

Applied Thermodynamics for Marine Systems

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Lecture - 7

Ideal Gas Laws, Different Processes

Let us continue with our discussion on the steam table. More or less, we have discussed most of the important features of the steam table. I just like to give one example to study how it looks and what are the values that we get.

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Steam Table (Temperature Based) © IIT KGP

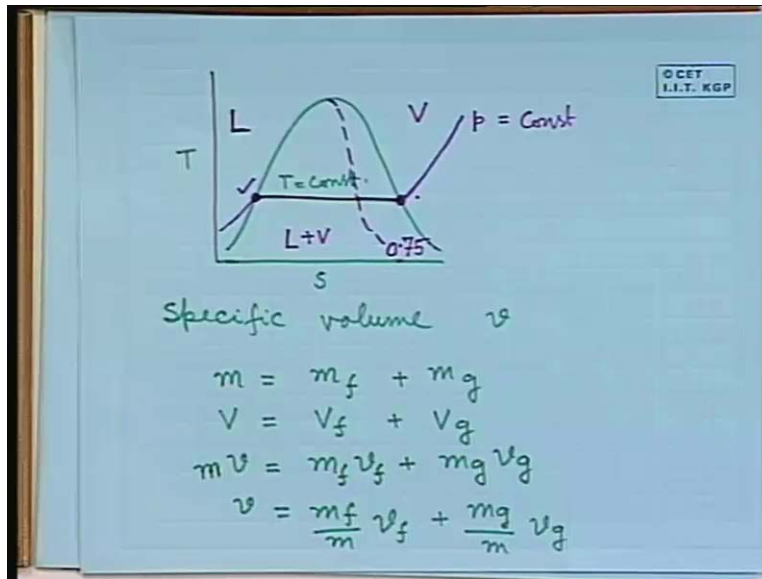
t	P	v_f	v_g	v_{fg}	h_f	h_g	h_{fg}	s_f	s_g
100	1.0135	1.044			419.04		2257.0		
			1.6729			2257.0 2676.1		1.3069	
									7.3549

The steam table is temperature based and we will have the columns like this: t p v_f v_g and v_{fg} . We will have h_f h_g h_{fg} s_f and s_g . Due to shortage of space I will not write down the units here. Let us take the example of steam properties at a temperature of 100 degrees Celsius. If we refer the steam table we have to go for temperature value at 100. Once we specify this, other values can be directly read from this steam table. The pressure we will find is in kilo Pascal and the value we will see that is 1.0135. This is the pressure value. We know at 100 degrees Celsius the water boils under atmospheric pressure; basically, this is the atmospheric pressure. The corresponding specific volume of a saturated liquid will be 1.044 meter cube per kg, corresponding specific

volume of steam that will be 1.6729; v_{fg} one can calculate, I am not giving the value. h_f , which is the enthalpy of the saturated liquid at 100 degree Celsius at atmospheric pressure will be 419.04 that is kilo Joule per kg; h_g will be 2676.1 kilo Joule per kg and h_{fg} will be 2257.0 kilo Joule per kg. s_f will be 1.3069 kilo Joule per kg Kelvin and s_g will be 7.3549. These are the values that we will get. That means at atmospheric pressure or at a temperature of 100 degrees Celsius the latent heat of evaporation or condensation is 2257.0 kilo Joule per kg or for the evaporation of 1 kg of water at 100 degrees Celsius to 1 kg of vapor at 100 degrees Celsius, we will need this amount of thermal energy.

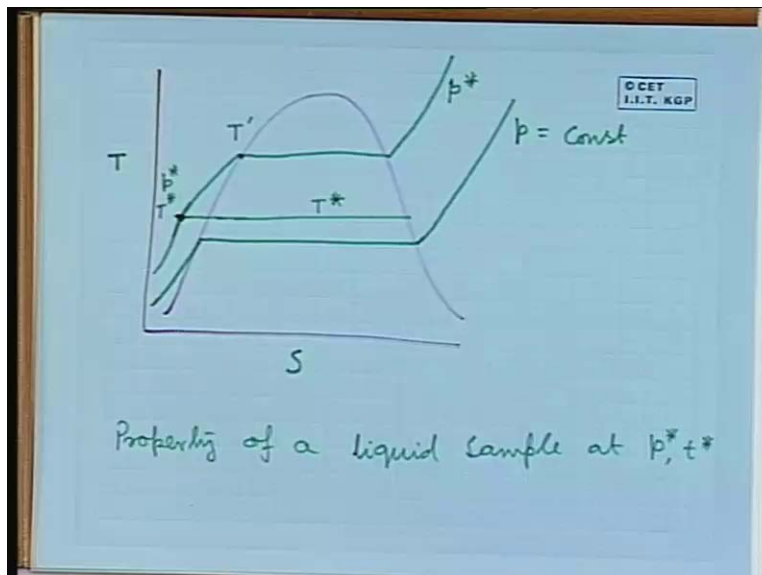
If we see this steam table we will see that the h_{fg} values will go on decreasing with temperature. As we go for higher temperatures or higher values of pressure we will see this value of h_{fg} will go on decreasing and it will diminish at the critical point. As I have said earlier, at the critical point there is no demarcation between the liquid phase and the vapour phase. We will see that, gradually, the latent heat or the difference of enthalpy between the saturated liquid state and the saturated vapour state will go diminishing and will vanish at the critical point. That is what we will find. The same thing happens in case of the specific volume. The difference between the specific volumes will be higher at low pressure and low temperature but as we go towards the critical point this difference will go on diminishing and will vanish at the critical point. This is for the first part of the steam table where we have got property data for the saturated liquid and saturated vapour. Now, in this steam table we have three parts as I have mentioned a number of times.

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This part is liquid, this part is a mixture of liquid plus vapour, this part is vapour or superheated vapour. This liquid part is known as either sub-cooled liquid or the compressed liquid. Why is it called sub-cooled liquid?

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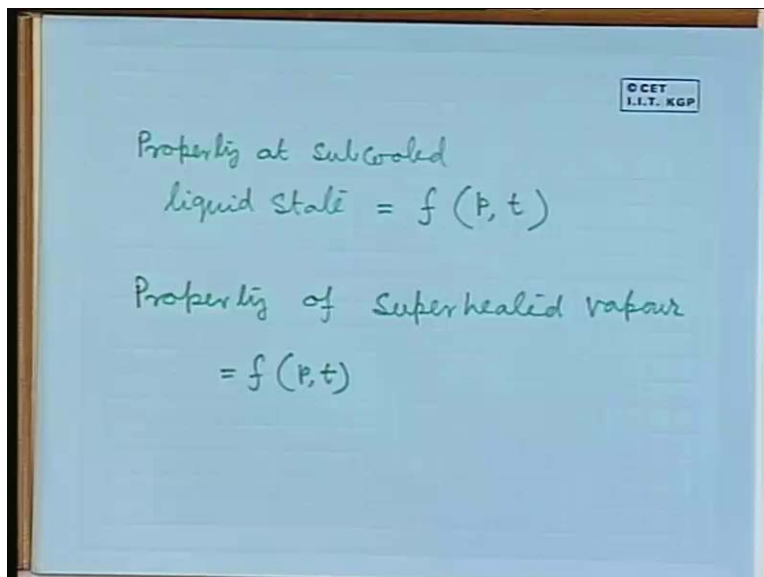


Let us take this part in detail and then explain. Let us take the help of a TS diagram. This is the TS diagram and here we are having a constant pressure line like this; p is constant. We are

interested in determining the property of a liquid sample at p^* t^* . We are interested in that. This is actually p^* , pressure and t^* , temperature. Let us say through p^* t^* , if I pass a constant pressure line this will be something like this and a constant temperature line is something like this. This is your t^* . This is your p^* line and this is your t^* line. For p^* we are having the saturation temperature at let us say, T_{dash} . Corresponding to p^* the saturation temperature is at T_{dash} . What is the relationship between t^* and T_{dash} ? T_{dash} is definitely higher compared to T^* . That is why this state is sub-cooled state.

Corresponding to the pressure the temperature is below the saturation temperature. This is in sub-cooled state. That is why we call the liquid state as sub-cooled state or sub-cooled liquid. If I take T^* we can send through T^* a constant pressure line and the constant pressure will be something like this. Let us call this constant pressure line or constant pressure as p_1 . What is the relationship between p_1 and p^* ? p^* is greater than p_1 . If we take this temperature corresponding to the temperature, the saturation pressure is p_1 but the pressure of the liquid is more than the saturation pressure. That is why this liquid is also called compressed liquid. The liquid state is denoted either as a sub-cooled liquid state or compressed liquid state.

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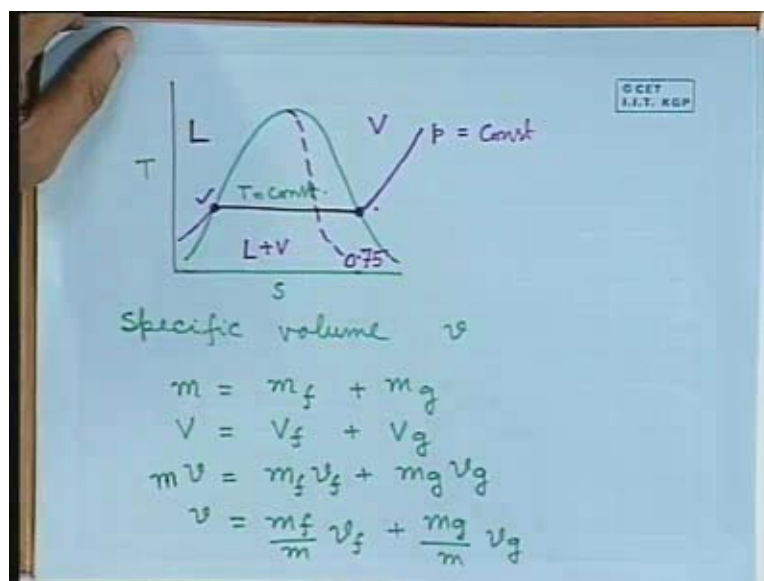


The property at sub-cooled liquid state will be a function of pressure and temperature. In general, this is true as I have discussed earlier that for a pure substance if it is in a single phase condition,

then the property will be dependent on two independent thermodynamic properties. Two independent thermodynamic properties which are easy to measure are pressure and temperature. Any property of the sub-cooled liquid state can be expressed as a function of pressure and temperature. But what has been seen is that the liquid property or property of the sub-cooled liquid is a weak function operation whereas, it varies with temperature. For determining the property of the sub-cooled liquid what do we do? This t^* and p^* , though these two independent conditions or state of this sample is given, we determine the property at the saturated state corresponding to t^* .

We do not bother what its pressure is. If we know the temperature then the saturated liquid property corresponding to that temperature, we take as the property of the sub-cooled liquid. That is how the liquid property is determined or the property of the sub-cooled liquid state is determined. Here, the temperature is the only concern. The temperature we take and corresponding to that saturation temperature we determine the property. We have our steam table. Here the properties are given for saturated liquid condition. We can determine the property using the table very easily. I have described how we can determine the property of the sub-cooled liquid state. Then, we go for property of liquid and vapour.

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Here also, I have already described how using the saturated properties and the dryness fraction the property at any point in this two phase region or in the mixer region can be determined. Here also, we do not have any difficulty. Then, we go to the other side of the dome, the right hand side of the dome which is the superheated vapour region. The property of super heated vapour will be a function of two independent thermodynamic properties and as I have mentioned, the pressure and temperature are two independent properties which can be measured easily, based on which other properties can be expressed. So, this is a function of pressure and temperature. Here, we cannot make any compromise. The property of the superheated vapour depends both on pressure and temperature. In the second part of the steam table we have the property of superheated vapour or superheated steam.

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Second Part of Steam Table CET
I.I.T. KGP
 → Property of Superheated Steam

$p = (0.10 \text{ MPa}) \rightarrow \text{saturation temp} = 45.81^\circ\text{C}$

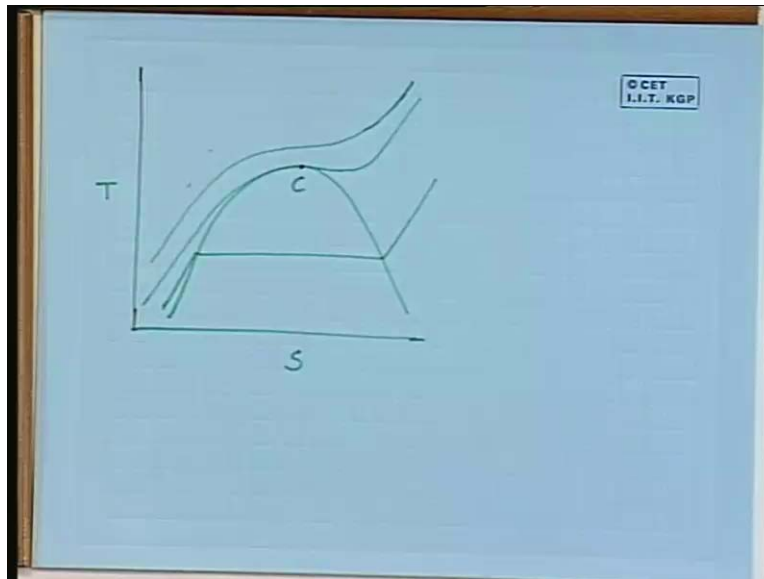
t $^\circ\text{C}$	v m^3/kg	h kJ/kg	s $\text{kJ}/\text{kg}-\text{K}$
sat	14.674	2584.7	8.1502
50	14.869	2592.6	8.1749
100			
150			
⋮			

The second part of the steam table will give you the property of superheated steam. Again, they are functions of pressure and temperature and it is generally tabulated in this form. Let us take a particular value, let us say, the pressure value is given. That means we have the tabulation of steam properties at this 0.10 mega Pascal. The pressure is equal to this value. This gives the saturation temperature of 45.81 degrees Celsius. We can have the tabulation of the property of superheated steam for a pressure of 0.1 mega Pascal, which corresponds to saturation temperature of 45.81 degrees Celsius. The table looks like this. We will have values at different temperatures. What property values will we have?

We will have specific volume, we will have enthalpy and we will have entropy. This is in degree Celsius, this is in meter cube per kg, this is kilo Joule per kg and this is kilo Joule per kg Kelvin. First, we will have saturation temperature. We will have 14.64, then 2584.7, 8.1502. Actually this is the property of saturated vapour. Then, we can have at 50 degrees Celsius, the saturation temperature is 45.81 degrees Celsius; 50 degree Celsius means it is superheated. Then it is 14.869, 2592.6 and 8.1749. Similarly, one can have values at 100, at 150 and on. This is how the property table for superheated steam looks like and in the first part of the steam table where properties of saturated liquid or saturated fluid is tabulated and in the second part of the steam table where the properties of superheated vapour is tabulated, there at some regular interval the property values are given. That means, for in between parameter values if we have to determine the property we have to go for interpolation and we go for linear interpolation. This will be clear when we solve some problems and probably sometimes we have to go for double linear interpolation, which means linear interpolation we have to do for two different parameters. That is what we will learn when we will solve some problems. This is all regarding the description of steam table.

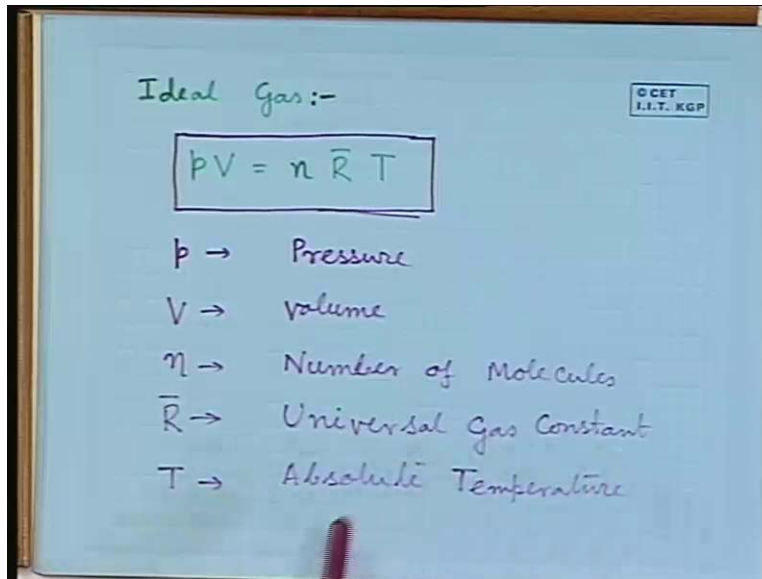
Steam tables are available from different publishers and we can get any one of them which is in SI system and use them for solving problems. The purpose that is served by this steam table, almost the same type of calculation one can do using a Mollier diagram or h x diagram. The only thing is that in h x diagram, sometimes, we have to read in between the graduation and so we have to take some sort of high estimations and that may induce some sort of an error. We have to draw some diagram and from that diagram we have to take the readings. Some sort of error may creep in due to the geometrical construction, due to high estimations, etc. But in general those errors are negligibly small. If one is careful then those errors are small. In general one can use either a steam table or a Mollier diagram. But it is always advisable if you are using a Mollier diagram, then you sketch the process. Whatever you are using for calculating the property values on the Mollier diagram, you have to give the sketch also in the answer scripts or in your verbal description of the process. That sketch has to be a written description of the process, you have to give that sketch; that is mandatory. So that is it regarding the steam table and calculations regarding the steam table.

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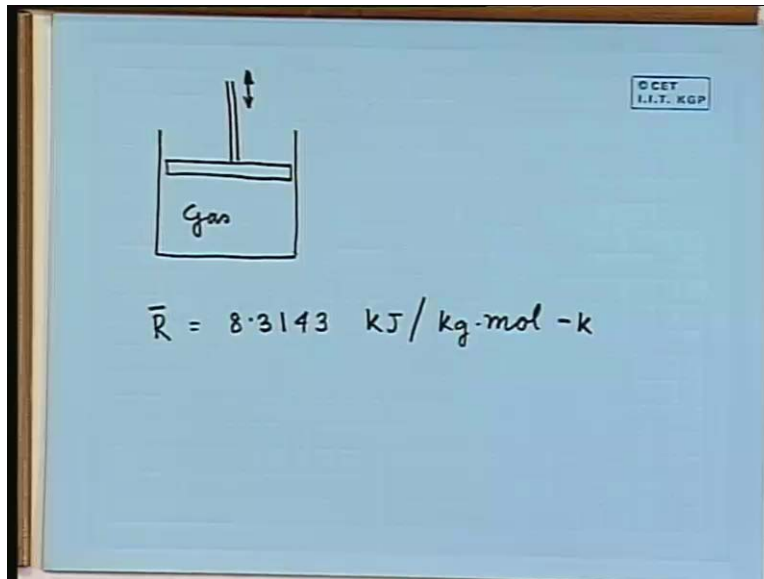
If we see the property of the pure substance and any standard thermodynamic diagram if we consider, like the TS diagram, we have got the critical point here. This is C or critical point; this is a constant pressure curve. Through the critical point you will have a curve like this; beyond the critical point you will have a curve like this. If the state of the fluid is such that it is somewhere above the critical point, then, we consider it to be a gas. In our engineering thermodynamics we will get lot of examples or in day-to-day engineering practice we will get lot of examples where a gas is the working substance for the equipment or for the engineering cycle which we are operating. We should have some idea regarding the properties of gas and different processes involving gas as the working medium. Though the behavior of a gas can be different at different ranges of pressure and temperature, there is some sort of idealization.

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When we talk of an ideal gas we have some sort of idealization. From physics point of view or from a molecular point of view, there are certain assumptions by which this idealization can be made. I will not go into those. But the macroscopic behavior which describes the ideal gas, that behavior we are familiar with and that is given by a very well known law like this. For an ideal gas we can write pV is equal to nRT . This is the ideal gas law. Though one may argue that no gas is ideal, because if we go through the assumptions which are made for ideal gas, we will see that they do not hold good for any of the gases but we will see that there are ranges of pressure and temperature, where lot many gases behave like ideal gases. We use this law and we analyze different engineering processes. This is known as law for ideal gas. What are the different symbols here? p is the pressure, V is volume, n is number of molecules, R bar is universal gas constant and T is the absolute temperature. These are the symbols of pressure, volume, number of molecules, universal gas constant and absolute temperature.

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It denotes a closed system, something like this piston cylinder arrangement. It can be some other arrangement also but basically, it is a closed system where the mass of the gas remains constant. Then, the volume, pressure and temperature can vary and we have methods for measuring them. If we can measure them, then for any particular measurement pressure, volume and temperature will follow. This is the gas whose mass remains constant. Piston movement is possible and we can measure the pressure, volume and temperature. At any instant, the pressure, volume and temperature will follow this type of a relationship. This is valid for any ideal gas. The universal gas constant R or R bar, whatever I have written its value is 8.3143 kilo Joule per kg mol Kelvin. This is the value of the universal gas constant.

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$pV = n \bar{R} T$
 $pV = m R T$
 $n = \frac{m}{\mu}$
 $m =$ Mass of the sample of gas
 $\mu =$ Molecular weight of the gas sample
 $R \rightarrow$ Characteristic Gas Constant

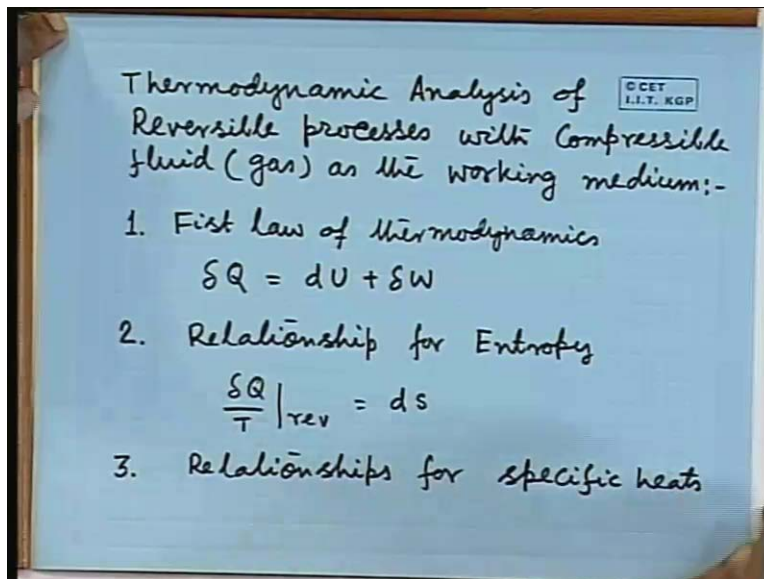
The law which I have written is pV is equal to nRT or nR bar T . This can be rewritten in this form as pV is equal to mRT where, n I have replaced by this formula m by μ . m is the mass of the sample of gas. The gas which is confined in this piston cylinder arrangement, m is the mass of that sample of gas and μ is the molecular weight of the gas sample, R is characteristic gas constant. This is the characteristic gas constant. What we have got here, let me write down once again different relationships.

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$pV = n \bar{R} T$
 $pV = m R T$
 $p \frac{V}{m} = R T$
 $p v = R T$
 \rightarrow specific volume

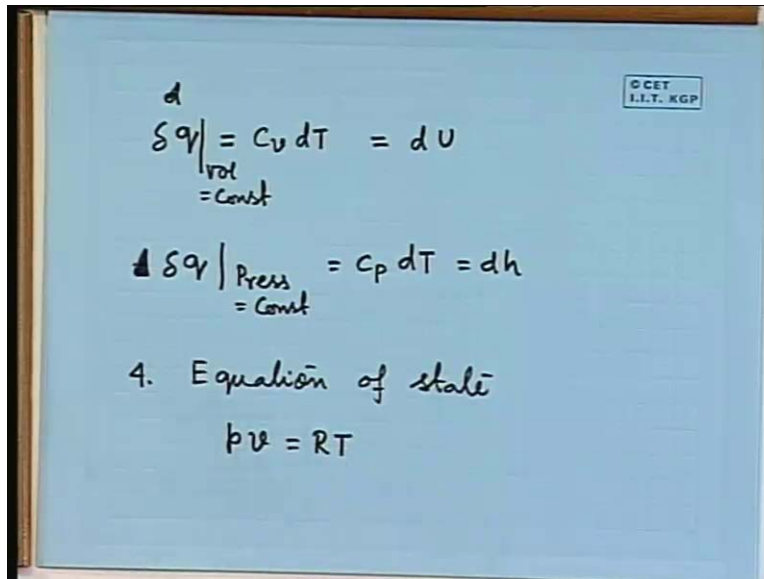
pV is equal to nRT . In other words we can write pV is equal to mRT where n is equal m by μ . In the next step, we can bring m on the left hand side. So, pV by m is equal to RT or pv is equal to RT . This is your specific volume. These are the different forms of ideal gas law. Sometimes this is also called combined Boyle's and Charle's law as you know from our elementary physics. This law we will use for determining different properties and determining work done heat transfer etc., using thermodynamics laws.

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Basically, we want to do thermodynamic analysis of reversible processes with compressible fluid, which is nothing but a gas as the working medium. We can start or we can take the example of different processes and then we can analyze. In this analysis we will use the first law of thermodynamics that is, we will use dQ is equal to dU plus dW . Second, we will use the relationship for entropy. What is that? dQ by T reversible is equal to ds ; this we will use. Third, we will use relationships for specific heats.

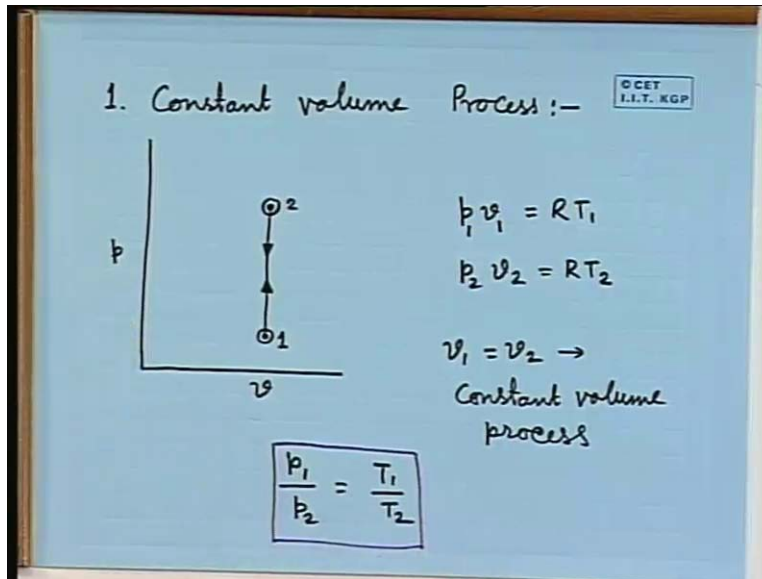
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How can we express the relationship of specific heat dq ? Let us say, this dq is equal to C_p . First let us see $C_v \Delta T$ for constant volume process. This we can write volume is equal to constant and this also is equal to dU internal energy. Then we can have dq pressure is equal to constant is equal to $C_p dT$ is equal to dh . That we will see. Then fourth, we will use the equation of state that we have discussed just now, that is pv is equal to RT . These are the relationships which we will use for determining or for the thermodynamic analysis of a reversible processes with compressible fluid that is a gas as the working substance.

Let us start with some simple process and see how you can proceed.

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First, let us take a constant volume process. Let us try to plot the constant volume process on a $p-v$ diagram. This is a $p-v$ diagram. In a constant volume process, volume will remain constant. Either one can have this to be the initial point and this to be the final point or reverse. That means either the process can go from 2 to 1 or 1 to 2; this is a constant volume process. If it is a constant volume process, first let us try to apply the equation of state. One can write $p_1 v_1$ is equal to RT_1 and again $p_2 v_2$ is equal to RT_2 . This is valid for any thermodynamic process. This, we have not written for a constant volume process or constant pressure process, but this is valid for any two end states 1 and 2, we can write these relationships and if it is a constant volume process then we can get v_1 is equal to v_2 . If v_1 is equal to v_2 , this is a constant volume process, then we get p_1 by p_2 is equal to T_1 by T_2 . This is the property relationship for a constant volume process, p_1 by p_2 is equal to T_1 by T_2 .

Next we go for the work done, ${}_1W_2$ in a constant volume process.

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The whiteboard contains the following handwritten equations and text:

$${}_1W_2 = \int_1^2 p \, dv \overset{\rightarrow 0}{}$$
$$= 0$$
$${}_1Q_2 = U_2 - U_1 + \overset{\rightarrow 0}{{}_1W_2}$$
$$= C_v (T_2 - T_1)$$

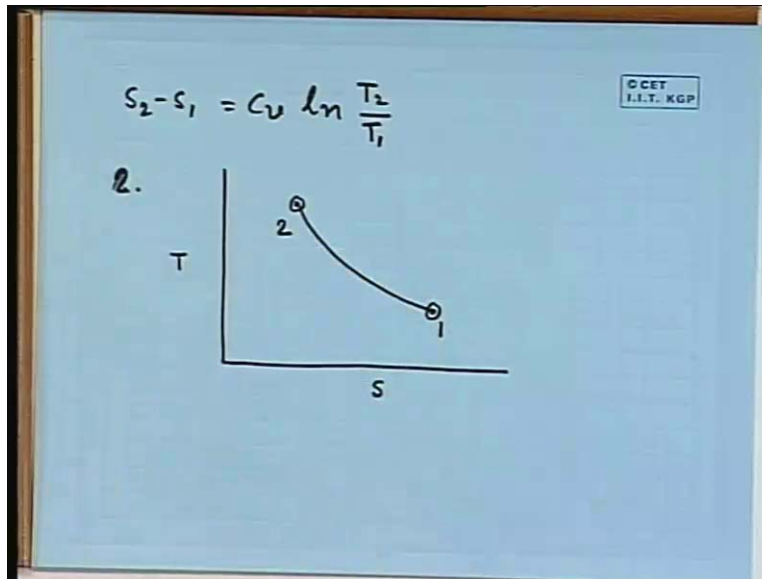
Change of Entropy

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} = \int_1^2 C_v \frac{dT}{T} = C_v \int_1^2 \frac{dT}{T}$$

${}_1W_2$ is equal to, for a compressible fluid, 1 to 2 $p \, dv$. $p \, dv$ gives you the work done during the process. As dv is equal to 0, change in volume is equal to 0, we will have ${}_1W_2$ is equal to 0. This comes from this diagram also. If it is a constant volume process then the area under the curve is 0. The work done during this process will also be equal to 0. The work done during a constant volume process for a fixed mass system is equal to 0.

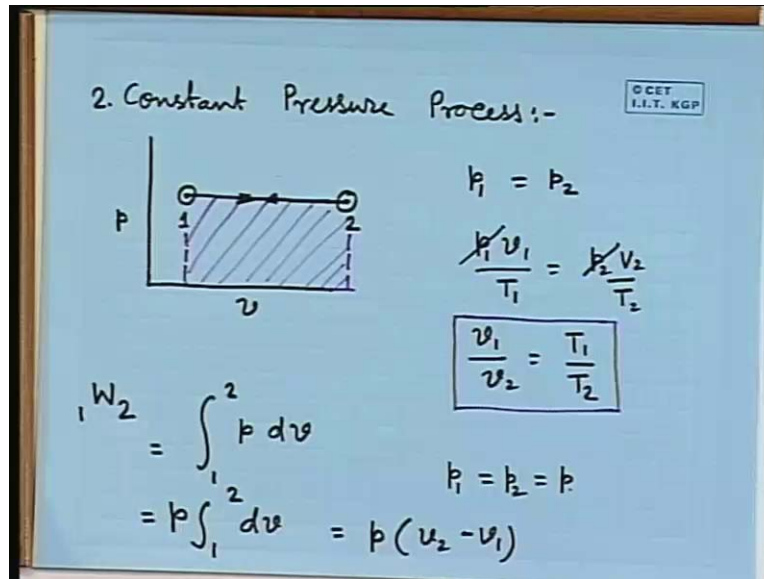
What is ${}_1Q_2$? What is the heat transfer during this process? For the heat transfer during this process, we can apply the first law of thermodynamics. ${}_1Q_2$ is equal to U_2 minus U_1 plus ${}_1W_2$. This is equal to 0 and in this case, this will be $C_v T_2$ minus T_1 . That is how we will get the heat transfer during this process. This is again equal to the change in internal energy. What is the change of entropy during this process? The change of entropy will be S_2 minus S_1 and that is equal to dQ by T that is equal to 1 to 2 $C_v \, dT$ by T and then we can write $C_v \, dT$ by T 1 to 2.

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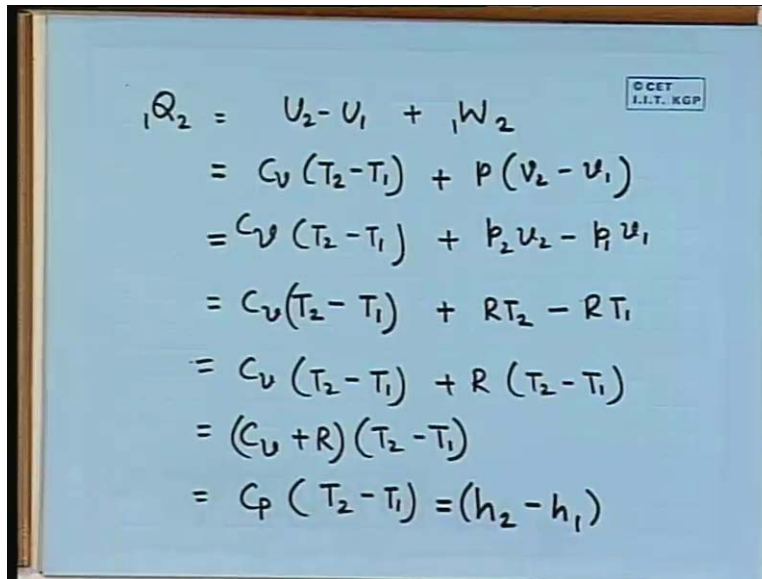
S_2 minus S_1 is equal to $C_v \ln T_2$ by T_1 . We have started with a constant volume process which is one of the basic process, simplest process involving a compressible fluid. We can determine the property relationships and then we can determine the work done, the heat transfer and the change in entropy. Similarly, we can proceed with other processes. The second process let us take as a constant pressure process. Before doing that, if we know this is the change in entropy S_2 minus S_1 , how can we plot the process on a TS plane? This is your T and this is your S; TS plane. On TS plane how do we plot this? How will this process look on the TS plane? It is some sort of a logarithmic or exponential relationship. We will have something like this; 1 to 2. This is 1, this is 2, so, we will have a process like this. Either we can have a cooling process or a heating process something like this. The next process which we can think of is a constant pressure process.

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A constant pressure process, again it is easier to visualize in a pv plane. You will have p_1 is equal to p_2 . If p_1 is equal to p_2 , then from the equation of a state we can get a relationship between v and T . $p_1 v_1$ by T_1 is equal to $p_2 v_2$ by T_2 and p_1 and p_2 are equal. So we get v_1 by v_2 is equal to T_1 by T_2 . This is the property relationship for a constant pressure process. Next we can determine the work done. ${}_1W_2$ that is equal to integration 1 to 2 $p dv$. Here, p remains constant. Actually p_1 is equal to p_2 is equal to p . At any point during the process one can take this p outside the integration sign and 1 to 2 dv this will become $p v_2$ minus v_1 . As we have discussed earlier, this work done will be given by the rectangular area under the constant pressure curve. This is how we will get the work done during the constant pressure process. What is the heat transfer?

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The image shows a whiteboard with handwritten mathematical derivations. In the top right corner, there is a small logo that reads "CCET I.I.T. KGP". The derivations are as follows:

$$\begin{aligned} {}_1Q_2 &= U_2 - U_1 + {}_1W_2 \\ &= C_v (T_2 - T_1) + p(v_2 - v_1) \\ &= C_v (T_2 - T_1) + p_2 v_2 - p_1 v_1 \\ &= C_v (T_2 - T_1) + RT_2 - RT_1 \\ &= C_v (T_2 - T_1) + R (T_2 - T_1) \\ &= (C_v + R) (T_2 - T_1) \\ &= C_p (T_2 - T_1) = (h_2 - h_1) \end{aligned}$$

${}_1Q_2$ that is equal to U_2 minus U_1 plus ${}_1W_2$ and this is equal to $C_v T_2$ minus T_1 plus $p v_2$ minus v_1 . Then, one can write it like this: $C_v T_2$ minus T_1 plus $p_2 v_2$ minus $p_1 v_1$. One can express it like this C_v into T_2 minus T_1 plus, what is $p_2 v_2$? $p_2 v_2$ is equal to RT_2 minus RT_1 and this is C_v into T_2 minus T_1 plus R into T_2 minus T_1 . So this is C_v plus R into T_2 minus T_1 . This quantity is nothing but C_p . So, basically it is C_p into T_2 minus T_1 or one can write it in terms of enthalpy. This is h_2 minus h_1 . Heat transfer during the constant pressure process, we can determine by either of these formulae; either it is $C_p T_2$ minus T_1 or this is nothing but the change in enthalpy that is h_2 minus h_1 .

I think I will stop here. In the next class we will see what the change in entropy is.