Cryogenic Hydrogen Technology
Prof. Indranil Ghosh
Cryogenic Engineering Centre
Indian Institute of Technology Kharagpur
Week - 07
Lecture 32
Cryo Hydrogen Storage

You are welcome to this lecture on Cryogenic Hydrogen Technology. We were talking about cryogenic storage in the liquid form, ah cryogenic storage in liquid form. So, in continuation to our earlier lecture where we have stopped ah at ah you know designing of the ah liquid nitrogen storage container. Now, today we will be looking into another aspect which is need to with the design of ah this storage container that is the insulation. So, it is the topic is hydrogen storage at cryogenic conditions, but we will in continuation to that as I have said we will talk about the insulation and in particular we will talk about the multilayer insulation. So, ah to start with ah about insulation, insulation is an essential part of any cryogenic storage vessel and it is highly application specific.

So, which means that ah some ah insulations which are recommended for a particular ah type of storage vessel may not be suitable for a different application. So, it maybe you know for a very large storage capacity tank some type of insulation is you know ah is ah suitable, but that may not be ah like in a small storage container ah like we are talking about the storage of hydrogen for vehicular application which is typically a small container. There the type of insulation that we are going to use may not be suitable for a tonnage liquid hydrogen storage tank. And as we have learned in the previous ah class that the shape of the container is equally important for you know storage of the liquid ah cryogenic fluid.

So, in cryogenic fluid means particularly if we are talking about liquid hydrogen, we will see that there are certain restrictions like you know we cannot you know make it ah open vented or we just cannot allow the hydrogen to be vented I mean ah just like that to the atmosphere. It has to be a closed container or any release of hydrogen has to be in a proper way ah. So, that you know this hydrogen and oxygen ah particularly of the air is not making a combustible mixture. So, looking at this requirement if we now look at the ah insulations particularly for the application specific as we have said ah it has we have to look into different aspects like ease of application for example. How easily we can wrap the insulation or you know put the insulation around the ah in the annular space.

Now, then ah of course, it is effectiveness whether this insulation is adequate to have this enough or prevent enough heat in leak from outside because we have said that outside most of the time it is around room temperature that is around 300 Kelvin or so, but inside depending on the cryogen for us it is liquid hydrogen which is at around 20.3 k and ah that is a you know it is a quite large temperature difference. So, we have to apply certain you know insulation which will be effective or it will try to reduce the heat in leak from outside. Then comes of course, the strength and weight I mean after wrapping or you know putting the insulation it should not be such that ah with time there you know out of their own weight or you know there I mean accumulating at a particular point making thermal short circuit or it should not weigh too high you know to ah make it very bulky. And then of course, ah it is cost is equally important I mean ah at some point or other it should not be such that it is very very costly.

So, looking at this kind of requirements ah we have ah different type of ah insulations those are in cryogenic application. One of them is the extended foam which is ah the popularly known as you know polyurethane or polystyrene foam. So, these foams are basically made ah you know passing some foaming agent like CO2 or some other gas which will make the things porous and mostly it is open or closed porous ah these foams. And ah, but the problem with this expanded foam insulation is that ah this foaming gas which are often interrupt inside this foam will be condensing when it is applied ah particularly to very low temperature application. So, there are ah I mean, but for ah I mean applications where ah I mean it is not that stringent requirement is there for the I mean insulation then we can think about this kind of foam again ah I mean there are ah mechanical point of view you know there are certain limitations like it should not ah have you know ah a I mean it should not be brittle at low temperature.

So, that is another required I mean for I mean low temperature ah insulations. So, now, coming to the other type of insulations it is called gas filled powders like pearlite and fiberglass or Santocel these are the kind of ah you know ah insulations which are ah also in use ah what we have to keep it in mind that ah this insulations should be able to arrest 3 basic mode of heat transfer that is conductive heat transfer, convective heat transfer and the radiate radiation heat transfer. So, basically if we try to reduce all these 3 modes of heat transfer this gas filled powder is definitely not suitable for this kind of application. So, we have to ah keep it in mind that we must you know evacuate this annular space and we have to you know this vacuum insulation is ah often very effective to reduce the convective heat transfer. So, ah it is one of them I mean ah though ah basically if we look at this annular space and if we do not put any other thing and just we evacuate ah I mean that means, vacuum insulation is standalone vacuum insulation if we put we will achieve certain amount of you know ah reduction in the what is called ah I mean heat in leak, but it will not be able to prevent ah one basic mode of heat transfer that is ah the what is called radiation heat transfer and not only that ah it will reduce the convective heat transfer, but this ah free molecular conduction that will also be ah you know present at low I mean at reduced atmosphere or in vacuum.

So, we will talk about this vacuum insulation in details in the following slides. Then comes ah another evacuated powder. So, that is ah basically the fine or the coarse ah pearlite powder and along with that we are now putting the insula I mean vacuum insulation. So, it is evacuated powder, but as I was telling that evacuation ah will definitely reduce the convective heat transfer and pearlite powder the you know this is in powder form. So, it will reduce the ah convective sorry conductive ah heat transfer also, but it cannot take care of what is called this radiative heat transfers.

So, in order to reduce the radiative heat transfer what we do is that we ah put some opacifier or ah you know some reflecting material inside. So, that is having a very ah I mean very small or high reflective ah surfaces or very low emissivity. So, this opacifiers will be ah you know used and finally, what we find is that ah you know multilayer insulation ah where we put alternative layer of conductive ah sorry ah non-conducting material along with ah spacer like ah silk net and etcetera. We will look into that in details later on. So, this is the these are the type of insulations we mostly use in cryogenic application.

So, let us go ahead with the typical thermal conductivity ah basically we do not talk about the thermal conductivity of a particular ah you know type we talk it talk in terms of the effective ah thermal conductivity or apparent thermal conductivity. So, let us have a let us have a look into the type of you know or the number. So, you can see ah this the effective thermal conductivity ah and it is ah in terms of milliwatt per meter Kelvin and the expanded foam ah is having of the order of ah 33 milliwatt per meter Kelvin. But when we talk about ah this vacuum insulation as I said that it is about 1 to 2 milliwatt per meter Kelvin and it is ah the advantage of vacuum insulation is that ah often we will find that if you have very intricate passage it is basically easier to you know evacuate it and get a reasonably good insulation that also you know depends on the type of temperature between the two ah surfaces they are maintained at. Then comes evacuated powder it is ah definitely better than the gas filled powder as you can see, but this ah opacified powder of course, this is copper centrocell it looks not that good, but there are other ah you know the aluminium centrocell etcetera are there ah and the problem with this opacifiers are that since we use some metallic kind of chips or you know highly reflecting surfaces often they create a kind of ah I mean short circuiting thermal short circuiting of course, ah in the in in the annular space.

So, we have to be very careful about the ah conglomeration of this kind of ah you know ah opacifiers. Then comes this multiple multi layer insulation if you look at the value of this insulation thermal conductivity it is way different than the rest of it ah it is a you know order of magnitude several order of magnitudes ah lower than the other one. So, the reason the being ah it is a very I mean low thermal conductivity or it is ah I mean effectiveness of this particular insulation is ah because of the what is called we we could reduce all the basic modes of heat transfer basically the radiation conduction and convection. So, let us have a look in detail about this ah super insulation or sometime we call it multi-layer insulation as super insulation also and let us have a look. So, before that we we will look into this vacuum insulation ah because this vacuum insulation ah I mean along with that we will be able to understand better this ah multi-layer insulation.

So, if we have a storage vessel like this ah this is the horizontal storage vessel we have liquid in the safe some kind of liquids maybe you know ah it is liquid nitrogen or liquid hydrogen. So, that is what is being stored here and then we find that the radiative heat transfer ah will be proportional to the emissivity factor then you know we have configuration factor F12 and sigma the Stefan Boltzmann constant the area ah A1 we have put it as this is the area A1 and this is the area A2 and then we have this temperature this outside temperature is that Th this inside temperature of the container is that Tc. So, since these two temperatures are widely different we have a very high you know rate of ah I mean radiative heat transfer. So, that is given by this formula and this varies with the fourth power of this temperature difference and here this F12 that is the configuration factor this inner surface is being completely confined by the external ah you know surface. So, this is supposed to be ah equals to 1 and then comes this Fe factor emissivity factor which will be given in terms of the emissivity of the two surfaces A1 or A2 and this A1 and A2 where this A 1 we are talking it as a in internal surface A1 and this surface this outside surface is e2 with the corresponding emissivity factor e1 and e2 for the inner and the outer respectively.

So, this is what is that ah emissivity factor ah and if we just put some value for this emissivity factor of ah 0.7 for each of them we find that we have something like Fe equals to 0.5385. So, that will lead to this kind of you know without any basically if you ah look at this ah we have no ah I mean internal ah radiative shields or etcetera just one internal ah tank and it is enclosed by the outside tank. So, we do not have any kind of ah you know intermediate ah shields or any layers in between.

Now, comes ah in in a let us put some kind of insulation in between. So, now, we have several layers of insulations and ah that these are basically let us say let us say assume that we have some n number of shields. So, if there are some N number of shields and these shields are basically very with comes with very high reflectivity ok or highly shining surface with very small emissivity factor ok. So, if ah this emissivity is of this individual plates are very low then we can ah you know write down this emissivity factor effectiveness ah you know effective value of this emissivity factor would come as you know epsilon c that is the for the low temperature where we have talked you know it has been in the earlier expression this is epsi e1 and this is ah eh is epsilon 2 or e2 and es is the emissivity of the shields which we are putting in between. So, there are N number of such shields.

So, the effective ah ah I mean value of this emissivity factor would become 1 by Fe and this whole expression. So, now, if along with say e1 ah this is e2 of course, this is e2 equals to e1 equals to 0.7 and also we will put epsilon equals to 0.05. So, you will find that if you do this calculation you will find that Fe is coming to be a very small value.

So, that means, with the ah you know insertion of intermediate ah radiation shields we could ah you know reduce the ah radiation heat transfer ah and that is exactly what is done in a multi layer insulation. So, we will have the many reflecting surfaces intermediate in between the annular space and ah you know these surfaces comes with the very high ah reflectivity or very small emissivity. So, now, if we look at this ah now we will go back to our discussion on the multi-layer insulation as we are talking. So, ah this is what is the multi layer insulation. So, we have ah basically aluminized mylar.

So, mylar is basically a polymer and on both sides of it ah we have you know micron thick ah layer of aluminium and that will be very shiny in shape and in between between the 2 ah what is called aluminized mylar we have one silk net. So, this is the silk net or paper or sometime you know the fiberglass mat we put in between. So, this is the way you know we make a several layers. So, here this silk net or paper that will be acting as the ah I mean non-conducting medium and the aluminized mylar will act as a radiation shield and this is what is multilayer insulation. So, now, ah it is of course, and very exploded view ah in reality you will find that they are very I mean pretty much close to each other ok.

So, ah this is what is ah multi layer insulation. So, this part are this is aluminized I mean the central one this red colour one is mylar and this is ah you know there is a thin coating of aluminium on either side. So, that gives you the shiny surfaces, but you know we cannot just put one over the other because that will create a kind of thermal short circuiting. So, ah in between we put the silk net or the fiberglass or this is the fiberglass mat or paper or silk net that is what we keep in between or between the 2 layers as we have ah drawn schematically here. So, that is about the multi-layer insulation and along with that we must have you know some kind of I mean very good amount of the vacuum we will talk about that the vacuum requirement for this kind of the multilayer insulation.

Now, ah if we have to wrap this kind of insulation around the inner vessel the immediate question that will arise ah let us look into a practical situation ah this is the multi layer insulated tank ah it is a quite a old tank ah you know this is basically meant for ah liquid nitrogen transportable they were in the ah I mean in the lab. And this is next supported basically this is an FRP tube which is connecting the inner vessel and the outer vessel this is the inner most vessel where you know the liquid nitrogen will be or this is basically a liquid nitrogen storage vessel and this is the outer vessel where ah you know it is exposed to ambient temperature. This is what is that you know insulation we are talking about of course, this is in ah kept in open condition for long and it has deteriorated with time, but you can understand that there are alternating layers of ah you know the mylar and some papers this is pretty old. And this particular vessel if you look at this is the inner vessel this is the outer vessel, but I will you know ah I mean I want to stress upon one particular aspect to look at the welding joint this is I mean aluminium welding has been done. Just think about ah the welding procedure that one has to adopt because this you know inner ah cylinder or inner container is wrapped with the insulation super insulation and it is containing you know the ah multi layer insulation where alternating layer of paper and mylar will be there.

And you are subjecting it to this kind of you know high temperature welding. So, it it is something you know which is to be done very ah I mean ah it it is done ah after doing all the assembly. So, it is very very tricky. So, how do you do that ah you should think about you can think about ah ok. But this particular one as I told you that this is the next supported one ah where the outer vessel and the inner vessel is connected with the help of an FRP tube ah fiber reinforced plastic tube and that is typically a very low thermal conductivity material.

And that is inserted there just to you know reduce the heat yield from the ah outside to inside through that neck. So, ah if you look at this you know this is a ah exploded view particularly where we have talked about this ah you know mylar insulation where we have mylar insulation separated by this ah paper type of insulations in between ok. So, this is another ah I mean these are ah comparatively recent kind of ah um aluminized ah mylar and along with the you know ah this is fiberglass ah ah separating plates. But ah what I would like to mention here that there are ah this days it is possible ah I mean technologies manufacturing technologies quite ah improved and advanced. So, that if you need if you estimate that we need this many number of layers and ah there are technologies to give you in the format of that many numbers of layers.

And just you what you have to do is that you have to wrap around your particular cylinder. But keeping in mind that ah this type of insulations are ah very much ah I mean effective thermal conductivity depends in the direction ah or highly directional. Thermal conductivity in one direction ah will be ah in a quite different from the other direction of I mean that in the other direction. So, one has to be very careful about handling this kind of ah materials. And though you know it is shown that it is ah handed with ah handled with ah you know bare hands, but in practice it has to be handled with ah I mean with the globes and all.

So, that the darts or the walls which are ah you know attached to our hands, bare hands are not getting you know transferred to these highly reflecting surfaces that is going to again change the ah emissivity of the material. So, that is about the multilayer insulation. Now, let us look ah on the parameters on which this kind of you know ah materials depends on or the ah effectiveness of this multilayer insulation depends. So, first of all ah obviously, we have seen that there were n number of ah intermediate layers and that was reducing the effective thermal conductivity now. So, that means, we ah find that this the effective thermal conductivity of this ah you know ah insulation will depend on the number of radiation shields or the number of layers we are putting.

Ah As such they are very thin in nature and ah you know within ah few centimeters there will be some 20, 25 number of layers depending on the particular um separating sheet that is in use. And of course, what kind of compressive ah loads that is there on it, but you may argue ok fine we have put it in the ah annular space what kind of compressive load ah people will be expecting. Ah sometime it may so, happen that it is over because of it is own weight ah it may you know change the multilayer insulation. If we are putting any kind of what I have told that you know after ah putting the insulation or wrapping it around the inner vessel or like that ah if we are putting a band you know to hold it in position that can also change the effectiveness of this ah multilayer insulation. So, by effectiveness what we mean is that ah the effective thermal conductivity of this multilayer insulation.

Then we have the gas pressure in the annular space ok. So, what is the amount of gas that we are putting in the ah I mean chamber ah that is again ah important ah. Then comes the number of perforations why we do need we need a perforation. So, if you look ah back into that you know diagram where we have said fine we have an inner vessel, we have an outer vessel and we have you know we are wrapping ah insulation like this all around it. So, you must have the kind of evacuation ah in a port attached to it.

So, that we can you know create a good amount of vacuum around this vessel, but the point is that if you are enclosing it with different number of layers ah how this ah gas will come from the innermost layer ah. So, that means, we have to provide some kind of perforation on this kind of you know insulation. So, here you can see this is the kind of perforation you can expect and that perforation the number of perforations that we are ah putting or the much that we are making in the MLI that is again you know going to that is again that is going to determine the effectiveness of this multi layer insulation. Then finally, we will see that when we look into the expression for this effective thermal conductivity, we will find that what is the terminal temperatures or the temperature between the innermost and the outermost or the boundary temperatures because that will also determine the level of thermal conductivity effective thermal conductivity and the number of inserts like fill or vent lines ok. So, it is not like that you know this is the tank and we have a evacuation port ah and we do not you know ah have any means of putting the liquid or taking the liquid out of this container.

So, we must you know provide the filling and the drainage or the venting lines along with that you know we may have the electrical feed throughs, then you know pressurization vacuum or temperature sensors electrical sensors everything. So, the number of inserts are again you know going to change the ah effectiveness of this thermal conductivity, but we cannot probably make out you know theoretical estimation of that effectiveness. But as such the ah effectiveness of this ah thermal conductivity it will depend on the number of ah layers or radiation seals that we are putting and that you know the number of radiation seals per unit length ok. So, it depends on the ah conductance of this ah material or you know this space this is the ah we have already talked about this sigma that is the Stefan Boltzmann constant is the emissivity of this material and this effectiveness as such depends on the temperature terminal temperature or boundary temperature levels. So, ah if we look at this parameters ah along with that we will also have the ah as I told you that the vacuum level or the gas pressure in between ok.

So, in the annular space. So, it depends on ah let us look into the min apparent thermal conductivity variation with the gas pressure given in Torr. So, this is how it varies. So, it is you know nearly had to room temperature ah sorry atmospheric pressure this value will be of the order of you know few ah milli watt per meter Kelvin, but when it comes to ah a gas pressure of you know almost 10 to the power minus 5 Torr or you know on nearly about 1 milli bar milli Pascal or so, ah ah it is apparent thermal conductivity will come to that ah 10 to the power minus 3 milli watt per meter Kelvin. So, that is the about the ah effectiveness or the min apparent thermal conductivity ah as it varies with the internal or annular space vacuum. Then let us look into ah this expression for this overall effective thermal conductivity as we can understand that it will depend on this value of the number of layers per unit length.

So, it will be something like this as it the layer density is increasing there will be a decrease in the effective thermal conductivity, but eventually if you are putting too many layers of ah you know ah thermal conductivity layer that will you know squeeze the things or ah make thermal you know contraction or thermal short circuiting to eventually ah make this thermal conductivity of this ah ah MLI I mean again taking a higher value. So, we must have you know we we must try to put ah then optimum layer number of layers for this ah multilayer insulation ok. So, ah as we have seen ah in this expression that ah this multilayer insulation depends on the end temperatures just a small numerical ah estimation will show you how ah you know ah the effective thermal conductivity is varying with the the end temperatures. So, there is a small problem you can try to solve this problem it is a very I mean trivial just you have to put the conductance of the space material ah you know is ah this is basically hc and epsilon is basically 0.05 and this temperatures between 300 k and 20.4 K ah and between temperature 20.4 and 4.2 K you will find that the ah things are the effective thermal conductivity is varying ah between the two limits. So, ah that is about the MLI thermal conductivity ah then ah you can consult these are the references that Thomas Flynn and Barron's book for this ah study. So, in conclusion we can say that liquid nitrogen storage needs a double walled vessel ah obviously, with a good number of insulation and ah there are though it is application specific for a very large storage vessel maybe this ah MLI will not be the best option ah, but ah for a small storage capacity vessel MLI can be a good option. Thank you for your attention.