Cryogenic Hydrogen Technology
Prof. Indranil Ghosh
Cryogenic Engineering Centre
Indian Institute of Technology Kharagpur
Week - 06
Lecture 29
Cryogenic Liquefaction – Contd.

Welcome to this lecture on Cryogenic Hydrogen Technology. And we were talking about hydrogen liquefaction. In that connection, we have talked about the pre-cooled Linde-Hampson cycle, Claude cycle. And today, we will also try to learn you know some more relevant hydrogen technology or cryogenic liquefaction cycles. And there are different variants of the liquefaction cycles.

So, probably we will talk in this lecture about those variations. So, the topic is basically the cryogenic liquefaction cycles, we are continuing along with that. And today, we will ah mostly focus on the pre-cooled Claude and maybe you know the reverse Brayton in cryocooler, cryocooler based liquefaction process. So, here this ah Claude cycle we have learned and in that Claude cycle, we have seen that there are turbines.

And I mean sometime it is more than one, they are in sometime in series and they can also be in parallel. But in the pre-cooled Claude cycle, there is a pre-cooling as you can understand and that pre-cooling is of liquid nitrogen. It is not mandatory, but we will find that the pre-cooling is giving some kind of advantage I mean in the liquid yield and that we will have a look into this process. And this reverse Brayton cryocooler basically that is a new term for you probably that is a cryocooler, where that cryocooler is basically ah refrigerator and it is in a closed loop, but we are taking help of that cryocooler to liquefy hydrogen. So, this it is basically a mixture of ah I mean liquefier plus ah refrigerator, it is a refrigerator-based liquefier. So, we will talk about that part in this lecture.

So, now, just to recapitulate this is the pre-cooled Linde-Hampson cycle, where pre-cooling is mandatory. This is a completely ah isenthalpic expansion-based system, where you will find that we were completely you know taking help of this ah liquefier based on this isenthalpic expansion in this expansion valve. And this being you know ah isenthalpic expansion-based system, we must keep you know this temperature before expansion, it must be below the maximum inversion temperature and for liquid hydrogen, it has to be below 205 Kelvin. We have seen that and we have learned about it, we have analyzed this system, we have seen what is the liquid yield, what is the requirement for the work and what is the necessity I mean what is the amount of nitrogen that will be used.

So, already we are aware of this part. Then we have talked about the Claude cycle, here also we have seen ah that the expansion engine based and not only that we have that isenthalpic expansion and it is also assisted by this turbine. And this combined effect is giving us this liquid yield. Here we have told you earlier that it is not necessary that or it is not mandatory to have a liquid nitrogen system, here liquid nitrogen pre-cooling. Today we will try to put an ah I mean liquid nitrogen assistance and how this ah I mean work input is enhancing or how this liquid yield is increasing, we will have a look into that part.

So, this is the dual pressure just again in the last class, we have talked about the dual pressure system or dual pressure Claude cycle, where we have used you know two compressors to reduce the ah work requirement, but it you know we have to compromise with the liquid yield a bit. So, we have seen this ah we have derived this ah you know expression for the liquid yield as well as the work requirement. Here ah if we are taking help of the work ah you know generated by this turbine to assist the compression process. So, there would be some ah you know ah reduction in the work requirement, but there would be ah as well as there would be slight decrease in the liquid yield that also we have seen. There is another variation of the ah dual pressure system, where ah you can see that this is a combination of I mean there are two ah turbines, this is turbine 1 and turbine 2 and then we have you know dual compressors.

And here of course, you can see that the maximum pressure is getting depressurized earlier to that we were I mean ah expanding the intermediate from the intermediate pressure we were expanding the gas, but here in this case you can see that the gas which is being pressurized to the maximum pressure will be expanded and that will join to the intermediate pressure line. So, this is from the maximum pressure to the intermediate pressure. So, the high-pressure gas is coming getting expanded through two turbines and finally, the remaining portion which is not passing through the turbines you can see that it is coming through the JT valve and getting expanded, but this is getting expanded to the lowest pressure. So, here you can see that if it is one atmospheric pressure, then this is at somewhere like you know the intermediate pressure is some 8 bar pressure or 8 atmospheric pressure and then you have from here say 50 atmospheric pressure. So, this 50 atmospheric pressure is getting expanded to say 8 atmospheric pressure and then again in another ah I mean say this is we can say it as hot turbine though it is not hot, but you know for relatively it is hotter and this is say the cold turbine because this is very close to the lowest temperature.

So, these two turbines are in you can see that they are in ah I mean parallel, but finally, this gas at 50 atmosphere is getting expanded to one atmospheric pressure to give us the liquid and finally, this one atmospheric pressure low pressure return gas is going back to the suction of the first stage. So, this is how the dwell pressure Claude cycle works. There can be an variation of this also and we call it as Collins liquefier though that Collins liquefier is traditionally used for the helium, we can also use it for the ah hydrogen liquefaction also. So, these are the kind of variations one can think about you can try to analyze this already you have learned about the analysis of this ah you know cycle. So, you have to what you have to do is that ah you will find that there would be a control volume like this and finally, you can ah take ah this control volume to calculate the liquid yield taking help of these two ah turbines in a dwell pressure Claude cycle.

And then comes ah what you can have it have it in this reference also. ah Then precooled Claude cycle as we were talking today ah that this precooling is supposed to enhance the liquefaction yield or the liquid yield ah though it is not mandatory as we have learned that precooling of liquid nitrogen is not mandatory, but ah we have to ah we we can use it for ah you know enhancing the liquid yield. So, let us have a look ah how it works say if we look at this cycle here you will find that the liquid nitrogen is coming and the liquid nitrogen is you know getting evaporated by allowing or when the high-pressure gas is coming and passing through this ah I mean what is called this three-stream exchanger followed by the liquid hydrogen tank. Now, ah liquid nitrogen storage vessel. So, rest of the things if I just you know suppress this part you can see that this is just nothing, but the Claude cycle.

So, this Claude cycle along with that we have added this part additionally this you know highlighted part you can see that this part is in addition and this additional part is giving us ah you know certain advantage. It is ah you have seen similar kind of arrangement in the precooled Linde-Hampson cycle. So, you can say that in a sense that this is the precooled Linde-Hampson cycle cooling part and here this is what is that is the this is the Claude cycle and this is the cooling part of the precooled Linde-Hampson cycle. So, those two have been as if combined. Now, ah if you ah again do the analysis we will find that we have this is the control volume you can say and this control volume you have already learned how to analyze this ah.

So, in this control volume assuming that there is no external heat leak and there is no work input that is going and you can analyze it to have this liquid yield. So, here this is the additional part if you compare it with the previous expression of the Claude cycle you will find it was up to this part that was there for the ordinary Claude cycle, but because of that you know ah ah additional precooling you will find an additional term which relates to the mass flow rate of ah liquid nitrogen. And of course, ah this term which is nothing, but this is the enthalpy of the vapor part sorry this is the liquid enthalpy and this is the liquid sorry the vapor enthalpy h_N ah this is the vapor and this is ah h_N for the nitrogen and this is the liquid. So, it is coming as liquid and getting evaporated as a vapor. So, this enthalpy we are trying to utilize and the corresponding mass flow rate.

So, you can think that you know as if ah if I increase the rate of liquid nitrogen and we can have something like 100 percent liquid yield. Now, the it is not so, whatever be the liquid nitrogen you know ah that is going into the system you will find that this temperature T4 ok ah it cannot be colder than this liquid nitrogen temperature. So, it definitely it is depending on the liquid nitrogen flow rate, but you cannot you know cool it down before T4 and this T4 will be you know controlling this ah what is called the ah ultimately determine what is the maximum liquid yield that you are going to find. So, ah it is not like you know by changing it to ah very high value you can get 100 percent. So, it will be governed by ah as I told you that the temperature at point 4. So, ah that is what is the liquid yield, but definitely there is an enhancement compared to the Claude cycle and that is I mean this term is giving that additional benefit, but at the cost of liquid nitrogen. So, there would be ah obviously, some ah work associated with the liquid nitrogen part and this is the work requirement of the ah you know ah this is going to be an enhancement in the liquid nitrogen ah related to ah production of liquid nitrogen, but there is an associated decreasing ah the ah work input because if we are taking the output of this turbine and assisting it to do the compression. So, this is about the work requirement. Now, this pre-cooled Claude cycle and earlier we have talked about the dual pressure ah system. Now, we will move to another cycle which is where the liquid nitrogen I mean is ah liquefied or nitrogen sorry liquid hydrogen is obtained ah from the assistance of ah helium.

So, helium boiling point is normal boiling point is 4.2 K ah, but we are taking this helium as if there is a refrigerator called helium refrigerator and that refrigerator is providing the refrigeration to liquefy the helium. Say this is ah for example, the ah liquid precooled liquid nitrogen system where you know this will be entirely dependent on this expansion by isenthalpic process. Here there is no ah helium refrigeration assistance or any assistance, but only thing is that it is cooled by ah it is basically if you ah compare it with your earlier lectures you will find that this is a pre-cooled Linde Hampson cycle. But if I want to use the refrigeration of helium or helium refrigeration we will ah you know remove this part say from here you know we will make a break at this two points and ah before we basically expand it we will try to have some ah you know cooling effect given by the helium refrigeration.

So, that is the refrigerator because that is the in a closed loop let us have a look into that how it works. Say here this is the helium circuit this is the helium circuit and the same liquid nitrogen precooling is used and this is what is that helium refrigeration cycle. You can see that there is no ah what is called make up gas here so that means, it is in a closed loop we at any time this is the helium is not taken out of the system it is in a closed loop in a as usual in a refrigerator. But you see this is a liquefaction because we are withdrawing some liquid with the replenishment of the hydrogen. So, this is a ah liquefier part and here this is a refrigerator and this refrigerator is helium refrigerator.

Basically, this is a helium refrigerator you can see that the helium gas is getting compressed cooled by the liquid nitrogen in the same tank you know which is cooling the hydrogen it is also cooling the ah helium and the evaporated ah gaseous nitrogen is moving out from you know this tank and cooling the ah incoming high-pressure helium as well as incoming high-pressure hydrogen. So, these are the three stream exchangers. Now this is a high-pressure helium is getting you know ah cooled by this heat exchanger then it is expanded. Now this expanded gas which is the I mean at very low temperature that cooling and will be you know ah heat will be taken from here. So, basically this will give this cooling to the high-pressure helium hydrogen gas and hydrogen gas will be cooled.

So, here comes the load of that heat exchanger. So, here we are adding heat to this refrigerator and that heat is being provided by the incoming hydrogen gas. So, it is cooling the hydrogen gas and in turn this you know helium gas is getting heated up and finally, it is going back you know to this incoming I mean the compressor suction. So, this is how the helium refrigerated hydrogen liquefaction system works. What is the advantage of this system? First of all, you see if you look at this the hydrogen ah based pre-cooled Linde Hampson cycle you might have seen that the ah hydrogen has to be compressed to a very high value or you know nearly about 50 all these examples that we have saw saw you know nearly 40 to 50 atmospheric pressure.

It has to be you know reasonably high pressure it has to be ah pressurized, but with respect to this helium refrigerated hydrogen liquefaction system you will find that this can be you know compressed to a very small value. So, the size or the sorry the size of the compressor or the piping thickness etcetera will be relatively smaller because we are operating with small you know amount of small ah pressure, but you need additional compressor of say helium compressor or you have to have the helium refrigeration system. So, that is how it is different, but we have the advantage and as well as the disadvantage also. So, this is about this helium refrigerated liquefaction and ah one can you know it is going to be attractive in terms of ah say this overall ah pressure and the overall effectiveness of this system or the FOM could be ah very high for this kind of ah refrigeration processes. So, then we come to another ah I mean these are basically as I said that these are refrigerated based system where you can see that we have as if ah reverse Brayton ah cryocooler and that cryocooler ah here this is the reverse Brayton cryocooler you can see this is a compressor the gas is being compressed maybe this gas is there as helium as the refrigerant or you know as the medium or the gas which is flowing into the circuit.

Again this is the closed loop because there is no replenishment and it is in a closed loop it is flowing in and this is where you are putting the heat load the helium gas is getting compressed it is you know being cooled here then it comes over here goes to the turbine and in the turbine it is getting expanded this expanded and cold gas will be utilized you know or it it will be absorbing heat from the system to be heated up then it will again pass through the heat exchanger and come back to the turbine ah sorry the suction side of the compressor. So, who will provide this ah heat basically it is the helium sorry hydrogen that if you want to get it cooled we can you know put it here this hydrogen say at some temperature it will be you know ah will be cooled down to a low temperature from high temperature it will be cooled to a low temperature and finally, we will have this refrigeration provided by this reverse Brayton cycle. So, if we look it at in the TS diagram you will find that this is where we have the compressed you see this is atmospheric line that is high pressure line and this is for the gaseous helium. So, helium if the helium is the refrigerant that is used here. So, from state point 1 to this ah I am sorry this is state point 2 it is here then it is coming to state point 3 and from state point 3 it is coming to state point 4 and from there it will be going to state point 5.

$$\dot{Q}_a = \dot{m}(h_5 - h_4)$$

So, this is how it ah works ah I mean the medium is basically the helium and they are in a closed loop and where is the refrigeration that we are obtaining? We are obtaining the refrigeration between T4 and T5 we have cooled it to T4 and that gas is getting heated up in the heat exchanger up to state point 5. So, this is where we are putting the heat in and Qa ah dot is the amount of heat that is going inside. So, if we want to ah find out what is this Qa ah or how much heat I mean hydrogen we can ah you know ah be cooled basically this would be say if we take a control volume around this body we can see that either it would be ah in terms of m dot h in minus m dot h out and the corresponding Cp m Cp delta T has to be taken into this part and Qa is that is going to provide you that refrigeration. So, Qa dot can be m dot into h5 minus h4 h5 is the output enthalpy and this is the enthalpy of the incoming helium. So, this is the helium and this Qa dot can be taken from the flow rate of the hydrogen gaseous hydrogen.

$$\dot{Q}_a = \dot{m}[(h_1 - h_2) + (h_3 - h_4)]$$

Now, this h5 minus h4 can also be ah you know put in terms of this 1 and 2 or I mean 3 and 4 ah basically if we do an energy balance across this heat exchanger you will find that ah h 2 minus h 3 is equals to ah h1 minus h5 because this is the high pressure ah high temperature gaseous helium which is coming in and this is moving out in the heat exchanger and this is the low pressure helium that is going in at T5 and coming out at T1 if this heat exchanger is 100 percent effective. If the effectiveness of this exchanger is different then accordingly you have also learned that this will come at 1 prime and we have also ah I mean taught you how to calculate that state point. Now, ah you can say that h2 minus h3 that is equals to ah h1 if it is 100 percent effective. So, it would be at 1 and this is coming out h5. So, if you do this and replace this h5 you will find that it would come as Qa dot equals to m dot into h1 minus h2 and h3 minus h4.

So, ah this h1 minus h2 part as you know that it would be basically give you ah I mean what is called ah contribution negative contribution as long as this temperature T1 or T2 is ah basically higher than the maximum inversion temperature and if you look at the maximum inversion temperature of helium it is ah well below the ambient temperature. So, you can expect that this would be ah negative contribution, but you can also there are very different variations of the reverse Brayton cycle. There also you can see that liquid nitrogen ah pre-cooled ah Linde I mean Brayton reverse Brayton cycles are possible. So, this is again as I told you that these are refrigeration-based system where we are taking help of additional refrigerators to cool the incoming ah I mean this hydrogen gas and this hydrogen gas can be you know coming from a compressor or all these processes that we have ah learned so far, but only thing is that we are taking help of additional refrigeration. So, this is about the reverse Brayton cycle and these are the references ah here ah you can see also you have seen additional references that we have talked about. So, thank you for your attention.