Upstream LNG Technology
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Lecture – 75
Cryogenic refrigeration and liquefaction in natural gas systems - V

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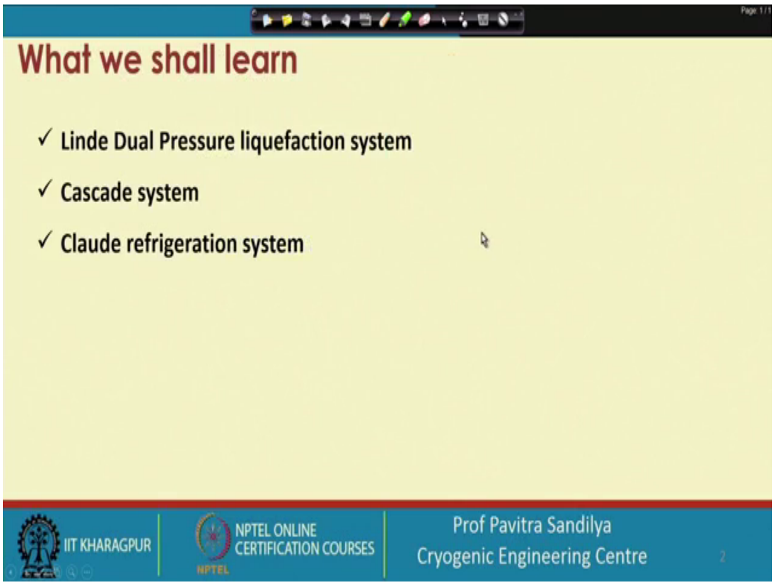

What we shall learn

- ✓ Linde Dual Pressure liquefaction system
- ✓ Cascade system
- ✓ Claude refrigeration system

Welcome. In continuation to our earlier lectures on the refrigeration and liquefaction systems, which are relevant to the processing of the natural gas, here we learn something more. So, in this particular lecture, we shall be learning about some other techniques for liquefaction and refrigeration that is one is Linde dual pressure liquefaction system, then cascade system, and Claude refrigeration system.

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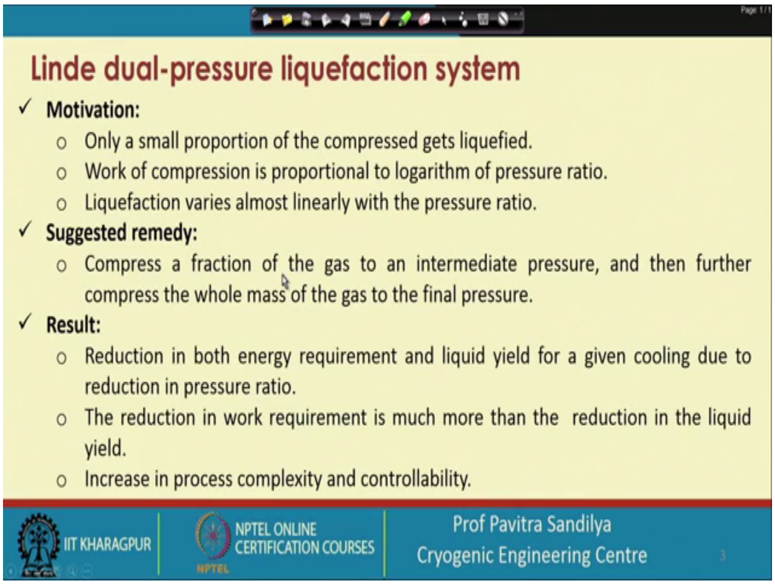

Linde dual-pressure liquefaction system

- ✓ **Motivation:**
  - o Only a small proportion of the compressed gets liquefied.
  - o Work of compression is proportional to logarithm of pressure ratio.
  - o Liquefaction varies almost linearly with the pressure ratio.
- ✓ **Suggested remedy:**
  - o Compress a fraction of the gas to an intermediate pressure, and then further compress the whole mass of the gas to the final pressure.
- ✓ **Result:**
  - o Reduction in both energy requirement and liquid yield for a given cooling due to reduction in pressure ratio.
  - o The reduction in work requirement is much more than the reduction in the liquid yield.
  - o Increase in process complexity and controllability.

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Now, first let us come to the Linde dual-pressure liquefaction system. Now, let us see; what is the motivation of the dual-pressure of liquefaction. The motivation is this that it has been found that in the Linde liquefaction system that whatever the amount of the gas is being compressed, only a small fraction of that gas is liquefied. So, naturally which are investing quite an amount of work for the compression of the total gas without a able to get as much amount of liquid from the gas.

So, what is happening that the which is found that the work of compression is proportional to the logarithm of the pressure ratio. For example, you might have remember that if it is the ideal gas, then the work of compression comes to R T into log of the compression ratio, so that is how we see that the work of compression is proportional to about the log of the compression ratio.

On the other hand, liquefaction varies almost linearly with this compression ratio. So, what we find that if we can reduce this compression ratio, then we shall be able to reduce the work requirement, but, at the same time the liquefaction will also be reduced. Now, it has to be seen, whether the reduction in the work requirement can offset the reduction in the liquefaction, if that is so, then this kind of system is workable.

So, thus in this view of this, we just suggested that a compress a fraction of the gas, not the whole of the gas, but a fraction of the gas is compressed from intermediate pressure, and then further compresses the whole mass of the gas to the actual pressure (Refer

Time: 02:44). Then and this way what happens that it reduces both the energy requirement for work of compression as well as the liquid yield for a given cooling due to reduction in the compression ratio.

Now, it has been found that the reduction in the work requirement is much more than a reduction in the liquid yield. And but what happens the disadvantage is this that even though we are able to reduce the work requirement without sacrificing much of the liquid yield, but it will increases the process complexity, and that is how the controllability of the process is becomes all very difficult.

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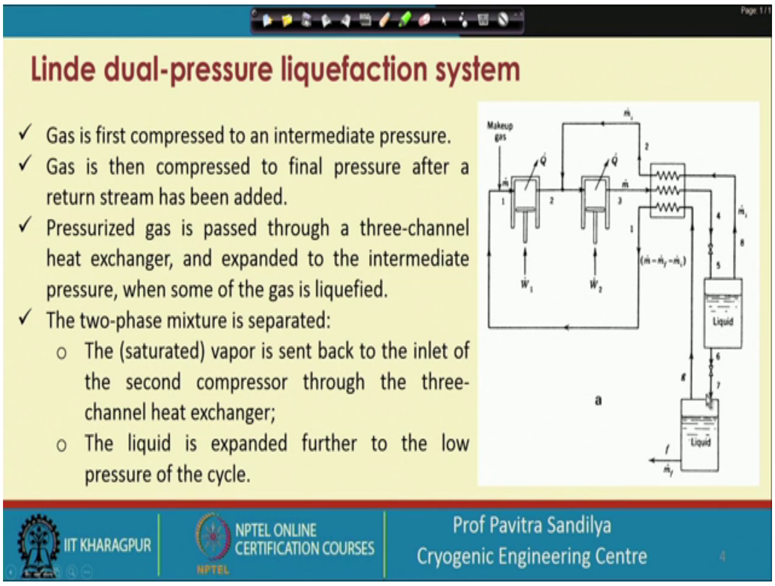

Linde dual-pressure liquefaction system

- ✓ Gas is first compressed to an intermediate pressure.
- ✓ Gas is then compressed to final pressure after a return stream has been added.
- ✓ Pressurized gas is passed through a three-channel heat exchanger, and expanded to the intermediate pressure, when some of the gas is liquefied.
- ✓ The two-phase mixture is separated:
  - The (saturated) vapor is sent back to the inlet of the second compressor through the three-channel heat exchanger;
  - The liquid is expanded further to the low pressure of the cycle.

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Now, here is a typical Linde dual-pressure liquefaction system. Now, as you can see here there are two compressors, and this is first compressor, and second compressor. Now, what we find here is this the particular compressor is getting some amount of the gas that is m dot. And this gas is compressed with some intermediate pressure in the state 2, and then this gas is joined by the return stream from first evaporator this is coming here.

And then what happens is together, the total gas is now going to the second compressor, and it is going to this three channel heat exchanger, where it is being cooled by the return vapor streams from the two evaporators, and then it is going to the j t valve, where it is getting expanded and two phases are being formed, the liquid is stored here. Whereas, the gas is this vapor is send back through this three channel heat exchanger back to this, and it is joining here ok.

So, this particular liquid now what is happened, this is again taken to the second j t, and here again it is getting into two phase. And from here, this liquid is a final liquid reservoir. And from here, we are getting the whatever liquid we want. And this vapor is going back through this three channel heat exchanger, and it is going to this the inlet of this particular first compressor.

So, we find that we need two liquid receivers. So, and from these two receivers, we are getting some amount of this total gas. And here we find this first from the one whatever you get in the first one that is about m i dot; i signifies intermediate. And this particular thing is m minus m f minus m dot. This m is the total mass, this m f is the amount of the liquid withdrawn from this reservoir, and m i is the amount of the gas it is coming through this particular reservoir.

So, this is simply obtained from them material balance ok, and that is how we are able to get the total amount here. Now, here we find that by doing so, we are having the two work done on these two particular compressors, and we have to supply the makeup gas, so that we can compensate for the lost liquid from here. So, this is the overall Linde dual-pressure column.

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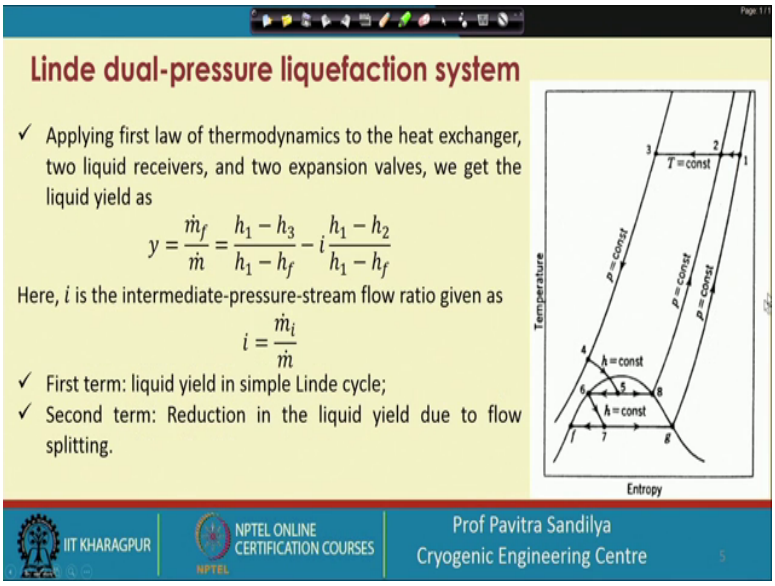

Linde dual-pressure liquefaction system

- ✓ Applying first law of thermodynamics to the heat exchanger, two liquid receivers, and two expansion valves, we get the liquid yield as

$$y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_3}{h_1 - h_f} - i\frac{h_1 - h_2}{h_1 - h_f}$$

Here, i is the intermediate-pressure-stream flow ratio given as

$$i = \frac{\dot{m}_i}{\dot{m}}$$

- ✓ First term: liquid yield in simple Linde cycle;
- ✓ Second term: Reduction in the liquid yield due to flow splitting.

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5

And this can be represented or name T s diagram like this that we start with some initial pressure at 1, and then we isothermally compress it to some intermediate pressure to point 2, and then it is ultimately going to the final pressure to 3. Now, here please understand that here we are not showing the various types of streams. The amounts we are not showing in this T s diagram, it is just that any T s diagram or any kind of phase diagram just show the states of the various equipment. So, here from the now what we are finding that from 3, we are now cooling it down isobarically, and then we are going to the first one.

So, in the first evaporator, now here what we are doing that we are getting a liquid and the vapor. And ideally, we assume that both the liquid and the vapor are at their saturated conditions. Now, the vapor stream is sent back through the three channel heat exchanger, and here we are again this it is getting heated up at the intermediate pressure, and the liquid is again partially evaporated to another this initial pressure that is p 1. And we find here that we are getting a liquid, this liquid is a part of this liquid is withdrawn. And the vapor is taken, and it is isobarically heated up to the inlet pressure of the first compressor. So, (Refer Time: 07:35) that this is a first compressor, so this is a second compressor, and that is how we are getting this dual-pressure operation and on the T s diagram.

And if we do a first law analysis what we find that this is this will be the yield of this particular system. Now, here we find that this i is signifying the intermediate-pressure-stream flow ratio, which is given by this m i dot by m dot. Now, here we find this for first term on the right hand side is the liquid yield as obtained in the symbol Linde system. Whereas, this particular term is signify the reduction in the liquid yield due to the dual-pressure, but this reduction is not so much as a reduction in the work of compression.

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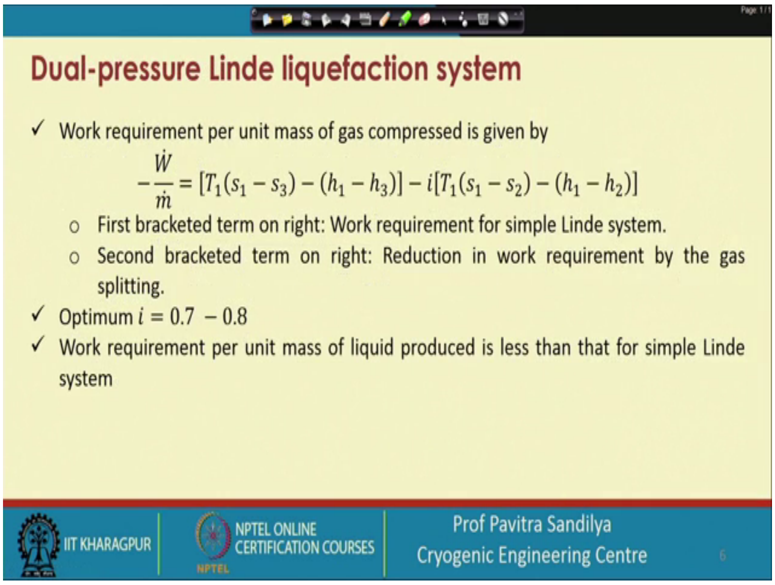

Dual-pressure Linde liquefaction system

- ✓ Work requirement per unit mass of gas compressed is given by

$$-\frac{\dot{W}}{\dot{m}} = [T_1(s_1 - s_3) - (h_1 - h_3)] - i[T_1(s_1 - s_2) - (h_1 - h_2)]$$

  - o First bracketed term on right: Work requirement for simple Linde system.
  - o Second bracketed term on right: Reduction in work requirement by the gas splitting.
- ✓ Optimum $i = 0.7 - 0.8$
- ✓ Work requirement per unit mass of liquid produced is less than that for simple Linde system

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Now, here we see the work requirement given for the dual-pressure system. And here we see that this first term is the same for the Linde system, and this particular term represents the reduction in the work requirement. And generally it has been found that optimum value of i is about 0.7 to 0.8. And the work requirement per unit mass of liquid produced is found to be less than that for the simple Linde system, so that is how this Linde dual-pressure liquefaction system proves to be better than the simple Linde liquefaction system.

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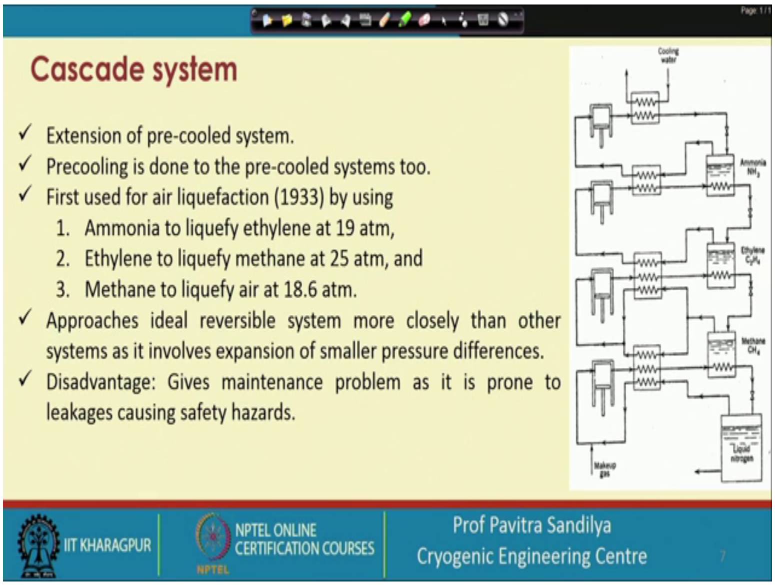

Cascade system

- ✓ Extension of pre-cooled system.
- ✓ Precooling is done to the pre-cooled systems too.
- ✓ First used for air liquefaction (1933) by using
  1. Ammonia to liquefy ethylene at 19 atm,
  2. Ethylene to liquefy methane at 25 atm, and
  3. Methane to liquefy air at 18.6 atm.
- ✓ Approaches ideal reversible system more closely than other systems as it involves expansion of smaller pressure differences.
- ✓ Disadvantage: Gives maintenance problem as it is prone to leakages causing safety hazards.

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Next, we go to a cascade system. In fact, cascade system is the one, which came into the technological advancement for the first time before the Linde, and this was basically to liquefy the air. So, here we are taking (Refer Time: 09:27) so that we after learning the pre-cooled systems, we can appreciate this particular cascade system. So, this is an extension of the pre-cooled system. And the precooling is done to the pre-cooled systems too that means whatever we have found earlier that we were doing only one precooling to the actual system. Now, in this cascade system, cascade means there are there is a series of systems. And this series is coming due to the use of the precooling for the pre coolant taking.

So, here we can see that there is a cascade of the various refrigeration refrigerations. And here is the actual system; here we are getting the liquefaction. And for this particular liquefaction system, we are using this particular pre coolant ok. And this for this particular pre coolant circuit, again we are using another pre coolant circuit here. And again, for this pre coolant circuit, we are using another pre coolant circuit.

So, we see that the pre coolant circuit that there is a series of pre coolant systems for this kind of cascade systems. And here for example, we have shown for the liquid nitrogen production that we are using ammonia, then ethylene, then methane. Now if you see that these pre coolants have been arranged in the decreasing order of their boiling points ok and ultimately, you find that for the ammonia, we are using the cooling water as the heat sink ok. So, this is how we are carrying out the cascade system.

And here the typical values have been given that ammonia is to liquefy ethylene at about 19 atmosphere the ethylene is to liquefy the methane at 25 atmosphere, and methane is to liquefy the air at about 18.6 atmosphere. And this particular system came into being as early as 1933. And this way whenever we are using so many pre coolants, it even the more the number of pre coolant systems what we find, this will be I am moving towards a reversible system. Why, because we shall be expanding the gas at a smaller pressure ratio, and we know for thermodynamics. If the pressure ratio is small, the system becomes more and more reversible.

But, the disadvantage is this that because we are having so many systems subsystems rather then it becomes difficult to maintain. And in kind of cryogenic systems if there is any kind of heat a leak or the material a leak that becomes problematic. And some material may be posing some kind of safety hazard to the personnel or the environment. So, this kind of cascade system becomes a bit difficult to operate. However, in case of LNG, such cascade system that is to produce the liquefied natural gas such kind of cascade systems are being used.

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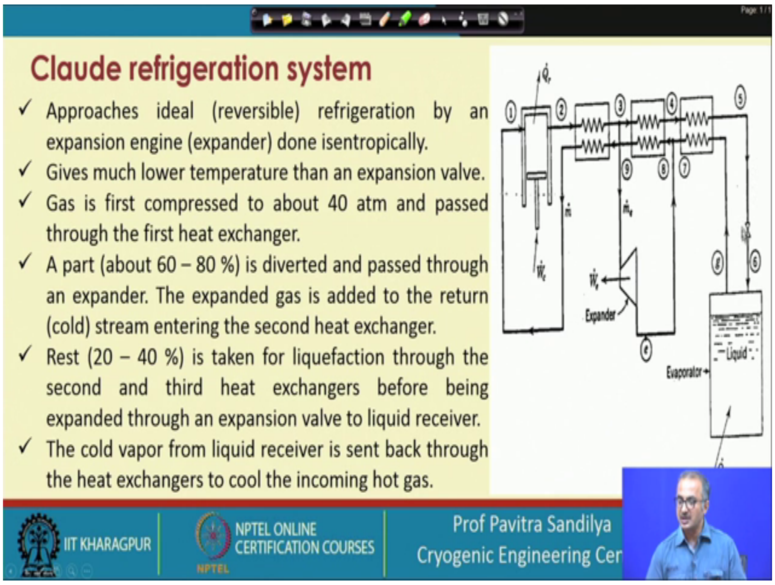

Claude refrigeration system

- ✓ Approaches ideal (reversible) refrigeration by an expansion engine (expander) done isentropically.
- ✓ Gives much lower temperature than an expansion valve.
- ✓ Gas is first compressed to about 40 atm and passed through the first heat exchanger.
- ✓ A part (about 60 – 80 %) is diverted and passed through an expander. The expanded gas is added to the return (cold) stream entering the second heat exchanger.
- ✓ Rest (20 – 40 %) is taken for liquefaction through the second and third heat exchangers before being expanded through an expansion valve to liquid receiver.
- ✓ The cold vapor from liquid receiver is sent back through the heat exchangers to cool the incoming hot gas.

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Now, next we come to another very important system that is the Claude refrigeration system. And this system approaches reversible refrigeration by an expansion engine done isentropically. Now, this as we learnt earlier that there are two ways of expanding either by the internal work that is done in the expansion valve or the external work that is done in the expansion engine. So, in this way, we find that the expansion engine we are using. And Claude was the one, who first used the expansion engine. And expansion engine can give better cooling and more reversibility than the expansion valve.

So, we find that expansion engine gives a lower temperature. And in this case, what we find that the gas is first compressed to about 40 atmosphere that means, in this particular compressor from 1 to 2, the gas is compressed to about 40 atmosphere, and then it is taken to a cooler. And from the first cooler main cooler a portion is diverted, and this portion about 60 to 80 percent is diverted and passed to an expander. And after the expansion, the gas becomes quite cool. And this is taken back to the inlet of the returned stream to the second heat exchanger, so that means, this portion is mainly to cool down the rest of the incoming hot gas.

Now, after this the things are pretty simple that this gas is taken to another heat exchanger for further cooling, before it is taken to the expansion valve. And here the Joule Thomson expansion happens, so that we are getting the liquid here, this is the evaporator. And this evaporator is taking the heat load from the refrigerated space, and it is getting vaporized that means, it may be assumed to be an isothermal source of heat and then the vapor stream return going back through these heat exchangers.

And here after this heat exchanger, it is getting joined by this particular cold stream, and slowly and though it is going back to the inlet of the compressor and that is how this particular the system is going on. And here we find that a part of this particular case is m g, and the m e is the amount which is being diverted from the main stream through the expansion engine ok. So, on this particular system, we are getting only m dot minus m e dot amount of the fluid.

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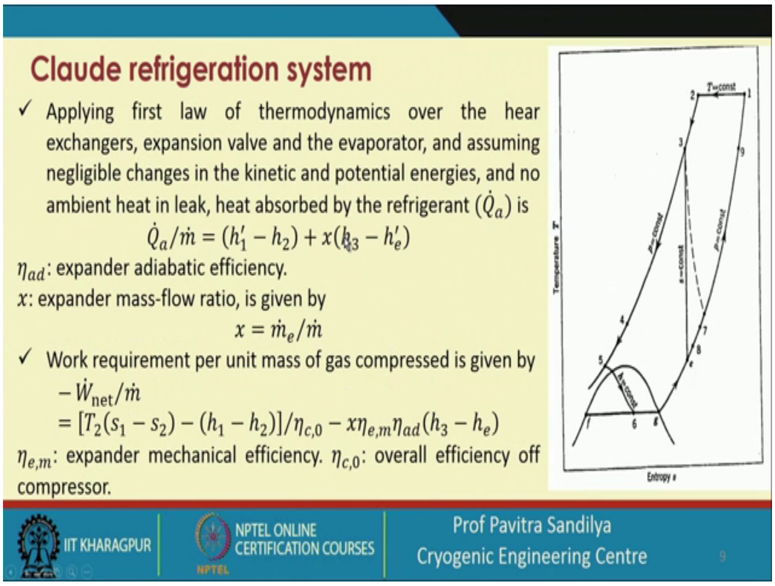

Claude refrigeration system

- ✓ Applying first law of thermodynamics over the hear exchangers, expansion valve and the evaporator, and assuming negligible changes in the kinetic and potential energies, and no ambient heat in leak, heat absorbed by the refrigerant ($\dot{Q}_a$) is

$$\dot{Q}_a/\dot{m} = (h_1' - h_2) + x(h_3 - h_e')$$

η_{ad}: expander adiabatic efficiency.

x: expander mass-flow ratio, is given by

$$x = \dot{m}_e/\dot{m}$$

- ✓ Work requirement per unit mass of gas compressed is given by

$$-\dot{W}_{net}/\dot{m}$$
$$= [T_2(s_1 - s_2) - (h_1 - h_2)]/\eta_{c,0} - x\eta_{e,m}\eta_{ad}(h_3 - h_e)$$

$\eta_{e,m}$: expander mechanical efficiency. $\eta_{c,0}$: overall efficiency off compressor.

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9

Now, going further into this system, first you look at the T s diagram for this system. Here we find that the gas is first getting compressed isothermally from state 1 to state 2, and then it is isobarically getting cooled down. From this is the first heat exchanger, after that a stream is not diverted to the expansion engine, and ideally it is undergoing an isentropic expansion. And this particular dashed curve is showing that if it is not isentropic, it is simply (Refer Time: 15:48) adiabatic, but not reversible, then we find that it is taking another path. And in this path, we find that the entropy is more as we know that the irreversible processes will have more entropy, so we find that this is taking, when the right hand side of the isentropic line.

And the rest of the gas is going further in a stage wise manner to the other two heat exchangers, and then we are finding that it is going to state 5. And then from here, we are isenthalpically expanding it through the expansion valve, the liquid is coming on the saturated liquid line. And this liquid is taken out, and that vapor is going to the saturated vapor line, and it is again getting isoned isobarically heated and here it is being joined by that stream, which is coming from the expansion engine. And then these are getting further heated up isobarically and through the various heat exchangers is 7, 8, 9, they are all signifying their heat exchangers. And then ultimately, they are reaching the point 1 that is the inlet of the compressor.

Now, if we do a first law of thermodynamic analysis on these system comprising heat exchangers, the expansion valve, the evaporator, and we assume that the kinetic energy and the potential energies are not changing appreciably. And we are neglecting any kind of heat inlet to the system then we find this is the amount of heat absorbed by the refrigerant in the liquid reservoir. And here we find this h 1 prime is coming this is the actual enthalpy, which is there, and this is the isentropic the h e prime shows the actual entropy, which is of the coming at the outlet of the expansion engine, if the expansion is not isentropic. And if we take this as the expander adiabatic efficiency, and this x is the expander mass flow ratio. And we put this expander mass-flow ratio as the ratio of the amount which is diverted to the total amount of the gas.

And then we can find this is the work requirement. And in this work requirement, we are finding that these are the various efficiencies. This is the overall efficiency of the compressor, and this is the mechanical efficiency of the expander, and this is the adiabatic efficiency of the expander. And now, we are finding that these are ideal values, we are putting here as s 1, h 1 and h e, so there are ideal values. So, this is how we are able to find out the net work requirement for the gas compressed. Here please understand that this particular portion shows that this work is the work, which is being produced by the expander.

Now, in case, we are integrating the compressor and the expander, only then this particular term will come that means, the actual work requirement for the compression will get reduced. However, if we are not integrating the expander with the compressor, then this term will be absent, then it means that the work requirement will be same as in case of the simple Linde-Hampson. So, this is how if so that is how we should be integrating the expansion engines to reduce the work requirement of the compressor from the external source.

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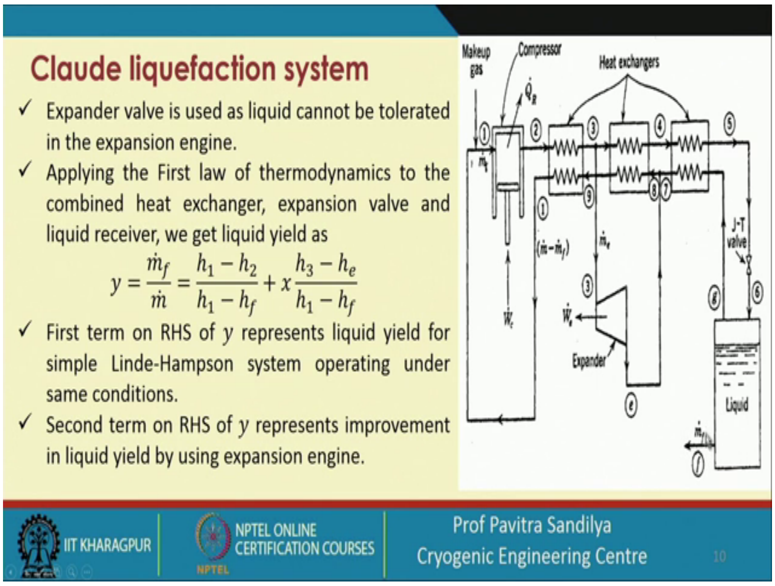

Claude liquefaction system

- ✓ Expander valve is used as liquid cannot be tolerated in the expansion engine.
- ✓ Applying the First law of thermodynamics to the combined heat exchanger, expansion valve and liquid receiver, we get liquid yield as

$$y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f} + x\frac{h_3 - h_e}{h_1 - h_f}$$

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

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Now, moving on to the Claude liquefaction system, here we find the system remains almost the same, except that we are having a liquid withdrawal from the reservoir. And this is not an evaporator is a reservoir. And here whatever amount we are withdrawing that amount has to be compensated for and that is being done by the makeup gas. So, this m f is coming out, and this m f is again given as a makeup gas, so that the total amount of the fluid inside a system remains the same.

So, here we find the same three heat exchanger are there. And here from the after the first heat exchanger, we are diverting a stream to the expansion engine. And the outlet of this expansion engine is going to the inlet of the return stream to the second heat exchanger, and rest of the processes are the same as in case of the Claude refrigeration.

So, because of the liquefaction, so we need to know; what is the liquid yield. And if we apply the first law of thermodynamics to the combined heat exchanger expansion valve and the liquid receiver, we get this particular expression. Now, in this expression, what we find that the first term on the right hand side is the same as the one, we obtained for the simple Linde-Hampson cycle. And this particular term is showing the enhanced a liquid yield due to the Claude liquefaction, so that is how we are finding that Claude liquefaction gives us a better liquid yield than the simple Linde-Hampson.

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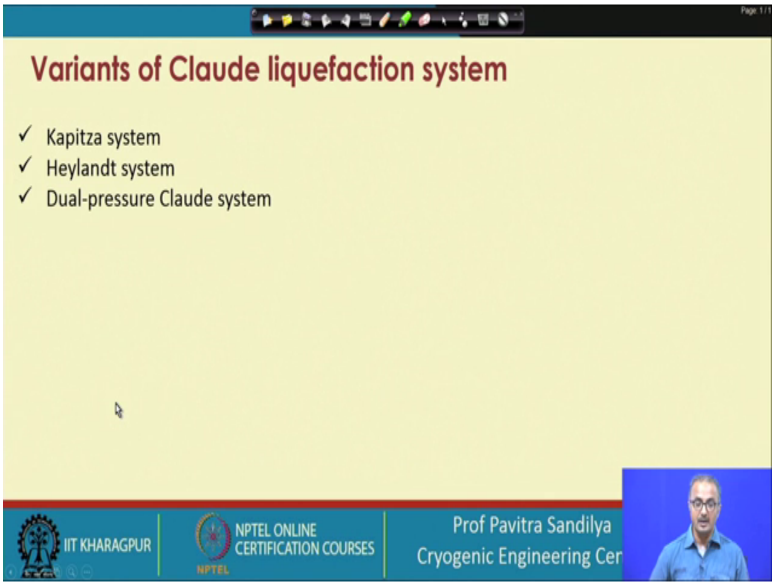

Variants of Claude liquefaction system

- ✓ Kapitza system
- ✓ Heylandt system
- ✓ Dual-pressure Claude system

And these are some of the other variants of the Claude liquefaction system that Kapitza system, Heylandt system, Dual-pressure Claude system. These I am not going into detail, because all these systems are basically developed for the air separation purpose. And as and when we get some special kind of liquefaction or refrigerant system for the natural gas processing, I shall be talking on that under that particular heading.

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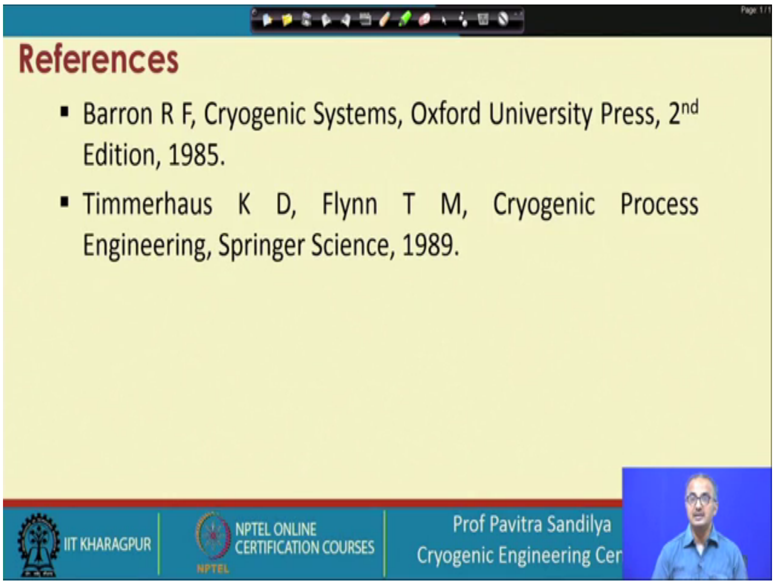

References

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

And these are some of the references. You can refer too, to get the details about these types of system.

Thank you.