Upstream LNG Technology
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Lecture – 78
Tutorial on refrigeration and liquefaction - V

Welcome. Today we shall see a few more problems on the refrigeration liquefaction.

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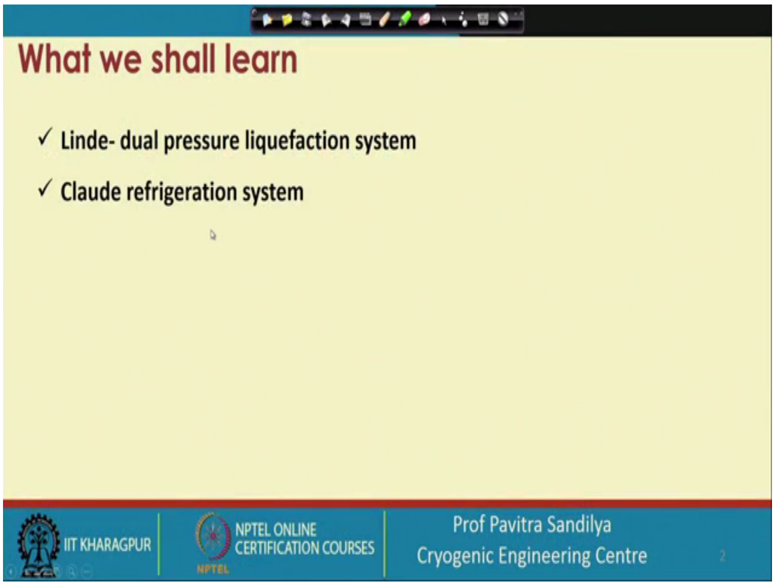

What we shall learn

- ✓ Linde- dual pressure liquefaction system
- ✓ Claude refrigeration system

In this we today we shall be looking into the Linde dual pressure liquefaction and Claude refrigeration.

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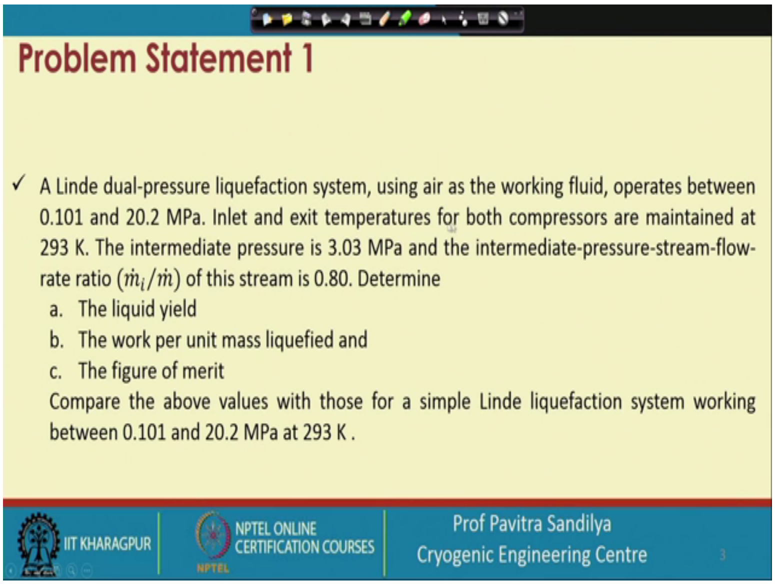

Problem Statement 1

- ✓ A Linde dual-pressure liquefaction system, using air as the working fluid, operates between 0.101 and 20.2 MPa. Inlet and exit temperatures for both compressors are maintained at 293 K. The intermediate pressure is 3.03 MPa and the intermediate-pressure-stream-flow-rate ratio ($\dot{m}_i/\dot{m}$) of this stream is 0.80. Determine
  a. The liquid yield
  b. The work per unit mass liquefied and
  c. The figure of merit

  Compare the above values with those for a simple Linde liquefaction system working between 0.101 and 20.2 MPa at 293 K .

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First let us take a problem on the Linde dual pressure liquefaction system. In this problem the air is taken as the working fluid and it is operating between the minimum pressure of 0.101 mega Pascal and 20.2 mega Pascal that is about 1 atmosphere and 202 atmosphere.

Now, the inlet and exit temperatures for both the compressors are maintained at 293 K that is the two compressors are working isothermally. The intermediate pressure is 3.03 mega Pascal that is about 30.3 atmosphere. And the intermediate pressure stream flow ratio that is m i dot by m dot is about m 0.80 that is the 80 percent of the main stream is being taken out for the dual intermediate pressure.

Now, we have to determine the liquid yield the work per unit mass liquefied and the figure of merit, and we have to also compare these values for a simple Linde liquefaction system which is working between this minimum and the maximum pressure and at the same temperature. So, this problem will demonstrate how the use of a Linde dual pressure liquefaction system compares or improves upon the performance of a simple Linde liquefaction system.

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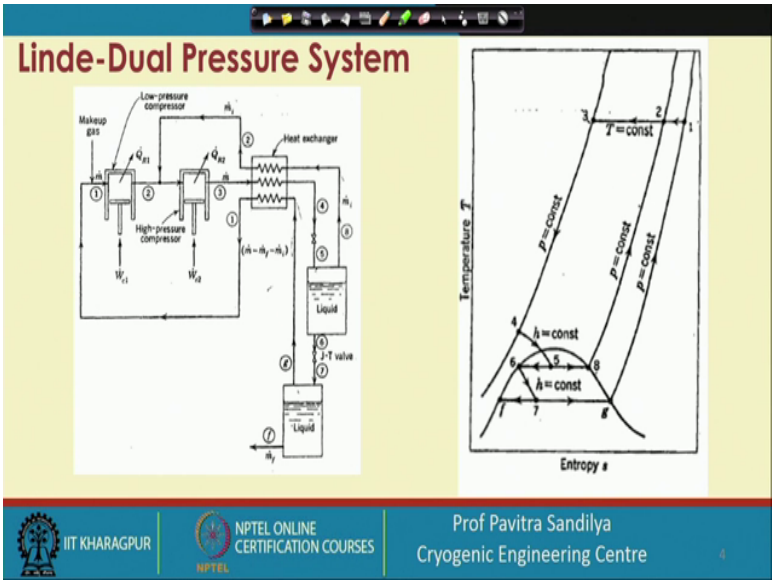

Linde-Dual Pressure System

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Now, just let us recapitulate first, that how this dual pressure works that we have these two compressors. So, this first compressor is taking the whole mass and it is taking to the intermediate pressure and the second compressor is taking to the final pressure; that means, here at 0.1 we will be having that minimum pressure of about 1 atmosphere, and here we shall be having about 200 atmosphere. And in between we have the 30 atmosphere.

And here we see that here we are getting the liquid withdrawal; and this is the TS diagram of the same system. So, here we have the initial pressure, the intermediate pressure and the final pressure and these are the two isenthalpic processes this represents this particular one and this represents this one. So, this we did earlier. So, I am not going into the detail of these explanations. So, let us now go to the problem.

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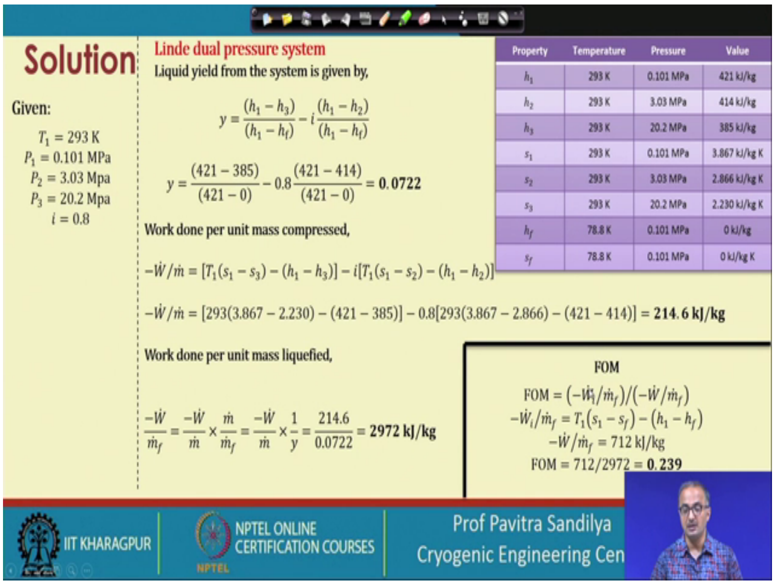

Solution

Given:

$T_1 = 293$ K
$P_1 = 0.101$ MPa
$P_2 = 3.03$ Mpa
$P_3 = 20.2$ Mpa
$i = 0.8$

Linde dual pressure system

Liquid yield from the system is given by,

$$y = \frac{(h_1 - h_3)}{(h_1 - h_f)} - i\frac{(h_1 - h_2)}{(h_1 - h_f)}$$

$$y = \frac{(421 - 385)}{(421 - 0)} - 0.8\frac{(421 - 414)}{(421 - 0)} = \mathbf{0.0722}$$

Work done per unit mass compressed,

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

$$-\dot{W}/\dot{m} = [293(3.867 - 2.230) - (421 - 385)] - 0.8[293(3.867 - 2.866) - (421 - 414)] = \mathbf{214.6\ kJ/kg}$$

Work done per unit mass liquefied,

$$\frac{-\dot{W}}{\dot{m}_f} = \frac{-\dot{W}}{\dot{m}} \times \frac{\dot{m}}{\dot{m}_f} = \frac{-\dot{W}}{\dot{m}} \times \frac{1}{y} = \frac{214.6}{0.0722} = \mathbf{2972\ kJ/kg}$$

Property	Temperature	Pressure	Value
h_1	293 K	0.101 MPa	421 kJ/kg
h_2	293 K	3.03 MPa	414 kJ/kg
h_3	293 K	20.2 MPa	385 kJ/kg
s_1	293 K	0.101 MPa	3.867 kJ/kg K
s_2	293 K	3.03 MPa	2.866 kJ/kg K
s_3	293 K	20.2 MPa	2.230 kJ/kg K
h_f	78.8 K	0.101 MPa	0 kJ/kg
s_f	78.8 K	0.101 MPa	0 kJ/kg K

FOM

$$\text{FOM} = (-\dot{W}_i/\dot{m}_f)/(-\dot{W}/\dot{m}_f)$$
$$-\dot{W}_i/\dot{m}_f = T_1(s_1 - s_f) - (h_1 - h_f)$$
$$-\dot{W}/\dot{m}_f = 712\ \text{kJ/kg}$$
$$\text{FOM} = 712/2972 = \mathbf{0.239}$$

So, first write down all the conditions which are given to us here. So, these are the initial temperature pressure, this is the intermediate pressure and this is the final pressure and T 2 and T 3 are also equal to T1 and T 1. So, T 1 T 2 T 3 are all the same. So, we have not written those things separately temperature is constant.

So, first let us look into the Linde dual pressure system, and in this the liquid yield is given by this particular expression and what we have to do? We have to refer to the thermodynamic chart or thermodynamic table whatever. So, we have seen those TS diagrams are given. So, you refer to the TS diagram and read out the values of the enthalpies from the TS diagram, and here are the values given for the various temperatures and various pressures these are given.

So, you plug in these values appropriately in this expression of the yield, and find out the yield as 0.07. So, this is the value of the liquid yield. So that means, the 7 percent; that means, if you have multiply by 100 it will be about 7 percent; that means, 7 percent of the total mass of the gas that has been compressed has gone into the liquid.

Now, let us look at the work done per unit mass of gas compressed, and this is the expression for that and again we find that here we have at in addition to the enthalpy values, we have the values of entropies; even the entropy values have been listed in this particular table. So, what we can do? Now, you can plug in the values of the various the enthalpies and entropies and we get this as the work done per unit mass of the gas compressed. Next we have been asked to find out the work done per unit mass of the gas liquefied. And, here we have it that we take this value and divide by the yield and we get this is the value of the work done per unit mass of the gas liquefied

Now, we repeat the similar thing for the simple Linde system, before that we also find the FOM value. And FOM is the work that way this W i, there is a ideal work divided by the actual work and ideal work can be given by this, this is we will learnt earlier. So, the ideal works we find the ideas work here and we find this is the ideal work is this and this is the actual work and this is a we see that this is this FOM is 0.239 it is quite low ok.

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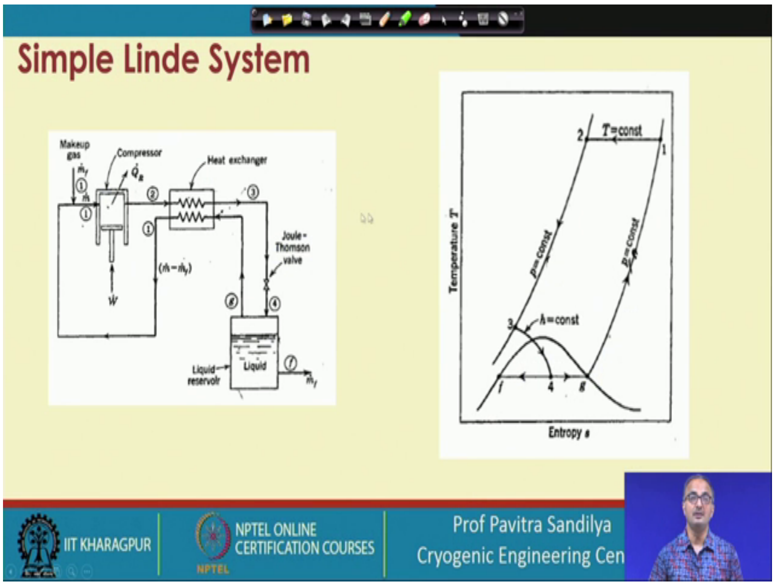

Simple Linde System

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Here we have the simple Linde system, here we have that again only one compressor here, this heat exchanger and the liquid reservoir from where we are withdrawing the liquid and here is the TS representation of the same process, again here we find this is we are doing the isenthalpic expansion here to get the liquid.

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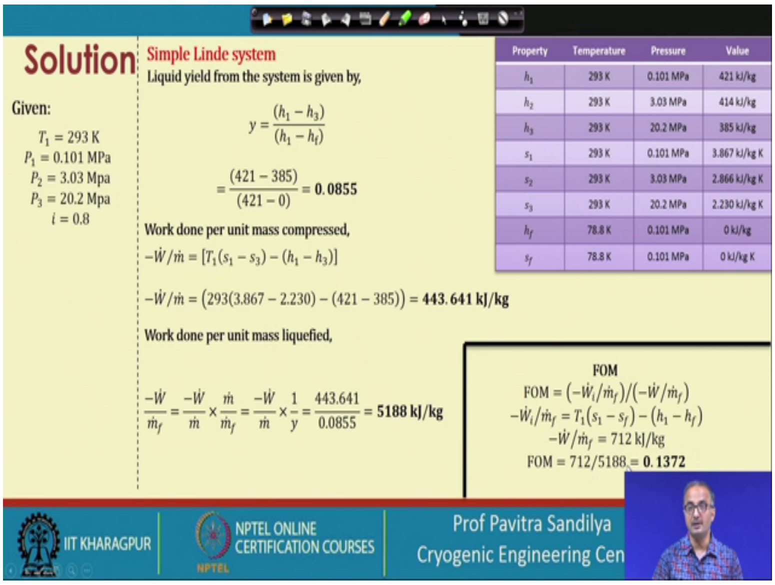

Solution

Given:

$T_1 = 293$ K
$P_1 = 0.101$ MPa
$P_2 = 3.03$ Mpa
$P_3 = 20.2$ Mpa
$i = 0.8$

Simple Linde system

Liquid yield from the system is given by,

$$y = \frac{(h_1 - h_3)}{(h_1 - h_f)}$$

$$= \frac{(421 - 385)}{(421 - 0)} = \mathbf{0.0855}$$

Work done per unit mass compressed,

$$-\dot{W}/\dot{m} = [T_1(s_1 - s_3) - (h_1 - h_3)]$$

$$-\dot{W}/\dot{m} = \left(293(3.867 - 2.230) - (421 - 385)\right) = \mathbf{443.641\ kJ/kg}$$

Work done per unit mass liquefied,

$$\frac{-\dot{W}}{\dot{m}_f} = \frac{-\dot{W}}{\dot{m}} \times \frac{\dot{m}}{\dot{m}_f} = \frac{-\dot{W}}{\dot{m}} \times \frac{1}{y} = \frac{443.641}{0.0855} = \mathbf{5188\ kJ/kg}$$

Property	Temperature	Pressure	Value
h_1	293 K	0.101 MPa	421 kJ/kg
h_2	293 K	3.03 MPa	414 kJ/kg
h_3	293 K	20.2 MPa	385 kJ/kg
s_1	293 K	0.101 MPa	3.867 kJ/kg K
s_2	293 K	3.03 MPa	2.866 kJ/kg K
s_3	293 K	20.2 MPa	2.230 kJ/kg K
h_f	78.8 K	0.101 MPa	0 kJ/kg
s_f	78.8 K	0.101 MPa	0 kJ/kg K

FOM

$$\text{FOM} = \left(-\dot{W}_i/\dot{m}_f\right)/\left(-\dot{W}/\dot{m}_f\right)$$
$$-\dot{W}_i/\dot{m}_f = T_1\left(s_1 - s_f\right) - \left(h_1 - h_f\right)$$
$$-\dot{W}/\dot{m}_f = 712\ \text{kJ/kg}$$
$$\text{FOM} = 712/5188 = \mathbf{0.1372}$$

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So, for this we write down all the conditions except that we do not need the intermediate pressure ok. We need only P 1 and P 3 and what we do we do all these things and we again list out the values of the enthalpies and we find out that liquid yield is this. And as we learnt earlier that the liquid yield get a bit decreased due to this dual pressure system, but on the other hand we said that we gain something in terms of the work.

So, let us see how that compares. So, first let us find out the work done per unit mass of the gas compressed and here it is, we find that that it is this value. And, then we similarly we find out the work done per unit mass of the gas liquefied and we find this is the value; and here also we find the value of the FOM like this. Now, after getting these all these values for the Linde dual pressure system and the simple Linde system what we do we put all these parameters in a table to compare them.

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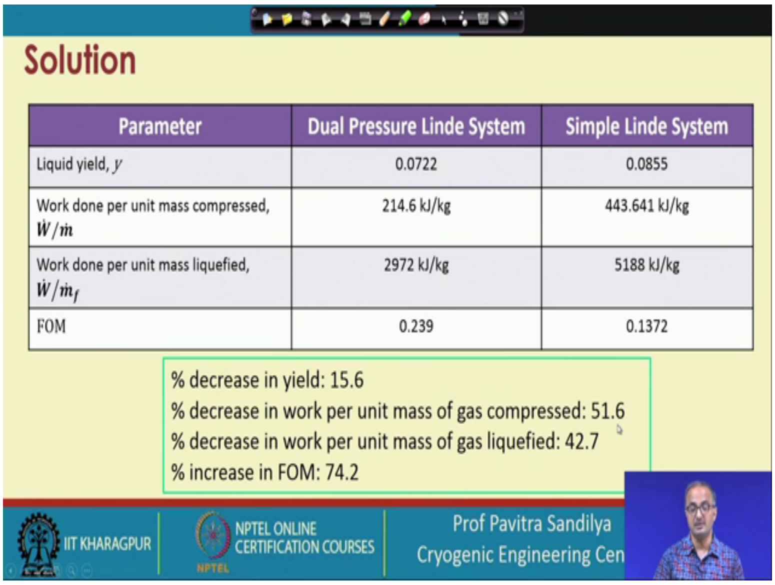

Solution

Parameter	Dual Pressure Linde System	Simple Linde System
Liquid yield, y	0.0722	0.0855
Work done per unit mass compressed, $\dot{W}/\dot{m}$	214.6 kJ/kg	443.641 kJ/kg
Work done per unit mass liquefied, $\dot{W}/\dot{m}_f$	2972 kJ/kg	5188 kJ/kg
FOM	0.239	0.1372

% decrease in yield: 15.6
% decrease in work per unit mass of gas compressed: 51.6
% decrease in work per unit mass of gas liquefied: 42.7
% increase in FOM: 74.2

So, here we find the liquid yield is given for the dual pressure system, which is a bit less than the one we are getting for the simple Linde system, then with the work done per unit mass compressed, it is also a bit less than the simple Linde system. This work done per unit mass liquefied this is also quite a bit less than simple Linde system and this is a FOM value; FOM value we find its a bit more than the simple Linde system.

So, to understand that how much more or how much less let us take a comparison the percent increase or decrease. We find the liquid yield has decreased by about 15.6 percent. On the other hand the work done per unit mass of gas compressed has decreased by about 51 percent. On the and the work done per unit mass of the gas liquefied has also decreased by about 42 percent and the FOM has increased by about 74 percent.

So, looking at these three figures, we find that it is quite justified to use a Linde dual pressure system even though we have to sacrifice some amount of liquid yield. So, overall economics or overall decision will be based on these all these parameters and just note on the liquid yield and this justifies the use of the Linde dual pressure system.

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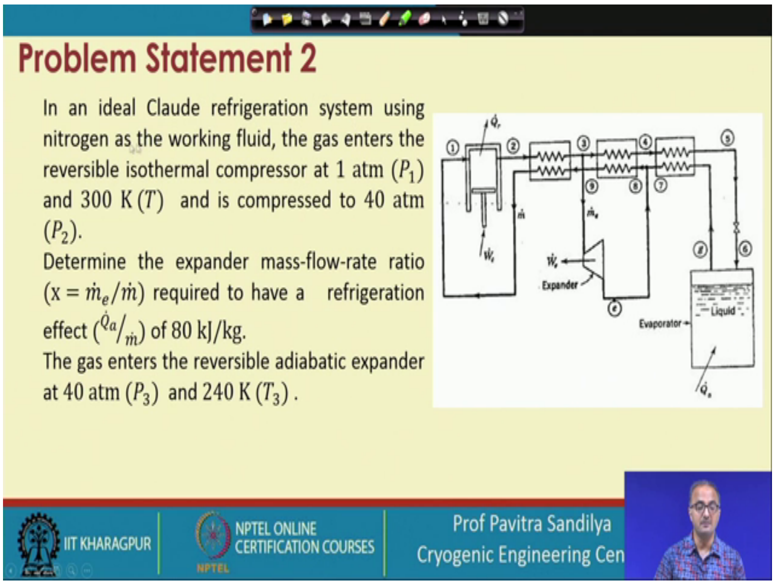

Problem Statement 2

In an ideal Claude refrigeration system using nitrogen as the working fluid, the gas enters the reversible isothermal compressor at 1 atm (P_1) and 300 K (T) and is compressed to 40 atm (P_2).

Determine the expander mass-flow-rate ratio $(x = \dot{m}_e/\dot{m})$ required to have a refrigeration effect $(\dot{Q}_a/\dot{m})$ of 80 kJ/kg.

The gas enters the reversible adiabatic expander at 40 atm (P_3) and 240 K (T_3).

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Next we come to another problem on the Claude refrigeration. So, here we have the Claude’s we are know that here we are using an intermediates expander to get further cooling and here we have the three heat exchangers. So, here we have given the problem that we have a Claude refrigeration system, in which we are using nitrogen as the working fluid and the gas enters the reversible isothermal compressor here ok. It is entering at about 1 atmosphere and 300 Kelvin and it is compressed to 40 atmosphere isothermally. So, it is at 0.2 it is 40 atmosphere and temperature remains the same at 300 K.

Now, we have been asked to find out the mass flow ratio this expanded mass flow ratio; that means, how much fraction or total flow has been taken to the expander. So, this we have to find out and we have been given the refrigeration effect that this is 80 kilo joule per kg, that is a refrigeration we are obtained this is a here. Means, how much Q a we are taking from here this is the one, which has been given to us per unit mass of the gas compressed. And, the gas enters a reversible adiabatic expander at 40 atmosphere and 240 K. So, this is these are the given over here.

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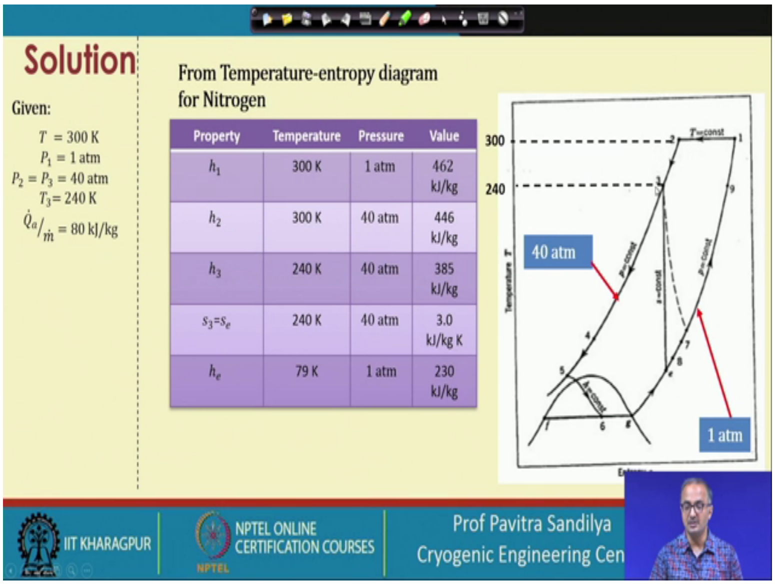

Solution

Given:

$T = 300$ K
$P_1 = 1$ atm
$P_2 = P_3 = 40$ atm
$T_3 = 240$ K
$\dot{Q}_a / \dot{m} = 80$ kJ/kg

From Temperature-entropy diagram for Nitrogen

Property	Temperature	Pressure	Value
h_1	300 K	1 atm	462 kJ/kg
h_2	300 K	40 atm	446 kJ/kg
h_3	240 K	40 atm	385 kJ/kg
$s_3=s_e$	240 K	40 atm	3.0 kJ/kg K
h_e	79 K	1 atm	230 kJ/kg

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Now, with these data what we do? We first write out all the values which have been given to us and what we do? We form this TS diagram. So, this is a TS representation of process which I am not going into and we know that it is working at this is the maximum temperature, this is an intermediate temperature. And, at this temperature it is going into the expander and this is the maximum pressure and this is the minimum pressure ok.

So, these in this way and of course, I told you that this dashed line is showing that it is a non ideal behavior, but we are not considering that we are considering the expander to be isentropic. So, we shall be sticking to this straight line. So, we at this various conditions what we do we find out the values of the h 1 and h 1, h 2 etcetera and the entropy also we know that the entropy at the to inlet and outlet of the expander are same because, we are taking them to be isentropic.

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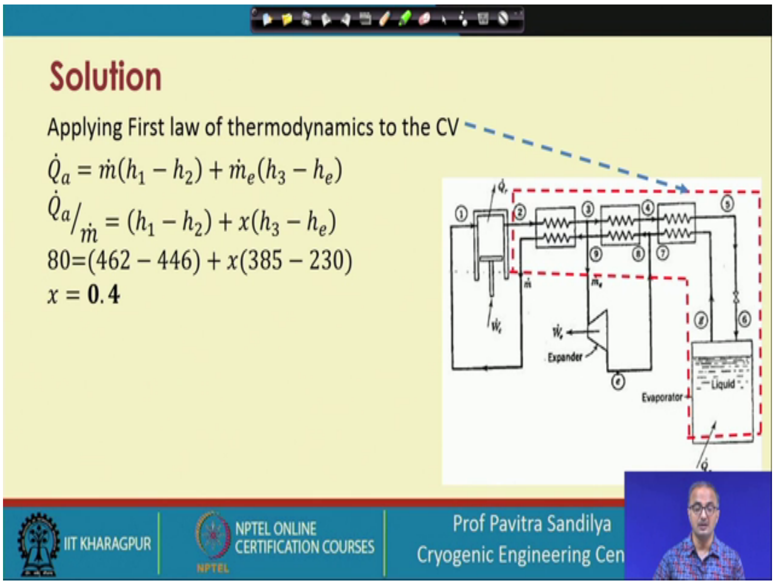

Solution

Applying First law of thermodynamics to the CV

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

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

$$80 = (462 - 446) + x(385 - 230)$$

$$x = 0.4$$

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So, with these conditions we find out the make a this first law of thermodynamics we make a energy balance, that is the first here we do and what we find this is the energy balance over this particular control volume. Please understand that whenever you are making the energy balance always remember to make the control volume. Without control volume it does not make any sense to draw any kind of balance mass balance, energy balance etcetera it does not make any sense.

So, first make out the control volume, only then you make this kind of balances. So, we are making the steady state balance. So, we get this thing. So, this is this Q a this value, is obtained from this mass flow rates and the enthalpies and the enthalpy this flow rate into the expander and the enthalpy at the expander outlet.

So, what we do that we simply take this divide this equation by m dot ok. When we divide by m dot so, we obtain this and this m e dot by m dot is the x which we have to determine. So, we plug in the values of the various in enthalpies in this equation and we get this x has 0.4; that means, we have to divert 40 percent of the actual mass flow of the from the main stream to the expander to obtain this much the given amount of the refrigeration. So, this is how we are using this Claude refrigeration cycle.

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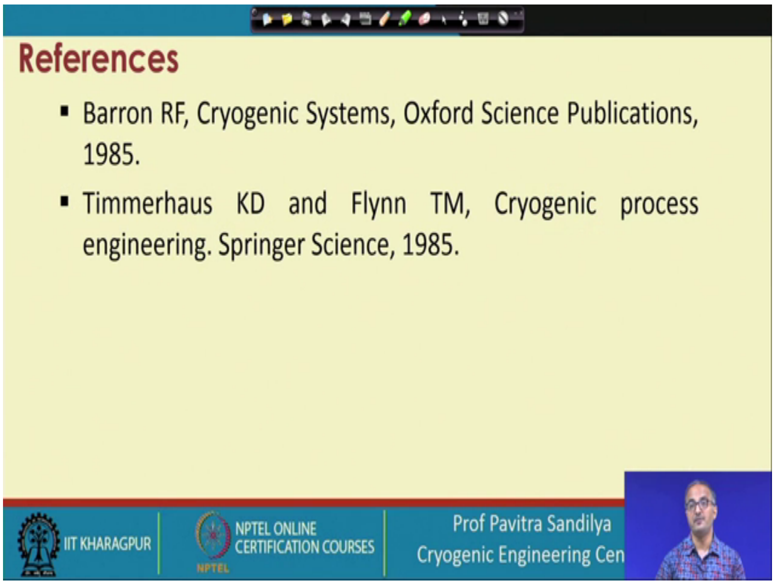

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- Timmerhaus KD and Flynn TM, Cryogenic process engineering. Springer Science, 1985.

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And more details you may find out from these two references.

Thank you.