Cryogenic Hydrogen Technology
Prof. Indranil Ghosh
Cryogenic Engineering Centre
Indian Institute of Technology Kharagpur
Week - 01
Lecture 02
Hydrogen Properties

Welcome to this online lecture on cryogenic hydrogen application or cryogenic hydrogen technology. So, today we are going to ah talk about the hydrogen properties. In the previous class we have seen that the hydrogen properties are very important and we will try to learn some of the fluid properties or you know the properties ah of this gaseous or ah hydrogen. And if we have to liquefy this hydrogen, we will start from gaseous hydrogen and then finally, we will come to liquid or sometime you know to densify we have to go to the solid phase. So, we will now try to look into the different phases of the hydrogen and along with that we will also try to find out what are the different physical properties that we often come across you know while compressing heat or you know expanding gaseous hydrogen and so on. So, let us now look into it ah you know this is the concept that we will cover in this lecture today.

And later on, we will look into the different ah production means. These are the keywords normal boiling point, triple point, critical point, phase diagram I mean these all three parameters are basically related to the phase diagram of the hydrogen. And then we have T S diagram we will also try to learn about the T S diagram in this ah lecture. So, this is what is called the phase diagram.

In this phase diagram ah, it is a relation between the pressure and the temperature and we know that this hydrogen exists in different forms ah be it solid, liquid, gas and vapor. So, and there are different regions ah I mean separated by some lines we will see what are those lines. So, here comes the critical point and this is the triple point. So, now, let us look into the different ah regions. So, it is called in this part ah it will be solid and here comes the liquid between the triple point and the critical point.

This is the this is where you know the vapor phase ah will be existing. So, between the critical point I mean if it is below the critical point pressure and if it is below the critical point temperature then you know ah we have ah this is what is critical point and from here if we vertically drop down this is the critical point temperature and if we move on this side it is the critical point pressure. Similarly, we have the triple point temperature and the triple

point you know pressure. So, if we move from ah this end to this end if we move from ah say the liquid part to the vapor region we say that the liquid is ah vaporizing and from vapor to liquid we say that it is condensing. Similarly, from here to here when we move from the solid the solid will melt and I mean solid will liquefy or it melts to the liquid and from here it you know the liquid solidifies to you know the I mean liquid will be ah moving to the solid region.

So, when it moves from this solid to directly the vapor we call it sublimation and when we move from this direction from vapor to the solid part we call it deposition. So, these are the different you know ah activities or phenomena which occurs and we are mostly familiar with this if if not you know ah it will be a kind of ah recapitulation for you. So, as cryogenic engineer we are concerned about this region between the triple point and the critical point in this region it will be existing as the liquid. So, we have identified vapor liquid and the solid. So, where comes this gas is it different from gas and vapor yeah in terms of ah I mean ah strictly speaking this gas and vapor are different.

Vapor is only when you know it is below the critical point ah temperature and pressure and here this is the vapor, but when it is above the critical point then it exists in the form of gas. So, in gaseous form most of the time you will find hydrogen to exist. So, if hydrogen has been given ah to you know some quantity at room temperature we call it as gaseous phase. How do we know it is state we will see later on that it is 2 physical parameters 2 parameters will be necessary. So, that is given given by the Gibbs phase rule C minus P plus 2 those are the parameters you know that will determine the number of phases present in that sorry the number of independent variables that we need to specify or know the state of that point.

So, here is the ah C is the number of components say here this is a single component hydrogen and the number of phases if it is you know a single phase then we have this is 1, this is 1 and this is 2. So, for gaseous hydrogen I mean it is a pure component single phase we need at least 2 parameters to identify say maybe it is pressure and temperature. So, whenever we are talking about say hydrogen or any gas any cryogen and we we have to specify if it is in single phase and single component we need to specify 2 state points. So, now let us look ah into the phase diagram of hydrogen in reality I mean say now we that was a generalized I mean diagram here comes the actual diagram of hydrogen ah phase diagram this is the critical point this is what is the critical point. So, corresponding value we will check later this is the triple point where all these 3 phases will coexist vapor liquid and the solid.

So, here this is the solid region and here this is liquid and, on this side, you have the vapor. Now, above and this side you know you have the supercritical zone we have the gaseous zone and here comes the compressed liquid part and here it is solid. And now ah this is you know from this chart we can find out the normal boiling point. So, what is mean is that you know at atmospheric pressure what is the boiling point it may be difficult to figure it out from this diagram we will try to locate it in another diagram later on. So, it is the normal boiling point is 20.

3 then comes the triple point temperature ah sorry critical point temperature that comes from here. So, if we drop a vertical line from here we see that this is 33.2 kelvin. Next is the critical point pressure. So, if we move from this end to this end it is nearly 13 point 13 bar or nearly 1.

3 MPa. So, it would not be again I tell you that it is not very difficult I mean it is difficult to figure it out from this graph, but the triple point temperature and the triple point pressure is ah you know 13.9 this 13.9 can be ah you know easily ah obtained from here, but the corresponding pressure it is difficult to understand from this graph. So, these are some parameters or numbers we have to remember particularly for the hydrogen. Now, from this diagram you see here this pressure has been plotted in the logarithmic graph and from here ah you know it will be easier to figure out all these numbers once again.

This is the critical point ah and the corresponding temperature would be on this side and critical point pressure would be on this side. Similarly, this is the triple point and we know that ah the boiling point normal boiling point would be corresponding to one atmospheric pressure that is nearly 1 bar and from here if we drop a vertical line it is 20.3. So, we have normal boiling point once again this T c is the critical point temperature critical point pressure and this is the triple point temperature. Now, it is not that difficult to figure it out that this is 13.

9 and the corresponding pressure on this side is you know sub atmospheric it is ah 7.2 kPa. So, we will try to remember this numbers. So, that you know we can easily distinguish if we state ah you know ah the temperature and pressure for a ah gaseous hydrogen not you know vapor hydrogen. If it is you know in vapor state or in the gaseous state or in the liquid phase we can make out if someone tells about it is temperature and pressure and sometime both of both of it ok.

And we will also try to find out this region is basically what we have said that you know it is solid hydrogen and the solid plus liquid mixture is you know that is what is called slush hydrogen. We will also try to look into that later on when you know during appropriate time. So, that is about this phase diagram that is in the pressure and temperature relation for hydrogen. Now, comes ah this T s diagram this temperature entropy diagram will often be necessary because if we want to compress hydrogen if we want to expand the hydrogen and we need to know what is the initial enthalpy, what is the final enthalpy, whether it is expanded ah isentropically, whether it is expanded isenthalpically. So, all this information will be you know obtained from this kind of graph or the T s chart we will refer to this kind of T s chart.

So, now let us try to identify some of the regions. This part is the critical point. So, first of all we need to locate this liquid vapor dome this is what is called the liquid vapor dome and here comes the C p critical point. This is this point is again important this is the triple point already we have learned it in the phase diagram. This critical point temperature and pressure we have already learned about this critical point temperature.

We have also learned about this critical point triple point temperature for this hydrogen. So, now, corresponding to this we have the entropy values also. So, this is where you have the solid and completely solid this region is solid plus liquid this is liquid and vapor inside this dome we have the liquid plus vapor and it can exist in the ah liquid form only up to this region ok. This is we call it as saturated vapor this is saturated vapor this is on this side we have the complete saturation I mean not at the triple point ah on this side if we draw a line like this this will be the saturated you know liquid on this side we have the saturated vapor. So, there are ah what is called isothermal lines.

So, these are these straight lines are the isothermal lines then you know isentropic lines are on this side these vertical lines are the isenthalpic lines. So, these are the isenthalpic lines these are the isotherms and ah we have moreover ah other lines which have not shown here. So, let us you know first remove it saturated vapor ok. So, let us try to draw some isotherms sorry isobars the isobars are you know the constant pressure lines. So, it would be something like this, these are called isobars or isobaric lines.

So, this will now come like this, this will come like this from here. So, if it is one atmospheric pressure corresponding to that line will you know be your 20.3 Kelvin. So, that is the normal boiling point. So, if we are somewhere here you know near room

temperature that is 300 K if we assume or roughly speaking you know it is 27 degree centigrade and one atmospheric pressure.

So, if you have to liquefy this gaseous hydrogen you know from this temperature and this pressure you have to come down to 20.3 Kelvin or at this point it will be the saturated vapor from there at this point it will be the saturated liquid. So, if you are at a higher pressure as we move from this point to this point you know it will be like this and till this point you can you know have it in the liquid form this pressure is nearly 13 bar or 1.3 MPa as we have noticed in the earliest line. So, there are now different kind of other lines now we will try to locate the isenthal I am sorry we have identified the isotherms and then we have identified the isobaric lines.

Now we will try to locate the isenthalpic lines on this diagram. So, the isenthalpic lines will look like you know it is let us try to draw you will find that there are ah this kind of lines which are called the isenthalpic lines ok and some of them will come inside the liquid vapor dome. So, these are isenthalpic isenthalpic lines. So, on this line the enthalpy will remain constant the enthalpy remains constant along this line. So, we have also seen the ah what is called ah isobars.

So, these are the isobars these are the isobaric line and say if we have to move from this higher pressure to a lower pressure following an isenthalpic process. So, you will find that there is a drop in temperature by this amount of you know. So, this is higher enthalpy sorry this is higher pressure this is a low pressure. So, when we expand the gas from high pressure to low pressure and in an isenthalpic process or you know sometime we call it in a free expansion there would be a temperature drop according to this. So, this is a typical T S diagram and ah you know from here if we move say from this kind of pressure ah if we move from this pressure to following an isenthalpic process we will come inside this liquid vapor dome.

So, as I have said that you know if we want to come from this we have to have some refrigeration unit or available. So, that it can be it can low one can lower the temperature from this end that is nearly room temperature to the liquefaction temperature of hydrogen. But you know we need to have a refrigerator to produce that kind of ah you know temperature. Otherwise there are other ah liquefaction cycles we will talk about it later on and in that process, we will find that you know we are expanding the gas from here to here and we follow an isenthalpic line from this point to this point. So, this informations will be necessary now we will now look into the actual T S diagram.

We will find this is the liquid vapor dome that we have talked about this is the liquid vapor dome here and these are the isenthalpic lines what we have talked about like this these are the isenthalpic lines. And also, we have talked about the you know pressure lines or isobars say for example, this is what is one atmospheric pressure lines we will see it in details later on. So, 1, 1.5, 2, 3 these are the isobaric lines like this say this is you know what is called about 10 bar isobaric line. And later on, this is the triple point where what we have learned that beyond this part it is not in the you know liquid or this is you know it it will be compressed liquid or near critical region.

So, if it is if we follow this line you will find that this is one atmospheric pressure it is coming over here and corresponding temperature is nearly 20 Kelvin. So, this graph this T S diagram is ranging between 14 K to 100 ah Kelvin and you see the enthalpy which is having an unit of joules per gram mole. So, here this these are the as we move up you will find that the enthalpy values are increasing. And as we you know move inside you will find that this enthalpy lines are you know negative enthalpy lines. So, it is very important to note this ah values or this unit sometime you will find that we are expressing it in terms of the joules per gram mole sometime it would be in terms of joules per mole also or joules per gram also.

So, you have to be careful about the unit. So, this graph or this you know charts will be supplied to you ah and you have to ah read or learn reading this particular ah chart. So, this is in continuation to the earlier graph which was there from you know ah from it was here between 14 Kelvin to 100 Kelvin. Now, in this case it is ah between 80 Kelvin to 300 Kelvin. So, if someone wants you to find out what is the enthalpy at 20 K and 1 bar say this is the temperature you know 200 K and 1 atmospheric pressure.

So, you have to locate the 1 atmospheric pressure this is 1 atmospheric pressure how it is going and this is 200 you know K temperature. So, there is no you know line passing through. So, you have to interpolate ah something like here say this is this corresponds to 2700 and on this side, you have 2800. So, it is an interpolation it is a it is a value between 2600 to 2900 this sorry this is 2900 this is 2800 ok. So, ah we have to interpolate ah linearly between these 2 points.

So, it maybe you know around 2000 ah ah what is this is 2700 in between and it will be say about half of it you know 2650 or so. But look at the unit now it is you see here this is not in joules per gram mole rather it is in joules per gram. So, we have to carefully look into it is unit when you are choosing this is the ah enthalpy values. And when you have to

corresponding enthalp I mean entropy if you have to know you have to come down here and it is say 56, 57, 58, 59, 59 then you have joules per gram per kelvin.

So, that is the unit of the entropy. So, this is how we use this T S diagram for calculating the I mean to find out the enthalpy and the entropy value. Next comes ah ah this is in ah I mean ah an enlarged version to ah show it to you that ah as I was telling that this is the 20 K and the corresponding pressure value is like this. This is for 1 atmosphere this is for 1.5 atmosphere. So, that means, when as you were increasing the pressure from 1 atmosphere to 1.

5, 2, 3 like that the boiling point is keep on increasing and it will be this is the triple point. So, with the increase in pressure on top of the liquid you will find that there is the corresponding increase in the boiling point of the liquid. Or in other words if we reduce the pressure on top of the liquid we will find that it is boiling at a lower temperature ok. So, this is about that ah T S diagram and say this phase diagram ah if we want to calculate ah I mean say imagine that we have some amount of liquid hydrogen you know given in a container. So, generally they are double walled vessel this is inner vessel this is the outer vessel and we have some amount of liquid hydrogen.

So, liquid hydrogen if it is stored at a particular pressure you know if we know the temperature of this liquid ah you know we can determine what is the pressure on top of it or if we know the pressure on top of it we can say that what is the amount of liquid I mean what is the temperature of the liquid or what is the boiling point at which this liquid is getting stored. So, there ah this will you will find useful ah later on ah while you know ah doing the ah I mean different generation of the solid phases ah. So, here comes this you know what we are trying to figure out is this you know this critical point and this is the triple point how this boiling point of the liquid is varying between this point to this point with the pressure. So, this is the relation you know and there are constants ah say C 1 to C 5 and this are given like this. So, once we ah have these constants and this relation given we can find out the pressure or the temperature depending on the other.

So, for example, if you know that the temperature of this liquid is 15.09 Kelvin you will find that the corresponding pressure you know from this relation if you put all this coefficient you will find that the corresponding pressure is coming to be you know how much ah nearly 14 kPa. So, you can check this value ah corresponding to 15.09 kelvin if you are putting this value over here then it comes to be 14 kPa.

So, here this P 0 is you know 101.3 kPa that is the atmospheric pressure. So, this is P 0 and T 0 is the corresponding you know boiling point. So, that we have learned to be 20.3 Kelvin. So, if you apply this values in this equation you will find the corresponding pressure comes to be P 0.

So, this is about the phase diagram which we will use to you know determine the different phases in the coming lectures. So, now let us conclude ah and let us before that we will have the references. So, the same references we have given early in the earlier lecture. So, there is no more additional references you can go through this. And in conclusion we have learned that the normal boiling point of liquid hydrogen is 20.3, then we have learned the critical temperature, then the critical pressure and the triple point temperature and the triple point pressure. So, thank you for your attention.