Engineering Thermodynamics
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Lecture-27
Properties of a Pure Substance: Ideal gas behaviour. Equations of state. Specific heat

This is the 3rd section on Properties of a Pure Substance and we continue from where we left of yesterday which was we are looking at the properties and started discussing what is an ideal gas. So, we had looked at properties of vapors and we said that the equation of state which we have.

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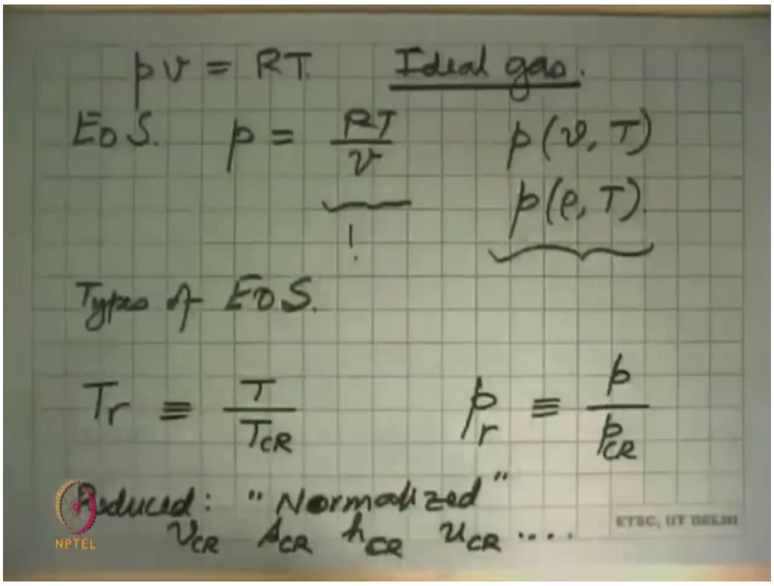

$pv = RT$ Ideal gas.

EoS. $p = \underbrace{\frac{RT}{v}}_{!}$ $\qquad \underbrace{\begin{matrix} p(v, T) \\ p(\rho, T) \end{matrix}}$

Types of EOS.

$T_r \equiv \frac{T}{T_{CR}} \qquad p_r \equiv \frac{p}{p_{CR}}$

Reduced: "Normalized"

$v_{CR} \quad s_{CR} \quad h_{CR} \quad u_{CR} \ldots$

So, familiar with p v equal to RT this present apply to the vapor states and this applies when we do an ideal gas and this is the simplest form of the equation of state is called let us say EOS where we have p is equal to RT upon v.

So, basically we have expressed pressure as a function of say specific volume and temperature or rho and temperature. The reason for putting this form up that we will see in a minute that as we start deviating from ideal gas behaviour. This equation will get modified and essentially it will remain something like this, but with more additions and modifications to make it fit the experimental data. So, we will come across many different types of equations of states and each one of them has their own advantages and disadvantages, but remember that all these are for an ideal gas only. So, last time.

So, last time what we had seen is that we had defined the reduced temperature TR T upon T critical and we defined reduced pressure as the pressure upon the critical pressure. The reason we did that is that it gave us an uniform set of parameters that are independent of the material. So, in some way these reduced properties, these are some sort of a what we call a normalized on a known constant and we can then talk in terms of different materials having same reduced temperature behaving in a similar way.

So, we define these two and turns out that these are the critical states are the properties of the substance and along with that we have other critical states like the critical state specific volume, the specific entropy, the specific enthalpy, specific internal energy and so on. For a given substance all these are unique and we can just look up any tables and we can pick up on these numbers to that. So, this is what we defined and then, we went about doing an exercise of saying that if we plot this side, the reduced pressure and this side the y axis we plot the compressibility factor, then what will the graphs look like.

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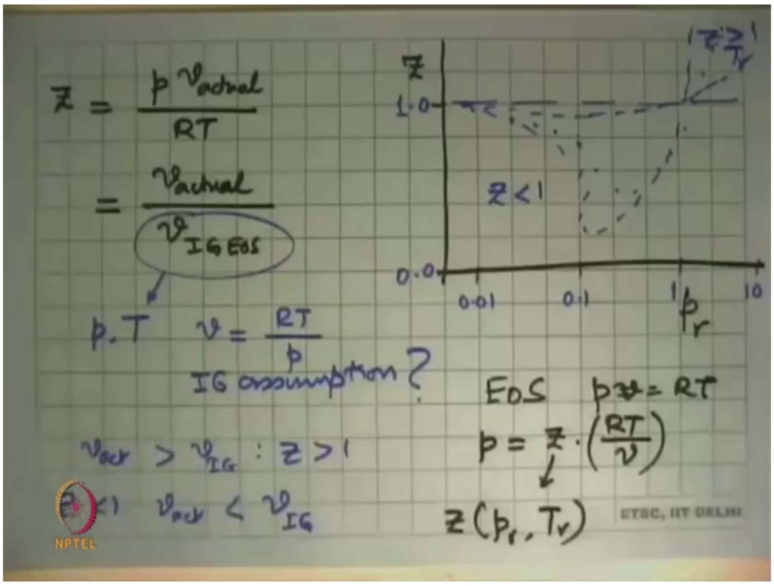

For that we defined yesterday the compressibility factor z as p v actual divided by RT or this is a ratio of the actual specific volume of the material divided by a specific volume that would be calculated from the ideal gas equation of state. What basically we are seeing though is that when we talk of v ideal gas equation of state, this lower part if you have any pressure, any temperature for a material, nothing stops us from saying that I will calculate v as RT upon p, but the question is this is from the ideal gas assumption and the question is how good is this assumption.

And that is what if this ratio tells us that we measure something in the laboratory divided by what the ideal gas equation of state tells us and we get the compressibility factor z and we went about drawing this curve and saying that ideally if z is equal to 1, and this is 1.0, this is 0 and this is a logarithmic scale going from 0.01 reduced pressure to say point 1 1 and say 10 and even further that to 100.

And we argued yesterday that at very low pressures when we start plotting you say well at a certain reduced temperature what is the z. You may start getting one problem. We say well now at this reduced pressure and another, the same reduced temperature what do I get? That is a point at this and the same reduced temperature I may get this. So, like that if we go about doing plots, we will get a series of points. When they start looking something like this, this would be at some particular value of reduced temperature at some other value of reduced temperature, it begins to look like that in some cases, it goes like that and then goes so around here not like 1, but something like more than 10.

We see that z becomes much greater than 1 whereas, on this side z is less than 1. That means, as pressures remain low and temperatures keep increasing, the straight of z which is divergence from ideal gas anywhere you can just and z more than 1 means that v actual is greater than v ideal gas. This is then z is greater than 1. If z is less than 1, it means and this is less than this; so, v actual is less than what v ideal gas.

That means actually the material the density would be the opposite. So, we can look at it that way that here density is less than the ideal gas prediction and here it is opposite. So, in one case the molecules are actually closer than what ideal gas predicts, in the other case they are further apart them of ideal gas predicts. That is what these two are telling. This complicates life quite a bit. Now, what has happened now is that the nice equation of state that we had p v equal to RT has now to be changed and we have to modify this as p is equal to z times RT upon v.

And z as you can see here, this is the function of reduced pressure and reduced temperature or for a substance it is a function of pressure and temperature. We reduced take reduced pressure and reduced temperature you will get a common graph which I will show you anyway. So, how do we get this and that equation for z this is what again one has do curve fitting and it comes out to the big equation, ok. So, before that let us look at how this curve actually looks like.

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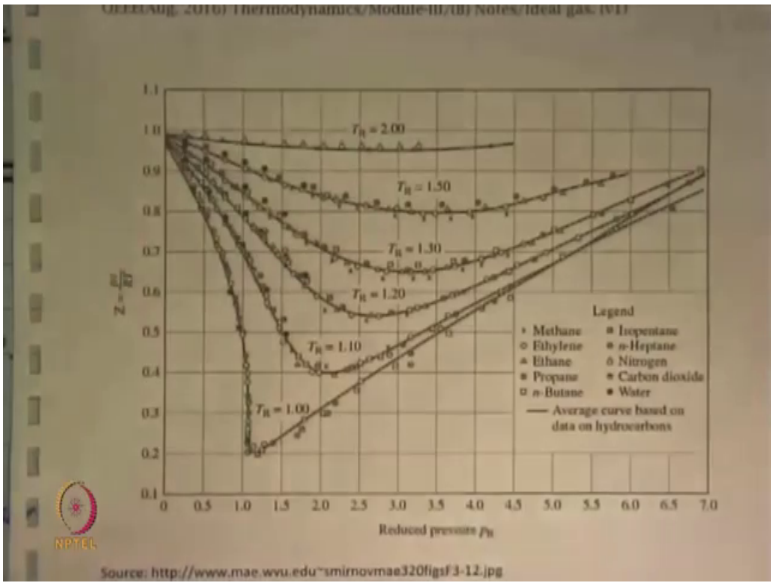

Source: http://www.mae.wvu.edu~smirnovmae320figsf3-12.jpg

So, if this is the real graph with real data from substances and here what you see on this picture in the legend it says there is data for methane, ethylene, ethane, propane, butane, isopentane, n heptanes, nitrogen, carbon dioxide and water. So, we took the real data measure calculated z and plotted these and you can see sp.

Let us take the first curve at the top here this one and you can see that there are some points that are there these circles which are there, the triangles which are there, some crosses which are there and then, they all fall within accurately narrow band through which curves fit has been done. The same thing was done with reduced temperature of 1.3 and we get this sort of a fit and at reduced temperature of 1; that means, temperature is equal to critical temperature we get all these points here and then, they go off here they all fall one one line.

And this axis for reduced pressure is the liner axis and z is also a linear axis and the maximum here is reduced temperature of two which means we have twice greater than the critical temperature. So, this is the reason why the generalized compressibility chart as this is known is so nice that irrespective of what materials you were looking at and there are so many of them here all their properties can be described by one set of one family of equations which is based on reduced pressure and reduced temperature.

So, that is what we have here the same picture on another scale.

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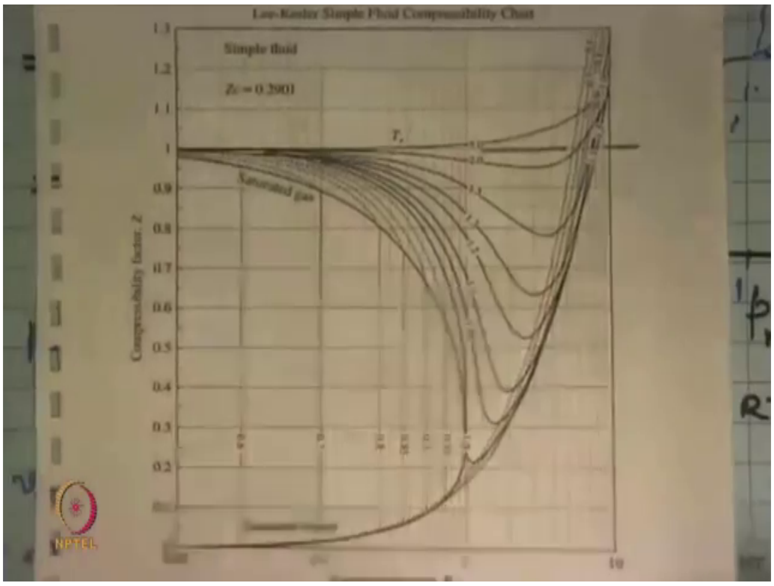

This is this is a same data, but now what has been done is a curve fit was done to that data and the model is called Lee Keslar Simple Fluid Comparability chart. So, there is a Lee Kesler equation of state which was based on the data fit and once we have got an equation, we can put as many points as we want and generate nice continuous curves and that is what you see on this picture here.

So, of the x axis is reduced pressure on the logarithmic scale 0.01 0.11 10 and on the y axis is the compressibility factor from 0 to 1 and they actually going up to 1.31 and for all substances the critical value of the compressibility factor turns out to be 0.29 and here I have the curves, the top most curve which is very close this is the line z is equal to 1. Thus this is 1.

So, if they are close to this line ideal gas behaviour is pretty much good and so let us look at this first line here. These temperature is 5 and what we say is this line goes up there and it stays very close to 1 almost on the way through and then, slightly goes up and then after this the diagram is not given, but they all rise very sharply after this.

So, at the reduced temperature of 5 that means, five times greater than the critical temperature at up to like for this case reduced pressure up to 1; that means, you are very close to the critical pressure. The compressibility factor is very close to unity and that is quite a nice thing to know, but what if you are at not that high a temperature that the next line here you see reduced temperature is equal to and the line comes like this.

Now, there is it is pretty much close to one after this point which is reduced pressure point one after that it decreases reaches the minimum and then,, again go back and then, there is a big change between 2 and 1. This is 1.05 1.1 1.2 1.3 and 1.5. At reduced temperature 1.5 again all the curves start here, but at 1.5 it goes down there and then, again rises up here.

So, now the deviation if you see here this is about 0.8 z 0.8. So, you have 20 percent of from what ideal gas equation tells us and for most calculation that is not acceptable. We want to be within mainly 1 percent 2 percent of the true value. We can never be exact that is the real volume, then 1.2 it dips the minimum here, dips further down, they are down, very close just about 0.5 0.55 something like 0.53 something here. So, it dip it stay below at 1 above 0.1 and then, drops very drastically and then, the pressure increases a lot and again goes up and at 1 it comes down there and then goes up.

So, if you look at this part, they are all start converging towards 1. So, if you go to even lower reduced pressures, all these curves will come very close to 1 and that tells us that as long as you have a vapor, then if the pressures are reduced, pressures are less than 0.1, then at reduced temperature the substance will behave like an ideal gas. That is one nice criteria to have.

The second criteria is that if TR is relatively high between 2 and 5 say like that that is even at reduced pressure up to almost like may be 1 or even may be 2, we can say that there is ideal gas behaviour at these temperatures. So, that is two things are that we have two nice conditions that reduced pressure less than 0.1 defiantly less than 0.01 any reduced temperature the vapor phase will behave like an ideal gas, the liquid phase will of course not be anywhere like an ideal gas.

So, what you are seeing in below is this line which is a saturated liquids. So, as I mentioned any pressure and temperature we can always calculate the specific volume, but the real specific volume in the liquid is going to be several orders of magnitude different from that and so, you see compressibility factors of point or below 0.1 0.1 0.2 something like that and these are lines of constant dryness fraction ah. Sorry the constant is z 0.7 0.8 0.85 0.9. This reduced temperature is constant and because the saturated state at this reduced pressure and this reduced temperature, many states are possible. The saturated liquid state is very poor as a behaviour. It has very poor behaviour like an ideal gas, not an ideal gas at all.

There is the saturate vapor state is pretty getting close to ideal gas, but within still about like 0.95. So, this is about 5 percent off, but we come further down, then this difference goes down and at such low pressures even the saturated vapor which is what they call here saturated gas can be reasonably approximated as an ideal gas. So, very low pressures this would behave like an ideal gas, but not at higher pressure this will this is what this picture tells us enough things.

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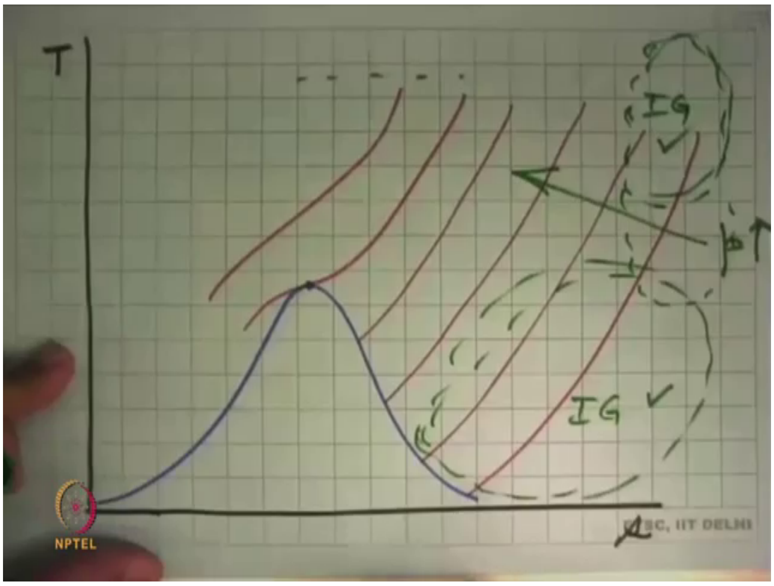

Yesterday when we were looking at many of the property charts let us go back and see what would happen to the Ts diagram

This is temperature and specific entropy here and we had talked about in all cases that if we are dealing with a substance or a system or a problem in which there is vapor like behaviour, then we make a property diagram. We must always show the dome and that is what I am going to do now is that on this case let us say that the dome looks like this. That is the critical point. This is the dry saturated vapor, this is the saturated liquid and what that compressibility chart just told us is that we should look at constant pressure lines that we had discussed earlier they will go off like this, but they are definitely not linear because that difference here is not the same as this. This is going in a very non-linear fashion. These lines are going up like this. The critical pressure isobar goes like this and go up like that.

So, what compressibility chart told us that if you are far away from this, that means if you are somewhere here reduced temperatures are very high. That means, this is there and you are much above that and at low reduced pressures. So, remember this is increasing pressure, ok. So, this is increasing pressure, this could be 0.01 mega Pascal, 1 mega Pascal, this is 220 mega Pascal, 300, 400 mega Pascal. So, at low reduced pressures and high temperatures means we are somewhere in this region over here something like this and that is where we say that the ideal gas behaviour is good.

And it also told us that even pressures are very low, then you could even get down in this region and say that in some cases this would also be reasonably type of an ideal gas. So, this region and far away from this would qualify for classification as an ideal gas. So, if I have to now shrink this diagram and say well where are we dealing with say in the case of air where we are looking at many these processes say diesel, engine, petrol, engine things like that.

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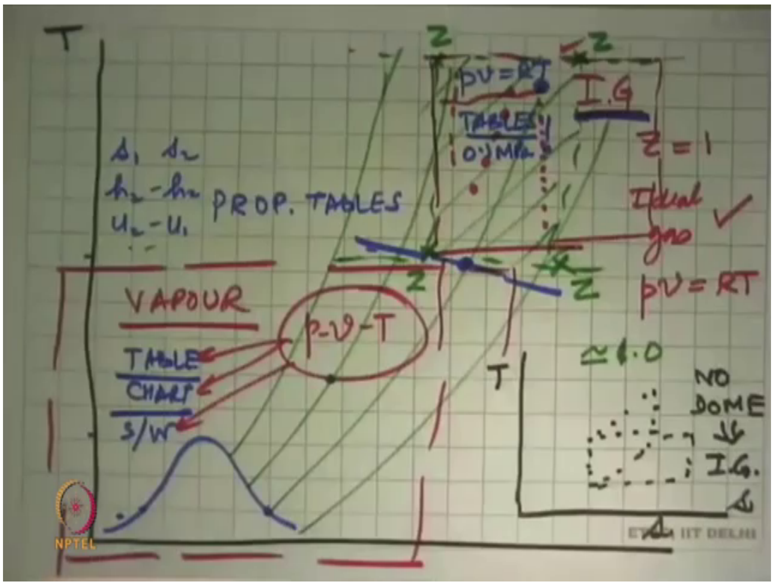

This is s, this is t and for things like nitrogen oxygen, the saturation dome would be somewhere over there. This temperature being like 120 Kelvin 150 Kelvin something like that and ambient temperature is 300 Kelvin which means we have at we have in this air that we have around us, reduced temperature is 2 or of the that order like 2 2.2 or something more than that.

So, we have quite high on that and if you look at pressure, pressure here are low. So, we are far away that means look at the constant pressure line over there. These lines would go off there ambient air would be temperature would be somewhere there. So, we are looking at this part and if you look at any process where we heat the air like say burning fuel in a boiler or in a diesel engine or a petrol engine or in a furnace or compression in all those cases, temperatures would further rise. So, you could say that some 300 Kelvin we might be going up to the as much as 1000 Kelvin; so, that would be a line somewhere over there.

And pressures and then pressure would be say one could be say there and maximum pressures we deal with many of these applications would be something like that. So, we are dealing with the region where many of our applications lie in this zone and that is nice to know that at the extremes of this if we check what is the value of z in each one of them, then it turns out that if all of this z is very close to 1, it means that any state inside this can be assumed to be an ideal state and any process that happens in this region for example, say there is a constant pressure heating which is like this or constant temperature or constant isentropic expansion which will be like this say a turbine gas, turbine aircraft engine or a compressor which is working. So, that would be something like this.

So, throughout this process at any instant z is equal to 1 which means that throughout this process ideal gas behaviour is fine and that means, that we can have complete analysis of this by just going back to p v is equal to r t and that is what we do in first course like this on thermodynamics that when we look at analysis of cycles like these, we will treat them as ideal gas cycles, use equation of state p v equal to r t. Life becomes much more easier and we can get lot of instants is to how this system work, right. As the more advanced level when we go in to detailed engineering of this, we will start relaxing this thing and do many more things to it and get this to be much more realistic.

But the first analysis that we are looking at is good enough to know what the cycle what the basic pictures are. So, that is not going to change. So, what does this tell us? So, that if we have cycle is in this region this part is, so what we will be doing now is that whenever we look at a problem in which we say that the substance is always an ideal gas and we are going to plot these processes and states on Ts diagram, we will not show the saturation zone.

So, in the diagram if it is not there and we show bunch of states like that over there say or there we are implicitly saying that this is an ideal gas state. So, if the dome is not there implies this is problem involving ideal gases and if you have problem where we do not have an ideal gas behaviour and we want to depict those processes, we must work with this part of the chart and we have to show the dome as a necessity.

So, this is a vapor cycle or a vapor process and far away here is the ideal gas cycle and in this course fortunately for us these two properties are quite different from one another and so need not worry too much about this that does not feel that there are no problems where we have both behaviours coming in. At the same time we will take small instance air or say nitrogen which is cooled to produce liquid nitrogen at constant pressure. So, that cooling process will follow like this over there and end up over there. So, it has started and ended conditions with behaving as an ideal gas at some point. It says that now you cannot use ideal gas equation of state, but I still want to know what is the energy transfer in the process.

But it means that in this type of a problem we say that here there is a line and that line we decide based on what data we have in the property tables. So, this line will be decided by the upper limits of the property tables. We calculate changes in properties say from here to there or there or there using the tables data you calculate change in properties from here to there based on ideal gas equation of state and the total change in the process will be the sum of change in both of these. So, that is how we will have to handle problems where we know that somewhere I have ideal gas, somewhere I have vapor like behaviour or non ideal gas behaviour then we must make this.

Just assuming ideal gas all the way through is going to be quite a mistake, ok. So, this is the part of this and now we ask the question that in vapour table tricks the moment I know the state from the tables we could get all the properties and so, if we needed to compare s1 s2 or we use at change in specific enthalpy or change in internal energy or any other property as soon as we have two independent properties at the state, we could go to the tables and pick up all the properties and then do any calculations we want.

So, that is how we use the tables and charts or the software that is there and if we do not have the software, you can go online and there are many brief thing where is the whole properties, then you will get the all the other properties. So, that is what you do here. Here we have two options. One if of course we use ideal gas equation of state. That means, there are no tables and no charts which is, ok. It does not mind the second is there are some tables, but these are largely for a pressure of 0.1 mega Pascal. So, you can say that air or nitrogen or oxygen at 0.1 mega Pascal I want to know that enthalpy change from 100 degree Celsius to 200 degree Celsius, one can look up this table and get those data.

But that is for 0.2 mega Pascal for higher pressures. These tables are of no use at very low pressures also. We can get some idea from these data, but that is not the best thing. So, tables are of limited use and so, there are very few limit tables as far as the ideal gas properties hold the best option. We have in both cases is that we take the full equation of the state which is a relation between p v t and solve it.

That is a much more complicated process unless you have to do it, you do it otherwise we let others do it and we use that formulation for solving our problems. This is what we will do in the tables and charts. Anyway that is how these things came about and so, it stop there here also we can make tables, but there is no real point in many cases this table.

So, now what we will do is we see that how do I calculate property changes for ideal gases and we will concentrate first on change in specific enthalpy change in specific internal energy, then we look at change in specific entropy and then,,we will look at some other process, ok.

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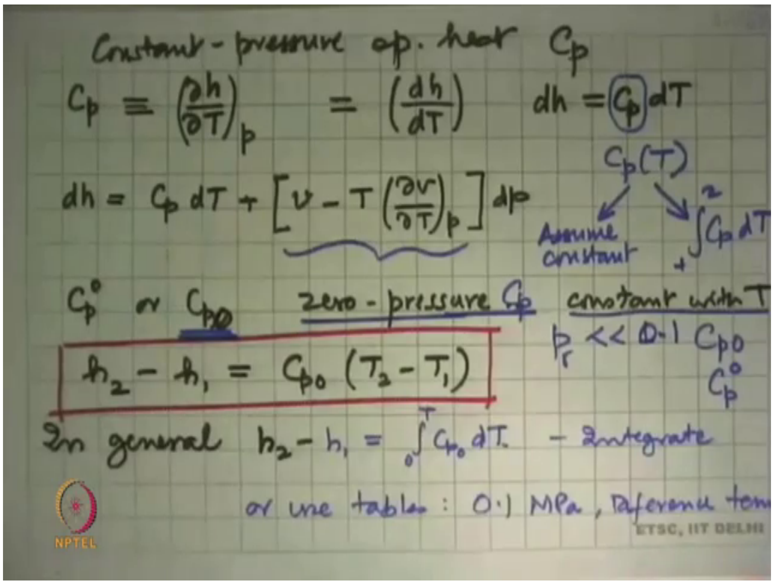

Constant - pressure sp. heat C_p

$C_p \equiv \left(\frac{\partial h}{\partial T}\right)_p = \left(\frac{dh}{dT}\right)$ $dh = \boxed{C_p} dT$

$C_p(T)$

Assume constant

$\int^{2} C_p\, dT$

$dh = C_p\, dT + \underbrace{\left[v - T\left(\frac{\partial v}{\partial T}\right)_p\right]} dp$

C_p^0 or C_{p0} zero - pressure C_p constant with T

$p_r << 0.1$ C_{p0} C_p^0

$$\boxed{h_2 - h_1 = C_{p0}(T_2 - T_1)}$$

In general $h_2 - h_1 = \int_0^T C_{p0}\, dT$ - Integrate

or use tables : 0.1 MPa , Reference tem

So, the next thing we have to do is we define two properties. The first is constant pressure specific heat we denote this by c p and its defined as dh by dt at constant pressure, ok. So, that is what we have and we can also write this we want as dh is equal to c p dt for constant pressure process.

So, if h is only a function of temperature, then we can write this as an exact differential and that is how we do this. The difficulty is that in the real world this c p is a very strong function of temperature and I will show that data for some substances. So, we have two options. I will assume that this is constant and in this course we will assume that, but we should remember that that is only an assumption and the real thing would be that we integrate c p with t from state 1 to state 2 whatever temperature. So, if you want to do this part and write the full equation, then this is what you will get dh equal to c p d t plus whole bunch of things. Here you do not need to worry about it, but I am showing you how there is a dependence on temperature, how there is a dependence on pressure

The point to note here is that in the square bracket we have specific volume temperature, specific volume temperature at constant pressure. So, this entire thing is something that can be evaluated from the p v t relationship or the equation of state and from there you can do some differentials on it, put it in there and we can calculate dh from this. So, what we do is we will say that if we define another some category with this c p which is zero pressure specific heat at constant pressure, zero pressure means that the pressure is a reduced pressure is very much less than 1 or say 0.1 at that low pressures. It is reasonable to assume that it is constant with temperature and below that it is different from c p which is in reality a function of temperature. We use a new symbol which is c p 0. Some books write this as c p 0 over there both have the same meaning.

So, we put that and integrate it and the relation that we will use in this course is now coming up which is at h 2 minus h 1 is c p 0 t 2 minus t 1. A very nice and a simple equation that it is that related to the temperature that we have written. So, that tells us how to evaluate specific enthalpy change between two temperatures. So, here if you needed to my special enthalpy change from here to here, we just needed the two temperatures and enthalpy change will be c p t 2 minus t 1 and if it was up to the limit to where the tables work, then we could get this number from that equation and the remaining enthalpy change from that tables and add that.

The differences are independent of the reference state from its property measurements are given here. So, we are with that. So, that is one new thing that has come up the constant pressure specific.

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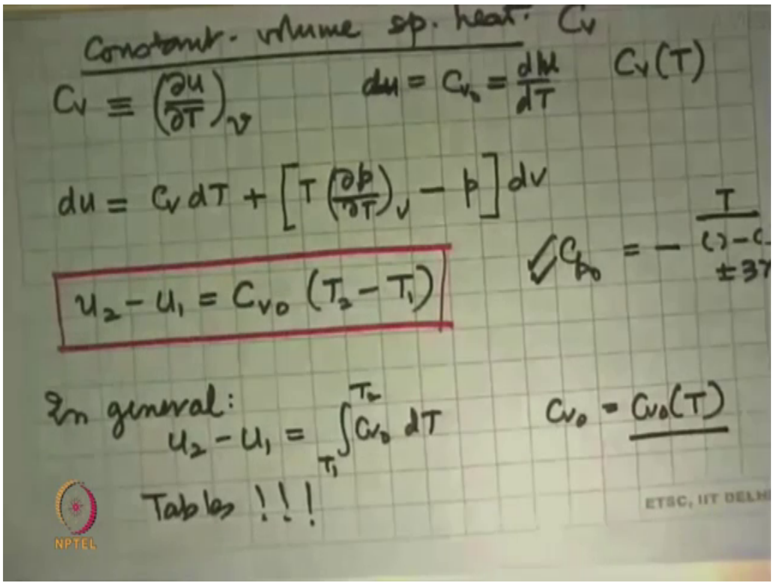

Constant - volume sp. heat: C_v

$C_v \equiv \left(\frac{\partial u}{\partial T}\right)_v$ $\quad du = C_{v0} = \frac{du}{dT}$ $\quad C_v(T)$

$du = C_v\,dT + \left[T\left(\frac{\partial p}{\partial T}\right)_v - p\right]dv$

$\boxed{u_2 - u_1 = C_{v0}\,(T_2 - T_1)}$

$C_{p0} = -\frac{T}{(\,)-c}$ ±37

In general:

$u_2 - u_1 = \int_{T_1}^{T_2} C_{v0}\,dT$ $\quad C_{v0} = \underline{C_{v0}(T)}$

Tables !!!

Heat c p we will now look at its counterpart which is the constant pressure constant volume specific heat or C v. C v is defined as dU by dT at constant and if you workout the full relation using d U is equal to all the expression that we have we will get this type of a dependence. So, basically we are seeing that this is the function of only T and V. So, we get equation on this side. This big bracket term we will write earlier a function or pressure temperature only.

So, an equation of state will enable us to calculate this whole thing and if we have to get that exact internal energy change, we integrate this whole equation in some sort of an equation like this and then, get the answer knowing when that C v 0 like C p 0 is the function of T. C v also is a strong function of temperature that is long and tedious. We won't do that. We will do what we did before with specific enthalpy and we say that C v 0 is dh by dt and sorry dU by dT and when you take it to the other side integrate it, we get the next equation that we can use in our analysis which is that u 2 minus u 1 is C v 0 T2 minus T1.

And that is a nice compact equation to use for solving purpose. So, you got two new properties coming that came out specific c p and c v and a sub classification which is C p zero C v 0 which is zero pressure and we got now two equation. How to evaluate changes in those properties and what it tells us is that the only a function of temperature question is how do I get C v 0 and C p 0. These are standard data that have been measured and over a range of pressures these are given in various temps. So, what is done there is that it says that C p 0 for this material is equal to this much on a temperature range from this temperature to this temperature and it also will tell you that this is good enough. There is a minus 3 percent of and that is good enough for our purpose.

We will follow this where 3 percent is not acceptable. We have to go for the full equation of this one. So, these are available in various books, charts and even on the web and we can pick up by knowing the material where the temperature is. In this we can get the specific heat there and then used it in a problem solving. So, that is how the story done for the ideal gas change in specific enthalpy now we have how do I calculate entropy change or in a ideal gas.

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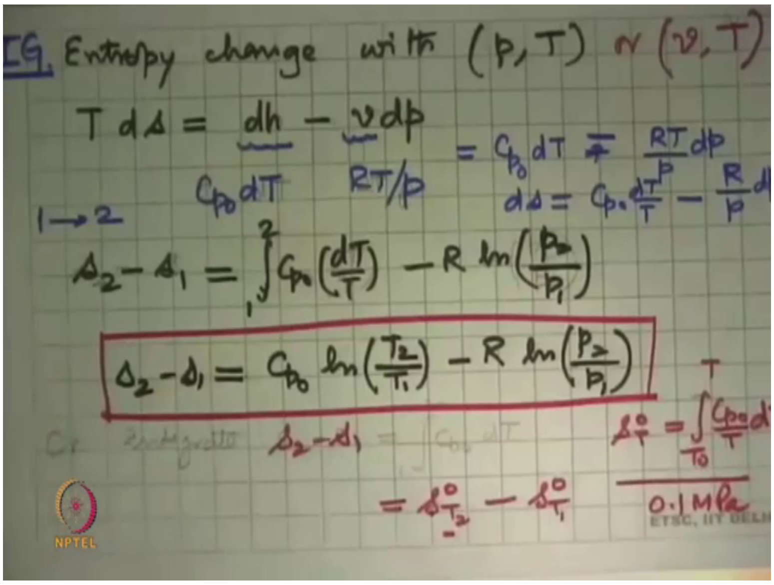

IG Entropy change with (p, T) or (v, T)

$$T\,ds = \underbrace{dh}_{C_{p0}\,dT} - \underbrace{v}_{RT/p}\,dp = C_{p0}\,dT \mp \frac{RT}{p}\,dp$$

$$ds = C_{p0}\frac{dT}{T} - \frac{R}{p}d$$

$1 \rightarrow 2$

$$s_2 - s_1 = \int_1^2 C_{p0}\left(\frac{dT}{T}\right) - R\ln\left(\frac{p_2}{p_1}\right)$$

$$\boxed{s_2 - s_1 = C_{p0}\ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right)}$$

$$s_2 - s_1 = s^0_{T_2} - s^0_{T_1}$$

$$s^0_T = \int_{T_0}^{T} \frac{C_{p0}\,d}{T}$$

0.1 MPa

So, this could be a process where there is a say irreversibility in a compressor or where you say heating of a gas taking place and we want to know what is the entropy change, enthalpy change. We got now we want to worry about entropy change.

So, we have two options here. Entropy change can be obtained either from a combination of pressure and temperature or specific volume and temperature. So, we will get two equations. Both are identical and we can use either of them in our problem solving. So, what we will do first, we will look at p T, then we will look at v T. So, what we get with this is that Tds. We start with the relation that we already had this is equal to dh minus v d p. All the equations that we have derived in the Maxwell's equations that we have talking earlier and now we do some simplifications on this by saying that d h we have already just seen the definition of specific heat at constant pressure can be written as C p 0 d T.

And since it is an ideal gas, so remember this is now only for an ideal gas v can be written as r t upon p and so, this gives us an equation which is C p 0 d T plus sorry minus r t upon p and there is a t on the left side. If you take it to the other side, we get an equation which says d s is equal to c 0 d t upon t minus r upon p. No sorry into dp and that is can be integrated and to make that simple we use C p 0. So, this becomes independent of temperature. So, when we integrate it, this comes out of the integral and we do a simple thing from state 1 to state 2 and the answer is we can just look at it and know that what it looks like.

S 2 minus s 1. This will be integral of 1 to 2 C p 0 d T upon t minus r ln p 2 upon p1. This term there is no problem. The straight forward r is constant. We take it out and that what you get and this if C p 0 is constant. This final equation becomes C p 0 ln t 2 upon t 1 minus r l n t 2 upon t 1 and that is equation that we have been looking for. We have an option of willing some property data where a property called s t 0 listed in the tables which is zero pressure standard stage entropy defined as t 0 to t c p 0 upon t d t and s 2 minus s 1. It may be then s t 2 at the zero state minus s t 1 at zero state and we get the answer which means that you take the temperature look up the table, get the value of this one, then at this temperature get this value subtract the two you get s 2 minus s 1.

But the question is same. This is for 0.1 mega Pascal and at low pressure zone. So, this is quick way to get numbers. In some places these two numbers will be very close to one another, then pressures are very high. This may not be good enough to this. So, for our purpose in this course we except that and we will use this equation that is good enough, ok. So, this is one thing. So, as I said entropy change for the ideal gas can come from two parts pressure and temperature. So, this is pressure here, temperature here. The second formulation is temperature and specific volume and we will look at that next.

So, here we have entropy change, but now we use a different equation T d.

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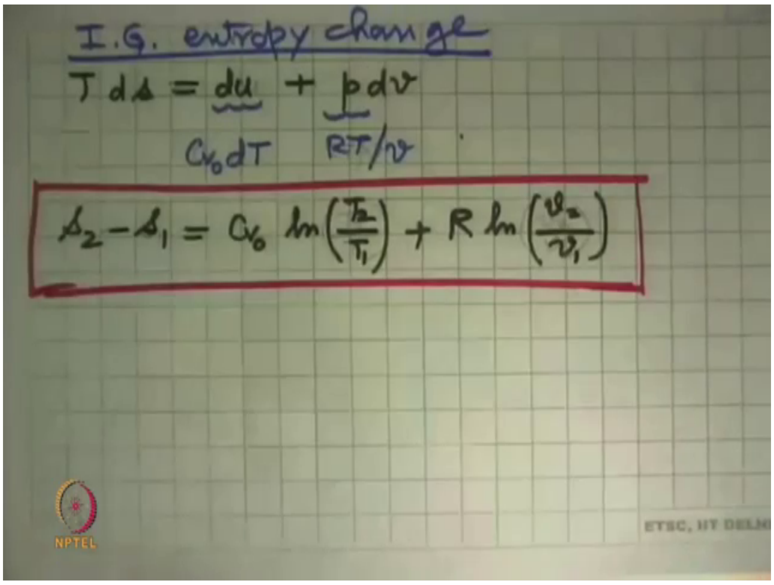

I.G. entropy change

$$T\,ds = \underbrace{du}_{C_{v0}\,dT} + \underbrace{p}_{RT/v}\,dv$$

$$\boxed{s_2 - s_1 = C_{v0}\ln\left(\frac{T_2}{T_1}\right) + R\ln\left(\frac{v_2}{v_1}\right)}$$

S is equal to du plus p dv and here we make the substitutions there before du. We now know is C v 0 dT and p is r t upon v. The ideal gas equations state ideal this is ideal gas entropy change and like before we do that simple calculation simplification y integration and you get s 2 minus s 1 is C v 0 ln t 2 by t 1 plus r ln v 2 by v 1 and that is the 2nd equation that we have been looking for.

So, now what we have got we know how to evaluate change is specific internal energy for ideal gas change in specific of enthalpy and now we have equations for change in specific entropy and that completes everything that we wanting for. So, we are in now a good change that knowing some state points. We can calculate all the other properties even for an ideal gas. We did not use any tables for the non ideal gas behaviour. We use only tables for ideal gas. We have these four relationships. Life becomes much easier when we look at all these things

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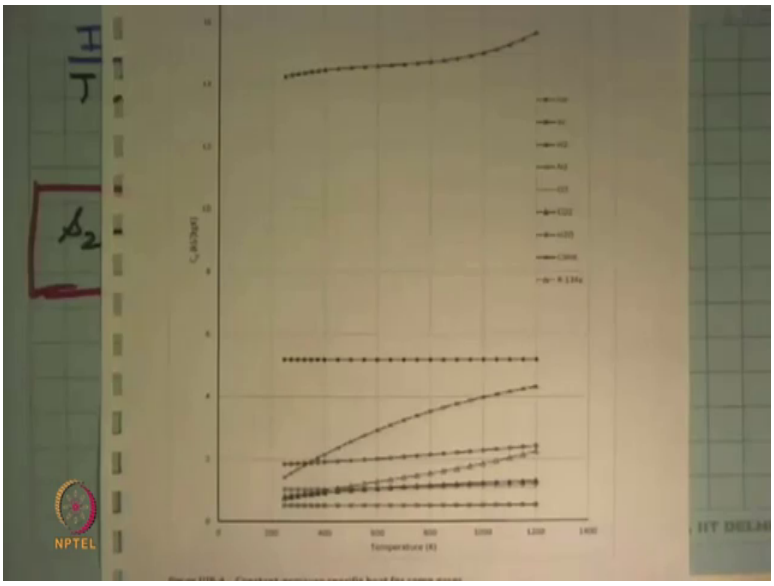

Now, I mentioned that C p is a function of temperature. So, let us spend a few minutes looking at this data which is real data for on the x axis. It's temperature in Kelvin starting from 0 400 800 1200 1400. On the y axis C p in kilojoules per kg per Kelvin and starts from 0 and goes up to 18 and what you see on this curve is that there are lot of curves that are over here. First over here one slightly above that and this one way above. That means, here is a material whose specific heat like 14 kilojoules per kg per Kelvin will it can take in lot of energy or its temperature to raise by 1 degree Celsius and this substance is hydrogen.

So, that is what we have a very common substance. We can happily produce it by neutralizing water and entire this wonderful property for very large specific heat. So, where that is coming huge that if we want to cool something, you would like to have a substance which can absorb a lot of energy, hence temperature does not raise too much those otherwise then the differential of temperature between the coolant and the material will decrease and retransfer rate will come down due to Newton's law of cooling and that is not a very nice thing.

So, here is hydrogen which are at tremendous specific heat and that is why in large electric power generators in all power stations in the nuclear or the cooling of the generator which is like cooling an electric motor means generating heat because of square losses that cooling is done by hydrogen. So, all these big machines are filled with hydrogen to like 3 bar pressure 4 bar pressure and that is the reason why we do certain chemical which actually is from safety view point is somewhat dangerous, but it was excellent thermal properties. So, this is way out line hydrogen is way out on this chart.

So, let now move on somewhere look at the next big chart that comes out way up here and this is helium. So, here is a helium, ok. So, here is a helium and by looking at this looks like this line is almost straight and that is the case, but as the value goes it is 5 point something which is again a very high specific heat. So, helium has a nice high specific heat and it completely independent of temperature. That is what we see from this chart.

Now, let us go down further in this with the with the last line here. This also looks pretty much straight, hence we see what this is this is argon. So, argon specific heat does not change with temperature. Helium specific heat does not change with temperature and you can extend that and come with the thing that helium and argon are monatomic gases. They are very little manners in which they can absorb energy in the atom and so, the specific heat does not change not with temperature.

So, we have two monatomic gases. It depends on temperature in very weak now it could that all the other thing that are lying in between here. We then have nitrogen. There we can see this nitrogen. The specific heat increases slightly as you go up there is oxygen which is the a cross we can see this is going up there. So, what has happened now is that these are diatomic gasses, they have vibrational modes of storing an energy and so, their specific heat is now dependent on temperature much more strongly. Their monatomic gases are nothing hydrogen would also that on a gas. So, there is a slightly increase we see there.

So, monatomic gases specific heat do not change much with temperature. Diatomic gases some more strong dependents bigger molecules, carbon dioxide and water and this is the propane and R134 which is bigger molecules and you can see that they all have dependents on temperature, but qualitatively if you see their specific heats we have including that of water and even nitrogen and oxygen or way below hydrogen the way below helium and way below argon. So, there is a huge difference there and this curve which is you can see this is for water this is going up and we can see that water in a liquid state that we know there is a specific heat of about 4.180 kilo joules per kg Kelvin.

And we know that water is one of the materials which has the highest specific heat amongst all new materials. That is another way why water is the good thing is first is the abundant and second is good for cool. So, water is source we used it chemically very good high specific heat metals, the specific heats are much more, but when it comes to other substances you had helium and hydrogen as two material with very high specific heats and this is good for engineers whereas, hydrogen is dangerous.

So, you have to be little more cautious in designing your equipment helium is inert and you can quite happily use helium and do not worry about any corrosion or reactions. Helium is a very very it is the rare gas very expensive you can buy it yes, but use it only in a absolutely need.

So, that is what we were looking at integrating C p with t. This is the. So, now we look at something at you had learnt in school days, but it now comes out in 2 minutes by looking at what thermodynamics we have learnt and which is that what is the relation between the two specific things.

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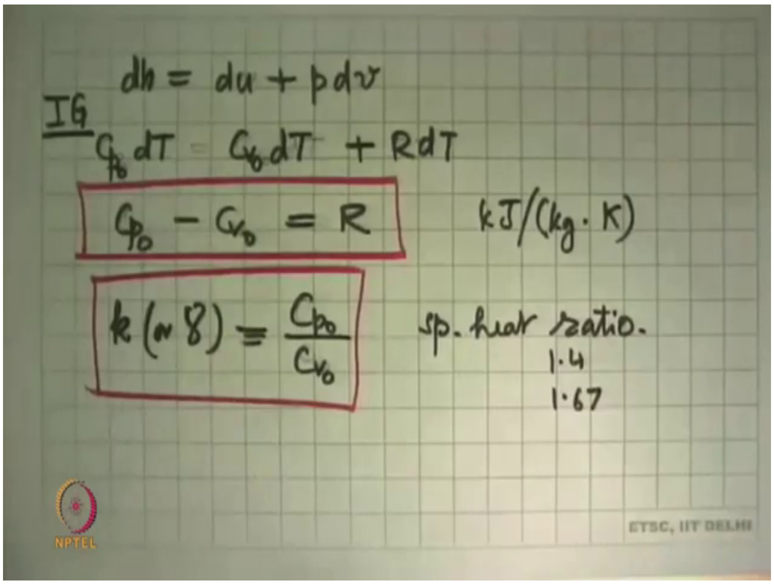

IG

$$dh = du + p\,dv$$

$$C_{p0}\,dT = C_{v0}\,dT + R\,dT$$

$$\boxed{C_{p0} - C_{v0} = R}$$ kJ/(kg · K)

$$\boxed{k\ (\text{or } \gamma) = \frac{C_{p0}}{C_{v0}}}$$ sp. heat ratio.

1.4

1.67

So, we have this relation. The definition of specific enthalpy dh is equals to du plus p dv true for everything. No issues. Now, I will say what about an ideal gas and we said this dh will be C p 0 dT du becomes C v 0 dT and this becomes p dv becomes r dt hmm and you remove t from there and you will get Cp 0 minus C v 0 is equals to r something you have known from school days units of all three in a si units or kilo joules per kg per Kelvin.

And the second thing a number that we will now exploit more and more for gases we do it that is the ratio of C p 0 to C v 0 which is defined as k or in some cases gamma the specific heat ratio and if you remember your physics from other courses you see that for it is 1.4 for monatomic gases. It is about like 1.6 7 for bigger molecules. It is small.

So, that is something that comes up and this k comes up many many applications. So, we have two more relations that we can use that k define that the specific heat ratio and C p 0 minus C v 0 is equals to r. So, this came over from a very next way from the first law of Thermodynamics. We define this ideal gas approximation came this, then comes this is always true, but this is that approximation assumption that we had made. So, this relation is only true for ideal gases and for no other substance.