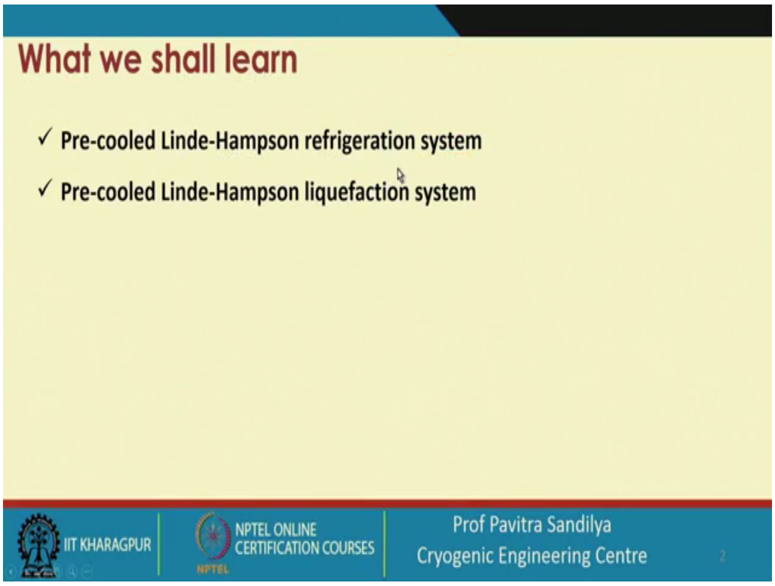
Upstream LNG Technology
Prof. Pavitra Sandilya
Department of Cryogenic Engineering Centre
Indian Institute of Technology, Kharagpur

Lecture - 74
Cryogenic refrigeration and liquefaction in natural gas systems – IV

Welcome, before this we have learned about the various types of cooling techniques and based on the expansion valve and the expansion engine. And then we moved onto the applications of these techniques to the simple Linde refrigeration and liquefaction cycle, based on the Linde-Hampson method. Now, as I told you last time that those have some restrictions that is that the liquefaction cannot be used for the hydrogen, helium, neon, etcetera.

And there are some other restrictions based on the liquid yield, so to improve upon the system performance. Another modification has been done on this simple Linde-Hampson, and those things we are going to learn in this particular lecture.

(Refer Slide Time: 01:09)

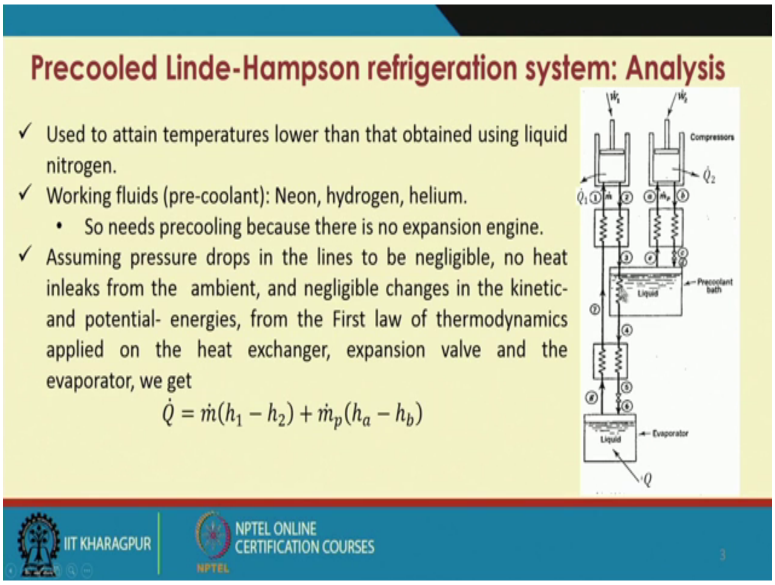


What we shall learn

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

So, in this lecture, we shall be learning about the pre-cooled Linde-Hampson refrigeration system, and pre-cooled Linde-Hampson liquefaction system.

(Refer Slide Time: 01:18)



Precooled Linde-Hampson refrigeration system: Analysis

- ✓ Used to attain temperatures lower than that obtained using liquid nitrogen.
- ✓ Working fluids (pre-coolant): Neon, hydrogen, helium.
  - So needs precooling because there is no expansion engine.
- ✓ 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

$$\dot{Q} = \dot{m}(h_1 - h_2) + \dot{m}_p(h_a - h_b)$$

So, first let us see the pre-cooled Linde-Hampson refrigeration. Now, in this thing we find that as I told you that this is the modification done to the simple Linde-Hampson, in order to achieve a lower temperature then what we can achieve using the liquid nitrogen. And here the generally the working fluids or the working are neon, hydrogen and helium which are what we call the pre-coolant that means, pre-cooling the particular actual process fluid.

And this pre-cooling is done why, because we are not using any expansion engine, have been using expansion engine then we would not have needed this kind of pre-cooling. Now, if we assume that the pressure drops are negligible in all these things, we can also achieve an ideal cycle. Now, first let us understand this cycle, here we have you see there are two systems here; one is the main system and other is the pre-cooling system.

So, first let us look at the main system. In this main system again we have a compressor, and this compressor we are doing some work W 1, and then from this compressor this is particular gas which is going inside the compressor, and this gas is compressed ideally we are doing it isothermally, so that we are rejecting some amount of heat Q 1. And then this is coming into the system, and from point 2 to 3 it is exchanging the heat to get cooled down, and this is done from the return stream from the liquid reservoir, and then it is getting cooled down.

Now, what we are doing that here, we are applying the further cooling. So, here this particular cooling is being done by another system, this system looks the same as the simple Linde-Hampson. Now, only thing is this; this gas is passing through this liquid reservoir for this auxiliary system. So, we will come to this later.

First, let us see that it is further cooled; and then after this again it is taken to another heat exchanger for still more cooling and that is why we are finding that from point 2 upto this thing up to the expansion valve, there is series of cooling being done ultimately taking it to the expansion valve, where it is being expanded isenthalpically and so that we are getting a two phase mixture that is a liquid and a the gas.

Now, we find this is evaporator; and this evaporator is taking the heat from the refrigerated space to get the phase change from the liquid and again as we learnt earlier this kind of a heat source is can be called as isothermal heat source. Now, once the vapour is generated it is taken back into the system, again is going through the heat exchanger to get heater heated up by the incoming gas and it is.

Now this particular thing is not going through this, but these particulars auxiliary thing, because here we are not trying to cool it down; because so we want to heat it up, so we are not taking this stream into this evaporator, it is going out and is going to the another heat exchanger and to get still further heated up by the incoming stream. And ultimately it reaches the state 1 ideally, where could we see that it is attaining the same temperature as the inlet temperature of the compressor. So, this is the main circuit for the refrigeration.

Now, the as I said we are using an auxiliary circuit and here we have the same simple Linde-Hampson some kind, here also we are using the pre-coolant. And that is now the pre-coolant is undergoing, the same process that it is (Refer Time: 05:18) compression. And here we have shown, some work W 2 is being used, and this is getting compressed, and here we are rejecting some amount of heat Q 2.

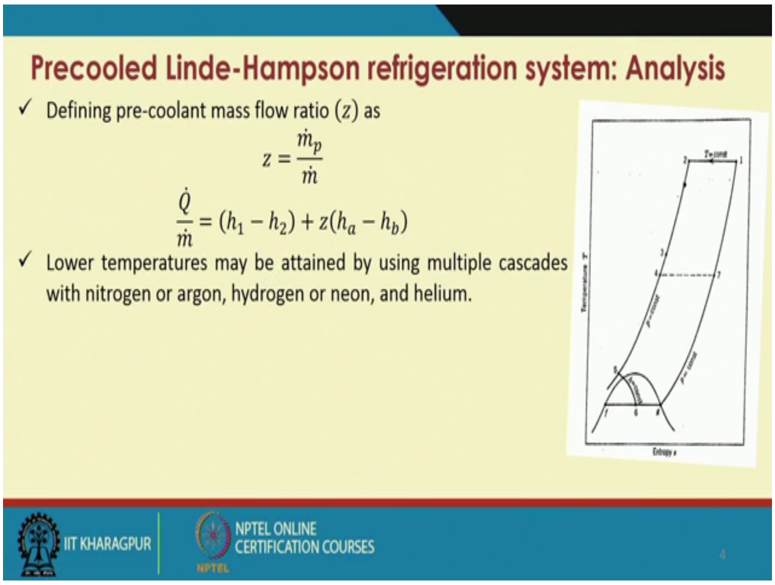
And then it is, here it is going to a state b; and state a is the inlet state, the state b is the outlet state of the compressor and we have to remember that t a is equal to t b whereas, the pressure at a is less than the pressure at b. Now, after compression it goes to the cooler and again here in this the cooling is being done from the return stream from the evaporator.

And there is a isenthalpic valve, again the state exchanging from state c to state b where the pressure is reducing, and temperature is also reducing so that we are getting a two phase mixture. And the two phase mixture there this mixture is taking the heat from the main line, and then the vapour is generated and it is going back to the compressor through the through the heat exchanger, to attain the same temperature as inlet temperature of the compressor.

So, we are finding that we are now using an auxiliary system to get them pre-cooling. And we will find that if we apply the first law of thermodynamics, assuming that there is negligible change in the kinetic and potential energies. And we assume that there is no change in the pressure during this flow; so with these assumptions and there is no heat leakage from the ambient. From that these assumptions, we can find out from the applying first law of thermodynamics, the expression for the Q.

And this Q, these are Q here; and this Q is dependent also, you see that first term is same as the one we have got in the simple Linde-Hampson. Although, these are thing additional is this term and in this term this particular m p dot it represents the flow rate of the pre-coolant. So, this is how in this h a and h b are the enthalpies at this point a and point b. So, we find this is the only additional term which is coming for the pre-cooling.

(Refer Slide Time: 07:27)



Precooled Linde-Hampson refrigeration system: Analysis

- ✓ Defining pre-coolant mass flow ratio (z) as

$$z = \frac{\dot{m}_p}{\dot{m}}$$

$$\frac{\dot{Q}}{\dot{m}} = (h_1 - h_2) + z(h_a - h_b)$$

- ✓ Lower temperatures may be attained by using multiple cascades with nitrogen or argon, hydrogen or neon, and helium.

And here, we cited rearrange the equation, and we put that we define another term what we call the pre-coolant mass flow ratio; and that is the ratio of the pre-coolant mass flow rate to the total mass flow rate in the main system. So, we put the Q by m that is the heat removed per unit mass of the actual fluid process fluid as this particular term and we respect to z. And we see that if we want to achieve lower and lower temperature, we can use multiple cascades that means, we have not only one auxiliary system, we can use another auxiliary system to still get further cooling.

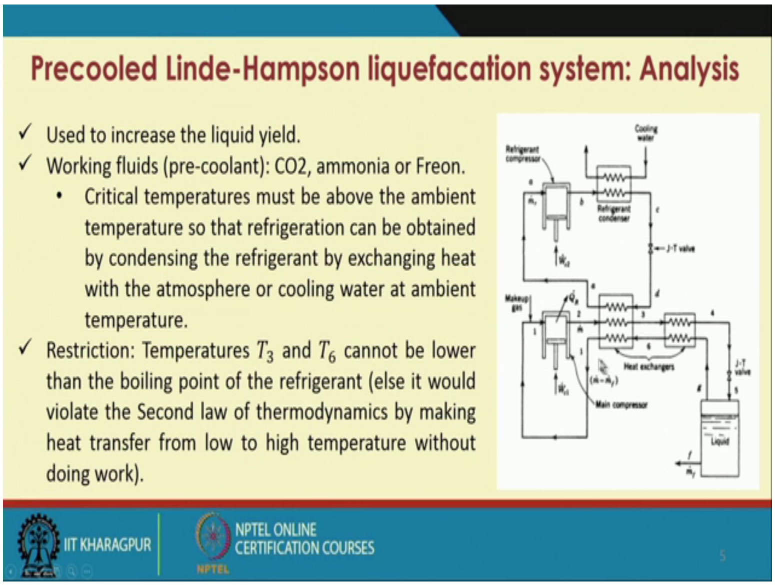
Now, if I want to represent this whole process on this T s diagram, what we shall see? The basic system remains almost similar to the simple Linde-Hampson. We find that the if you look at overall system, it goes undergoes an isothermal pressurization, and there is a isobaric cooling and to some point, and there is a isenthalpic expansion that causes the two phase formation. And the it is goes to the original temperature at the inlet temperature of the particular compressor and then it is again heated back to the inlet condition of the compressor.

Only difference from the simple Linde-Hampson is this in between we are doing some and of pre-cooling this point 3, 4 and 7. If you go back to this thing, we find this point 3, 4 is giving the further cooling and because there is isobaric. So, it is lying on the same isobaric line. And this point 7 is the point, where we are finding that it is getting again heated up. So, we find that in this is isobaric also and this pressure is taken to be the pressure as the same as the inlet pressure of the compressor; so that is why, this point 7 is lying on this inlet pressure, and this point 4 and 3 are lying on this particular exit pressure of the compressor.

And here we are finding that this point 4 and 7 are almost having the same temperature that is we find that this temperature, and this temperature; that means, totally balanced heat exchange is occurring, so that this temperature and this temperature ideally are the same; so that is why we are finding that this 4 and 7 are ideally at the same temperature. So, this is this the only modifications by introducing these point 3, 4 and 7 to the simple Linde-Hampson system to get the T s representation of the pre-cooled Linde-Hampson refrigeration system.

And we can attain lower temperature by using multiple cascades. And those cascades maybe, we can use one auxiliary system with nitrogen or argon; then second one we can use hydrogen or neon; and the third one can be helium. So, we can see that we can extend it up to 3 stages, we are starting from nitrogen or the argon; then I can add hydrogen or neon and that will be helium, so that is the how we can go up to these 3 stages for the pre-cooled refrigeration system.

(Refer Slide Time: 10:57)



Precooled Linde-Hampson liquefaction system: Analysis

- ✓ Used to increase the liquid yield.
- ✓ Working fluids (pre-coolant): CO2, ammonia or Freon.
  - Critical temperatures must be above the ambient temperature so that refrigeration can be obtained by condensing the refrigerant by exchanging heat with the atmosphere or cooling water at ambient temperature.
- ✓ Restriction: Temperatures T_3 and T_6 cannot be lower than the boiling point of the refrigerant (else it would violate the Second law of thermodynamics by making heat transfer from low to high temperature without doing work).

Now, we go to the pre-cooled Linde-Hampson liquefaction. And again we will find the basic system, remains the same as that for the pre-cooled refrigeration. So, here first we see that why do we need it, we are needing it; because we want to increase the liquid yield, because in liquefaction we are concerned about the yield, in the refrigeration we are concerned about the cooling. So, we want to increase the yield, beyond what we got in the simples Linde-Hampson system. And here, we are not working with any of the cryogens, though here the working fluids or the pre-coolants are something like the carbon dioxide, ammonia or some Freon.

And in this also we have to figure out see that the critical temperatures must be above the ambient temperature, as I told earlier, because if it is not so then we will not be able to get the phase change. So, the critical temperatures must be above the ambient temperature, so that the refrigeration can be obtained by condensing the refrigerant by exchanging heat with the atmosphere or cooling water at ambient temperature. So, we want to minimize the utilization of any other external source of cooling. So, we want to utilize on the ambient air the ambient water and so that for that we want to make sure that the critical temperature is above the ambient temperature.

Now, first let us understand this whole process. Again we see that as per the pre-cooled Linde-Hampson refrigeration here also we find that this is the main circuit. In this main circuit what is happening? The gas is going in the compressor, it is compressed isothermally and so that we are rejecting some amount of heat here. And then this is going into the heat exchanger, and then it is getting cooled down, and it is getting further cooled on another heat exchanger before it is going to the JT valve.

And here we are getting the two phase system, this is a liquid reservoir from which we are withdrawing some amount of the liquid, and the vapour which is formed, it is going back to the circuit, and going passing through these two heat exchangers. It is exchanging heat with this incoming gas and it is getting heated up and this and then it is going to the another heat exchanger is getting further heated up and ultimately it is going into the inlet of the compressor.

Now, here we can seen that here typically it is shown that instead of a two-channel heat exchanger, we are using a three-channel heat exchanger. And this third stream in this three-channel heat exchanger is coming from the auxiliary refrigerant system. So, here we are using this refrigerant system which is again based on a simple Linde-Hampson system.

And what is happening here, we are using these refrigerant and this refrigerant is helping to cool this particular process stream further. And here it is going through this cycle and as I was telling you that here we are trying to use the cooling water or from the ambient, or the ambient air to cool down this refrigerant. So, in this we are not trying to reduce our cost of refrigeration.

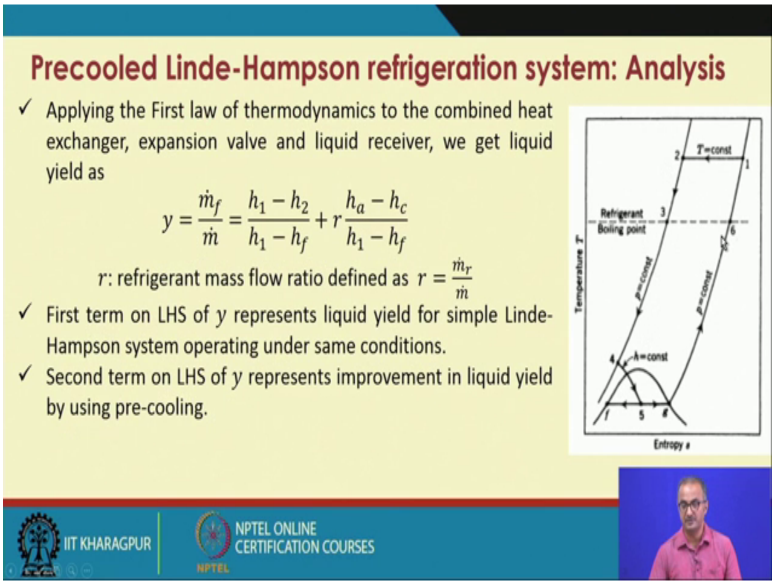
And here again we have the JT valve, and we are getting this cooling and please understand this, these cooling may be that you can imagine that this particular thing is representing a and the liquid reservoir. So, the here we are showing by the three-channel heat exchanger.

Now, here we find that again we are doing some work in the auxiliary system. And one more thing to be noted is this that because this some amount of liquid is withdrawn and that is about m dot f. So, the resultant fluid rate, mass flow rate in the vapour will be total flow rate that is m dot and minus m f, so that is that much flow rate is coming; so here we find that the mass flow rate is m dot minus m f dot. And this m f dot, will be have to be supplied by putting this make up gas, so that is how we are running this pre-cooled Linde-Hampson liquefaction system.

Now, there are some restrictions, the restriction is this the temperatures at point 3 and 6 that is point 3 is this point, and point 6 this point. Now, ideally this point 3 and 6 are almost the same ideally. Now, these two temperatures cannot be lower than the boiling point of refrigerant that is the refrigerants coming on here.

So, naturally you can see that they can be lowered, because if they become lower, then there will be a reverse heat exchange means that means, as if the heat is going from a lower temperature to the higher temperature, and that is not possible from second law of thermodynamics says it is not possible to transfer the heat from the lower to higher temperature without any external work done. And since here, we are not doing any kind of work on the system, so we must ensure that the this temperature 3 and 6 cannot go below the temperature at the point d. So, then there will not be any kind of evaporation of this pre-coolant, so that is the restriction on this particular system.

(Refer Slide Time: 16:27)



Precooled Linde-Hampson refrigeration system: Analysis

- ✓ Applying the First law of thermodynamics to the combined heat exchanger, expansion valve and liquid receiver, we get liquid yield as

$$y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f} + r\frac{h_a - h_c}{h_1 - h_f}$$

r: refrigerant mass flow ratio defined as $r = \frac{\dot{m}_r}{\dot{m}}$

- ✓ First term on LHS of y represents liquid yield for simple Linde-Hampson system operating under same conditions.
- ✓ Second term on LHS of y represents improvement in liquid yield by using pre-cooling.

And we can represent it on the T s diagram. It is again similar to the one we have just studied for the refrigeration system using the pre-cooled Linde-Hampson. Again this is the main circuit that the main valve 1, it is going to 1 to 2 and then it is going to point 3, and the point 3 and point 6 are ideally balanced, so that they have the same temperature, and as we say that at the limit that it can attain the refrigerant and boiling temperature point, there is a the limit.

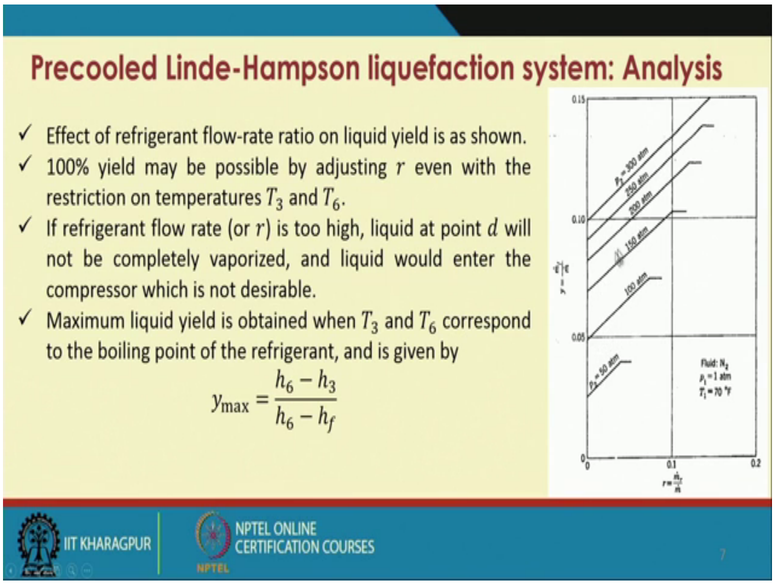
And then it goes to the further cooling, and it is getting cooled and then isenthalpically it is going to expanded in the expansion valve, we are getting liquid and getting vapour, the vapour is sent back to the compressor through the heat exchanger, and to the inlet condition of the compressor. So, this is how we are carrying out the liquefaction in a pre-cooled Linde-Hampson system.

Here the other things we have this work done and the heat rejected will be the same, only additional thing will be in this case will be the liquid yield. And in this case we find this is the expression, if we apply the first law of thermodynamics to the system we can see that this will be the expression for the yield. And here if you look at, you find that the first term; the first term is same as the one which you are finding in the simple Linde-Hampson.

The additional thing is this particular term, and in this term we have some r which is the refrigerant mass flow ratio, it is similar to the pre-coolant mass flow ratio in the pre-cooled Linde-Hampson refrigeration. So, here we are getting this, sorry this will be a liquefaction system, then correction. So, we find this ratio if we see, then this ratio is also determining the liquid that we if we increase this ratio that means, if I increase the m the flow rate of this m r in the secondary circuit is a auxiliary circuit we can increase the liquid yield.

So, there is we need not play with the temperatures as we found that in the simple Linde-Hampson there is a restriction on the temperature to be attained, but here we can play with the this r to increase the liquid yield. And so much so that it can also, move towards 100 percent liquid yield. The 100 percent is so all of the incoming gas is liquefied fully.

(Refer Slide Time: 18:55)



Precooled Linde-Hampson liquefaction system: Analysis

- ✓ Effect of refrigerant flow-rate ratio on liquid yield is as shown.
- ✓ 100% yield may be possible by adjusting r even with the restriction on temperatures T_3 and T_6.
- ✓ If refrigerant flow rate (or r) is too high, liquid at point d will not be completely vaporized, and liquid would enter the compressor which is not desirable.
- ✓ Maximum liquid yield is obtained when T_3 and T_6 correspond to the boiling point of the refrigerant, and is given by

$$y_{\max} = \frac{h_6 - h_3}{h_6 - h_f}$$

IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

Now, we find that when we see these thing that here we find if we plot the yield versus this r, and for different pressures we find that the with the increase in the r, we find that yield is increasing.

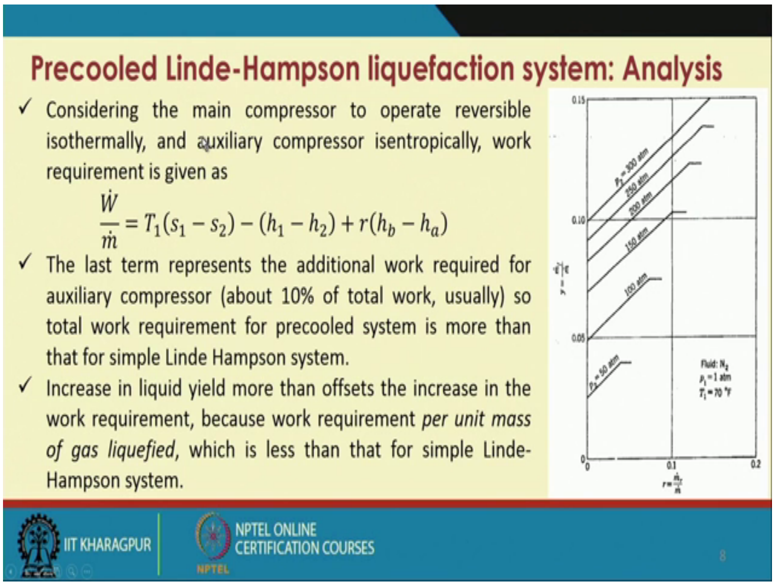
So, and this is given for the nitrogen at 1 atmosphere and 70 degree Fahrenheit. So, this is this particular plot shows that how the liquid yield is affected by the refrigerant mass flow ratio; so that is how we find that as I told you the restrictions on the temperatures at point 3 and 6 that is they cannot be below the boiling point of the refrigerant. So that can be overcome by increasing the r, but there is also a restriction on how much flow rate can be increased for the pre-coolant.

And we find that if we increase the flow rate of the pre-coolant, what will find that there the it will not get enough time to get vaporized that means, at point d if you look at this point at point d, we will not be able to get the full vaporization of the refrigerant. And if there is not a full reflection what will happen, at this point a we will find that people get a two phase mixture.

And two phase mixture means, some of the liquid will also be going out from this thing; and if some liquid goes out, that is not desirable for the compressors, because compressors have generally are having those blades. So, we do not want to use any kind of liquid in the compressor. So, we cannot indefinitely increase the refrigerant flow rate in this circuit, to increase the liquid yield. So, this is the restriction that why we cannot go for high amount of refrigerant flow.

And so we find the maximum yield that is possible will be given by this particular thing, that h 6 minus h 3 by h 6 that means, this is the thing we can find from here that these two things, these two temperatures are determining that how much will be the maximum yield we can get from this particular system.

(Refer Slide Time: 21:09)



Precooled Linde-Hampson liquefaction system: Analysis

- ✓ Considering the main compressor to operate reversible isothermally, and auxiliary compressor isentropically, work requirement is given as

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

- ✓ The last term represents the additional work required for auxiliary compressor (about 10% of total work, usually) so total work requirement for precooled system is more than that for simple Linde Hampson system.
- ✓ Increase in liquid yield more than offsets the increase in the work requirement, because work requirement *per unit mass of gas liquefied*, which is less than that for simple Linde-Hampson system.

IIT KHARAGPUR
NPTEL ONLINE CERTIFICATION COURSES

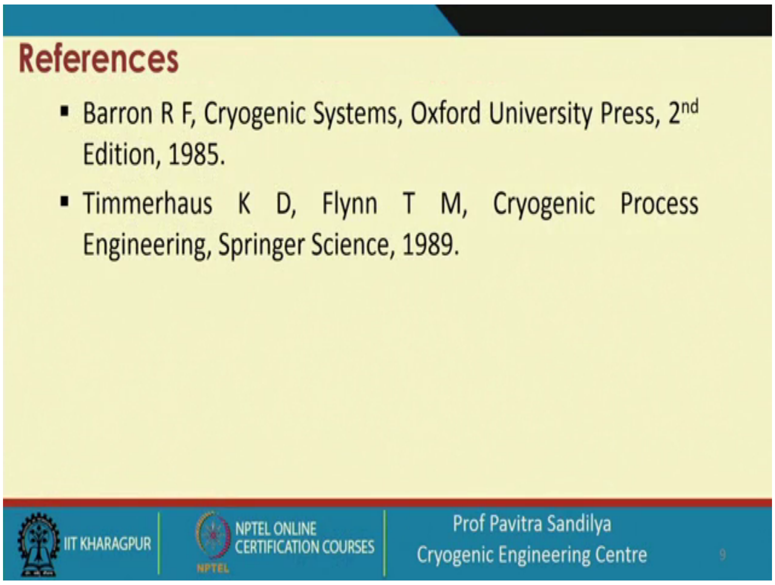
And if we consider the work, this is the work requirement here and we will find that in this case the work requirement is found from two things that first that we are saying the main compressor is compressing it isothermally whereas, the auxiliary compressor is doing it isentropically. So, these are the things so, in this case we find that this particular term if you look at these two terms, these are the same as in case of the simple Linde-Hampson only additional term is coming, through this one.

Now, we find that if I look at the total work done per unit mass of the gas flowing through the system, it is getting increased. Now if it is increased on the one hand, we are increasing the liquid yield on the other hand we are also getting it at the penalty of the work. So, question comes is it worthwhile then to use the pre-cooled system, the answer has to be looked into by seeing that how much increase in the work done is obtained and at the how much increase in the liquid yield is obtained.

Generally it is found, this additional work is only about 10 percent of the total work that is not very high increase in the work requirement. On the other hand, the liquid yield increased so much that it offsets the increase in the work requirement, and if somebody calculates the work requirement per unit mass of the gas liquefied.

In that case it is found that is instead of m we are putting m f; so if you put m f, we will find that in this case we find the work requirement becomes less for the pre-cooled system than for the simple system. So, this also justifies the use of the pre-cooled system at the increase of some increase in the work done, but at the same time much more increase in the yield of the liquid.

(Refer Slide Time: 23:12)



References

- Barron R F, Cryogenic Systems, Oxford University Press, 2nd Edition, 1985.
- Timmerhaus K D, Flynn T M, Cryogenic Process Engineering, Springer Science, 1989.

So, these are the books you can refer to for further details on these two systems.

Thank you.