Cryogenic Hydrogen Technology

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Lecture 18

Compressed Hydrogen Storage

Welcome to this lecture on Cryogenic Hydrogen Technology and we were talking about the hydrogen storage. In particular ah we were talking about the compressed hydrogen storage and that is for that is basically ah the compressed hydrogen storage we are looking for vehicular application and we have the DOE targets ah to achieve a particular ah the gravimetric as well as volumetric ah ah concentration or the storage capacity of hydrogen. So, in that connection we have talked about ah the different type of storage vessels that we have come across and we have in the last class talked about an all metal ah cylinders ah which is ah which can give a very poor kind of gravimetric as well as volumetric storage concentration. So, ah in that connection we also understood that we need certain amount of work to be spent towards the compression part because we have to compress it to nearly about 30 MPa or 35 MPa to a maximum about 700 MPa ah and that is not coming free of cost we need to have some gaseous I mean compressors to compress the hydrogen gas ah using different type of compressors. So, we will try to look into that. So basically, we will be talking about the compressed hydrogen storage and this is in continuation to that compressed hydrogen ah in ah for vehicular application.

$$W_{adia} = Z \times \overline{R} \times T_{in} \times \ln \frac{V_2}{V_1}$$

So, now let us look into the compression work part ah we have the isothermal ah compression part which is generally given by Z R T inlet temperature and then ln V2 by V1 ah. So, here this is the ah most ideal kind of ah I mean compression work you can say because this most of the time though we say that it is an isothermal compression because that is ideally gives you the minimum work requirement and in reality, it is very difficult to get such kind of ah in isothermal compression. Whenever there is compression there is a tendency of the gas you know to dissipate that heat of compression and there will be evolving I mean heat will be evolved and we have to get rid of that ah heat and often we go for ah I mean multi stage compression part. So, the more commonly ah common you know is ah an isentropic work of course, that is given ah here this expression is the compression work and that is an ideal compression.

$$W_{isen} = \frac{\gamma}{(\gamma - 1)} \times \bar{R} \times T_{in} \times \left\{ \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\}$$

That means, we are ah adiabatically compressing it from state 1 to state 2 that is from P1 initial pressure to P2 final pressure if we are compressing the gas using ah I mean it is in in an isentropic fashion keeping the entropy constant or trying to keep the entropy constant to be very precise ah because it is not that ah I mean ah it is not that easy to keep the entropy constant. So, there will be definitely some entropy generation. Now, ah this gamma is the ah specific heat ratio for the gas involved since ah gas we are now talking about is hydrogen. So, this is a this is a diatomic gas and gamma would be taken as mostly 1.4. So, that is about the gamma part and P2 by P1 is the pressure ratio and ah so that means, if we have to ah pressurize it to 700 pressure and if we have been given some gas from 1 atmosphere. So, it requires something like you know 700 ah ah times you know this would be 700 you know that is not ah feasible because from 1 bar to 700 bar ah if we compress it there would be enormous ah temperature rise. So, you can understand that this P2 by P1 in case of isentropic compressor will be limited by the temperature rise it can withstand and as a matter of fact, you will find that about 4 is to 1 P2 by P1 that is the very typical in case of the isentropic compressor particularly with respect to the compressor that we are we will be talking about. So, finally, if it is a piston type in a compressor we will have that kind of limitation with this isentropic compression part and with respect to the isothermal work we will also ah you know have it in mind let us see how a best you know the other compressors can ah you know do that. So, now, the actual work as I told you that it is ah this W isentropic or the work in the isentropic ah manner ah would be not possible.

$$\eta = \frac{W_{isen}}{W_{actual}}$$

So, we have the adiabatic efficiency and that will be I mean if we divide the I mean the ideal work divided by the adiabatic we will have the actual the work requirement and typical adiabatic efficiency is about 75 to 85 percent. So, if we calculate ah with respect to this ah the isentropic work and then if we divide to you know with respect to 0.75 or 0.85 depending on the adiabatic efficiency given efficiency we can calculate the real work, but here this compressor work that has been calculated in terms of joule per mole of compressed hydrogen then this is only this ah I mean ideal ah thing that we have ah come I mean calculated. So, here one of them is the isothermal ah compression work you can understand that that gives you ah quite low value, but whereas, the real ah or ah I mean isentropic I mean compression the work requirement is quite high compared to the isothermal work.

And in actual process of course, it will be again you know divided by 0.75 or 0.85 and that will be quite higher. And there is another we have not talked here, but it is neither isothermal neither isentropic it is in between there is a polytrophic expansion ah which we will not talk in this class, but those who are interested can also look into that polytrophic expansion and polytrophic index will be ah there associated with that. So, accordingly that polytrophic work can also be ah you know calculated.

So, here ah in this connection so, once we you know have calculated this compressor work in terms of joule per mole and also, we have learned about ah in the in sometime about the LHV that is the lower heating value. So, we will be interested to know ah what fraction of this lower heating value we have to invest while compressing the gas. Because finally, we are going to store this hydrogen in a container maybe in the compressor in the form of compressed hydrogen gas and we had to spend some energy. So, let us have a look what fraction of that light I mean say lower heating value we are consuming towards this compressor work. As I was telling before going to that part ah that you know if we have a multi staging ah part then we have definitely some reduction in the ah compression work you can see that you know this in between this if we have say P1, P2 and P3 where this P3 is the ultimate pressure we have to achieve ah say in our case this maybe 350 ah bar or you know 700 bar.

And you know the this is say if we have you know 1 or 2 or something other than that here in this context I will also tell you that this is a first of all you know we are compressing it from P1 to P2 and from P2 to P3 ah. Then this will give you slightly you know less than the compressor work requirement. And if you remember sometime back we have said that this pressurized output from any electrolyzer ah while producing hydrogen we have said that we are producing hydrogen from a ah SPE solid polymer electrolyzer and it is possible there to have you know pressurized hydrogen output. So, now, you can understand that if we are having some gas at you know instead of 1 bar if we are taking the delivery from that SPE cell at nearly 30 bar or so, they will enhance I mean the you know or reduce the work requirement of any isentropic compression part. So, the it is better you know ah if we have to ah get a target of say 300 bar pressure ah for example, and if we start with a 30 bar in between you know we can choose another pressure.

So, we have a target of say 300 bar to 30. So, it is about say a 10 ratio, but ah 10 times we have to compress, but if it is you know starting from 1 bar obviously, the requirement would be way higher. So, that means, if we are able to ah I mean produce the hydrogen at a higher pressure higher initial starting point in this compression part will be of always advantageous. So, now, let us go and try to look at that requirement of the compression work what fraction of the lower heating value we are going to use. So, here you may remember that we have talked about the lower heating value of ah gaseous hydrogen and this is ah or I mean the hydrogen particularly.

So, if this is related to when we have combined this hydrogen and oxygen and we have produced the liquid that is related to the higher heating value and when these two are combined to give ah you know the water in the form of vapor that gives you the lower heating value. So, we have chosen the lower heating value because many a times you will find that the operating system is such that ah this water is generated in the form of vapor and in that case ah this lower heating value is mostly appropriate otherwise depending on the ah I mean state of this ah water we can also use in terms of the higher heating value this is basically and way of expressing our the results. So, this is ah you know we have already calculated that work requirement you know isentropic compression and isothermal compression now we have divided it with respect to the ah lower heating value. So, if you go back we will find that we have say particular say 5 50000 ah joule per mole and now we have to divide it by ah this many what is that number ah we have this many mega joule per kg or say this many kilo joule per this is since it is in the mole we have to take this lower value sorry this ah 241.83 kilo joule per mole and accordingly you will find that this graph is obtained when you have of course, multiplied it with 100. So, that it is giving you the percentage. So, that means, you can understand that if we are compressing it to ah 700 bar nearly we ah spent about you know something about 25 percent of the lower heating value. That means, still you have 75 percent of the hydrogen content you can use and you can understand another thing from here that if you are storing it at 300 bar and if we are storing it at 700 bar there is not much you know that energy that we are going to spend. So, but compared to ah you know 1 to ah 300 bar ah sorry here this is a nearly from 1 bar to 300 bar if we have to pressurize then we are spending lot of energy compared to that if we are you know pressurizing and storing it at ah 700 bar this needs ah relatively lesser amount of energy towards compression. So, it is always advantageous to I mean store it in the form of you know ah what is called 700 bar provided we have the adequate infrastructure to pressure I mean ah stored it in that kind of container.

Now, this is of course, this compression work as ah sorry this was already there ah here and we have this compression work ah given we have calculated this in the earlier slide and from there you know if we divide it with the help of lower heating value we can ah come to this ah I mean this ah graph we can obtain. So, now let us look into the volumetric energy content ah since we have already ah done the density calculation in the first class ah in this ah I mean while talking about the storage part we have the ideal gas equation then we have of course, 2 real gas equation one is for this is where one with the ah equation of generalized equation of state and then of course, this 2 are basically the real gas equation and this is the ideal gas equation. So, for the real gas equation we have used 2 equation of state one is the generalized equation of state another one is the van der waals gas equation. So, we have the density of the hydrogen with us and we have also ah you know the volumetric density of the hydrogen. So, now, let us just have a look into ah this numbers again ah with respect to the liquid hydrogen and with respect to this gaseous hydrogen.

So, we have this volumetric energy density as well as the inner I mean this is of course, the density in terms of mole per meter cube. So, now, if you look at you will find that these are the ah I mean from here you can calculate it this is the gaseous hydrogen and since the density of hydrogen is varying with the pressure we have the volumetric energy density also changing with the pressurized hydrogen storage. Now, with respect to the liquid hydrogen. So, what is the density of liquid hydrogen we have said at normal boiling point this is 70.8 kg per meter cube. So, we have that ah you know with respect to the liquid hydrogen we have this 2 numbers one is the higher heating value and this is with the lower heating value. Corresponding to lower heating value and the higher heating value. So, we have this is lower heating value as 120 mega joule per kg and the higher heating value nearly 141 mega joule per kg. So, if we multiply it with this numbers ah for the lower heating value and the higher heating value we will have this 2 numbers then you know it will give us the volumetric energy density say 120 multiplied by 70.8 and 141 multiplied by 70.8 this will give you this may nearly 10000 ah the sorry the lower one is ah nearly around 8000 and the higher heating value would be corresponding to 10000 mega joule per meter cube. So, that is the kind of ah energy density we have for the lower heating value and the higher heating value for the liquid hydrogen. But with the gas you know that there it is continuously changing the density of gaseous hydrogen will be changing with the density I mean with the pressure and the the pressure this is the ah real gas equation and this is ah of course, one is the higher heating value corresponding to the real gas equation this will be with respect to the lower heating value corresponding to the ideal gas equation and this is with the real gas equation higher heating value and this is the lower heating value corresponding to the real gas equation. So, this is how the volumetric energy content of the compressed gas is changing. This part we will come back again while talking about the liquid hydrogen storage.

So, now let us look into the practical compressors those are in use. So, as we have told that we need to compress it to nearly 300 or 700 or 350 to 700 bar. The corresponding you know if we look at this ah compressor selection chart particularly with respect to this gives you the capacity versus final pressure. This is ah simply ah kind of schematic ah it is not to the scale and ah, but you can understand that this when you have a very high-pressure requirement then either it has to be ah a cylinder piston compressor or it has to be a diaphragm compressor. So, cylinder piston compressor you have a cylinder and then you have a I mean and this is a piston probably you are familiar with it. Then you have the inlet valve and there is an exhaust valve. So, when the piston is at its lower end the intake gas will come this intake valve will open then the piston will move up and this valve will of course, close and this will also close and when the desired pressure has been reached this valve will open to discharge the gas that is about the cylinder piston kind of ah compression process and this diaphragm compressor will come again. So, this you know it is ah basically this is moving back and forth with the particular ah frequency and depending on that frequency you will have the capacity of this particular compressor and of course, the suction pressure that will also decide it is a I mean what is that you are going to get at the exit. So, the other compressors are not that much in use particularly for the compressed hydrogen storage. So, we have mainly this two-diaphragm compressor as well as the piston compressor.

So, now, if we look at this piston compressor we will find that the ah we need you know to minimize this lubrication or I mean we have to lubricate this ah the between the ah piston and the cylinder. So, we need lubrication and that will ah cause certain kind of problem. So, we we will come to that part. So, let us look into the ah part I mean the material of construction mostly it is the alloy steel or basically the stainless-steel ah where the molybdenum based and chromium based steel will be in use because we have the problem of ah hydrogen related embrittlement problem. So, we have to be careful about the selection of the material.

Now, as we as I was telling that this pulsating ah speed of the piston will determine the flow rate of this compression process and you will find that this ah you know if you have to achieve a higher flow rate then obviously, we need to reciprocate it ah and there would be wear and tear at the same time we need ah you know the lubrication. So, well lubricated hydrogen compressor can you know have ah of course, is it is needed for the reliable operation and 5 percent leakage ah will be ah very typical because of ah we need to provide the lubrication. So, that we have a smooth operation we need to provide some kind of clearance. So, that you know this there is a less wear and tear and that causes you know this ah 5 percent typical loss and since there is wear and tear ah you know continuous operation is not always possible and we have to frequently ah you know go for I mean what is called maintenance of it. So, ah well lubricated hydrogen compressor will have nearly about 3 ah years you know between 2 maintenance, but ah if it is not so you will have you know frequently you may have to open it and it is a efficiency will of course, depend as I was telling that it is the lubrication system and the suction pressure typical system efficiency is a non-lubricated one is about 75 to 65 to 75.

And then we ah come to ah another type of compressor as we have talked about that is the ah what is called diaphragm compressor. So, here the there is a you know we have the this is the gas side, this is basically the oil filled part and there is a perforated plate, then this is there is a piston cylinder again here, but here the ah I mean interesting part is that this this is on this side you have the gas and on this side you have the oil and they are not matching I mean mixing with each other at any time and this blue colored one is the piston sorry the diaphragm. So, the diaphragm is separating the oil and the what is called hydrogen gas and this is the say may be intake and this is the exhaust ah of it. So, you have this chamber ah for the gas chamber and this is for the oil chamber and there is a perforated plate to uniformly distribute the I mean oil into this over this ah what is called diaphragm. So, now let us look into this ah action.

So, if it you know ah first of all this gas will be taken and ah and this piston will be moved towards it and there is it is not shown this piston will be moving towards the right and the diaphragm will also move towards the right and the intake hydrogen will be taking place. Then what happens it will this will come I mean stop this intake will be stopped and this will move towards the left with the movement of this piston this you know oil will be pressurized and that will also pressurize this gas when the required pressure is achieved this will open to ah exhaust that gas again it will come back to ah and this cycle will repeat. So, this is how ah this diaphragm compressor works and that gives us the advantage of not mixing the oil at any time with the ah gas and there the contamination part is ah much less as compared to the previous one reciprocating one and also this there is no lubrication problem. More so, ah you can understand that there is a very large ah you know ah heat transfer surface area. That means, when the gas is getting compressed the heat of compression could be taken by this oil and this oil can be cooled.

So, that means, ah you know the compression ratio we can achieve with this kind of compressor is pretty high. As compared to the cylinder piston compressor where if it is you know about 5 is to 1 kind of compression ratio we can go as high as 15 is to 1 almost like you know we can achieve ah kind of isothermal compression with the help of this diaphragm compressor. So, one has to be you know careful about selecting this diaphragm often ah they may in if they if it fails then this whole process will you know collapse. So, ah leakage problem as we have said earlier will be small compared to the ah reciprocating one then H2 contamination is also chances are less with the help of oil because ah they are in separation and diaphragm failures are ah you know often take place particularly with respect to the ah contamination in the gas or in the lubricating oil system. And moisture condensation if by chance you know you have any kind of ah moisture ah introduced into it then also there is a chance of you know this diaphragm failure and improper tightening of the compressor cover bolts will also cause a kind of diaphragm compressor I mean failures.

So, these are the possible ah you know type of failures that can occur with this kind of compressors. Otherwise typical operation between two I mean ah successive maintenance is about 4.5 that is ah good and the as I told you that it is efficient heat removal process makes it the compression ratio achievable with this type of compressor is 15 is to 1. And ah it can also deliver to a very high pressure nearly about 1000 bar and efficiency is quite in the range of 80 to 85 percent. So, with this we come to ah conclusion about this compression part, but we have not talked about ah so far about this is the basically we have talked about the ah vehicular storage.

But if it is a high-pressure stationary storage for example, we can store it in a ah there is no weight limitation and there is no I mean space limitation also. So, we can use a different you know the ah I mean stainless steel based containers and it can I mean this is a basically type 1. And for small storage ah you know gaseous storage we have about 50 liters, but ah it can be stored to a very high pressure typically ah the kind of you know storage we have in the laboratories. And then for larger capacity we have to go for a larger diameter then obviously, the pressure has to be reduced to ah you know nearly about 50 bar or so. And the length there is no restriction we can make it ah very long because it is the stationary ah hydrogen storage particularly when you are not moving the things you can go for this kind of ah pressurized storage ok.

So, these are the references you can ah look into. Thank you for your attention.