Cryogenic Hydrogen Technology

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Week - 04
Lecture 17
Compressed Hydrogen Storage

Welcome, to this lecture class on Hydrogen Technology. To be very specious cryogenic hydrogen technology in that context we were talking about the hydrogen storage part. And in that connection we have talked about in the previous class about the compressed hydrogen ah storage. And if you remember that this is not about the bulk hydrogen storage, we are looking for the hydrogen storage for a specific reason. And the specific reason is ah you know for driving the vehicles. So, vehicular application for vehicular application we are looking for this hydrogen storage.

So, there is a limited storage I mean capacity for the hydrogen as you can understand that it is meant for light vehicle. And not only that it will be mostly it is desired or desirable that it will be run with the ah fuel cell. So, the hydrogen requirement ah has been ah decided ah or there has been certain targets made by the DOE of USA. And we are trying to follow that in that connection we have learned that there is a possibility of compressed hydrogen storage and that is what we are going to talk about in this lecture.

So, in the compressed hydrogen storage ah we will today try to solve one small problem and this is the keyword. So, let us try to look at the problem definition. So, ah before going to the problem definition what I would like to emphasize that ah in the last class we have talked about that DOE ah target where we have seen that in the near future ah what is ah the target set by the DOE. And that is about the mainly we want to emphasis on two aspects that is the gravimetric storage density and the volumetric storage density. There are other parameters that we have discussed in the previous class particularly with respect to the filling time, dormancy as well as temperature there is a bar or limitation on the temperature and we have said that ah it is limited to minus 40 degree centigrade to minus 50 degree centigrade it should not go below that.

So, it is a non-cryogenic basically in our definition of cryogenics this does not come under cryogenic purview. So, we were talking about the compressed hydrogen and let us look into the requirements or on-board hydrogen storage targets something like in near future 2025 we should have or we should be able to carry about 0.05 kg of hydrogen per kg of the system. That means, if you have 1 kg of weight of the total weight and then that will be hydrogen out of that hydrogen has to be 0.055. And in the near I mean ultimately, we should have we should be able to achieve a target of 0.065. On the other hand the volumetric storage capacity ah it would be I mean what is that volume that will be necessary it is about 0.04 ah that is the target and if it is in percentage it is 40 percent of hydrogen should be there out of you know 100 ah liter or say volume of the total system and ultimately there should be about 50 percent hydrogen should be you should be able to carry ah with 100 you know volume of the system. So, that is about the target.

So, with that target let us look if we have a storage vessel made of all metal. So, this is the problem definition let us have a cylindrical vessel and it is having a finite thickness and it is ah I mean circular in shape and ah on the dishend part there are quite a few dishend here it looks up you know we have used the hemispherical dishend there are ah I mean elliptical distant then there are torispherical dishend and etcetera, but for this class we will be limiting our self to the hemispherical and system only and let us look what are the things that are given what are the value that has been you know set already. So, outer diameter has been finalized that it is 175 which should not be more than 175 mm and then the dishend is as I told you that it is hemispherical and then ah comes the construction material this is made of stainless-steel ah. Later on, we will see that this is not a very good choice ah particularly with respect to ah I mean hydrogen embrittlement we will find that this may create some kind of problem particularly as we ah as we want to store hydrogen under high pressure. So, we need ah I mean material with high ah I mean strength material and high strength material will always I mean sometimes create a problem with respect to the hydrogen embrittlement.

So, it is not a very good choice though ah let us still look ah how it happens in if we if we go for an all metal construction. Then ah comes ah the cylinder length let it be ah 1 meter and then becomes the material density it is stainless steel as we have said. So, it is density is 7860 kg per meter cube and it is ah allowable stress is 130 MPa. So, these are the some of the material properties and the dimension. So, the reason for choosing the ah outside diameter or final fixing the outside diameter diameter that means, we are restricting the volume of this container.

$$PV = n\bar{R}T$$

$$PV = Z\, n\bar{R}T$$

So, since it is a high-pressure storage let us have a look what is the pressure requirement we are trying to calculate the volumetric and the gravimetric ah storage capacity of compressed gaseous hydrogen at 35 MPa. So, 330-350 bar would be the pressure and temperature would be say 300 or 298 Kelvin ah and we have to use ah the ideal gas equation PV equals to $n\bar{R}T$ or you know PV equals to $Zn\bar{R}T$ that is idealized or generalized gas equation with the compressibility factor. So, this is the real gas equation the either other one is the ideal gas equation. So, we will try to find out ah the volumetric and the gravimetric ah storage capacity with respect to this 350 bar and say this is let us slightly change this parameter because all the calculation that has been done with respect to ah the 298 Kelvin subsequent calculations have been done with respect to 298 Kelvin. So, let us try to do the problem or solve this problem at 298 Kelvin and 350 bar or 35 MPa.

So, for this ah you know first of all we need to know what would be the thickness ah requirement because it has not been told in this problem or it has to be decided depending on the diameter of the outside diameter on inside sometime you will be specified the inside diameter and then you have to calculate the thickness sometime we need to ah I mean sometime this OD will be given and with respect to that OD we have to calculate the thickness of this cell. So, here comes this definition and when it comes ah to in terms of pressure vessel it is not like that we can decide anything of our own there are pressure vessel codes and there are standards and this particular calculation has been done as per ASME section ah 8 ok. There are British standard there are German standards. So, you need to follow one of them and there are recommendations for I mean the thickness calculation particularly with respect to this material properties also you will find there are standards. So, we need to find out the thickness of this cylindrical part then we also need to find out the thickness of this hemispherical part or if it is elliptical then it will be different ah ok and that depends on the value of k this k value basically tells you you know this D1 is the minor diameter of an elliptical if it is an elliptical surface.

So, for ah a hemisphere this D equals to D1. So, D by D1 equals to 1 and k would be obviously, if you look at you will find it would be 0.5 for hemispherical ah dishend. Then as we have learnt that this is the ah thickness this will this formula will give you the thickness of the dishend and this is this formula will give us the thickness of the ah cylindrical part. So, with this basic information we have to do the calculations.

So, first of all we will try to calculate the internal volume why do we need the internal volume because we want to calculate what is the amount of hydrogen that is present in that ah container. So, we need to calculate both the cylindrical volume as well as the dishend volume and particularly the internal volume. So, that will decide what is that internal volume available for the compressed hydrogen gas. So, if we look at that ah let us come to that calculation part. So, here is the thickness ah if you ah put P equals to 35 MPa P you put as 35 into 10 to the power 6 Pa and D0 is the diameter of the external diameter of the tank that is 175.

So, D0 is basically 175 into 10 to the power minus 3 meter and Sa is the allowable stress that is ah given as in the earlier ah I mean slide. It was given as 130 or 135 ah P s MPa and accordingly you can find out that the thickness of this ah shell will be coming as 21.3 mm.

So, 21.3 mm thick ah you know shell has to be there ah you can understand it is quite not very small ah thickness.

So, let us try to calculate the value of k already we have already talked about it it is 0.5 for the hemispherical dishend and with that value of the k ah if we calculate the thickness of the dishend you will find that the dishend s are 10.6 ah millimeter thick. So, ah these are the thicknesses of the ah 2 I mean parts with that you know information we can also calculate ah this is of course, the internal diameter this will be this is D is the internal diameter. So, once we know the thickness of this ah what is called this dishend ah and the ah thickness we can calculate the internal diameter ah and accordingly we can find out ah this will be slightly different ah than the other one or if we look it look like this ah it is the D part ah and ah this is D part and this is here this is also let us consider it to be ah slightly you know this is D ah if we though this thickness would be slightly you know this is ah 10.6 10.6 mm and this thickness is 21.3 mm 21.3 mm. So, this diameter and this diameter will be slightly ah different. So, you can take that ah difference also.

So, accordingly we will be calculating the internal volume we have taken this 2 as the same and as per that it is coming as 15 meter 0.015 the meter cube. So, that is the internal volume and we also calculate the material how much is the material volume that means, the volume of this blank portion that is what is the ah material volume because we need to calculate the weight of that ah stainless steel vessel. So, with this information we find that the vessel volume is I mean the solid part of the material part is 97.63 meter cube and accordingly we can calculate ah the I mean based on this I mean generalized ah equation that we will be using.

So, for 35 ah MPa ah we have this Z factor as 1.236. So, while calculating the density we will be ah particularly with respect to the real gas equation we will be using this value. So, ah you can do it by I mean hand calculation or one can also do it on the excel sheet. So, in the excel sheet you have the advantage that you need not ah type all I mean you have to type the equations, but ah you need not do the calculations physically you can easily get it done in the what is called automatically it will be done in the excel sheet.

So, here comes the excel sheet ah. So, these are the parameters which are already given to us and I mean 35 MPa length is 1 meter this is the cylindrical length I am talking about this D0 is the outside diameter of the shell and this is the allowable stress that is ah maximum allowable stress 130 MPa. So, accordingly we have calculated the thickness of the ah I mean vessel or the cylindrical part this k and thickness of the ah this is in milli ah this is in meter this is also in meter the diameter in ah I mean internal diameter of the vessel and this is the thickness of the ah spherical hemispherical head. So, this is the inner volume already we have talked about the material volume and now we find that if we multiply this material volume with ah the density of ah stainless steel you will find that this is the weight of this material. So, so these are the things that we have calculated and now let us try to ah find out what is the density of or the amount of hydrogen that we can store within this volume at 35 MPa and 298 Kelvin.

$$PV = n\bar{R}T$$

So, ah we have used you know this is the amount of ah hydrogen in mole ah that can be stored inside this vessel if we assume the gas equation as ideal. So, yesterday in the last class we have talked about PV equals to $n\bar{R}T$ and ah this n by V now we have calculated earlier, but here what we will try to do is that we know P we know V P is here 35 into 10 to the power 6 P a and ah the volume of the vessel is 0.015 meter cube and then you have the number of moles that we are trying to find out and R is 8.314 joule per mole per Kelvin and you have this temperature as 298. So, these values if you this 298 Kelvin.

So, with this value you can find out that this will come as 210.47 mole of hydrogen, but ah as we have said that we are supposed to also calculate the ah real gas using the real gas equation. So, generalized ah equation of state with the compressibility factor and there we have the z value given in the earlier slide 1.236 and with that value we can calculate the hydrogens content will be 170.28 mole of ah gas. So, in terms of ah the kg or in terms of the mass we find that it is 0.43 kg of hydrogen we can store at 35 MPa and 298 Kelvin whereas, the actual one or the real gas equation would tell you that this amount is only 0.34 kg. So, this one you know meter length cylindrical cell with you know of course, distend is about another you know point ah how much of D into this ah this ah multiplied by 2 ah that is ah I am sorry this would be the diameter of that hemispherical head. So, on both sides along with that length it has to be added ah or with the what is that is given is D0 is given.

So, ah the total length would be 1.175. So, that is the kind of length we have for this total ah hydrogen storage and there we can store only about 0.34 kg and whereas, the material weight itself is 97.6 kg. So, the gravimetric storage capacity you know we can calculate just dividing this 0.34 ah kg of hydrogen and then you have 97.6 plus 0.34 kg. So, this is what is that gravimetric storage capacity ah with respect to the real gas equation we have not done it for the ideal gas equation because that is not the actual one, but ah with respect to now with respect to this outer ah vessel diameter. So, this is the volume of the outer diameter that means, how much volume it is occupying and it comes out to be this has been done with respect to this D0 and this is the outer volume.

With respect to that if we calculate the volumetric storage capacity we find that it comes to be only 12.8 kg per meter cube whereas, the ah actual density if you look at you will find that the volumetric density is coming to be 22.9 kg per meter cube. So, you can understand that if it is an all metallic cylinder ah obviously, the storage capacity in terms of both gravimetric as well as volumetric storage capacities are not up to the mark. So, we need to look for a different kind of ah I mean storage ah vessels and sometime in 1960 onwards actually the necessity for this kind of lightweight storage vessels cropped up and along that time during that time you know there was I mean ah a different kind of thought about the storage vessels lightweight storage vessel was cropped up particularly for the space applications and there we find that there are different kind of alternative storage ah vessel design as or you know it has come up.

So, these are the high-pressure storage vessel there are primarily 4 types we will look into it. So, there is the first type already we have talked about it is all metal and we have seen that the storage capacity is not that good both in terms of the volumetric as well as gravimetric storage capacity. Then comes ah you know there was ah yes type 2 ah ah I mean pressure vessel was designed where there is a ah metal liner this red colour one is the metal liner and along with that metal liner there was a hoop stress I mean hoop lap was given. So, this hoop lap is basically ah glass fibre reinforced plastic and that takes care of I mean basically ah the some of the load will be taken in by this ah hoop layer and as we are wrapping ah the material over this cylindrical part or fibre I mean glass reinforced plastic if it is ah you know wrapped over this cylindrical part over the metallic liner that takes care or reduces the thickness of the ah metal body ok ah. And this tensor not you know it is not hoop lap ah.

So, later on we will find there was modification, but with this modification itself there was a straight way 20 to 30 to 40 percent of weight reduction that could be possible. So, this was about the type 2 where ah it is the cylinder liners are ah basically metallic and there was hoop lap. Then comes ah type 3 ah metal ah I mean storage type vessel where this ah still we have the metallic liner, but ah there is a full lap I mean this is not only on this cylindrical part there is on the ah hemispherical or you know the elliptical part also there we have the carbon reinforced ah FRP is the fibre reinforced plastic. So, carbon fibre reinforced plastic is wrapped around the I mean entire body, but still we have the metallic liner. So, with this ah metallic liner and this ah I mean fibre reinforced plastic we find that there is advantage in terms of ah both load bearing as well as the cyclic ah you know loading and unloading that is I mean this all these vessels will be subjected to high pressure storage and then again it will be ah taken out whenever it is necessary.

So, there will be I mean fatigue load or cyclic pressurization and because of the cyclic pressurization and depressurization. So, that is I mean in terms of the fibre reinforced plastic we find that it takes the load in a better way than you know ah metal can handle. So, with that this type 3 we have ah I mean the advantage of you know this 20 percent will be ah as I was telling that load will be taken mainly by the composite material, but there is still about 20 percent of metal ah in it and the next generation was about the type 4 where all you know plastic material there is no metal at all. So, there is plastic liner along with that we have the full lap or you know everywhere I mean this is the hoop and this is where you know the distance all are you know lapped with the wrapped with the the carbon fiber reinforced plastic and the advantage is with this kind of carbon reinforced plastic is that it is corrosion resistant obviously, and it is you know as I told you that it can withstand the fatigue ah I mean quite well, but with this plastic liner another advantage is that this kind of metallic storage or any kind of high pressure storage will also come with certain inserts like later on we will find that there are pressure reducing valves, temperature sensors etcetera. So, all these things which are you know coming in basically they are not getting wetted or any since there is no metallic part in this vessel.

So, we do not have any problem with respect to hydrogen wetting ah which can take place with the metal liner ah fine. So, that is about this type 4 ah vessel and we find that it has as we told you know this is enhanced fatigue life because of the successive pressurization and depressurization part and there are commercially available ah things I mean this kind of high pressure vessels are available in the market this is with respect to this is the quantum designed ah I mean you can see it on this website if you wish to. So, this kind of you know this from this figure it is I mean well understood that there are this kind of hoop laps etcetera ok. So, this is about a practical system which are in use ah particularly in European countries this kind of high pressure vessels ah for hydrogen storage in the ah vehicular application. So, these are the references I think you should ah you know go through and let us conclude that we understood that the metallic cylinders have the low gravimetric storage density and with the application of I mean if we are going for a composite material that improves the ah gravimetric and volumetric storage capacity and ah next, we will try to look into the compression work ah.

So, that ah this complete part will be ah I mean that that will complete this discussion on the compression part because we understand that this gaseous hydrogen storage also no need some amount of work to be done ah in the compressor. So, thank you for your attention.