Upstream LNG Technology
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Lecture - 73
Cryogenic refrigeration and liquefaction in natural gas systems – III

Welcome. So, far we have learnt some basics about the refrigeration and the liquefaction methods using the expansion engine and the expansion valve. And we have also done some tutorial to know that how to analyse this systems based on the TS diagram and we have also found out the value of the this mu j t and mu s that is the expansion coefficient for the JT expansion and for the expansion engine. Now, we shall be seeing in this particular lecture the applications of this method for the Cryogenic refrigeration and liquefaction in the various natural gas systems.

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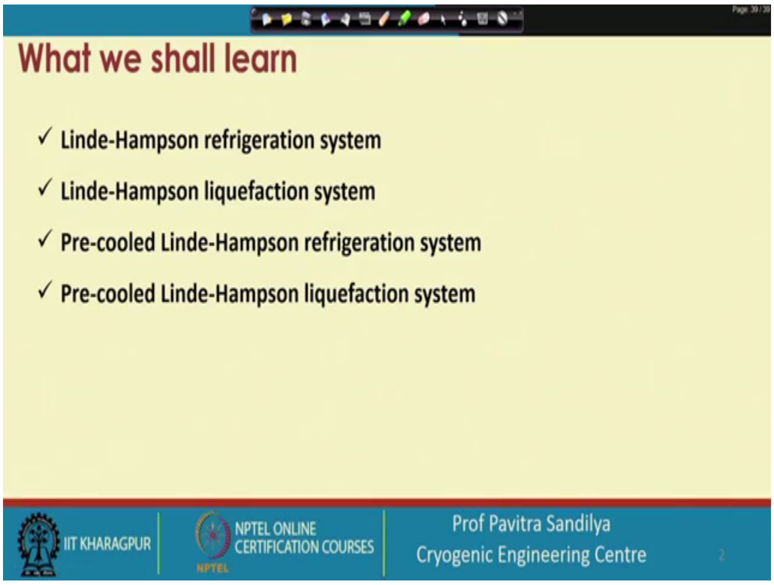

What we shall learn

- ✓ Linde-Hampson refrigeration system
- ✓ Linde-Hampson liquefaction system
- ✓ Pre-cooled Linde-Hampson refrigeration system
- ✓ Pre-cooled Linde-Hampson liquefaction system

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So, here in this particular lecture we shall be learning about these systems, Linde-Hampson refrigeration, Linde-Hampson liquefaction, pre cooled Linde-Hampson refrigeration and pre cooled Linde-Hampson liquefaction systems.

We have taken these methods in there because, we will find that the basic cycle remains the same whether we are going for liquefaction or the refrigeration. Only thing is this as we have learnt earlier that, the refrigeration is a closed cycle with a balanced flow while the liquefaction is an unbalanced flow situation and open cycle. So, only the that differs the otherwise the basic cycle remains the same.

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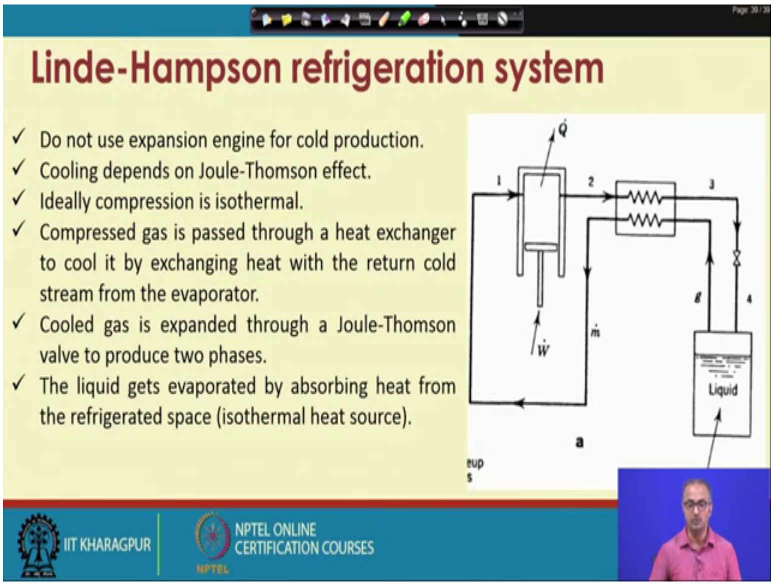

Linde-Hampson refrigeration system

- ✓ Do not use expansion engine for cold production.
- ✓ Cooling depends on Joule-Thomson effect.
- ✓ Ideally compression is isothermal.
- ✓ Compressed gas is passed through a heat exchanger to cool it by exchanging heat with the return cold stream from the evaporator.
- ✓ Cooled gas is expanded through a Joule-Thomson valve to produce two phases.
- ✓ The liquid gets evaporated by absorbing heat from the refrigerated space (isothermal heat source).

So, let us first start with the Linde-Hampson and in these series the Linde-Hampson and a pre cooled Linde-Hampson both of these use only the expansion valve for the cooling and not any other engine. So, that is why they have been grouped together. So, we see that Linde-Hampson refrigeration system, sometimes it is also called the simple Linde-Hampson refrigeration system is basically, do not use any kind of expansion engine for cold production and the cooling is obtained purely based on the Joule-Thomson effect to an expansion valve.

Generally, the compression is done ideally as a isothermal process. And as I said that whenever here we find that their compressions occurring, so as we said that, the this kind of compression needs the multi staging maybe in practice. And, be the multi staging is done we also need the intercoolers, the outer coolers etcetera to keep the temperature almost constant between the inlet and outlet of the compressor.

And in these cases for the analysis, we will be considering all the compressors and other heat exchangers etcetera to be ideal. And the once we compress the gas as we shown in the figure that this is the this 1, 2, 3, 4 etcetera they are showing the state of the particular fluid at different points. So, at this point 1, we are inputting the gas which has to be used for refrigeration and this is done compressed isothermally and here we are showing that

Q dot, this Q dot is the heat removed to keep the compression isothermal. So, this is the Q dot and once this is passing through the compressor it is going to another state 2 and at this state 2 ideally the temperature will be the same as a temperature at point 1, only difference will be the pressure will be increased.

And because the pressure has changed naturally, the other properties like the density, like the enthalpy entropy all these things will also be changing. And once this is compressed what happens, this particular thing is taken to a heat exchanger, where this is cooled. And by this cooling, we are able to extract the heat the cold from the this return string from the liquid reservoir. So, with this particular stream we are cooling it and after cooling it, we are taking it to the JT expansion valve and here we find that during this cooling the state has now changed from 2 to 3.

Now, if we consider the heat exchanger to be behaving isobarically that is there is no pressure drop within the heat exchanger then, we will find that the pressure at 0.2 and at 0.3 will be the same whereas, the temperature will be now, less at 0.3 then that a 0.2, that means t 3 will be less than t 2. Then once it has come to 3, then we take it for the expansion and here this at this particular symbol is representing the valve. So, here this is expanded and after expansion it reaches a state 4 where it is still low temperature. Now, this JT expansion causes a 2 phases to be coming. That means, this when what whatever this vapour was coming this vapour has been now converted to a 2 phase mixture with liquid and the gas.

And liquid and the gas and please understand that, to make the vapour possible we are trying to cool it down. So, that after expansion, we can get 2 phases and this state at this state at point 3 is the below the critical state otherwise, we will not be able to achieve a 2 phase mixture on expansion. Then, what we find that in this liquid space where this particular Q, this Q is coming from the space where we want refrigeration ok. That means, you can imagine that as if, the as the household refrigerator whatever heat is there in inside refrigerator, that heat is being taken away by this particular liquid.

So, this particular Q is deciding that how much Q heat needs to be extracted from the refrigerated space. So, once we are taking that quantity of heat from here and then, we find this liquid may get vaporized by taking this particular heat. Now when this liquid is getting vaporized, that means, there is a simple phase change and you know there is a phase change the temperature will not increased. That means, ideally this type of a system represents a isothermal heat source for the refrigerant ok. So, it is not that it has to be isothermal, but as we did learnt in our earlier lecture that, there can be two types of heat sources and one of them is isothermal heat source. So, this we are finding that by vaporization of the liquid we are able to ensure isothermal heat source.

Now, after this liquid is vaporized now, this vapour represented by the state g is now taken back and it is taken through this heat exchanger as I said earlier now, the exchanging the heat. And, now what is happening that this particular stream by exchanging the heat with this hotter stream is able is ideally, to attend the same temperature as the user temperature at the compressor. So, in this particular full cycle what we are assuming that, there is no temperature drop, that means, there is no heat exchange between the system and the surroundings, so that, whatever temperature is here the same temperature is also here.

And there is no temperature drop or gain within these particular lines. So, these are the assumptions and because of this all this idealities what we find that the if we do a energy balance we find that the this energy going out from the compressor would be the same as the energy taken in by this liquid. So, that is coming from the first law of thermodynamics under these or this assumptions. So, this is the a very simple manner and the simplest manner one can think of achieving refrigeration by an isothermal source.

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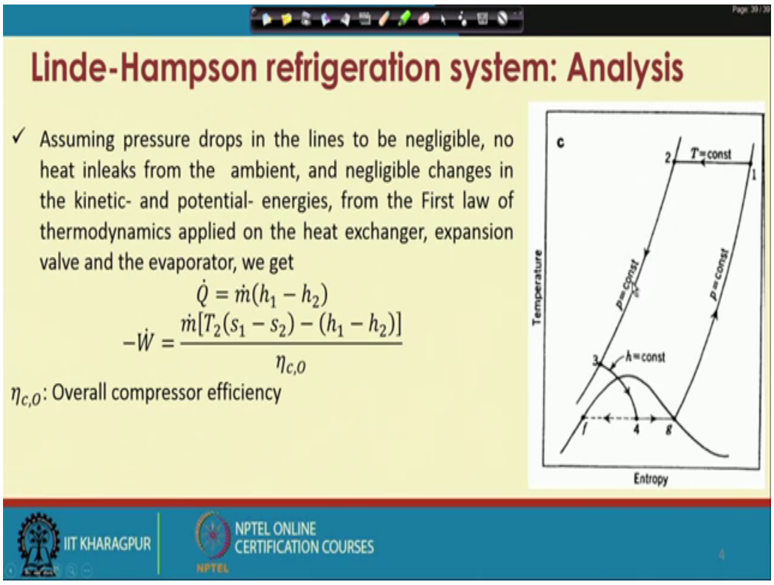

Linde-Hampson refrigeration system: Analysis

- ✓ Assuming pressure drops in the lines to be negligible, no heat inleaks from the ambient, and negligible changes in the kinetic- and potential- energies, from the First law of thermodynamics applied on the heat exchanger, expansion valve and the evaporator, we get

$$\dot{Q} = \dot{m}(h_1 - h_2)$$

$$-\dot{W} = \frac{\dot{m}[T_2(s_1 - s_2) - (h_1 - h_2)]}{\eta_{c,0}}$$

$\eta_{c,0}$: Overall compressor efficiency

Now, if we want to represent this kind of a system on a thermodynamic diagram and among the thermodynamic diagrams, you know that we can represent in various may ways one can be the PV diagram, that is pressure volume diagram. And, one can be the P h diagram that is a pressure enthalpy diagram.

And another very popular is the TS diagram, which is shown here that in this TS diagram, what we see that from point 1 to 2 and this temperature axis and this is entropy axis. So, we just ideally move horizontally and then, we reach a pressure and this is this pressure at this point is lower than, the pressure at this point as we have learnt are earlier in our tutorial how the pressure lines are there on the TS diagram. So, we find the pressure is increased isothermally 2.2 and then what happens that we have assumed that there is no pressure drop inside the pipelines and because of this now the another fluid is entering the heat exchanger and at constant pressure it is getting cooled.

And once it has cooled, it has reached point 3. And this point 3 may be adjusted somewhere that can be point of optimization, but somewhere we put the 3, so that from point 3 if we expand the gas isenthalpically and this particular curve is showing the isenthalpic line or the line where the enthalpy remains constant. So, from point 3 where isenthelpically expanding the gas and we are reaching at some point where the pressure is same as the initial pressure. And that is a reason you can see now that why we need to pressurize the particular gas to a higher pressure; so for that we can on expansion we can achieve almost the same pressure as the initial pressure or the inlet pressure to the compressor.

Here one should be careful about is this in practice generally, the this pressure should be more than the pressure here because, to take care of any of the pressure drops during the travel. So, this pressure ideally will be same as the inlet pressure of compressor, but in practice this will not be so. Now, once it has gone into this and this particular dome represents as, we learnt earlier the 2 phase zone. That means, within this dome we have 2 phases vapour and liquid coexisting. So, once this particular gas has been isenthalpically expanded now we get two phases, one is the gaseous phase another liquid phase.

Now, the we assume that the gas and liquid are at their saturated condition. So, that this gas will be on this particular curve that is the saturated vapour curve, where the liquid will be on the this curve that is the saturated liquid curve. So, this is liquid and this is a gas and this liquid will be now getting vaporized and once it will vaporized isothermally again it will tend to move towards the right. So, all these things are not to be shown on the ts diagram because, this phase diagram is just showing the change of the phases, it is not showing the amount. The amount is not shown on the phase diagram, but we have to understand that this liquid will undergo the phase change and it will again move towards right.

Now, once this particular vapour is obtained now, this saturated vapour is now being taken back to the inlet of the compressor and during this taking back as I said that ideally we assume that, there is no pressure drop in the pipelines. So, that the pressure remains constant whereas, this particular vapour gets heated up in contact with the hotter fluid which is coming from point 2 to point 3 and then, it is the temperature is ideally raised to the inlet temperature of the compressor. And this is how we are able to complete a simple Linde-Hampson refrigeration system. Now if we apply the first law of thermodynamics, to find out how much heat needs to be taken out from the compressor or has to be given to the evaporator and the work done.

We can easily find under this assumptions right the negligible pressure drop in the pipelines as, 0 heat in leak between from the ambient and we are neglecting any changes in the kinetic and potential energies then, we find this is the expression for the heat exchange across the whatever heat needs to be given out from the compressor and this is the amount of work to be done by the on the by the compressor and this compressor in this, we have also put the overall compressor efficiency. So, this particular these two expressions may be used to find out the work done for the overall system because, in the overall system the work is done only at the compressor and as we learnt earlier, the expansion valve does not involve any kind of external work.

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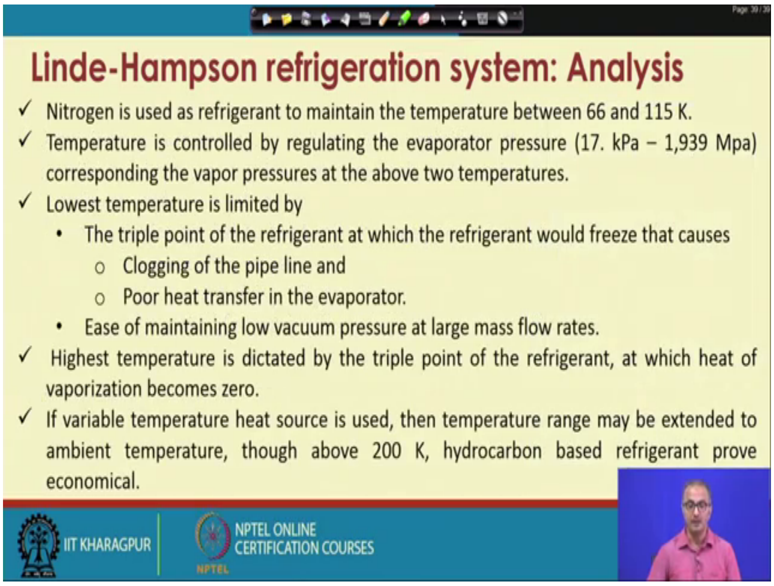

Linde-Hampson refrigeration system: Analysis

- ✓ Nitrogen is used as refrigerant to maintain the temperature between 66 and 115 K.
- ✓ Temperature is controlled by regulating the evaporator pressure (17. kPa – 1,939 Mpa) corresponding the vapor pressures at the above two temperatures.
- ✓ Lowest temperature is limited by
  - The triple point of the refrigerant at which the refrigerant would freeze that causes
    - Clogging of the pipe line and
    - Poor heat transfer in the evaporator.
  - Ease of maintaining low vacuum pressure at large mass flow rates.
- ✓ Highest temperature is dictated by the triple point of the refrigerant, at which heat of vaporization becomes zero.
- ✓ If variable temperature heat source is used, then temperature range may be extended to ambient temperature, though above 200 K, hydrocarbon based refrigerant prove economical.

Now, there are some points to be noted that in the Linde-Hampson nitrogen is used as refrigerant, if we want the temperature to be between 66 and 115 K. And if we want this kind of temperature to be varied then, what we need we need to change the pressure because, as we know that the with the change in the pressure the saturated temperature changes. So, if we can maintain the saturated pressure with respect to the temperature corresponding to this in within this range then, we can obtain the various types of temperatures. And it is found that, for the 66 K this is the vapour pressure of nitrogen and for 115 K this is the vapour pressure of nitrogen.

And as you can see from here that, at 66 K the vapour pressure is much lower than the ambient pressure that is about 101 kilo Pascal. So, we find that we need to maintain vacuum to achieve certain low temperature using nitrogen. And that is why we find that lowest temperature is limited by first is a triple point of the refrigerant at which the refrigerator to freeze that we know that at triple point in a substance would solidified. And then, we fill solidified what happens there could be the clogging of the pipeline the it will settle in the pipeline it will it will cause clogging and also during this when the settle they will put up some resistance to the heat transfer ok.

So, that is why we need to avoid any kind of triple point approach. And next is this if we talk of which very low temperature then, we need to maintain a very low vacuum pressure and this maintenance of the vacuum becomes a challenge especially at higher flow rates of the refrigerant. So, these are the generally the two limitations to attend the low temperatures by any kind of refrigerant. And then, the highest temperature is detected by the triple point why, because as I told you that we cannot liquefy a gas above triple point. So, we cannot move beyond triple point we should always have to stay within the triple point of the particular fluid.

And then there will be a as I said that we are using isothermal temperature source, but there could be a variable temperatures heat source also and then if you do that then perhaps we can increase the range of our the refrigeration temperature. But in this if you are using nitrogen generally it is 200 K is taken to be the limit and if you want higher temperature than 200 K then, we are use we are using other kinds of refrigerants which are based on the hydrocarbons like Freon's and perhaps, you know that in that also we have some issues on the on the achievement of that environmental issues etcetera in using the other this kind of Freon's.

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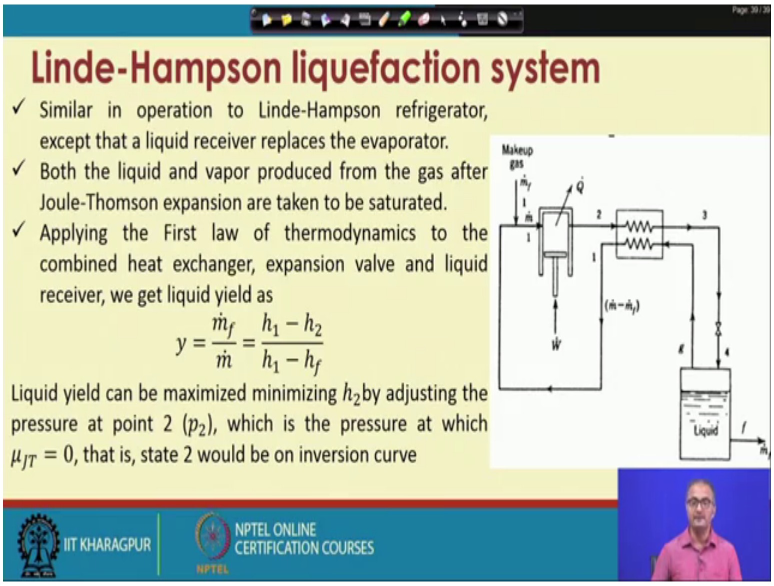

Linde-Hampson liquefaction system

- ✓ Similar in operation to Linde-Hampson refrigerator, except that a liquid receiver replaces the evaporator.
- ✓ Both the liquid and vapor produced from the gas after Joule-Thomson expansion are taken to be saturated.
- ✓ Applying the First law of thermodynamics to the combined heat exchanger, expansion valve and liquid receiver, we get liquid yield as

$$y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f}$$

Liquid yield can be maximized minimizing $h_2$by adjusting the pressure at point 2 (p_2), which is the pressure at which $\mu_{JT} = 0$, that is, state 2 would be on inversion curve

Now, we come to the Linde-Hampson liquefaction system. And as I told you the basic method remains the same and here if you see this in this particular again here we are compressing the gas isothermally and we are ejecting the heat to keep it isothermal. So, the point 1 and point 2 these are the same temperature and then, from point 2 to point 3 it is a iso body cooling. So, that there is no change in the pressure, but the temperature is brought down and then we are taking if the JT valve and JT valve we are getting the 2 phases, the liquid phase and the vapour phase. Again here we are assuming the liquid and vapour are saturated and this particular liquid is now taken out from the system.

And because we are taking out the some amount of liquid to the system, which is given by this m dot f as the flow rate, so that means, same amount has to be again given inside the system as makeup gas; otherwise, with time if we do not put makeup gas what will happen with time we shall be losing the material from the system ok. So, this is the difference between the refrigeration and the liquefaction and that is how if the becomes an open system. So, I will not going to till now, is as same as those are the Linde-Hampson refrigeration this vapour is taken, it is now getting then heated up by this incoming gas and the temperature ideally is attained is the same temperature as the inlet temperature to the compressor.

And that is how, this is done the work requirement and this amount of heat rejected remain the same as per as the total mass is concerned and here only thing that we are having another parameter that is the liquid yield. This is another parameter which comes into picture whenever we talk of the liquefaction systems. So, this liquid yield will be calculated if you are applying the, if you apply the first law of thermodynamics, we find this is how we find the liquid yield and it is it depends on the temperatures, across the compressor and also the temperature within this liquid reservoir.

And we find that this week this h 1 and h f they are generally, detected by the ambient because, we are taking the things from the ambient and all we also putting it back to the ambient. So, we cannot do much about h 1 and h f. But what we can play with is h 2 which will so, that we can change the liquid yield. And from this particular equation we see that, if we decrease the h 2, then we shall be able to increase the liquid yield. So, that is what we are saying the to maximize the liquid yield, we have to minimise the h 2 value and if we want to minimise it we should raise the pressure.

And what we find that, by why when we adjusting the pressure at point 2 that is at this point and we find that and we find that, this pressure at the max can go to the inversion pressure. So, that is how that is the limit that we can take it to the at the inversion pressure because, after if you go beyond that pressure we can means if you increase the pressure still further beyond the inversion pressure then, we shall be getting heating up if it is not getting cooling down. So, that is the limited inversion process limit to, so that we can maximize our liquid yield.

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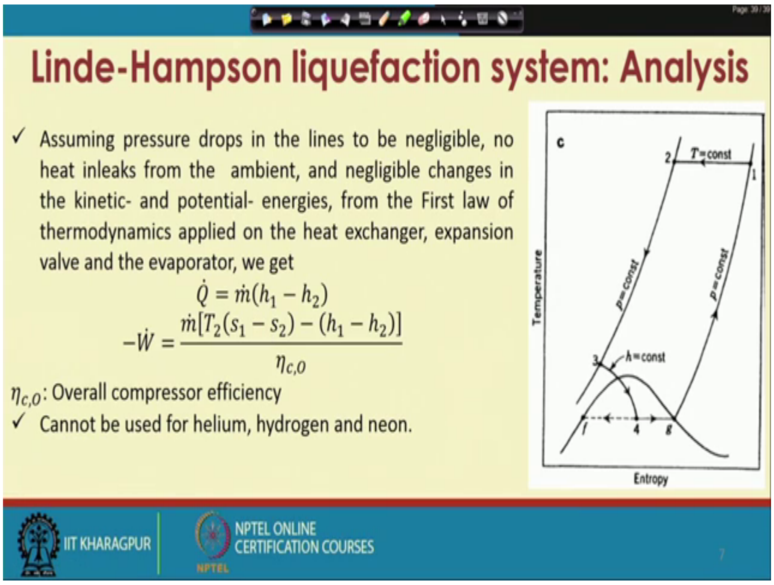

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$\eta_{c,0}$: Overall compressor efficiency

- ✓ Cannot be used for helium, hydrogen and neon.

So, this is how we are taking and here I am shown the work and the this energy transferred and they remain the same as per as the symbol Linde-Hampson's liquefication system. And one more thing is this we cannot use this kind of system for helium hydrogen and neon why because; these three gases have their inversion temperature much below the ambient. So, this is what we learnt earlier. So, this is not applicable why for these 3 gases. Further detail about this can be found out from these two books is Barron and Timmerhaus.

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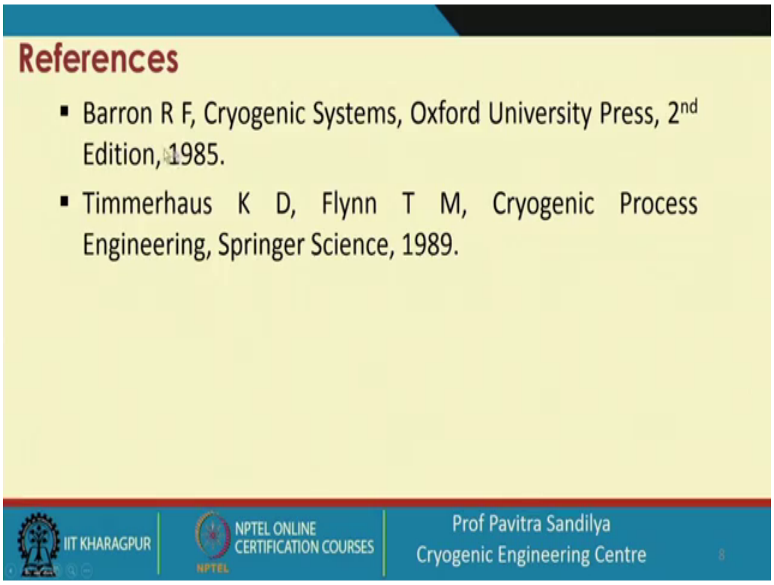

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Thank you.