Cryogenic Hydrogen Technology
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Week - 05
Lecture 24
Cryogenic Liquefaction… contd.

Welcome to this lecture class on Cryogenic Hydrogen Technology. We were talking about hydrogen liquefaction. In that context, we have already learned about the Linde-Hampson cycle and we have identified some problem with the Linde-Hampson cycle. So, based on that we will now go into the precooled Linde-Hampson cycle and we will be talking ah mostly about the analysis of the precooled Linde-Hampson cycle. So, we understand that ah I mean we have in the last class we talked about the precooled Linde-Hampson cycle in the context of simple Linde-Hampson cycle.

So, and also we have analyzed this ah simple Linde-Hampson cycle. We have also calculated the liquid yield for this analysis I mean for this cycle and we found that the liquid yield is depending on ah the enthalpy of the incoming gas, the enthalpy of the compressed ah gas and also it depends on the enthalpy of the liquefied gas. But we also understood that this cycle is not good enough ah this is the work requirement per unit mass of gas compressed. But this cycle works for gases like ah nitrogen, oxygen, but it is not recommended for the gases like helium, hydrogen and neon and we understood that this is because of the fact that this gases helium, hydrogen and neon they are having the maximum inversion temperature ah below the ambient temperature.

So, you can see that if we assume that the ambient temperature is around 30 300 Kelvin. So, all these temperatures are below the ambient temperature or ambient ah you know 300 Kelvin. So, that means, if we compress and cool it ah these gases at nearly room temperature if we have refrigerant or coolant available at room temperature ah this cycle is not good enough. So, we have seen that ok this simple in the Hampson cycle is not recommended for hydrogen, but what happens if we put hydrogen that also we have seen and we have seen that you know instead of giving any cooling ah it will start getting heated up. ah Just for an example on the numerical part if we look at if we are compressing the gas from 1 atmosphere to ah I mean 50 bar or 50 atmospheric pressure and keeping the temperature constant that is isothermal compression we are doing here.

So, we are rejecting heat and this is the work requirement for this compressor. So, ah if we look at it we find that the corresponding enthalpies at h1 that is here at atmospheric pressure and 300 Kelvin this is 8484 joule per mole ah and this is the according to the software that I am using. For the gas you know when it is getting compressed it is that 8528 joule per mole. So, that means, when you have compressed it and cooled it at 300 Kelvin its enthalpy is like this and the enthalpy of the liquefied hydrogen is minus 517 joule per mole. So, ah now if we try to calculate the liquid yield ah you can understand that this part h1 is 8484 joule per mole and h2 is 8528 giving you negative value for the y.

In the denominator you have of course, h1 is 8484 plus 517 minus of minus will become 5 ah plus 517. So, basically ah it is giving also I mean from this part numerical part also we are finding that the liquid is negative that indicates that means, you know there is no liquefaction or liquid production by this simple Linde-Hampson cycle. But this process is not you know ah I mean if it is a precooled Linde-Hampson cycle that means, if we are ah changing the enthalpy of this gas at after compression you know if we have some mechanism to change its enthalpy before it is you know expanded in this Joule Thompson valve or because this is completely you know there is no turbine there is no isenthalpic expansion ah isentropic expansion it is completely based on isenthalpic expansion. So, we have to you know cool it before it is expanding we understood that it has to be cooled below the maximum inversion temperature. So, so that is what is done in the precooled Linde-Hampson cycle and still you know we are having this compressor and we are rejecting the heat of compression we are isothermally compressing it from 1 to state point1 to state point 2 that is you know from here to here.

But we we are not you know ah directly expanding it from this point 2 onwards. When the process is starting you know at the initial stage what is happening this compressed gas will be coming over here where we have this liquid nitrogen bath where liquid nitrogen is coming in and the vapor ah it is coming out and it is cooling the incoming ah high pressure gas this is hydrogen and this hydrogen is again finally, you know it is passed through ah ah ah coil which is dipped in liquid nitrogen. So, you may ah ah you know argue why should we dip it in liquid nitrogen why not to directly dip it in light nitrogen ah what is the role of this exchanger ah this three-stream exchanger it could have been avoided as well. But the purpose of this ah you know ah to save or you know economically ah use this liquid nitrogen because this liquid nitrogen is not coming freely and ah of course, this liquid nitrogen is getting evaporated. So, we want to use this evaporated nitrogen.

So, that you know nitrogen vapor which is also at low temperature that cold we want to utilize and that you know will slightly cool this incoming high-pressure hydrogen. So, that when it comes over here ah this its enthalpy is slightly lower than the completely gaseous enthalpy at ah state point 2. So, we will have ah less load on the liquid nitrogen you can say. So, that is why you know we try to instead of you know just throwing it out to the ambient ah which is that cold condition we want to retrieve its cold and utilize it for high pressure incoming gas cooling. So, now, ah when the process is starting you know it has come to a point state point 4 which is you know that the cooling ah it is the boiling point of the ah coolant or the refrigerant here in this case it is liquid nitrogen.

And if the liquid nitrogen is boiling at normal boiling point or NBP 77 kelvin we can ah assume that it will be coming to nearly ah that same temperature if it is an ideal heat exchanger at this moment we are considering all these things are ideal. So, here it would come at around 77 Kelvin. So, now, from here if it is getting expanded you can understand that it will give you some degree of cooling when the process is getting started. So, we have some ah you know ah some cold vapor at the first stage or cold gas you know when it is expanded isenthalpically. And later on this gas you know high pressure sorry low pressure return stream will cool the incoming high pressure gas and that will ah come to a stage when this will give you ah you know some portion of the liquid in the steady state.

So, this is the steady state situation when 1, 2, 3, 4 and ah there would be say 5, 5 is missing here somewhere here 5 would be there ah I am sorry. So, I am sorry this ah this is wrong this is wrong this is 5 from state point 5 we are expanding it to state point 6 ah fine this is in 2 phase region and the vapor part is going back the liquid part is you know stored here this is the separator and we are separating or taking out the liquid from here. So, please note that this is state point 5 ah it is not the one ok fine. So, this is ah why the Linde Hampson cycle ah you know it is possible ah with the pre-coolant like LN2. So, now, we will try to analyze this cycle ah numerically.

So, for that ah first of all let us ah try to ah put a control volume around it and let this be ah you know encompassing the all the ah heat exchangers ah the 3-stream exchanger the 2-stream exchanger this reservoir and the liquid nitrogen that is coming in and the vapor or the gaseous nitrogen which is ah moving out. So, we have the mdot mass that is getting compressed from state point 1 to state point 2 isothermally the heat rejected by this is QR this is the W amount of work that has been given ah there is of course, this liquid nitrogen is not coming freely as I have told you for liquid nitrogen production we need to spend energy that will be you know ah calculated ah separately not in this ah I mean along with this. Let us try to first calculate the liquid yield which is ah possible with the precooled Linde Hampson cycle. So, we have this liquid nitrogen gaseous nitrogen and ah this is the compressed hydrogen that is coming in and this is the compressed you know the liquefied hydrogen that is moving out. So, first of all let us try to identify the streams ah which are going in and out and the corresponding enthalpy values.

So, here ah let us assume that ah this must flow rate for the liquid nitrogen is ah mN2dot and the corresponding enthalpies for the liquid and the vapour are hNg for the vapour and hNf for the liquid. So, this enthalpy is hf here we have told that this enthalpy will be h2 and what is the mass ah you know flow rate through this stream that is ah mdot is getting compressed and if we have taken out mfdot part. So, we have mdot minus ah mfdot that is the stream ah that is going back to the compressor and in the compressor, there is makeup gas of mfdot and that will be combined to give you this mdot. So, we have ah mostly ah identified the streams and the corresponding enthalpies. So, here h2 this is this enthalpy is ah h1 and h1 corresponds to again you know this is assuming it to be an ideal condition.

So, that ah this gas leaving this heat exchanger is at the same temperature at the inlet of this high-pressure ah gas. So, that that is an idealization ah if it is not we have to take the appropriate temperature for this ah three fluid stream heat exchanger. So, now ah with this ah let us ah just try to ah put them in the ah ah control volume. So, these are the ah incoming enthalpies ah sorry the flow I mean streams and these are the streams which are leaving this control volume and if you ah look back you will find that there is ah no work you know in this control volume that is ah no no work or no ah heat input I mean assuming that there is no external heat leak and the work requirement that is there associated with the I mean compressor we are not taking into ah account in this ah calculation because here we are trying to calculate the liquid yield and ah if we ah put the corresponding enthalpy values we will as we have said that this is hNf this is Hn ah l sorry hNg and this is ah h2 and this is h1. So, now let us apply the first law of thermodynamics for the open cycle ah then we will find that Q minus W ah is ah that is ah equals to 0 and then we can write it as the summation of the enthalpies of the outgoing stream.

$$\dot{m}_f\ (h_{\mathrm{f}} - h_1)\ + \dot{m}\ (h_1 - h_2) + \dot{m}_{N_2}(h_{N_g} - h_{N_f}) = 0$$

So, what are the streams leaving mdot ah mfdot and hf and then it is not the summation this is first this plus and then ah outgoing enthalpies are m minus mfdot plus mdot minus mfdot into h1 then another stream that is leaving is mN2dot and hNg. So, these are the outgoing streams then you have the incoming ah streams which are basically ah minus ah the incoming is mn2dot ah for hNf and then you have the incoming one is minus mdot h2. So, this is what we have for this control volume without any work or any ah this W is 0 and work is 0. So, now, if you ah you know some something or you know if you rearrange this ah let us put ah the mfdot terms together then you will have hf minus h1 then you have the mdot terms mdot of ah h1 minus h2 this is one term and this is another term here then we have another term involving mN2dot then you will have the hNg minus hNf that is equals to 0. Now, if we want to calculate ah the ah liquid yield that is ah mfdot by mdot that is equals to y.

$$\mathrm{y} = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f} + \frac{\dot{m}_{N_2}}{\dot{m}}\left(\frac{h_{N_g} - h_{N_f}}{h_1 - h_f}\right)$$

So, we have to take mfdot by mdot and then we can ah you know put it to the other side and if you ah take it to this side ah I mean on other side if you take it it would become ah h1 minus h2 by h1 minus hf this is exactly what we have seen for the case of ah simple Linde Hampson cycle along with that we have an additional term which involves the amount of liquid nitrogen that is given here along with hNg minus hNf divided by h1 minus hf. So, that is ah is the amount of ah you know liquid yield here ah this is y and this is this term we have learned earlier that this is a negative term, but this term ah hNg that is the ah stream leaving with this ah nitrogen that is the enthalpy this is the positive term. So, that means, ah liquid yield completely ah depends on this part because this is giving you a negative contribution and this is giving you a positive contribution from the ah enthalpy or the enthalpy drop or the cooling that has been obtained with the liquid nitrogen. So, is there any ah if it is giving basically a negative contribution why not to drop this term, but that will ah you know ah I mean in that case we have to ah remove the compressor itself. So, that is not the idea because finally, we know that we will be expanding the gas ah from high pressure to low pressure and it has to be there always.

So, this term will be there, but this term you know is ah actually producing the required amount of cooling. So, this term we ah term it as z that is the liquid nitrogen requirement per unit mass of gas compressed and this is of course, the h1 minus h2 by ah h1 minus hf and then ah this z multiplied by ah hfg minus h ah of Nf by h1 minus hf. So, that means, if you have to ah calculate the liquid yield ah you need to know what is the fraction of ah you know nitrogen per unit mass of gas or hydrogen compressed is used and then you can put it in this expression, but ah always it may not be possible you know to have this expression known to you unless otherwise specified. Rather ah we would be interested to find out this ah liquid nitrogen requirement, but if we have one equation and two unknowns then it is not ah you know something we can calculate. So, we have to ah use maybe you know we will be using this expression to calculate ah the nitrogen requirement.

Let us look ah some other equation to calculate the liquid yield ok. So, if we go back to our ah I mean cycle ah we we find that it is possible ah ah to identify another control volume involving this this cold end exchanger ah that is ah the two-stream exchanger and from there we can see that this could be the control volume. As a matter of fact, this ah part if we remove from this end this is basically just very similar to the Linde Hampson cycle, but only thing is that here this is ah coming at state point 4 which is at cold condition and this is at the temperature corresponding to the boiling point of this coolant. And this heat exchanger if it is 100 percent effective then it is coming out at the same temperature as you know as with which it is entering the heat exchanger at the cold I mean warm end. This is the warm end of the heat exchanger, this is the cold end of the heat exchanger and this is the vapor ah you know nitrogen sorry ah gaseous hydrogen vapor that is moving in.

So, now, if we try to analyze this cycle already we have ah done it this is where you have the mdot mass of hydrogen going in corresponding to an enthalpy of h4 and this is the stream that is leaving mfdot minus m sorry mdot minus mfdot at h7. So, we need to know the enthalpy at state point 7 and as we have learnt that this is the low pressure I mean return steam we know what is that suction pressure of this compressor. And of course, we have also assumed that there is no pressure drop in any components like ah heat exchanger or ah except that you know there is this JT is the only one which is ah giving the pressure drop we are neglecting the pressure drop in the heat exchangers and all. So, now, or piping etcetera. So, now, if you look at what are the terms ah involved in it we have you know this control volume and in that control volume this mdot is entering at we have learnt that this is entering at h4 and the stream which are leaving is ah hf mdot hf and this is mdot minus mfdot that is leaving at h7.

$$y(\frac{\dot{m}_f}{\dot{m}}) = \frac{h_7 - h_4}{h_7 - h_f}$$

So, the I mean it is not very difficult to ah find out that liquid yield from here you have the experience of ah solving the Linde Hampson cycle or simple Linde Hampson cycle with that similarity or you know if you just do the energy balance you will find that it would give you y equals to ah just nothing, but this is the outgoing enthalpy. So, h7 minus h4 divided by h7 minus hf. So, ah imagine that this is just ah it is a very similar to the ah precooled Linde Hampson cycle this was where it was ah earlier it was ah it was termed as h2 and this was living at h1 and this was of course, hf. So, earlier this expression was h1 minus h2. So, here this h2 is basically h4 and h7 is h1.

So, h1 minus h2 by h1 minus hf. So, here h1 corresponds to h7 and h4 corresponds to h2 ah h2. So, we can write or just you know following the steps ah you have ah done in case of simple Linde Hampson cycle you would be able to calculate the liquid yield. Now, ah there is another parameter which is called the ah work requirement because that is again very important particularly ah for hydrogen because this hydrogen boiling point is quite low and we will need a good amount of energy we have to spend for liquefying it. So, let us ah summarize it that you know the performance parameter is of course, the first one ah ah I mean this is where you can calculate this liquid yield using this factor and the other expression that we have used ah or initially that ah you know the control volume that we have ah used that also involves this liquid yield, but along with that there was a fraction that is called that the mass of ah nitrogen liquid I mean mass of nitrogen used per unit mass of the hydrogen compressed ah.

So, it is mN2 by mN2dot by mdot that is equals to z. So, this gives you the requirement of the liquid nitrogen per unit mass of gas hydrogen gas compressed. So, from this expression ah we can calculate the liquid nitrogen requirement where the liquid yield can be obtained from this expression. And the work requirement part this is ah the requirement of work requirement ah corresponding to ah the hydrogen liquefaction part this work requirement per unit mass of gas compressed this is where you have the work requirement for ah basically this is the work requirement for the nitrogen per unit mass of nitrogen compressed and multiplied by this z which is just nothing, but the nitrogen requirement you will find that if we are neglecting at some point ah we ah will be giving you this value or sometimes we will be for calculation purpose we will be asking you to neglect this part. And in that time you know this if this is considered to be ah you know negligible compared to this work requirement we have to take into account of this value only and we have to neglect this part, but otherwise we are supposed to calculate or include this work requirement also.

So, that is about the performance parameters and we will be solving some numerical problems ah with the help of this numbers or these expressions. So, these are the reference you are supposed to you can follow the Barron and the Thomas Flynn in the book ah and. So, let us look into the conclusions part we have for the hydrogen liquefaction the precooled Linde Hampson cycle with LN2 as the refrigerant ah we have seen and we find that the liquid yield depends on the boiling point of the LN2 refrigerant. So, this is an important ah part. So, maybe you know we would like to use this liquid nitrogen under reduced pressure ah whenever it is possible.

So, that will lower the boiling point of the liquid and as a result we can improve the liquid yield. So, ah with this we will conclude for this part of the session. Thank you for your ah attention.