Cryogenic Hydrogen Technology
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Lecture 31
Cryo Hydrogen Storage

You are welcome to this lecture on cryogenic hydrogen technology. We were talking about the hydrogen production so far. And then we have also talked about the liquefaction of hydrogen. And in particularly we have in particular I mean we have talked about the hydrogen liquefaction following I mean basically if we want to store it in the cryogenic condition. So, we have to put it in the liquid form or there are other means like we have the option to store it in the cryo compressed condition. And we have also told that there is a possibility of storing hydrogen in carbonaceous material so that is cryosorption storage.

But today in this lecture we will talk mainly about the cryogenic hydrogen storage or cryo hydrogen storage, where we will try to you know put it this how this liquid hydrogen container would look like. And what are the details that you know has to be looked into particularly if you want to store hydrogen in liquid condition. So, the topic of today's you know this I mean discussion is basically hydrogen storage at cryogenic condition, but as I told you that it will not include the cryo compressed hydrogen or cryosorption hydrogen at this moment, but later on if possible we will have a look into that also. So, it is basically hydrogen storage tank we are talking about.

Now, while talking about the cryogen storage we have to understand one thing that basically if we look at any cryogen storage or cryogenic fluid storage, we will see that most of the time I mean basically it deals with temperature below 123 Kelvin which is way lower than the ambient condition which is at 300 Kelvin. So that means, we have to take care of lot of heat transfer that means, if we are keeping the hydrogen or say nitrogen liquid nitrogen in cryogenic condition. So, immediately it will start evaporating because it will receive enormous amount of heat from the ambient condition. So that means, we need to protect it ah, but I hope all of us are familiar with the thermos that we use in our household ah basically to store ah hot I mean ah you know soup or you know tea or coffee or say you know sometime we put cold water. So, basically it is a double walled vessel.

So, this has been ah I mean invented long back by Sir James Dewar and to store ah liquid hydrogen and that concept has been followed thereafter you know till today ah. Basically of course, it has been modified a bit, but ah, but the basic philosophy of storing the cryogen is still ah the same. But ah there are you know if we try to ah ah I mean ah classify this storage vessel you will find that there would be mainly 2 type of ah storage vessels, one is the stationary another one is the movable one or transportable one. So, the stationary ones can be ah obviously, very large and sometime there you know several meter cube ah or tonnage capacity ah storage tanks which you cannot ah you know think of in a transportable Dewar their shape and size will be different. So, you know basically these cryogenic storage vessels can be from few cc to several meter cube and ah obviously, we cannot bring everything under the same umbrella, but just we will have a look into ah the basic ah necessity of any cryogenic storage vessel.

So, as I was telling that ah this cryogenic storage vessels could be stationary or transportable ah it can be classified ah for stationary or transportable one I mean wherever it is ah the ideal you know ah vessels type should have been you know a spherical one. Why spherical one? As we were discussing that outside we have you know nearly 300 Kelvin temperature inside depending on the liquid ah it can be you know for helium it would be 4.2 K say if it is ah for helium for hydrogen it is nearly 20 K. So, you can understand that the difference in temperature is enormous. So, we have to try to reduce the heat transfer from outside to inside ah and one of the key parameters we do not have much you know control on the temperature difference because the moment you are putting a cryogen inside its boiling point depending on the pressure inside it will be fixed.

The outside temperature also we know it will not ah be much different maybe you know around 20 or 30 degree you know depending on the location of this storage container or during the different season you know there would be slight difference, but the main difference will be between the I mean ambient temperature and the liquid ah boiling point or normal boiling point or the boiling point at elevated pressure. So, that is more or less is the governing ah you know ah factor to decide the heat transfer. The other parameter which is in our control is the surface area. So, now, we want to put a very large amount of cryogen and we want to have the minimum heat transfer surface area or exposed surface area in that condition we have ah the surface area per unit volume this is the best option. But imagine you know a spherical Dewar or spherical container ah ok this spherical vessels or cryogenic vessels ah are often called as Dewar because ah it is after the name of Sir James Dewar and often we call it as ah I mean cryogenic vessels as Dewar ok.

So, fine. So, this heat transfer surface area per unit volume as we have said that it is a minimum for a spherical vessel, but ah construction of such a spherical Dewar putting it one inside the other is not that very ah easy task to do. But why are we putting this in then you know in the under the stationary ah kind of storage vessels because most of the ah I mean large stationary vessels you will find that they are spherical in shape and not only that, but they are not it is not like that we have fabricated it ah in a ah workshop and we have you know transported it in that particular format. So, sometime you know this this could be ah 2 storage building ah long or I mean in size and that you know of course, we have to prefabricate some of the components and then you know it has to be assembled finally, in a what is called where it is going to be ah stationary I mean it is going to be ah installed or where it is going to be situated. So, that is why I mean for large ah spherical I mean for large stationary containers we have the advantage of making it in the form of spherical Dewar, but we cannot probably gain much you know when it is a transportable Dewar.

But for transportable Dewar or I mean for stationary Dewar I mean there it is not like that we cannot make this kind of horizontal storage Dewar ah it can also be ah you know made of in horizontal condition, but these are basically cylindrical ah vessels with the distents which or this heads basically they are ah either hemispherical or you know spherical in shape or basically they would be elliptical or ah torispherical ah dish ends will be provided here. So, this will definitely not ensure ah the minimum heat transfer surface area, but of course, it will be an optimum ah I mean in looking ah this ease of fabrication and etcetera probably this is the best option for storing the cryogen. Sometime we will have this kind of vertical storage vessels also and I mean it is a transportable as well as for the what is called ah ah stationary vessels also. So, these are the kind of storage vessels we can have ah in ah reality, but if you carefully ah note this you will find that I am not filling this container to the brim or I am not completely filling this container basically we will keep this face on top of this liquid as you know ah I mean this space will be vacant or we call it as hm ullage space. This space ah say is about you know 20 percent ah nearly 20 10 to 20 percent or many a times you know we put it as 15 percent of this space we keep it as vacant.

The reason is very simple we will find that whatever we do how much insulation we put around this ah inner vessel between the inner and the outer vessel ah basically this in the annular space, but we have to I mean ah admit that certain amount of heat will always come in or heat increase will always be there. So, if it is so, then we cannot stop you know evaporation of this liquid from the top surface ok. So, boiling will or evaporation of the liquid will always take place and there would be an enhancement in the pressure in the ullage space. So, that if we are not providing any ah I mean vacant space for this liquid to evaporate then there would be ah I mean excess pressurization and of course, there would be pressurization even if we provide the ah ullage space, but there would be some space you know for the vapor to be generated and it will not cause unnecessarily ah you know over pressurization of the tank or you know immediate release of the ah evaporated vapors. So, that is why you know we keep about 10 to 15 percent or 20 percent of this ah inner vessel has to be ah you know kept empty.

So, the liquid will be on the bottom side and there would be vapor on the top. So, now let us go ah to the ah I mean slightly in detail exactly what are there the components in a cryogenic storage vessel. So, here we have the inner vessel which will contain the liquid or cryogen. So, this is the cryogen for example. So, it could be nitrogen, it could be hydrogen, it could be oxygen or you know liquid helium whatever.

So, this is I am showing it in a horizontal ah condition because this is ah particularly we have it in mind that if we have to store ah liquid hydrogen in a ah movable ah vehicle ah what are the things that are to be there in a small cryo container. So, this is the cryogen and as we have said that this is at low temperature or cryogenic temperature. So, it must be insulated. So, it is the basically a double walled vessel. So, this is the outer vessel.

So, in between we must ah you know it cannot just hang on ok ah. So, or it cannot just be suspended ah like that. So, there must be you know suspension system adequate suspension system why and it has to be done judiciously because ah there would be a direct contact between the outer vessel to the inner vessel that suspension system will you know ah enhance basically the heat transfer. So, we have the suspension system here I am showing it you know ah a kind of suspension system like this where this has to be preferably insulated and it will be ah you know we have to ensure that there is a very minimum ah ah contact area between this ah surface to this surface and ah it must be an insulator. There are different kind of suspension system ah depending on the size of the container this is a movable one probably we can go for this kind of suspension system, but ah a detailed suspension system or the tie rod and etcetera for a larger container will be ah altogether different design problem.

But ah as such the suspension system of any cryogenic storage container is itself is a topic of research for a even today. So, now, ah let us look into ah this ah container where we have said that we have the inner vessel, we have the outer vessel, we have the cryogen in the inner vessel and this is ah the suspension system. So, you can understand that this outside container that is in contact to the room temperature whereas, this is in contact to the cryogen at low temperature and we must insulate this space. So, we have to insulate this ah you know around in the annular space must be insulated and the better the insulation we are ah you know in a better position to store it for a longer time. So, we can avoid you know heat in leak because of this ah you know good insulation ok, fine.

So, other than that ah so, if it is the I mean if I have sealed everything where the liquid will come from or how it will come out of this storage vessel. So, we must provide some you know ah access for this liquid, we have to fill in or we have to ah you know take it out as and when it is necessary. So, we must give some fill and drain piping we must connect, but it is not everything because you can understand that ah other than that ah we must basically ah just if we look at what are the materials of construction ah this is most of the time these are made of stainless steel sometime they are aluminium or in a nutshell ah they are cryo compatible materials ok. So, there are it is not like all the materials and ah you know are cryo compatible there may be ah what is called because of low temperature there can be ah what is called the ductile to brittle transition may be occurring and you may find that ah this will not be suitable for all the materials may not be suitable for cryogenic application and particularly for hydrogen we have to be very careful because there is a problem of hydrogen embrittlement also. So, most of the time as I said that this is made of stainless steel which is ah which can retain it is ductility ah down to very low temperature, but this outer vessel it is not always you know ah I mean ah we need not make it out of stainless steel because that is the costly ah material, but we do go for some time you know the stainless steel one, but there can be ah other cryo compatible material, but this will be subjected to room temperature mostly room temperature not only room temperature room temperature and pressure.

So, ah other than this that means, you know this ah how much cryogen that we are putting in that I have said ok fine we will be filling it with 80 percent of ah the cryogen. That means, ah I am not able to figure it out how much has been filled whether there is enough space whether it has been filled up to 80 percent so that means, we need to monitor the level. So, ah other than this ah 6 component that we have talked about these are the essential things, but along with that we must have ah a pressurization arrangement why do we need a pressurization arrangement because this you know draining of this liquid once we have filled in how do we transfer it it is not like that I will tilt it and you know take it out from this container. So, we have to make an arrangement for this ah you know pressurization of this liquid there are different kind of arrangements maybe we will talk one or two of them. One of them is you know to put ah and put an electrical heater and along with that electrical connections has to be taken out.

So, that for that you know we should provide a feed through system. So, that ah these electrical connections can be taken out of this ah you know annular space and ah if you electrically heat it up. So, some amount of liquid will be boiled and that liquid ah are evaporated from the top surface and then it will create pressurization and that will transfer the liquid from inside to outside. Now ah there are different arrangements as I am telling as I was telling that sometime you will find that we are taking the liquid from inside and then we allow it to evaporate and ah you know using the external heat sources ah like ah ambient air or water or whatever and then we put it back inside this ok. So, this liquid will be taken out evaporated and put back to the system.

So, that it is getting evaporated I mean sorry it is getting ah pressurized. So, that this transfer of this liquid will be taking place ah from inside to outside. Now there has to be some pressurization arrangement the moment you say that we have the pressurization arrangement we must have some temperature and pressure sensors and obviously, ah you know you need to monitor ah what is that liquid level inside. So, we have to have some kind of ah liquid level the gauge or because outside we know looking from outside we do not figure it out that how much liquid has been filled in. So, we must put some temperature and pressure ah sensors pressure sensors on the top whether you know it is getting over pressurized.

So, that you know it has to be within the design pressure or allowable pressure limit and if you are monitoring the temperature at this space ah you can probably predict what is the ah saturation pressure ah because why probably I am telling because ah you know this ah there may be stratification of ah this liquid in a stationary container that that stratification ah is much more compared to a movable one. So, ah you have to be careful about ah measuring the temperature and of course, ah you know this pressure this pressure will of course, be you know more or less uniform in the annulus ah sorry in the ullage space. So, other than that we have ah sometimes the anti-slosh baffle particularly when we are ah you know doing the road transportation of this cryogen ah anti slosh baffle will ah basically try to reduce the oscillation created by the you know dynamic ah force which are acting on this kind of storage vessels. So, ah a very common example is when we are the carrying ah the any liquid with us ah probably when we are riding a bicycle and carrying a liquid you will find that the liquid is trying to come out of the container and if you are not taking adequate ah measures. So, there are anti slos baffles to arrest that kind of you know sloshing of the liquids ah to avoid unwanted you know damage into the containers.

So, many of them we will not be able to discuss in this class, but some of them you know probably we will take up in the ah future lectures. So, that is about the cryogenic storage vessels. So, now let us try to look into this some of these components in detail ah one by one and ah let us start with the inner vessel. So, you probably remember that this has been taken up while talking about the storage vessel for ah cryo ah sorry ah the compressed hydrogen gaseous hydrogen and we have talked about the ah thickness that will be necessary for a metallic container. It is also ah basically the similar kind of thing except that it was stored earlier in the compressed condition in the gaseous condition now it is in the liquid condition, but it has to follow the same you know pressure vessel code and you have to follow some design ah you know ah standards like either ASME or DIN or you know British standards and all ok.

$$t = \frac{pD_0}{2s_a + 0.8p}$$

So, ah here ah most of the time we have said that ah that we are following the Barron's book where it is ah you know the given for the ASME code all these expressions that we are writing here it is basically the ok fine. So, let us look at this ah inner vessel if we take a cross section ah it will look like this. So, where D is the inner diameter and D0 is the outer diameter. So, it has a thickness of D0 minus D by 2 and then we have ah the straight cylindrical length of ah length L. So, the thickness of this ah you know the straight section of the cylindrical section is basically given by the P D0 by 2 Sa plus 0.8 into P, but P is the internal pressure ah inside this container at which condition we are planning to store the cryogen. It is not only that this is ah it is depending on the allowable stress of this material which is under you know you know for which we that is that is what we are using for fabricating this ah container and D0 is the outside diameter we can also try to correlate it in terms of the internal ah I mean the inside diameter the formulas are available in this book already I think we have talked it in the earlier lecture. But what is about the dished end ah thickness basically along with that we should have ah dished end like this ah you know ah these heads are to be covered up. So, ah we have the thickness of this ah end plates ah ok which is often ah hemispherical or torspherical or elliptical in nature and there ah are different you know ah I mean expression ah depending on this value of this k ah this also we have covered in ah the earlier lecture where k is that ah you know factor that is taking care of this ah minor diameter to the measure diameter particularly this D1 is the minor diameter of an elliptical ah container. So, all these details will be available if anybody who is interested to make a design of this cryogenic container can try to follow this book ok.

So, that is about the inner vessel ah part how it would be ah the thicknesses of this things will be determined. And of course, if you have the idea say we want to store a particular ah volume of liquid or ah volume of say LH2 that is to be ah you know known a priori. So, that we can decide the size of this container ok. There has there will be ah different parameters like the length, then diameter ah and obviously, you have to comply to the customers requirement of ah making it within that limit. So, most of the time people will be telling that we want to confine it within a particular volume and accordingly ah you have to ah decide your ah container size.

So, if we know the volume we can decide this L and D part and accordingly ah, but once we know the pressure internal pressure ah of this ah liquid nitrogen at which we are going to store, then we can also calculate the thickness of this ah ah inertial and the thickness of this dished ends. So, once we do that ah we have to look into the ah external vessel, but ah you imagine that this is something where we are storing the liquid ah inside. So, it is subjected to this vessel was subjected to the inner ah you know ah internal pressure, but for the external or outer vessel ah we have a different story all together. Here if we look at it is also similar to the other fixture, but we have say this is the outer vessel and this is the outer shell and inside this one we have the inner container where you know the liquid is ah stored it is a double walled vessel. Now, we are talking about the outer vessel this inner vessel has already been taken into ah considered or taken into consideration.

So, fine if we have this external or outer vessel this is subjected to the atmospheric pressure. So, ah that means, ah it is you know ah having ah it will take not only ah that it is not subjected to internal pressure rather it will be subjected to internally it will be subjected to the vacuum ok. Vacuum why vacuum because ah we will come to that part in the next slides in next couple of slides, where because we want to reduce the ah I mean um heat transfer from outside to inside and one of them is basically the convective heat transfer and the convective heat transfer will be reduced by ah putting it this annular space under vacuum ok. So, the moment we say that this vessel is not subjected this external vessel is not subjected to ah you know ah I mean external ah what is called pressure. Pressure is of course, the you know atmospheric pressure which we cannot neglect at all, but inside we have the vacuum.

So, ah there would be a problem of you know buckling of this ah vessel. So, we must take care of that in our design consideration. So, we have to provide sufficient thickness and the thickness of this ah you know outer vessel shell part is basically ah given by this where this E is the Young's modulus and gamma is the Poisson's ratio. And T0 is basically it is it has to be designed for some critical pressure and we will talk about that critical pressure in ah you know in some of this ah next slides ah. Then ah this is about this part then we have to also do it for the dished end or the end plates ok.

So, ah for the dished end thickness we will be having a different ah expression where this R 0 is the radius outside radius of the spherical head or it is equivalent radius for you know the elliptical head this value of k 1. It is available in that Barron’s book you can ah I have not you know given it here. ah If we are solving any problem relating to that this value will be supplied to you otherwise you can always refer to this Barron’s book where you will have these values listed for different ah diameter and diameter ratio basically and also this is for the total spherical one it is the crown head. So, that is about ah the dished end and the ah outer shell thickness, but ah what is about Pc? Pc is basically 4 times the Pa that means, ah if the atmospheric pressure is 101.3 kPa we have to consider 4 times this for designing the thickness of this ah outer shell or the dished end.

So, accordingly you know we can decide it and then ah of course, ah the suspension system as I told you which will not be probably take ah you know taken into consideration in this lecture, but ah it is by itself it is ah ah odd say sometime for a larger ah container you will find that we need to put some stiffening ring on this side ah along the with the internal ah I mean inner vessel. So, those are ah basically ah topic of the you know different lectures which will not be taken up in this class ok. So, that is about the outer vessel part. So, these are the references ah we will ah follow for these lectures. So, thank you for your attention.