Cryogenic Hydrogen Technology
Prof. Indranil Ghosh
Cryogenic Engineering Centre
Indian Institute of Technology Kharagpur
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Lecture 23
Cryogenic Liquefaction Cycles

Welcome to this lecture on Cryogenic Hydrogen Technology. We were talking about the hydrogen liquefaction process and in that context, we have already talked about ah we have learned about the isenthalpic process and isentropic expansion. So, these are basically the practical I mean we were looking into the practical liquefaction cycle because we have learned from the ideal refrigerations or ideal liquefaction cycle that we have to ah you know compress it and then we have to expand the gas. And in the ideal liquefaction cycle we said that it is an isentropic expansion, but it could not be done you know ah in reality that is first of all it is a it was compressed to a very large pressure and not only that if we have to expand it ah the gas ah from you know completely gas to completely liquid there is no practical expansion engine which can do that one. So, the alternative thing is that we have to compress the gas, but then you know we have to expand and we you know for expansion the easiest way of doing it is by isenthalpic expansion just you know you have to open the valve and in a JT valve we call it or isenthalpic ah valve or joule function valve. So, that is what is the JT expansion we have talked we have also learned about the isentropic expansion and there we have seen that mu s that always ah that always remains positive.

So, in this background now let us try to look into this cryogenic liquefaction cycles and we will ah you know ah today try to find out what is the Linde-Hampson cycle and then we will look into the pre cooled Linde-Hampson cycle for hydrogen liquefaction in particular, but in general we will be talking about the simple Linde-Hampson cycle for cryogenic liquefaction and then we will proceed towards the pre cooled Linde-Hampson cycle. So, let us go back to our ah I mean discussion where we said that we will be compressing the gas and then you know we will try to expand it from state point 2 and this compression as we have understood that this is an isothermal compression. So, ah that is basically an ideal situation where we are rejecting the heat of compression ah the moment you know we are compressing it and this is of course, ah again some idealization is there with this practically we will find this is quite different. So, in a way ah from state point 1 to 2 we have compressed the gas and from state point 2 ah we are following an isenthalpic line. So, the enthalpy remains constant. So, we have generated some amount of cooling ah that is ah the delta T will be generated by this isenthalpic expansion. So, if that is so, ah we will try to utilize this cooling later on and we will devise a cycle. So, basically, we can understand that we have not been ah able to generate any liquid out of here, but we have slightly cooled the gas. So, this delta T cooling we will be ah using it for ah you know cooling the high-pressure incoming gas and slowly we will try to you know move from this point initially we were compressing the gas and we have taken it to state point 2 and now we have expanded it ah.

So, we have come to some other point ah where we have generated some amount of cooling. So, that cooling we will be now using to move this point like on this part. So, so that you know later on when we expand this gas is somewhere here and from there we will be generating slightly the more cooling and like that our intention is basically you know to come to this point, but at least you know we should be somewhere here. So, that we get a fraction of the liquid and on this part ah it is saturated vapor. So, ah here ah this saturated vapor will of course, go back and that saturated vapor will be cooling the high-pressure incoming gas.

So, now we can understand that it is not only the compressor we need it is not only that expansion valve that we need we also need another component called a heat exchanger. So, that heat exchanger will be using I mean will be used to ah cool the high-pressure incoming gas and this who will cool it this return you know the low-pressure vapor will cool that high-pressure incoming gas. So, now if we try to convert it into a practically feasible cycle we will have something like we will have a compressor and we where we will compress the gas then of course, we will have a heat exchanger we will identify this stream later on that this is first let us talk about the high-pressure gas. And then we have you know the JT expansion and we are finding that when for the first time we are doing it this small amount of cooling will be generated then we are you know ah putting it inside this ah ah reservoir where we will have this liquid and then once it is liquefied you know we will withdraw some amount of liquid and the vapor is going back and it is coming to the ah I mean that compressed part again it will be compressed ah it is coming to the suction side of the compressor. And since we are taking the liquid out we have to replenish the ah gas from time to time otherwise there would not be any gas ah you know into the cycle.

So, basically this is an open cycle where we are putting some amount of ah mfdot and we are getting some liquid m f dot, but here this is you know we are compressing some amount of gas mdot say let us assume that we are compressing some gas. So, we are taking out the liquids. So, we will have mdot minus mfdot that is what is you know coming back to this compressor and when it is replenished with mfdot amount of you know new or additional gas we will have this mdot this is when combined here m minus mfdot and ah mfdot they are combined together to have mdot. Now, so, what we understand is that this gas will be compressed then high-pressure gas will be coming it will be cooled by the low-pressure ah return stream and here this JT expansion will take place ah to produce the ah liquid. This is what is called the simple Linde-Hampson cycle and if we try to analyze this cycle later on we will find how to ah I mean ah this is the one we were talking about.

So, now, we have to if we have to ah analyze this cycle let us try to look we have to first of all you know draw one control volume. So, this is the control volume ah which is encompassing the heat exchanger and the reservoir. So, we have this mfdot ah and we have the mdot gas which is going in and we have said that mdot minus mfdot that is what is you know ah leaving this control volume. So, here this is mfdot. So, let us try to identify the streams which are leaving the system this is mfdot which is leaving the system this mdot minus ah mdot minus mfdot that is leaving the system and what is going inside is mdot.

The compressed gas is going in and m minus mdot is leaving out mfdot is leaving out. So, if we have this control volume. So, once we have this control volume we can try to apply the first law of thermodynamics ah for this control volume. So, ah is there any ah heat input basically this is supposed to be inside a cold box I mean cold box is basically a container or you know envelope which put all the cold things or the cold ah bodies inside that one and it is basically insulated vessel and assume we we assume that there is no heat in leak no heat in leak the heat in this is 0 ah. So, basically that is also ah an assumption, but for time being let us assume so.

So, if we now try to find out the ah I mean the first law of thermodynamics for closed system I am sorry open cycle. So, we have the Qnet minus Qnet minus Wnet that is equals to 0 there is no Q input there is no work input in this control volume. So, we can write that is equals to summation of the outgoing enthalpies that is what is that outgoing one mdot minus mfdot and the corresponding enthalpy ah say here. So, this state point is say 1 as we have identified here this state point is 2 and then finally, you know it is coming over here and this is say after this cooling etcetera we will identify it as 3 say somewhere here ah or somewhere here we call it as 3 and state point 3 to state point ah this is ah the saturated ah when it is basically a combination of saturated liquid plus vapor. So, we have this is saturated vapor which is going back and the liquid is taken out.

$$Q_{net} - W_{net} = \sum(\dot{m} - \dot{m}_f)\, h_1 + \dot{m}_f h_\mathrm{f} - \sum \dot{m}\, h_2$$

So, this is hf this is the enthalpy of the saturated liquid and this is the enthalpy of the saturated gas and here this is you know coming back ah and of course, we are now assuming that this exchanger is 100 percent effective initially later on we will assume and or rather we will try to put some non-ideality in the heat exchanger and see what happens because of that. Also, the compressor is also considered to be ah ideal compressor that means, there is no non-ideality at the moment. So, this is ah the mdot minus mfdot and this is leaving with an enthalpy h1, but ah along with that we have some outgoing enthalpies. So, this is for the incoming one and of course, there was outgoing enthalpy of mfdot and hf and then ah we have for the incoming one that is ah mdot and ah that is equals to h2. So, this is ah this is ah all that is what we have and on this part is 0 and this is ah also 0 because in this control volume there is no work done and there is no ah heat input.

$$\dot{m}h_1 - \dot{m}_f h_1 + \dot{m}_f h_\mathrm{f} - \dot{m}h_2 = 0$$

So, in that case we can write mdot h1 ah minus ah mfdot h1 sorry this would not be there this would not be there ah plus mfdot hf minus mdot h2 is equals to 0. And now if we combine this ah h1 and sorry sorry mf and mf together and mdot together. So, we have mdot h1 minus h2 and then minus we have ah equals to mfdot ah h1 minus hf. So, then we can have this value mfdot by mdot equals to ah h1 minus h2 by h1 minus hf. So, that is what is the ah liquid yield ah or say what fraction of the mass of gas that has been compressed is ah is you know I mean this is the mass of gas compressed and this is what has been liquefied.

$$y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f}$$

So, that gives you this ratio or the liquid yield we call it ah y and that is a ratio between h1 minus h2 by h1 minus hf. So, later on we will try to calculate this h1 hf and for a practical hydrogen liquefaction cycle and we will see what happens. So, now, here ah this is what we have gotten one parameter performance parameter ah that is how much is the gas that has been liquefied out of the gas that we have compressed. We have compressed mdot amount of gas because that is what you know where we are spending the energy this is where we are spending that energy we are giving our work input to this and we are getting some liquid out of which that is mfdot. So, this is one performance parameter the liquid yield.

So, there is another performance parameter that is minus ah W by ah mfdot. So, ah or first of all minus W by ah mdot we can try to calculate and if we assume this compressor to be ah an isenthalpic ah I mean ah isothermal reversible compression process that is ah is a basically an idealization then you can try to calculate this ah work requirement. First of all, you will be able to calculate this minus ah you try it of your own if you have any ah in a problem we can talk to ah this is actually we have talked about the ah ah in connection to the ideal liquefaction cycle this will be very similar to that. So, here we will be having T1 s1 minus s2 minus h1 minus ah h2. So, we have this ideal work I mean ah in connection to the ideal work requirement we have calculated ah you you may remember that minus W by mdot or W by mfdot both are the same.

$$\frac{-W}{\dot{m}} = T_1(s_1 - s_2) - (h_1 - h_2\Big)$$

So, in that connection we have said T1 s1 minus sf minus h1 minus hf and it would be very similar to that and in that also ah in that derivation we have assumed that the compression process is isothermal and reversible. So, here also we are assuming that there is Qr amount of heat getting rejected isothermal in the isothermal compression process and we are giving some W amount of work work done on the system. So, that is why this negative part is there. So, minus W by mdot would come as T1 into s1 minus s 2 minus h1 minus h2. So, that is what is the work requirement.

So, we have obtained this both parameters ah one is the liquid yield, what is the amount of liquid that we can get out of this compressed ah gas and what would be the work requirement. So, these are the 2 parameters later on we will try to calculate ah W by mfdot just basically if we divide this parameter with the liquid yield we will have W by mfdot that is another parameter which will be necessary for finding out the figure of merit we will talk about that while doing the calculations later on. So, that is about the simple Linde-Hampson cycle. This is the generalized cycle for any cryogenic liquid, but if we put hydrogen what happens to it let us have a look and we see that ah on the T S diagram how this this is actually the practical one where you will find that when we come nearly to 40 Kelvin or 30 Kelvin and we are expanding the gas it is this is the liquid vapor dome and this is say one atmospheric pressure corresponding to 20 Kelvin. So, this is somewhere about 13 bar and if we are compressing it to still higher pressure and from there if we are expanding it ah we will be landing over here.

So, somewhere here is the saturated ah vapor of corresponding to one atmospheric pressure and on this side, you have the saturated liquid. So, we are not expecting to come over here ah by expansion process. So, we will be somewhere inside this liquid vapor dome and we will have a separator ah phase separator that is the you will separate the liquid just by gravity they will be collected at the bottom and the vapor will be taken back as we have learned in the ah simple Linde-Hampson cycle. But the point is that now ah if we go to the I mean if we have this simple Linde-Hampson cycle and we are applying this you know we have put ah this hydrogen ah in it. So, this is ah if we put hydrogen here ah do we expect ah any cooling or not the answer is no.

Why because the temperature at this point is most of the time you know we are starting point is nearly 300 Kelvin. So, at this point this 300 Kelvin is higher than the maximum inversion temperature. For hydrogen we have seen that the maximum inversion temperature is 205 K. So, we have to you know if we have to expand this gas isenthalpically and generate cooling out of that we must be well below this temperature. Because at this temperature if the gas hydrogen gas is there and if we are expanding this gas from high pressure whatever be the pressure we will find that a very you know almost mu JT is equals to 0 at this temperature.

So, that means, there would not be any cooling there would not be any heating ah at this point ok. So, but our starting point that we have taken some gas and we have seen that the gas is at 300 Kelvin or atmospheric pressure and atmospheric temperature. So, nearly 300 K to 305 K are depending on the temperature. So, it is around that value which is way higher than the ah maximum inversion temperature. So, now, if we have this gas at state point 1 and we have isothermally compressed it to state point 2 by just removing the heat of compression we have gone to state point 2.

And what we find is that you know this is this has gone these are the isenthalpic lines this is isenthalpic line and this is another isenthalpic line. So, this has gone to an higher isenthalpic line as we have removed the heat of compression ah, but still the state point 2 is at higher isenthalpic line. So, the moment you expand it you will find that the isenthalpic line will be followed and it will go to a state point ah you know some other value which is heated up instead of giving cooling what you will find that your initial point has gone to state point you know above state point 1. So, you have started at 300 Kelvin the moment you know it has come over here instead of any cooling you know ah of course, initially there is no cooling, but we were expecting some cooling and then you know we would have ah ah you know cooled the high-pressure incoming gas, but that is not possible now. So, this gas which is getting expanded from this joule joule tumption ah valve you will find that upon coming over here ah it is getting heated up because it has landed over here earlier you know had this been over here it would have come over here it was below this maximum inversion temperature and this is above the maximum inversion temperature.

So, that means, we have ah generated some amount of heating instead of getting a cooling. So, there is no liquid here at all. So, what will happen in simple in the hampson cycle if we are putting hydrogen we will find that this you know gradually giving us ah you know ah generated generate it is generating heating effect instead of producing any liquid. So, what is the remedy for that? That means, ah you have compressed this gas from 1 to state point 2 we cannot you know ah you know expand it from that point onward. So, what we have to do is that before we expand it ah ah we can say ok fine we have a heat exchanger, but the heat exchanger has to be cooled by something because this is not generate any cooling.

So, the additional cooling has to be there. So, the idea is ok fine we will have some you know additional refrigerant over here. So, that will you know cool this gas from 2 to some point which will bring it below the maximum inversion temperature. And ah one such you know cryogenic coolant is basically ah I mean it should be ah easily available, but this is not possible with the ah room temperature refrigerants because we have already you know come to ah understand that this temperature has to be around 205 K. 205 K is basically the maximum inversion temperature it is not the working temperature working temperature has to be well below this.

So, the natural selection would be ah you know 77 K ah that is the liquid hydrogen sorry liquid nitrogen. So, liquid nitrogen is the ah popular choice for the pre-coolant. So, we should have something ah you know in addition to this ah I mean if we have to use this Linde-Hampson cycle we must have some pre-coolant and that is what we call it as the pre-cooled Linde-Hampson cycle. So, in the pre-cooled Linde-Hampson cycle what we do is that ah we have ah you know if you look at this point onwards basically if you say ah that this is basically the Linde-Hampson cycle right. We have the heat exchanger high pressure gas coming in and then it is getting expanded, but ah this gas is you see if we have put liquid nitrogen in it ah this liquid nitrogen say if it is boiling at normal boiling point say here we have put the liquid nitrogen and this liquid nitrogen some vapor will always be generating that vapor will be you know taken to ah this 3 stream exchanger.

This 3-stream exchanger one fluid is ah you know the gaseous nitrogen and here this is also gaseous nitrogen this vapor of this nitrogen vapor which is which is coming from this ah you know reservoir will be cooling the high-pressure incoming gas this is the high-pressure incoming gas. And at this point this is coming at 77 K if the liquid nitrogen is kept at one atmospheric pressure. So, our purpose has been solved now that the gas you know before ah expansion it is already at 77 K well below the maximum inversion temperature. So, now, if we expand this gas we can expect some cooling not only some cooling later on if we are you know well below that ah I mean well near to that liquid vapor dome and if we are expanding we can expect some liquid also. So, as we have now you know this part we have you know this part is basically the pre-cooling of the high-pressure gas and now this ah expand I mean this return vapor can ah cool the high-pressure incoming gas.

So, this is about the what is called the pre-cooled Linde-Hampson cycle and for ah gaseous I mean for liquefaction of hydrogen we need some liquid nitrogen, but this liquid nitrogen that nitrogen if you look at you will find that the maximum inversion temperature for nitrogen is about 621 Kelvin. So, this is ah very much above the maximum inversion temperature that means, the simple Linde-Hampson cycle would be possible to you know ah would be able to liquefy this ah gaseous nitrogen. So, this liquid nitrogen that we are generating that can come from you know the simple Linde-Hampson cycle, but when it is ah ah the pre cooled Linde-Hampson cycle when we this gas is hydrogen we need to the precool it with the liquid nitrogen and then only if we expand it by isenthalpic expansion we you see in this process we have not used any kind of expansion engine. So, basically this is all about simple I mean isenthalpic process where the gas high pressure gas will be expanded to generate the cooling. So, we can now ah look into the ah what is called the analysis part.

So, what is the work requirement, what is the liquid yield, how is it going to change or that we will do it in the ah following class. So, ok ah that is about the references you can still follow these 2 books to ah arrive at this point. And in conclusions ah that we have learned about this hydrogen liquefaction and in that context we have seen that the simple Linde-Hampson cycle is not good enough and ah I mean it would not be able to liquefy the gas rather it will heat it up, but ah it is possible to use the pre coolant ah or pre cooled Linde-Hampson cycle where the pre coolant has to be ah well below the 205K and one such pre coolant is the liquid nitrogen. So, thank you for your attention.