Cryogenic Hydrogen Technology
Prof. Indranil Ghosh
Cryogenic Engineering Centre
Indian Institute of Technology Kharagpur
Week - 06
Lecture 26
Cryogenic Liquefaction… contd.

Welcome to this lecture on cryogenic hydrogen technology. We were talking about the hydrogen liquefaction in that context. In the last class we have talked about the hydrogen liquefaction using precooled Linde-Hampson cycle. And later on we have also talked about the effect of ah basically the heat exchanger ineffectiveness. And in that connection, we have tried to solve some ah I mean basically tried to calculate the effect on the ah liquefaction system.

But mostly ah we have talked about the heat exchanger ineffectiveness and how it is going to affect the performance we will today try to evaluate it ok. So, the topic that will be covered today is basically the heat exchanger ineffectiveness on the system performance. And later on, we will talk about another liquefaction process which is known as ah Claude liquefaction process or Claude liquefaction cycle. So, let us start ah basically it is a recapitulation of what we have done in the last class.

This is what is that precooled Linde-Hampson cycle. And in that connection, we have seen that this cold end exchanger that is ah this particular heat exchanger ah we have ah told that this exchanger is having ah 100 percent effectiveness. And when it is having 100 percent effectiveness the temperature T7 ah is equals to T4. And ah, but ah this is ah I mean no heat exchanger or no I mean unit is perfect. So, we know that there would be heat exchanger ineffectiveness and ah let us see how it affects the system performance if this heat exchanger is not 100 percent effective.

So, if it is not 100 percent effective ah then ah we have to look into the system performance particularly what is the change in the liquid yield or what is the work requirement whether there is any enhancement in the work requirement. So, let us have a look. So, this is ah when we have talked about epsilon equals to 1 and accordingly we found that the liquid yield was coming as this is the maximum liquid yield we can have is h7 minus h4. And you can understand that this temperature is ah important because that is determining this enthalpy ah h7. And also, the enthalpy of this ah I mean at this point ah that is the T4 and the pressure at that point P4.

So, the pressure we have assumed to be constant that is at the high pressure there is no pressure drop we are considering at this moment. And this T4 is determined by the ah boiling point of this ah liquid and the pressure basically what is that pressure that we are maintaining in this inside this tank. In the last time ah you know problem that we have solved we have solved it under reduced pressure liquid nitrogen was ah you know stored and it was at 70 Kelvin. That means, you know this T4 is determined by the condition of the liquid nitrogen. Now, ah, but we have assumed this heat exchanger to be 100 percent effective and ah naturally ah the T7 equals to T4.

And in the last class we have talked about that heat exchanger effectiveness how it is ah changing ah with ah this Ch or Cc ah that is the cold ah capacity cold fluid heat capacity and the hot fluid heat capacity. So, now, as soon as it becomes ah you know ah epsilon not equals to 1 that it means ah it is not 100 percent effective then this temperature is no longer ah 7 it is 7 prime. So, earlier we have seen that T7 equals to T4 now this T7 is no longer ah T7 it is T7 prime. So, the T7 prime being different from T7 ah it would be basically ah what will happen this will also change the enthalpy at that point. And now we need to find out what is the enthalpy at ah at ah what is called this T7 point.

So, that we can calculate the enthalpy and also if we similarly if we take the energy balance across this you will be able to find that ah this enthalpy is basically it will determine the ah we will come back to that part before that just let us also ah have a look into this part what we have talked about in the last class that if this ah 2 if the 2 fluids are coming in this heat exchanger assume that this is the heat exchanger. So, the hot fluid is coming in at ah T4. So, this temperature is T4 and ah this is coming out at T5 and the cold inlet is Tg this is Tg and this is coming out at T7 earlier it was coming at T7, but ah I mean T7 and T4 were equal that means, the heat exchanger effectiveness was 100 percent ah with the I mean the underlying assumption with this or basically you can understand that we have talked about ah or assumed basically that the cold stream is the low capacity fluid stream that C c ah is the C min this is the minimum capacity fluid it is because of 2 facts first of all you know this ah a part of the mass is moving out of the system. So, if we have compressed m dot mass and we have you know taken out some mfdot ah liquid from the system this is in the steady state condition and we have then mdot minus mdot that is you know going back. So, this ah cold fluid stream this is the flow rate of the cold fluid stream and the corresponding ah ah ah specific heat average specific heat of this ah return stream that is at low pressure and the average temperature of the Tg and T7.

So, this product m dot c multiplied by Cp average that is what is the Cc and that Cc is ah you know the minimum capacity fluid that means, this is less than Ch the corresponding ah mass flow rate m dot multiplied by the mass flow rate of the hot fluid stream multiplied by the average ah this Ch is basically mhdot multiplied by Cp h average. So, we are assuming this condition prevailing in this ah particular heat exchanger ah I just want to ah mention it here that since there is lot of ah fluid property variation particularly for hydrogen we have to be very careful ah before doing this ah or I mean implementing this condition ah it is better to check it before ah going ah this heat exchanger design. But as such for this kind of heat exchanger design or simulation ah since we do the property variation calculation ah we include that. So, ah I mean there should not be any problem. So, at this moment we what we understood that if this is the Cmin fluid ah if this Tg is supposed to reach ah or it will try to reach T7 prime will try to reach T4 and if it is not 100 percent effective then it will not be able to reach ah T4.

If it is 100 percent effective T7 is equals to ah T4, but if it is not 100 percent effective then this is there is a difference between T7 and T7 prime. So, that is what we have understood and now ah if we ah do an energy balance ah across this ah this ah you know this control volume that we have done earlier. So, we have this ah energy balance will lead to this expression. Now, earlier it was TI mean ah T7 and corresponding enthalpy was h7. Now, it is T7 prime the temperature is T7 prime and the corresponding enthalpy is now ah h7 prime.

$$\epsilon = \frac{T_{7'} - T_g}{T_4 - T_g}$$

So, ah in order to find out ah this ah h7 prime there are 2 ways to do that first of all ah we can try to find out this temperature T7 prime and the pressure being known we can evaluate this enthalpy h7 prime. How do I find out T7 prime? We can put it ah in this expression ah you can have a look into this expression ah here ah this expression for that ah what is called ah this heat exchanger effectiveness is epsilon. So, Tc out is basically T7 prime now and what is Tc in? Tc in is Tg and C is Cc and Cmin they are same because we have assumed it to be ah the cold fluid to be the minimum capacity fluid. So, they are cancelling out Th in is basically the T4 and ah what is Tc in? Tc in is Tg. So, this heat exchanger effectiveness if it is known we would be able to calculate T7 prime.

$$\epsilon = \frac{T_{7'} - T_g}{T_7 - T_g}$$

This is the straight forward we know T4 we know Tg, Tg is the temperature of this ah you know the vapor and T7 prime is the temperature at which this is ah leaving the low end ah sorry the warm end of the low temperature heat exchanger. So, this is one way of finding out the h7 prime. The other way of finding it out is like this we can still use this expression, but ah let us see how we can do that. So, epsilon we can write it as T7 prime minus Tg, T7 prime minus Tg divided by it was T4 and T4 we know that it is T7. So, T7 minus Tg we can write in that case now if we multiply it with Cc that is the cold fluid heat capacity then let us see what we will have epsilon would become h7 prime minus ah Tg into Cc.

$$\epsilon = \frac{h_{7'} - h_g}{h_7 - h_g}$$

$$h_{7'} = \epsilon\left(h_7 - h_g\right) + h_g$$

So, it should be hg divided by now we have h7 minus hg. So, this is the enthalpy this h7 enthalpy corresponds to what this corresponds to T7 and P7. That means, the temperature at 0.7 that is with 100 percent effective heat exchanger that is equals to T4 and the pressure corresponding to this basically that is the low-pressure ah return stream it is coming back. So, that gives you T7 we know the T7 and ah we can then calculate h7 prime as epsilon multiplied by h7 minus hg plus hg.

So, this would give you the directly the h7 prime. So, that can also be used here. So, there are 2 ways you can find a h7 prime, but please mind that this h7 cannot be written as h4 because that h4 is basically the enthalpy corresponding to high pressure we are multiplying it with the C c. So, if you are writing it as T4 and multiplying it with C c that is not corresponding to h4 because that temperature T4 multiplied by Cc that T4 corresponds to high pressure and Cc corresponds to low pressure heat capacity. So, that cannot be combined together.

So, you should be very careful about that part the that is the common mistake ah you know the students will be doing, but ah otherwise if you are using this expression both the I mean both way they should give you ah very similar ah or almost equal to equal enthalpy calculation. So, either you can do it by h7 directly or you find out this T7 prime from this equation and then you calculate the corresponding enthalpy at this point. So, once this enthalpy h7 prime is known to you, you would be able to replace it here and calculate the liquid yield. So, accordingly it will come as let us ah just have a look ah accordingly this ah with a little bit of algebraic ah manipulation you would be able to ah calculate the liquid yield as this expression would come. So, it involves ah see ah it is basically ah presented in a format with you know this 1 minus epsilon that is ah basically the heat exchanger ineffectiveness.

So, this ineffectiveness 1 minus epsilon epsilon is the effectiveness of the heat exchanger 1 minus epsilon is the ineffectiveness of the heat exchanger. So, this expression if you remember this is the expression we have obtained for ah the liquid yield in case of 100 percent effectiveness. Now, you can understand that there is a difference or you know ah because of this 1 minus epsilon or not this becomes if epsilon equals to 0 we will get back to the same expression ah sorry epsilon equals to 1, then this term becomes 0 and it will come back to the same original expression corresponding to epsilon equals to 1 or 100 percent effective heat exchanger. But if epsilon is equals to none 0, none 1 or ah none unity.

So, in that case this 1 minus epsilon becomes a fraction and according to this expression this liquid yield will decrease.

So, ah next time when we are solving the numerical problem we will try to see to that. So, this is about the pre-cooled Linde Hampson cycle where we have seen that the heat exchanger effectiveness is ah you know ah changing the liquid yield. So, similarly we will find that there is a difference in the ah what is called the heat exchanger the I mean depending on the heat exchanger in effectiveness ah there would be enhancement in the ah work requirement also. Now, ah with this we will now proceed towards another liquefaction cycle ah later on you know while solving the numerical problem will again come back to this use of this expressions either directly we will be using it or we will calculate this h7 prime and then we will ah try to calculate the liquid yield. Now, let us move ah to ah another cycle where we will be taking help of ah the isentropic expansion.

This precooled Linde Hampson cycle you can understand that there is no expansion ah related to isentropic expansion all this you know expansion that is there is basically an isenthalpic expansion. But in isentropic expansion ah let us have a look ah what is that the expansion processes that we have talked about this is about the ah what is called isenthalpic expansion ah where we have this is the isenthalpic line. And here we have talked about that isentropic expansion when you know the entropy remains constant and we have gotten a larger temperature drop. So, we will be using it I mean this kind of ah temperature drop is possible with the help of a turbine or expansion engines. So, this is ah basically ah that has been achieved in a JT expansion valve or JT ah valve or JT expansion or free expansion.

So, now, we will find that in case of Claude cycle it is the combination of both expansion ah I mean both this expansion isentropic expansion as well as isenthalpic expansion. So, ah here the advantage of this particular process was you know this mu S is always positive and ah it is always giving you know greater than 0 that we have learned earlier. But in case of this expansion we have seen that it can be greater than 0, it can be less than 0 or it can also be equal to 0. So, that means, we have ah certain uncertainty in getting the cooling with the help of ah this ah you know expansion. But with this expansion we do not need any kind of precooling because here you know this has led to that maximum inversion temperature we have to put the gas always ah below the maximum inversion temperature before we expand and expect a cooling.

There is such no such problem is there with respect to this expansion ah by isentropic process. So, isentropic process whatever be the temperature if you just expand it ah you will it will ah give you the cooling. So, let us look into the isentropic process-based ah cloth cycle. So, here we have this expansion ah we have not shown it here. So, there are 3 exchanger ah heat exchanger 1, heat exchanger 2 and heat exchanger 3.

So, 1, 2 and 3 these are the 3 exchanger and this is the usual you know expansion process. But what will happen in the cloth cycle from here point 3 a part of the compressed high-pressure gas will be diverted. So, like this and it will be the passing through this ah turbine. So, if medot mass of gas which is getting passed through the turbine and the rest of the gas that means, medot mdot minus medot will proceed towards ah the heat exchanger 2 and then it will move to heat exchanger 3. And from there you know it will come to 0.

5 and then it will be ah undergoing isenthalpic expansion. So, this is what is isentropic expansion and in isentropic expansion we know that there would be some amount of work generation. Here we have given some work input and here we are getting some you know work output. Now ah it is to be mentioned that if it is ah you know this work output that is received out of the turbine, if it is substantial we generally try to ah compress some of the incoming you know high pressure I mean this hydrogen gas in case of hydrogen or any other fluid if it is. So, we try to that means, you know utilize this work otherwise if it is not ah you know if it is a small amount it is not a big liquefaction cycle.

We try to you know dissipate it ah outside there are different ah dissipation mechanism. So, here ah what happens then? So, the compressed gas is coming from one first exchanger, second exchanger, third exchanger and after the first exchanger and before the second one a part of that high-pressure gas is passing through the turbine. And the expanded low temperature gas will join ah with the return stream of the you know vapors return vapor this is the ah return vapor that is coming that is at low pressure. And after the third exchanger this me or medot mass at temperature Te will be ah combining with the gas at T7 at this temperature this is T7. And they will get mixed and most of the time this temperature are similar ah I mean ah this heat exchanger will be designed in such a way that they should be ah of similar magnitude.

And this are getting mixed to have a resulting temperature T7 prime or so. Then they will proceed towards this. So, what will happen ah initially if when the process is getting started you see there is no liquid nitrogen requirement we can use it as a precoolant, but that is optional it is not mandatory to have this liquid nitrogen in this system. So, even if it is starting at the very initial ah you know point when it is at room temperature this will be giving some amount of cooling and that cooling will be able to cool the high-pressure incoming gas before it reaches to T3. So, gradually this T3 will come ah from you know this is an isenthalpic ah isothermal compression and this temperature T2 is same as the room temperature.

Then later on T2 is gradually you know ah reducing as it the time passes ah and in the steady state T3 will be lower than T2 and from T3 we are expanding this gas. So, now let us try to look ah the temperature and enthalpy ah curve. So, this is how it looks like. So, this is state point 1 there is 1 is to 1 corresponds ah correspondence between all the state points and this diagram. This is temperature on this scale and we have entropy on this scale.

So, this is at ah atmospheric pressure or low pressure and this is at higher pressure. So, this is state point 2 is on a higher pressure then it is you know getting cooled to state point 3. Then a part of it you can see that it is getting expanded to temperature E while the other part or remaining fraction is moving towards ah you know temperature 4 and coming to temperature 5. When it is coming to temperature 5 this is expanding in a jet evolve to get inside this liquid vapor dome to produce the liquid and the vapor. The vapor will be going back ah like this this is going back and the ah I mean the liquid part it will be collected over here and a fraction of it will be taken in back ok.

So, we have medot mass that is passing through this turbine this this is the work output and this work output if it is taken as I have said that will reduce the ah I mean work required measurement of this compressor. So, this is about this ah ah TS diagram corresponding to this cloth cycle. Now, let us look into ah the ah analysis part ah we have to ah again draw one control volume this will include ah say the ah temperature at this point T2. Let us ah try to this is the control volume and let us try to quickly ah find out what are the corresponding enthalpies what are the streams going out or coming in. This is the mass flow rate which is leaving the system this mass flow rate ah medot that is going inside this at ah an enthalpy he this is at an enthalpy ah h3 and corresponding to a temperature ah Te sorry T3.

So, T3 and h3 is the ah you know ah mass flow rate and mass flow rate is m e dot ok. So, this is what is leaving this ah control volume this is what is going inside the control volume along with that mdot and h2 that is going in and here as usual mdot minus me sorry mfdot that is leaving the system at h1. So, we have identified this and accordingly according to that first law of thermodynamics ah for the open cycle we will now ah summarize it here. So, these are the incoming ah things medot corresponding to h3 as we have identified m dot is entering at h2 and the streams leaving this is at he ah he dot I think ah this is coming in and this is I am sorry just let me check it in the previous system medot is he dot this is going in and the system that is leaving is ah medot h3 that is ah leaving the system ok. So, let us see what is ah leaving the system is ok ah this is leaving the system is h3 and this is he and this is hf.

So, if you now make an energy balance this is h1. So, this is what is leaving the system and this is sorry h3 is leaving the system and he is getting inside ok fine. So, ah let us make an energy balance we will find m dot ah and if you do that energy balance Q minus W is equals to summation of the m dot and hof the out ah going minus ah m dot into hof the incoming stream. So, here there is no heat in leak or there is no work input. So, we will ah put it as 0 is equals to ah the stream ah leaving medot and h3 and the stream leaving out is mfdot hf and the incoming things are ah mdot h2 minus and ah what else is there.

$$y\left(\frac{\dot{m}_f}{\dot{m}}\right) = \frac{h_1 - h_2}{h_1 - h_f} + (\frac{\dot{m}_e}{\dot{m}})\frac{h_3 - h_e}{h_1 - h_f}$$

Then here of course, we should have mdot minus mfdot multiplied by h1 and the streams leaving out is ah ah mdot I am sorry outgoing enthalpies are this is outgoing this is outgoing h3 medot and this is outgoing. So, in case incoming is mdot h2 and plus me dot ah he. So, then if we ah collect them mdot will be h1 minus h2 then you have mfdot and mfdot is hf and the other term is ah mfdot is h1 then another term involving medot and ah medot will be having h3 minus he ah this is plus I am sorry this should be having a negative sign because this is ah the term which is incoming ok. So, this is medot and right. So, this is equals to 0 now if I divide it by ah mdot that is this part this is m dot and this is mdot and then we have this is basically the y part and if I take it to this side you will have h1 minus h2 divide by ah h1minus hf plus medot by mdot multiplied by h3 minus he by h1 minus hf.

So, this is the liquid yield ah with this ah the Claude cycle where you can see that this part basically you know that this will be a negative contribution and this part is what is giving you the positive contribution into the liquid yield and h3 minus he this is the incoming enthalpy this is the outgoing enthalpy and h1 minus hf is of course, ah is there in both the system. So, let us conclude ah this is the work as we have done it in the just ah you know in the previous slide and this is the work requirement that is reduced by if you just do an energy balance across the turbine you will find this is the work that we are generating and this work will be you know assisting the our compression work it will be reduced by this factor. So, this is the in a nutshell about the performance parameters, but if we ah do not include or if we just allow the ah gas to you know ah without any we do not take that work I mean output if we allow it to dissipate then the work requirement remains unchanged. So, these are the references and ah and to conclude that we have seen in the pre cooled Linde Hampson cycle with that one we have seen that the system performance deteriorates with the heat exchanger in effectiveness and the Claude liquefaction cycle it is not you know dependent on the pre coolant it is not mandatory, but one can of course, use ah you know the pre coolant we will see it later how it is enhancing the system performance, but it is not mandatory. So, thank you for your attention.