Cryogenic Hydrogen Technology
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Week - 06
Lecture 27
Cryogenic Liquefaction - Numerical

Welcome to this lecture on Cryogenic Hydrogen Technology. We were talking about the cryogenic ah liquefaction processes and in that connection, we have talked about the hydrogen liquefaction by precooled Linde-Hampson cycle. Then we have also talked about the clotted liquefaction cycle, but most of the time we have talked about I mean the ideal ideal conditions and later on of course, we have talked about the non-ideality in the heat exchanger. We have not talked about the non-ideality in the compressor work requirement. So, ah today in this lecture we will be talking about this cryogenic liquefaction ah, but we will be mostly trying to solve some numerical problem where the precooled Linde-Hampson cycle will be solved with ah non-ideality in the heat exchanger. Earlier we have solved ah the problem with an ideal heat exchanger like 100 percent effective ah heat exchanger.

Today we will try first with non-ideal heat exchanger that is the cold exchanger of course. And later on, we will also talk about the Claude liquefaction cycle, we will try to solve one numerical problem ah for one ideal liquefaction ah clotted liquefaction cycle. And we will also try to in that connection we will also try to ah look into the ah cool prop software for ah using the or calculating the fluid properties. So, this is ah the problem that we have solved earlier where this is the cold heat exchanger ah that is ah this heat exchanger we have ah taken as ideal one.

This is the 3-stream exchanger we will not be able to ah talk about the non-ideality with this particular unit ah because that will be beyond the scope of this part ah this lecture ah series. ah Here of course, this this is the 2-stream exchanger and this cold exchanger we have seen that or we have talked that this heat exchanger effectiveness ah ah I mean affects the liquid yield ah to a large extent. So, let us try to see ah recapitulating the one we have done earlier. So, this is when we have ah assumed that the heat exchanger is 100 percent effective the liquid yield we have seen it to be 0.139 and the work requirement corresponding to this situation was ah 4885 kilojoule per kg of mass ah I mean gas compressed ah this is the amount of work that will be needed.

So, this already you have solved. Now, we will put some non-ideality with this heat exchanger and let us see how we have ah you know how this numbers will change corresponding to that non-ideality. So, let us move forward ah let us assume that this heat exchanger effectiveness is 95 percent. So, that is epsilon equals to 0.95 and if this exchanger is ah not performing ah I mean ah behaving non-ideally how it is is it going to change the liquid yield.

So, ah in the last class we have looked ah I mean for we have derived this expression for this ah liquid yield where we have seen that this is the in effectiveness 1 minus epsilon. So, here this 1 minus epsilon is 0.05 and we have this parameters ah I mean corresponding to this all this fluid properties given. So, this is the saturated liquid and saturated vapor enthalpies will be needed hg and hf. So, if we have these values we can directly you know calculate this liquid yield y, but it that that needs ah to you know ah a precondition that you have to remember this expression.

But if you want to ah I mean it is possible that you may not remember this expression only thing is that you have to remember is that this 0.7 ah if the heat exchanger is non-ideal this temperature would become ah I mean T7 prime and this point becomes you know h7 prime that corresponding enthalpy. So, we have learned about the different techniques of finding this T7 prime and h7 prime in the previous lectures. So, you can opt for that and then you know you can try to calculate it from that expression ah h7 prime minus h4 divided by h7 prime minus hf. So, that will also give you the same expression otherwise if you can remember this expression you can directly obtain that liquid yield.

So, here you can see ah that liquid yield is dependent on this performance of this exchanger and if you ah you know if epsilon is 0.95 you will find that the liquid yield is now reducing to 0.115 earlier this value was 0.139 correct. So, if it was 0.139 now it has reduced to 0.115. So, 0.139 just you know because of this small change in the heat exchanger effectiveness we find a you know deviation in the liquid yield. So, you can also try to find out the corresponding ah value ah or the value for the heat exchanger effectiveness for which ah for which there is no liquid yield at all ah.

That means, ah if we have to find out the heat exchanger effectiveness corresponding to that there would not be any liquid then what we have to put y equals to 0 and then you can try to find out the epsilon you know for which there would not be any liquid. So, the limiting value for the epsilon ah is can be obtained like this. So, 1 minus epsilon would become ah how much ah h7 minus h4 divided by h7 minus hg. So, you can try to calculate this value and the from there you know you will find that epsilon of corresponding to ah limiting value for the epsilon for which there would not be whatever you do ah if the heat exchanger effectiveness is you know less than that value it would be around 0.7 or so. Just let me have a look into it ah 0.74 it if it is you can calculate it it would be about 0.74 if it is less than 0.74 you will find that there would not be any liquid ah whatever you do I mean if even if you cool it to liquid nitrogen ah I mean of course, ah for this pressure and temperature and this value is about 0.74. So, that tells about the importance of the heat exchanger those are to be used in cryogenic applications. So, now let us move forward ah we have talked about this precooled Linde-Hampson cycle where we have ah used an ideal ah heat exchanger as well as we have used a non-ideal heat exchanger. Now let us look into one ah Claude cycle and in that connection, we will also try to find out what are the ah property values evaluate evaluated from the software. So, here comes this problem statement ah this hydrogen is liquefied in an ideal Claude cycle this ah this is important we have talked about an we are talking about an ideal ah Claude cycle. That means, we will not talk about any heat exchanger non-ideality or the non-ideality associated with the compressor or we will assume that there is no pressure drop except in the I mean JT valve or I mean there is no additional heat leak that is taking place in the process.

And the gas is compressed ideally from one atmospheric pressure to 40 atmospheric pressure. So, in terms of the kPa it is 101.3 kPa to 4.05 MPa and the temperature is 293 that is 20 degree centigrade. So, there is no liquid nitrogen precooling. So, as we have learned earlier that ah it is not mandatory for the Claude cycle to have liquid nitrogen and here of course, we have said that there is no precooling. So, after the first heat exchanger in the Claude cycle hydrogen gas when it is entering the ah turbine its temperature is 180 Kelvin and the pressure is ah you know 4.05 MPa that is 40 atmospheric pressure. And after the first exchanger 50 percent of the compressed gas is passing through the expansion device. So, the medot by mdot that would become 0.5. So, this is also been told and you are supposed to find out the liquid yield the we have already talked about the liquid yield expression and the work requirement part unit mass of hydrogen liquefied. So, whenever we are trying to find out this the y that is equals to ah basically ah mf sorry ah we are trying to find out the work requirement part unit mass of gas ah liquefied. So, for that you know first of all we will be calculating the y and then minus W by mfdot and for calculating this W by mfdot we need to first calculate the minus W by mdot and from there we have to divide this into divided by the liquid yield and that will give us the work ah part unit mass of hydrogen liquefied. Also, we have been asked to calculate the figure of merit this is a ah another performance parameter we have not talked so, forth. And we have to assume that the expander work is utilized in compression.

So, whatever work at that will be generated in the turbine we will be utilizing that work to compress I mean compress the hydrogen gas. So, this is the problem statement, now we will look into ah the different ah I mean points which are ah I mean corresponding the enthalpy ah requirements or the entropy requirements. So, this is the solution method first of all let us start with the ah definition of the figure of merit it is basically the work requirement you have ah you may remember that we have talked about the ideal work requirement of hydrogen. And that work requirement divided by the actual work requirement ah part unit mass of hydrogen liquefied. So, that gives you the ah this FOM this work requirement is the minimum work requirement the ideal cycle.

So, obviously, you can understand that this will be lesser than the actual one. So, that this FOM will always lie between 0 and 1. So, it will not exceed at any time the value of 1 it can be at the most you know ah equal to 1, but it would be otherwise lying between 0 and 1. So, this is the actually the the Claude cycle and we have to now ah look at the different state points. So, we have been told about this initial state point this is this gas is getting compressed isothermally.

So, this temperature and the pressure are known this temperature and pressure is also been given because after the first state exchanger it is at 180 Kelvin and the pressure is also known. From here 50 percent of the mass compressed gas is passing through the turbine it is coming at temperature at some lower temperature, but not given at this moment, but this compression is told that it is an ideal expansion and ah this there is no loss in it. So, this is isentropic expansion means you know the entropy will remain constant at the inlet as well as at the exit. So, that means, that is an additional information ah that we will be trying to utilize and here this is the saturated liquid this is ah is also known to us this is saturated vapor. So, let us see what are the ah state points that we will be needing this is the expression for the liquid yield and the work requirement.

That means, you can ah see that we have to go for h1, h2, h3, he. So, h1, h2, h3, he, hf that is the saturated liquid as well as we will also need ah the ah I mean this mass fraction that is passing through the ah turbine that has already been told that it is 0.5. So, it is also already known to us and moreover this s1 and s2 we have to find out that is the entropy at these 2 points. So, ah let us try to see how do we do this ah I mean how do we evaluate all these fluid properties.

So, here comes let this be there along with us ah. So, that we can try to find out the state point ah whenever necessary. So, we know P1 P1 is ah 101 ah actually the ah this is the 1 101.3 ah kPa and P2 that is the compressed condition it is 4.05 ah it is 4.05 MPa and then we have P 3 ah P 3 is basically the compressed I mean this is on this high-pressure line this is also the same P e that is at atmospheric pressure. So, this becomes 101.3 kPa. So, this is the ah low pressure we know about T1 that is equals to 293 Kelvin then T2 is ah again isothermally compressed. So, this is 293 Kelvin T3 that is 180 Kelvin and ah we have Te it is not known we have to find out this Te later on and s1 we will try to calculate s2, s3 and se will not be ah ah ah s3 will be necessary ah because that is the inlet of the entropy and this is the entropy at the exits.

So, these two are the same. So, let us try to utilize this ah property values ah as we have said ah earlier that ah we will be using this cool prop ah that is an open source ah software. So, let us try to see you have to ah install this software ah while doing it ah doing this calculation and if you have any issues you can talk to our ah team and they he will assist you to ah install it or you know use it. Let us try to see how we are using it. So, once we ah click to I mean once we open this one there are ah this installation process ah you can see this is cool prop installation guidelines is given here and then there are certain sample calculation ah and then ah you know this is about the water saturation table and here comes the property table. So, here this is ah basically ah here you have to try for the different fluids there are list of fluids available here like this and I mean whatever these are the pure fluids it it is not a mixture ok.

So, in that case ah it is to be ah typed as you can type or you can select. So, this is basically hydrogen and the output file that we are looking for is the enthalpy you can select there there are different ah parameters. So, some of the parameters which are relevant for us I have we have listed it here and the corresponding units also you have to look into. So, here we are trying to find out the enthalpy for example, for state point 1 that is at ah 101.3 kPa and that would become you know this unit for this pressure is in Pa.

So, that means, we have to put this unit ah in Pa ah. So, that is 101.3 and 320 that is in kPa ok and say the other part is 293. So, and here we have to give an enter and then you know it will come as 353858 kilojoule per the sorry the enthalpy is in Joule per kg. So, if you put it in ah the kilojoule per kg it would become 3858.178 kilojoule per kg. So, that is about the enthalpy at ah 1 atmospheric pressure at 293 Kelvin. Now, if we want to find it out at 4.05 MPa. So, then it has to be ah we have to put it in Pa.

So, it would become 4.08 then ah I am sorry it has to be in Pa. So, it would become 4040 8 then after that it has there has to be ah 1234. So, that gives us ah the correct one right 40405 I am sorry ok fine. So, this is what is that ah you know will come as 4.05 and after that you know there are 6 zeros ok fine.

So, let us give an enter over here and then it comes 3875.156 kilojoule per kg because this unit is Joule per kg. So, if you want to convert it into kilojoule per kg it would become 3875.156. So, now if we want to calculate ah say the entropy.

So, this has to be changed to ah capital s and ah you know corresponding to this temperature and pressure so that means, this is s2. So, now, if we give an enter this is ah the corresponding entropy, entropy unit is Joule per kg Kelvin. So, if you want to put it in kilojoule per kg Kelvin it has to be 37.876 kilojoule per kg Kelvin. So, like that you have to ah find out all this property values and particularly for the entropy ah at state point 3 and state point e ah let us just have a look because we have said that this is at 180 Kelvin.

So, this 180 Kelvin corresponds to this entropy 31.037 kilo 31.037 kilojoule per kg Kelvin. So, this is at this ah I mean ah value is basically s3 the entropy at state point 3 and thus entropy at state point e is also the same. So, ah that means, for in state point 3 we know the entropy and the pressure we do not know the temperature.

So, if we want to find out Te what we have to do is that we have to remember this value of this entropy and that we ah let us say ah copy this value and we will put this output name as temperature because we want to find out the temperature and the input name should be the s where we will give this value ah that was how much 31.037 31.03 I am sorry this has to be in 31037 because ah it is to be in Joule per 037 ah that is the Joule per kg Kelvin and the pressure is here 101320. So, we know the pressure and the entropy. So, the output file name is now temperature and this would become 46.617 that is the ah I mean temperature and if you want to ah find out the enthalpy of that state point you can also ah do that ah I mean you can calculate the enthalpy directly from there and it would become 731.585 kilojoule per kg. So, like that you can find out the different fluid properties using this cool prop. So, if you have any ah problem you can ah later on talk to us about this part.

So, let us move back. So, we have the ah you know using this cool prop I am sorry this is ah the enthalpy ah of h1 that is coming out to be 3858.178 kilojoule per kg all these are in kilojoule per kg and then 3875.156 kilojoule per kg this is 2285.187 kilojoule per kg and this would become ah this hf ah of course, we have not talked about this hf ah this has to be ah I mean another ah let us go back to this cool prop again. Here, ah we are trying to find out the enthalpy corresponding to ah the saturation point ah saturated liquid.

So, here what we would do is that we will put one input as ah the pressure of course, we need to know at atmospheric pressure and here we will put ah the quality. So, the quality is basically we have to put either 0 or 1 for the saturated liquid and saturated vapor. So, here we are putting it as 0 that means, ah the it is saturated liquid and the corresponding is enthalpy is ah 1.68. So, that is ah Joule per kg. So, we have to ah put the enthalpy as minus 1.68 into 10 to the power minus 3 as ah the corresponding enthalpy for the saturated liquid. So, ah we will have that value as ah the ah liquid enthalpy. So, let us go back again.

So, here the hf ah is basically minus 1.68 into 10 to the power minus 3 kilojoule per kg and there is he that we have also obtained and he is 731.585 kilojoule per kg. So, these values are also ah I mean you can obtain it from the ah chart I mean using that cool prop. So, this would become ah this many kilojoule per kg kelvin, then at ah s2 is 37.876 kilojoule per kg and s3 is equals to 31.037 kilojoule per kg and se and s3 they are equal. So, based on these values we have obtained from the cool prop, now we can calculate ah the liquid yield. So, we have the expression for the liquid yield and if we put these values you will find that ah the value of this part is coming to be say 0.004 with a negative sign and this is coming as plus 0.201. So, in total it will become 0.197. So, we already know that this is having a negative contribution because of that compression, but this positive contribution is coming ah from the expansion engine. So, all together you see even we do not have even without any precooling of liquid nitrogen we are getting a positive value of this ah liquid yield. So, here ah again if we now calculate ah say the work requirement we will find that we have two components one is the compression work and this is the expansion ah work that has been generated.

This is where we have given work and this is where you know we have obtained work from the system. So, if we ah try to calculate this we will find that this component is coming as 4486.3 kilojoule per kg ah while the you know work obtained of this system is 776.8 kilojoule per kg. So, all together it will become you know if we ah sum it up we will find that the overall work requirement is 3709.5 kilojoule per kg. So, out of this this is the compression work and this is the expansion work that we have you know received out of this system and this work will be utilized to you know basically compress the gas. So, the overall requirement of the compression work will be reduced to this value. This is we have seen that we this is the work input that has been given to the compressor and this is the work output fine. So, this is the work per unit mass of gas compressed and if we want to find out the work requirement per unit mass of gas liquefied we have to divide this number 3709.5 kilojoule per kg kilojoule per kg divided by y and y is how much 0.197 0.197. So, it will come out to be 188 18836.3 kilojoule per kg.

So, this much amount of work required per unit mass of gas liquefied. So, now let us just ah you know for sake of comparison we have earlier solved the precooled Linde Hampson cycle and you may remember that we have compressed it to nearly about 50 atmospheric pressure and we that was completely ah based on the isenthalpic process and there was a precooling of ah liquid nitrogen that was essential for that precooled ah Linde Hampson cycle. So, there if you remember you would ah find that we have obtained a liquid yield of 0.139 ok. So, you can see and or you can compare that even ah you know if though you know we have compressed it to ah less pressure of say 40 atmospheric pressure still we are obtaining ah higher value for the liquid yield and not only that there is a substantial you know reduction in the ah work done per unit mass of gas compressed because you know of course, we are compressing it to 40 atmospheric pressure rather than 50 atmospheric pressure and together with that ah we have you know here there is some ah work generation because of this expander and that is how the overall work requirement is going to be I mean less with this ah Claude liquefaction cycle. So, based on this ah value of this work required per unit mass of gas liquefied we can now calculate ah the FOM that would be the ideal work requirement divided by the actual work requirement.

So, now, we have the of course, per unit mass of gas liquefied. So, here this comes out to be ah ideal one is if you remember we have also solved this ah 12019 kilojoule per kg and ah kilojoule per kg and this is ah 188.8 18836.3 kilojoule per kg. So, this FOM becomes ah 0.638. So, this is the ah FOM for this ah Claude liquefaction cycle where we are not using any ah precooling. So, these are the references we have ah recommended earlier also and to conclude that ah with this lecture that liquid yield for the Claude cycle ah in terms of the Claude cycle definitely it is better than the precooled Linde Hampson cycle ah. The reason is very simple ah I mean the precooled Linde Hampson cycle makes use of isenthalpic expansion entirely and ah, but this Claude liquefaction cycle is basically based on turbine-based cycle and it is an isentropic process cycle. So, obviously, the performance both in terms of the liquid yield as well as the work requirement ah you know it would be better under the similar condition of course, ah similar pressure and temperature operating condition ah the Claude cycle is ah better one. So, thank you for your attention.