is not given and those number should be suitably assumed and accordingly appropriate formula can be used to compute the numbers. So, with this I will conclude for the lecture today.

Thank you for your attention.