Cryogenic Hydrogen Technology

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Hydrogen Liquefaction

Welcome to this lecture class on cryogenic hydrogen technology. We were talking about the hydrogen liquefaction. In that context, we have learned about the precooled Linde-Hampson cycle and which is mostly based on the ah basically isenthalpic expansion. It is taking care I mean no isentropic expansion has been used, no turbine has been used. Only thing is that some precoolant will be necessary that is liquid nitrogen we have chosen because that is the one ah which is available abundantly, but of course, we have to pay for that it is not like it is available freely on earth. But we go for this liquid nitrogen because in the air separation plant, we are separating this air into its constituent nitrogen and oxygen.

So, this nitrogen will be available with us and in the form of liquid in the air separation plant and that can be used as a coolant for this hydrogen liquefaction. So, we will be now in this lecture try to solve some numerical problem based on the precooled Linde-Hampson cycle. So, let us look into the problem statement, then we will try to calculate the numerical cycle. So, that we will have some idea about the kind of work requirement or the I mean just leaving aside the liquid nitrogen or including the liquid nitrogen.

So, here comes the problem statement, hydrogen is liquefied in an ideal precooled Linde-Hampson cycle. So, this word ideal is important here ah ideal means other than this JT there is no ah. So, non-ideality or reversible I mean ah all process is reversible process like there is no external heat leak, there is no pressure drop except in the JT valve and there is no pressure drop in the heat exchanger, piping, etcetera and the compressor and the heat exchangers are working ideally that is the 100 percent effectiveness. And the gas is compressed isothermally ah the heat exchanger sorry the compressor ah efficiency is 100 percent efficiency. So, this is not practical though ah we at least let us assume that this is an ideal pre-cooled Linde-Hampson cycle and where the compressor is also working ideally.

Later on we will try to introduce some non ideality with all these heat exchangers and ah you know the compressor part. Here the liquid nitrogen is the pre-coolant and liquid nitrogen bath is ah you know maintained at a reduced pressure I mean it is not at atmospheric pressure. So, the pressure is at 38.5 kPa 38.5 kPa is ah necessarily less than the atmospheric pressure atmospheric pressure is 101.3 kPa. So, at this point the boiling point the I mean the boiling point of ln 2 would be ah 70 Kelvin. So, ah it is ah I mean we have talked in the last class that we have seen that the ah performance parameter that is the liquid yield is based on the temperature of the boiling point I mean the boiling point of the refrigerant and it would be nice if if we can you know allow it to boil at a reduced pressure and thereby you know lowering the ah boiling point. So, here this is you know in this problem it is ah 70 Kelvin. So, now ah this is the ah there are two more points ah that is at the warm end of the low temperature heat exchanger.

Basically, this talks about the ah what is called ah the two-stream exchanger if you remember that cycle ah that is the two-stream exchanger and the temperature of the high-pressure gas entry ah is equals to the temperature of the low-pressure gas exit. So, that means, if you have that heat exchanger this is the low temperature warm end ah warm end of the low temperature and here this high-pressure gas that is entering this system and the temperature of the low-pressure gas at the exit that is equals to 70 K and this is also 70 K. So, you can understand that ah it means that this two-stream exchanger is 100 percent effective. Now for the three-stream exchanger ah ah if you again look at you will find that one stream is going in and two more streams are leaving and this is the low-pressure nitrogen sorry low-pressure hydrogen that is returning and this is the high-pressure hydrogen that is entering the three-stream exchanger and this is the low-pressure end to gaseous nitrogen that is leaving this heat exchanger. So, this is for the three-stream exchanger here also it is said that all the streams leaves.

So, that means, this gaseous nitrogen is leaving at 300 K and this stream is also leaving at 300 K. So, that means, this gas when it will be going back to the compressor ah it is also at the same temperature as it was there in the inlet condition I mean after the compression process. So, these are basically the ah what is called the ah conditions and based on these conditions we are now supposed to find out the liquid yield and the work requirement ah and the work per unit ah gas I mean hydrogen liquefied. It is said that the the work required to liquefy nitrogen has to be ah neglected at this moment and we have to find out the LN2 boiled away per unit mass of hydrogen ah compressed not only that we are also supposed to find out the LN2 boiled away per unit mass of H2 liquefied. So, this is per unit H2 liquefied.

So, we can ah just now ah try to see what are the things that we have to find out one is the liquid yield and the work requirement ah per unit mass of hydrogen liquefied and also that LN2 part. So, you can understand that with respect to our previous lecture we understand that we have to first find out the y and z that is the require hydrogen requirement sorry the nitrogen requirement per unit mass of gas compressed ok. So, then we can try to find out how you know per unit mass of gas liquefied. So, with this problem statement now let us ah try to look into the fluid properties. The fluid properties ah that will be necessary it is you can understand that ah it is not only for the hydrogen these are the hydrogen fluid properties those are given and also, we need to know the fluid properties of the gaseous and the liquid nitrogen.

So, here comes the ah nitrogen properties later on we will try to see ah how we can determine this fluid properties using some you know ah softwares. So, here ah comes the different you know enthalpies at different temperature and pressure. So, we will try to identify and then you know with respect to the actual process that we have learned. So, here comes ah this precooled Linde Hampson cycle where with respect to this ah this is an ideal and as as I was telling that this is the stream ah this is the low-pressure heat exchanger and this is the two-stream exchanger. So, the gas which is entering this heat exchanger at ah and the leaving and this is the LP stream this is the HP stream the temperature of the HP stream is same as the temperature of the LP stream at the warm end of the heat exchanger.

This is the warm end of the heat exchanger this is the cold end of the heat exchanger and this is the three-stream exchanger where these two streams which are leaving are same as and that is equals to and this is also at 300 K this two are also at 300 K. So, now it is ah you know and these are the values for the hydrogen that has been given and this is for the ah nitrogen that is given. So, now we will try to identify which is what ah this ah the this is at the inlet condition hydrogen and it is at 300 Kelvin and atmospheric pressure. So, 300 Kelvin and atmospheric pressure that means, this is the enthalpy and this is the corresponding entropy. So, we can understand that h1 is equals to 4226 kilo joule per kg this unit is very important if there in mixed form you must convert them into ah one particular type and then use it.

Here s1 is equals to 70.5 kilo joule per kg kilo joule per kg Kelvin. So, this is ah h1 and s1 similarly ah at this point this is compressed hydrogen isothermally compressed. So, this is QR and this is there is some work requirement that we will try to find out later on. So, here this h2 is basically 4251 and the corresponding entropy is s2 54.3. So, this is h2 and this is s2 we can write it like this h2 is equals to 4251 kilo joule per kg and this s2 is equals to 54.3 kilo joule per kg Kelvin. So, these are the values for the I mean before and after the compressor. Then comes ah this h4 do we know that state point? Yes, we know that this liquid nitrogen is boiling at a reduced pressure 38.5 kPa and the corresponding temperature is ah 70 Kelvin.

So, it is an ideal condition we assume that this state point 4 is at 70 K and there is no pressure drop in the heat exchanger in any one of this heat exchangers. So, it is at 50 atmospheric pressure. So, that is equals to you know 5.06 MPa. So, this state point is also known ah.

So, there are two it is in ah two I mean single phase gaseous nitrogen. So, two parameters would be necessary one is this 70 ah Kelvin temperature and the corresponding pressure is 5.066. So, this is temperature is 70 Kelvin and the pressure is 50 atmosphere. So, this h4 corresponds to let us use different color h4 ah would become ah this corresponds to this triple 1111 kilo joule.

So, 1111 kilo joule per kg and the state point 7 that is ah basically it is returning gas at low pressure and this temperature is 70 Kelvin. So, this is at atmospheric pressure and the enthalpy corresponding enthalpy is ah h7 that is equals to 1247 kilo joule per kg. So, we have identified h4, h7 and of course, this is ah hf that is the ah saturated liquid at the exit condition. So, saturated liquid is ah basically 271 kilo joule per kg. So, hf is equals to 271 kilo joule per kg.

So, these are the things that will be necessary ah mostly to calculate the ah liquid yield and the of course, the work required neglecting the work required for the sorry nitrogen ah liquid nitrogen. Ah along with that we understood that if we have to find out this ah nitrogen liquid requirement or mN2dot because that has not been specified, but we have to find out that with respect to the mass of gas compressed. So, we we have to also find out what is the enthalpy of the incoming ah nitrogen that is the liquid nitrogen. If it is liquid nitrogen that is saturated liquid and that is at 70. So, it is enthalpy is minus 137 kilo joule per kg and the gaseous nitrogen that is living at 300 Kelvin.

So, it is enthalpy is 311 311 kilo joule per kg. So, this is hNg and this is this is this part and this is hNf that is equals to minus 137 kilo joule per kg. So, with this ah I mean ah as we have identified all these parameters now let us go to the calculation page where we will be trying to find out the nitrogen requirement and the liquid yield. So, first of all if you want to ah find out the liquid yield ah what is the expression that we have? This is the expression if you remember that we have derived an expression involving the nitrogen requirement along with the ah what is called liquid yield. Now here in this case as we understand that we do not have the value for z known to us.

$$y\left(\frac{\dot{m}_f}{\dot{m}}\right) = \frac{h_7 - h_4}{h_7 - h_f} = \frac{1247 - 1111}{1247 - 271} = 0.139$$

$$\mathrm{z} = \frac{h_2 - h_1}{h_{N_g} - h_{N_f}} + y\ (\frac{h_1 - h_f}{h_{N_g} - h_{N_f}}\Bigg)$$

$$z = \frac{4251 - 4226}{71 + 137} + 0.139 \left(\frac{4226 - 271}{71 + 137}\right) = 2.76 \frac{kg\ N2}{kg\ H2}$$

So, we cannot basically use it for calculation of the liquid yield at this moment before that we have to for finding out the liquid yield we have to use the other expression involving h7 that is you know just immediately after the ah I mean precoolant bath ok. So, that was the enthalpy ah h4 and h7 that is the enthalpy of the hydrogen low pressure hydrogen leaving that heat exchanger two stream exchanger at the warm end. So, we have already identified these values and if we now look at it we will find that this is 1247 minus 1111 divided by ah I mean I am talking about this y part this is 1247 and then H f was the minus 271. So, these are the values with these values we are supposed to you know you also calculate I have gotten this value as 0.139. So, that is the liquid yield now we know the liquid yield or the mass of hydrogen that has been liquid per unit mass of hydrogen compressed. So, this value y is now known to us if we want to find out this ah I mean ah the nitrogen requirement we have to use this expression and for ah you know that expression we now know the y values. So, this y value if it is known ah we can now try to calculate this z the z is equals to basically h2 minus h1 h2 is how much h2 is 4251 minus 4226 that is for the incoming enthalpy and then we have ah ah what is called hNg that is the nitrogen gas you know that is leaving the ah system and ah there is the nitrogen you know incoming nitrogen enthalpy that is minus 137. So, it becomes positive because there is a negative sign over here along with that now we have 0.139 multiplied by h1 minus hf h1 is basically 4226 minus hf that is the enthalpy of the saturated hydrogen and this is 71 plus 137.

So, with these values you know this is supposed to come as a point this is the nitrogen requirement that is 2.76 kg of nitrogen per unit you know kg of hydrogen compressed. So, this is basically this parameter this is the mass of nitrogen and this is 2.76 ah you just try to calculate these values if I have gotten this value just a check whether it is matching with that appears ah. Now, let us try to ah look at this you will find that that has also been asked that what is the mass of nitrogen liquefied per unit mass of hydrogen liquefied ah this is the nitrogen required per unit mass of hydrogen liquefied.

$$\frac{\dot{m}_{N2}}{\dot{m}} = \frac{z}{y}$$

So, this can just be obtained by if we say z by y this z is basically mN2dot by mdot and y you know 1 by y is nothing, but mdot by mfdot. So, that is exactly what is necessary. So, this z is 2.76 and divided if we divide it by 0.139 that would give you the mass of nitrogen required per unit per unit mass of hydrogen liquefied.

So, this is supposed to come as 19.86 kg sorry ah kg of ah N2 per unit you know kg of hydrogen liquefied. So, that is this requirement of the nitrogen. Next is the work requirement as we understood that we have to calculate that part and we will be using this expression ok it is a bit unclear over here ah let us erase this part. So, this is we have identified all these parameters and now we will find that this is if this involves both the work requirement of the nitrogen also if we want to in this statement you know in this problem statement it has been asked to neglect this part. So, we will do only this part will be calculated ok.

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

So, we have already done this calculation for this work requirement sorry this ah this has come to be 0.139 then we have calculated this requirement this has come to be you know 2.76 kilo kg of N2 per kg of H2 and then we have also calculated this mN2 dot by mfdot. So, then you know this comes the work requirement as we were talking about here comes ah the one where if we neglect this work requirement for the nitrogen. So, according to this problem statement we have to neglect this work requirement for nitrogen and if we now put ah these values.

So, here we have said this temperature is 300 Kelvin s1 is 70.5 and this is 54.3 minus 4226 minus 4251 ok. So, this will be all together 4885 kilo joule per kg of hydrogen compressed. So, if you now have to find out minus W by m f dot then you have to divide this 4885 divided by y exactly the same way we can you know we have calculated.

So, this 4885 divided by 0.139 that will whatever that value is coming this is ah this is this many kilo joule per kg of hydrogen that is liquefied. So, this would be the kind of work requirement ah in a precooled in a Hampson cycle where we assume that the heat exchanger is heat exchangers are 100 percent effective and the compressor is also 100 percent effective. But ideally you will this non-ideality will come in picture there would be heating leak etcetera there would be pressure drop. So, lot of ah I mean non-idealities will come and definitely the work requirement will be much higher fine. So, that is about this numerical problem, but whatever what we have done in this analysis that we have assumed this ideal condition for all these heat exchangers.

So, particularly this heat exchanger which is at the lower end or that is the cold end exchanger this is the one ah this is a two-stream exchanger for which we can you know we have assumed it to be 100 percent effective. Now we will assume that this is not 100 percent effective and in that case what would be the change in the ah performance of the heat exchanger. So, ah so before going into that part let us just start with ah I mean what is the heat exchanger effectiveness ah if it is already known to you it will be a recapitulation for you. ah First of all this is a two-stream exchanger and this is a counter current exchanger. So, ah we know what is the effectiveness how do we define.

$$\varepsilon = \frac{Q}{Q_{max}}$$

So, it is ah I mean for any kind of two stream exchangers ah particularly which is ah in cryogenic ah conditions and this is at ah I mean 70 Kelvin in the previous problem and we have said that this is coming out at 70 K. So, if it is non-ideal we will find that this is no longer coming out at 70 Kelvin because this is the low-pressure stream and this is the high-pressure stream. Let us now look into the ah heat exchanger effectiveness first how what is the expression for that and how do we take into account in a ah process cycle like this. So, first of all the definition of heat exchanger effectiveness is the actual heat transfer divided by the maximum possible heat transfer Q by Qmax. We have the expression for Q that is the actual heat transfer it is very easily it can be determined it depends on the heat capacity of the hot fluid stream and the cold fluid stream and the inlet and the exit stream of the ah heat exchanger ok for the hot and cold fluid streams.

$$Q = C_{\mathrm{h}}\left(T_{\mathrm{h},in} - T_{\mathrm{h},out}\right) = C_c\left(T_{c,out} - T_{\mathrm{c},in}\right)$$

So, for the hot fluid this is ah Th in and Th out ah the difference multiplied by the heat capacity of the hot fluid and that is equals to this is there is no heat inlet and obviously, the ah it is equals to the cold fluid heat capacity multiplied by the Tc out that is the exit temperature of the cold fluid stream. This is in the generalized condition we are talking about and this is Tc in. So, before we go into that Q max what expression should we use let us have a look into this two-stream exchanger particularly with respect to this Ch greater than Cc and another condition would be obviously, Ch less than Cc. So, depending on that you know this the temperature profile would be looking like this. So, this is the hot fluid ah stream and this is ah the cold fluid stream the cold fluid stream being the low capacity ah Cc is the C minimum capacity fluid it will have a possibility to reach the you know incoming ah hot fluid stream temperature.

So, this this is Tc ah in and it can reach to the Th in. So, the maximum difference that can be obtained is Th in minus Tc in and who will be able to achieve that one the minimum capacity fluid. So, the minimum capacity fluid will experience the maximum difference in temperature. So, the Q max ah in that condition would be Th in minus Tc in multiplied by the Cc that is equals to the Cmin ok, but ah let us see what happens ah in case of Ch that is ah you know the minimum capacity fluid in that case the temperature profile would be like this and in that case this high temperature fluid will be able to almost reach to the ah minimum Tc ah in this Tc ah out or sorry Th out would be almost like ah Tc in it has the ah capability to reach that temperature at the extreme length ok. So, now, um what happens what is the maximum difference in temperature that can be achieved here this would be again Th in minus Tc in, but who will be able to achieve that one that would be achieved by the hot fluid or that is the minimum capacity fluid.

So, irrespective of this hot fluid being the cold capacity I mean cold I mean the minimum capacity fluid or the cold fluid or the hot fluid whichever is the minimum capacity fluid will experience the maximum difference in temperature. So, we can write that Qmax equals to Cmin multiplied by Th in minus Tc in. So, we have these two expressions both for the Q as well as Qmax. Now, we can in that case ah write this expression for the effectiveness Cc by Cmin we would prefer this expression because this Cc and Cmin will cancel for this expression. One can also use involving Ch and Cmin and Th in and Th out, but in that case Ch and Cmin will not cancel each other.

But in this situation this Ch is the minimum capacity fluid and we would prefer this expression where this Ch and Cmin will cancel each other. So, now, with respect to our ah previous you know expression where we have seen that the heat exchanger that was ah where the fluid was coming at h ah 4 and this was at T4 and this stream was leaving at ah this was the incoming one and this is leaving at T7 corresponding to h7. So, most of the time we will find ah that this is this stream is at high pressure this is at low pressure. So, we have to identify which one is having the high capacity and which is having the low capacity it will depend on the flow rate as well as the ah mean specific heat ok. So, we have to be very careful about the selection of this heat capacities and particularly for the cryogenic heat exchangers we will see that if we are not taking the what is called the temperature variation of the fluid streams we had ah you know there is a possibility that we will end up with some errors in finding out the actual sizing or the I mean rating of the heat exchangers.

So, that will be ah dealt in ah in details in the coming lectures. So, first of all if we assume some ah thing you know non-ideality that if it is not 100 percent effective. So, there would be some non-effectiveness or say be it depending on the heat exchanger it may be 0.9495 whatever 0.97 and accordingly we have to then calculate the temperature at the exit fluid stream as we have understood that it may not come exactly at the inlet condition of the high-pressure incoming stream.

So, we have to find out this T7 ah maybe we will be solving some numerical problem to find out exactly how do we calculate this T7 and get the corresponding enthalpy or whether we can directly link it with the enthalpy of this ah outgoing stream with the incoming stream. So, that will be taken up in the next sometime in the next lectures. So, now, ah with this one we can come to ah the conclusion and these are the references ah you can read the

Barron’s book or the I mean Thomas Flynn most of the time we are referring to ah you these 2 books for this lecture class. Thank you for your attention.