Chemical Process Utilities
Prof. Shishir Sinha
Department of Chemical Engineering
Indian Institute of Technology, Roorkee

Module No # 11
Lecture No # 54
Refrigeration System Components and Refrigeration Cycle

Hello friends welcome to the next lecture of refrigeration system under the aegis of chemical process utilities. Now in this particular lecture we are going to discuss about the refrigeration system components and refrigeration cycle. So, before we go into the detail of this particular content let us have a brief outlook that what we discussed in the previous lecture. In the previous lecture we discussed about the various type of components like condenser, evaporators we discussed about the throttling devices and auxiliary devices.

This includes the accumulator, receivers, oil separators, strainers, solenoid, valves, dryers, check valves, defrost controllers and then we had a discussion about the vapour compression refrigeration system.

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Topics to be cover in this lecture?

- ❖ Vapor-compression refrigeration cycle
  - ○ Energy analysis
  - ○ Exergy analysis
- ❖ Practical vapor-compression refrigeration cycle
- ❖ Multistage refrigeration system

Now in this particular lecture we are going to cover the vapour compression refrigeration cycle with respect to the energy analysis and exergy analysis. And I will give about the practical approach of vapour compression refrigeration cycle. Apart from this we will discuss about the multi stage refrigeration system.

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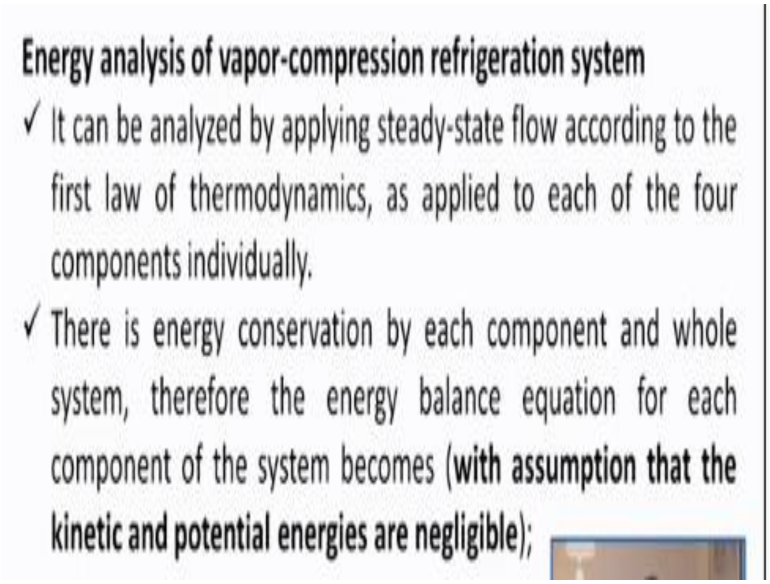

Energy analysis of vapor-compression refrigeration system

- ✓ It can be analyzed by applying steady-state flow according to the first law of thermodynamics, as applied to each of the four components individually.
- ✓ There is energy conservation by each component and whole system, therefore the energy balance equation for each component of the system becomes (**with assumption that the kinetic and potential energies are negligible**);

So, when we talk about the energy analysis of a vapour compression refrigeration system. Now it can be analyzed by applying steady state flow according to the first law of thermodynamics. Now you see that everywhere when we talk about the refrigeration aspect, we cannot overrule the importance of the laws of thermodynamics and usually all the cycles they are usually governed by the law of thermodynamics.

So, the first law of thermodynamics you see that as applied to each of the 4, component individually. So, if you recall the vapour compression cycle all the steps like compression, expansion, evaporation all these steps. So, the law of thermodynamics they always apply all stages of this vapour compression refrigeration system. Now there is an energy conservation by each component and the entire system therefore the energy balance equation for each component of the system becomes you can say very important.

Now with the assumption that the kinetic and potential energies are negligible so you can say that we are taking all these reversibility into consideration and we need to take the proper assumption.

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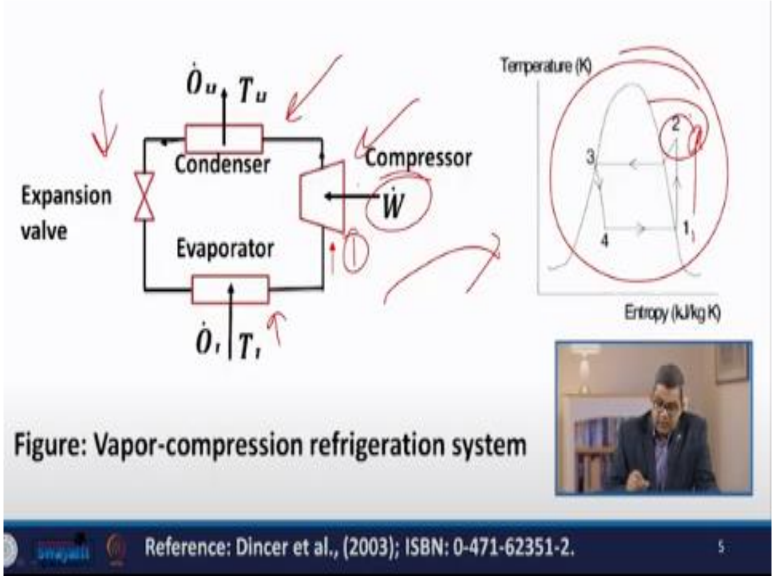

Figure: Vapor-compression refrigeration system

Reference: Dincer et al., (2003); ISBN: 0-471-62351-2.

Now here you see that these are the 4 integral part of your vapour compression representation system which we have already discussed. That the evaporator which is maintained at that particular temperature then the compressor, then condenser and then expansion valve. And if we try to draw these particular steps into the T S diagram here you see that this is the compression isentropic and then enthalpy operation. As well as so all these stages are depicted in this particular T S diagram.

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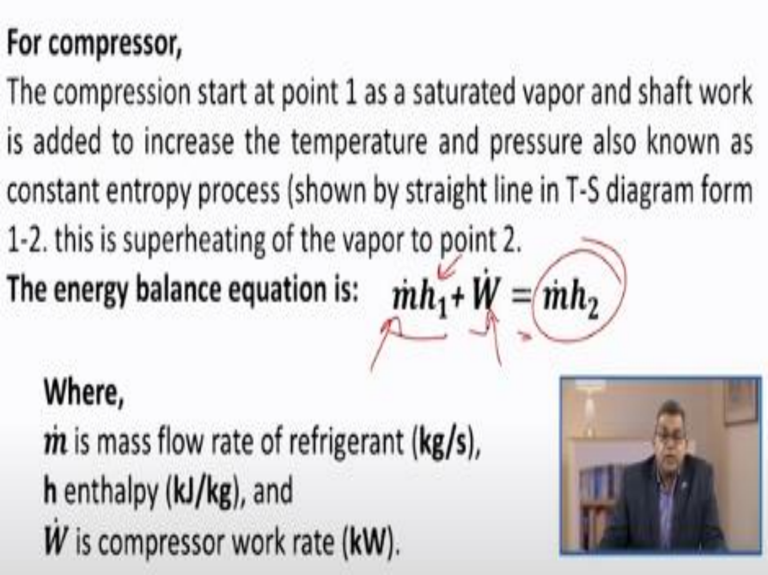

For compressor,

The compression start at point 1 as a saturated vapor and shaft work is added to increase the temperature and pressure also known as constant entropy process (shown by straight line in T-S diagram form 1-2. this is superheating of the vapor to point 2.

The energy balance equation is: $\dot{m}h_1 + \dot{W} = \dot{m}h_2$

Where,

$\dot{m}$ is mass flow rate of refrigerant (**kg/s**),

h enthalpy (**kJ/kg**), and

$\dot{W}$ is compressor work rate (**kW**).

Now if you see that the compression this starts at point number 1 here as a saturated vapor and shaft work is added to increase the temperature and pressure this also known as the isentropic operation or isentropic process. And you can see that this is represented as a straight line in the T

S diagram. Now this is super heating the vapor to the point number 2 that is this one. So obviously at this juncture we need to write the energy balance equation.

And that is this energy balance equation is m h 1 + w = m h 2 now where m is the mass flow rate this one is the mass flow rate of a refrigerant. And usually, it is represented ask the unit is kilogram per second and h is the enthalpy and having the unit of kilo joule per kilogram and w is the compressor work rate and represented as kilowatt so this is the w.

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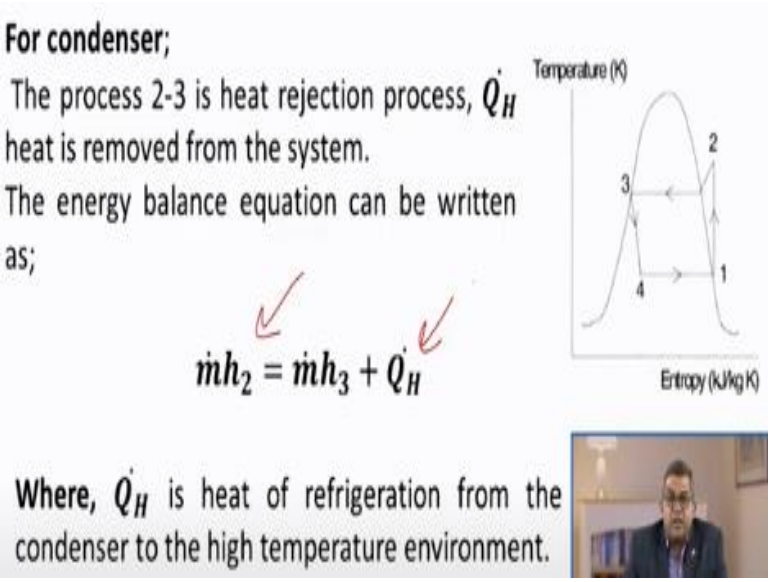
the energy balance equation is

$$\dot{m}h_1 + \dot{W} = \dot{m}h_2$$



For condenser;

The process 2-3 is heat rejection process, $\dot{Q}_H$ heat is removed from the system.

The energy balance equation can be written as;

$$\dot{m}h_2 = \dot{m}h_3 + \dot{Q}_H$$

Where, $\dot{Q}_H$ is heat of refrigeration from the condenser to the high temperature environment.

Now if we talk about the condenser, you see here, we are having the condenser the process is the heat rejection process and that is referred as Q H. Now heat is removed from the system so obviously when heat removal or additions take place then again, we need to write the energy balance equation. So, the energy balance equation can be written as m h 2 = m h 3 + Q H. Now here the Q H is the heat of refrigeration from the condenser to the high temperature environment.

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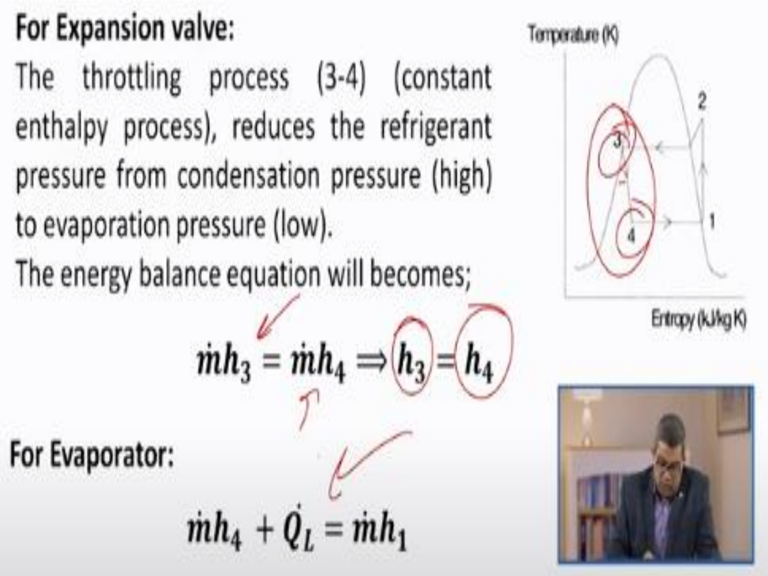
For condenser, the energy balance equation can be written as;

$$\dot{m}h_2 = \dot{m}h_3 + \dot{Q}_H$$



For Expansion valve:

The throttling process (3-4) (constant enthalpy process), reduces the refrigerant pressure from condensation pressure (high) to evaporation pressure (low).

The energy balance equation will becomes;

$$\dot{m}h_3 = \dot{m}h_4 \Rightarrow h_3 = h_4$$

For Evaporator:

$$\dot{m}h_4 + \dot{Q}_L = \dot{m}h_1$$

Now, next stage that is from 3 to 4 and that is called the expansion stage. So, if we talk about the expansion valve attributed to the throttling process and that is sometimes referred as isenthalpic process or the constant enthalpy process. This throttling process reduces the refrigerant pressure from the condensation pressure this is very high and for the evaporation pressure and that is low.

So, the energy balance equation that this can become the m h 3 = m h 4 and as, h 3 = h 4 because it is an isenthalpic operation. So, if we write the energy balance equation for evaporator side it becomes m h 4 + Q L = m h 1.

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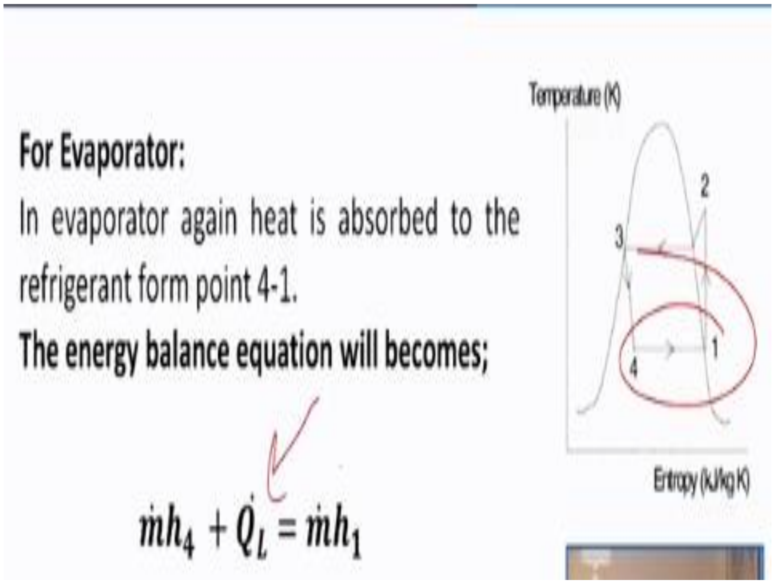
For expansion valve, the energy balance equation will be;

$$\dot{m}h_3 = \dot{m}h_4 \Rightarrow h_3 = h_4$$

For evaporators

$$\dot{m}h_4 + \dot{Q}_L = \dot{m}h_1$$



For Evaporator:

In evaporator again heat is absorbed to the refrigerant form point 4-1.

The energy balance equation will becomes;

$$\dot{m}h_4 + \dot{Q}_L = \dot{m}h_1$$

So, in evaporator again heat is absorbed to the refrigerant from point 4 to point 1 or station 1 to station 1 the energy balance equation will become m h 4 + q l = m h 1.

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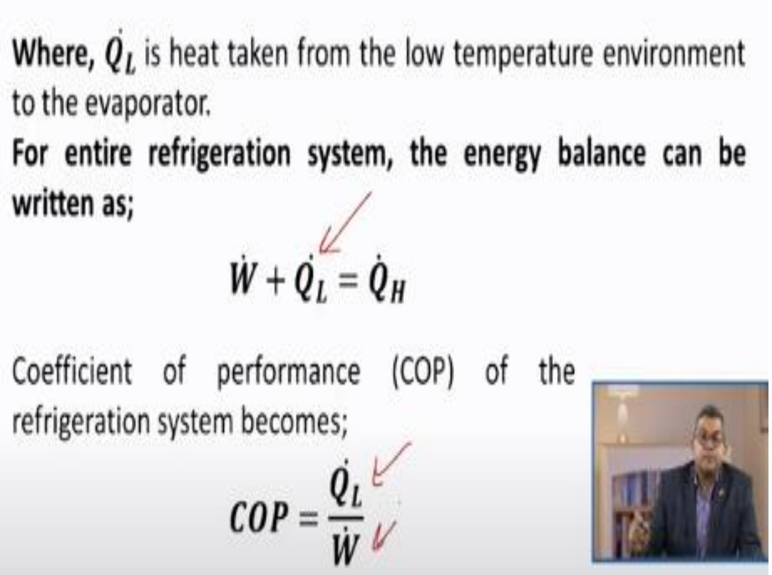
For evaporators, the energy balance equation will be;

$$\dot{m}h_4 + \dot{Q}_L = \dot{m}h_1$$



Where, $\dot{Q}_L$ is heat taken from the low temperature environment to the evaporator.

For entire refrigeration system, the energy balance can be written as;

$$\dot{W} + \dot{Q}_L = \dot{Q}_H$$

Coefficient of performance (COP) of the refrigeration system becomes;

$$COP = \frac{\dot{Q}_L}{\dot{W}}$$

Now here this Q L is the heat taken from the low temperature environment to the evaporator. So, for entire refrigeration system the energy balance can be written as W. W is the work done because you are externally supplying this quantum of work + Q L = Q H then we need to calculate the coefficient of performance. So, the coefficient of performance and sometimes referred as cop of the refrigeration system it becomes cop is equal to Q L over w.

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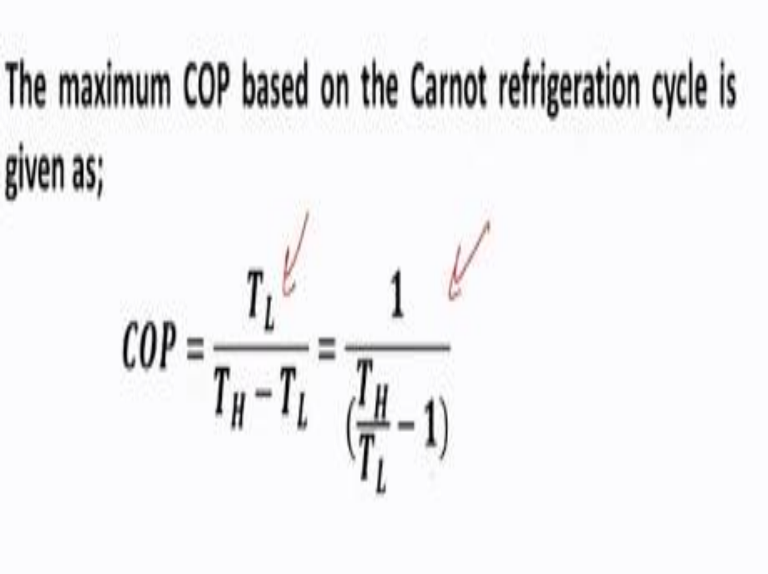
For entire refrigeration system, the energy balance can be written as;

$$\dot{W} + \dot{Q}_L = \dot{Q}_H$$

Coefficient of performance (COP) of the refrigeration system becomes;

$$COP = \frac{\dot{Q}_L}{\dot{W}}$$



The maximum COP based on the Carnot refrigeration cycle is given as;

$$COP = \frac{T_L}{T_H - T_L} = \frac{1}{(\frac{T_H}{T_L} - 1)}$$

So, the maximum COP that is the coefficient of performance based on the Carnot refrigeration cycle it is given as COP = T l over T H – T l and it is equal to 1 over T H over T L - 1.

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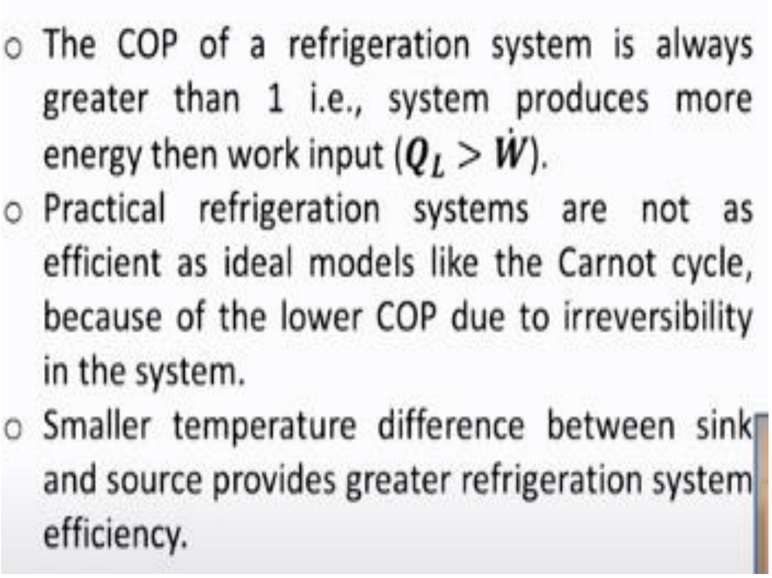
The maximum COP based on the Carnot refrigeration cycle is given as;

$$COP = \frac{T_L}{T_H - T_L} = \frac{1}{(\frac{T_H}{T_L} - 1)}$$



- The COP of a refrigeration system is always greater than 1 i.e., system produces more energy then work input ($Q_L > \dot{W}$).
- Practical refrigeration systems are not as efficient as ideal models like the Carnot cycle, because of the lower COP due to irreversibility in the system.
- Smaller temperature difference between sink and source provides greater refrigeration system efficiency.

The coefficient of performance or COP of the refrigeration system is always greater than 1 and that is the system produces more energy than the work input. So, you can say that Q L is greater than w the practical refrigeration system are not as efficient as ideal models like Carnot cycle because of the lower coefficient of performance due to irreversibility in the system. Smaller temperature difference between the sink and source it provides the greater refrigeration system efficiency.

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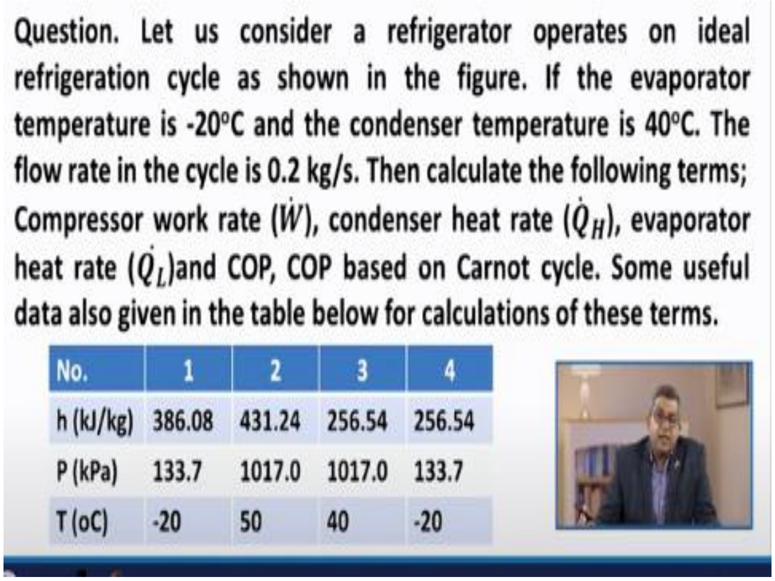

Question. Let us consider a refrigerator operates on ideal refrigeration cycle as shown in the figure. If the evaporator temperature is -20°C and the condenser temperature is 40°C. The flow rate in the cycle is 0.2 kg/s. Then calculate the following terms; Compressor work rate ($\dot{W}$), condenser heat rate ($\dot{Q}_H$), evaporator heat rate ($\dot{Q}_L$)and COP, COP based on Carnot cycle. Some useful data also given in the table below for calculations of these terms.

No.	1	2	3	4
h (kJ/kg)	386.08	431.24	256.54	256.54
P (kPa)	133.7	1017.0	1017.0	133.7
T (oC)	-20	50	40	-20

So, we discussed this particular theory in detail now it is time to have one question or one numerical question. Now the question is that let us consider a refrigerator operation on ideal refrigeration cycle as per the, this figure. Now if evaporator temperature is -20 degree Celsius and the condenser temperature is 40 degrees Celsius. And the flow rate in the cycle is 0.2 kilogram per second.

Then you need to calculate the compressor work rate that is W the condenser heat rate that is Q H evaporator heat rate that is Q L and the coefficient of performance. Now cop based on Carnot cycle this need to be addressed for convenience. We have given some useful data for the calculation purpose like different numbers 1, 2, 3, 4, enthalpy in kilo joule per kilogram the pressure in kilo Pascal and the temperature in degree Celsius.

So, as you know that for refrigeration cycle, we need to have a, 4 different stages so for every stage we have given this statistical data or the data required that is for stage 1. The enthalpy is 386.08. For stage 2 that is 4 31.24 kilojoule per kilogram and stage 3 and stage 4 these are the isenthalpic operation and that is why the enthalpy is constant and that is 256.54 for each stage. Similarly, if we are considering this the pressure perspective so the stage 2 and stage 3, they are isobaric in that case so the stage one is having the pressure of 133.7.

And stage 2 and stage 3 that are p 2 and p 3 they are equal and it they are 1017 each in the kilo Pascal unit and stage 4 is having 133.7 so stage, 1 and 4 they are isobaric. The temperature is stage 1 and stage 4 they are having the constant temperature -20 degree Celsius and stage 2 and 3 they are having 50 and 40 degrees Celsius respectively.

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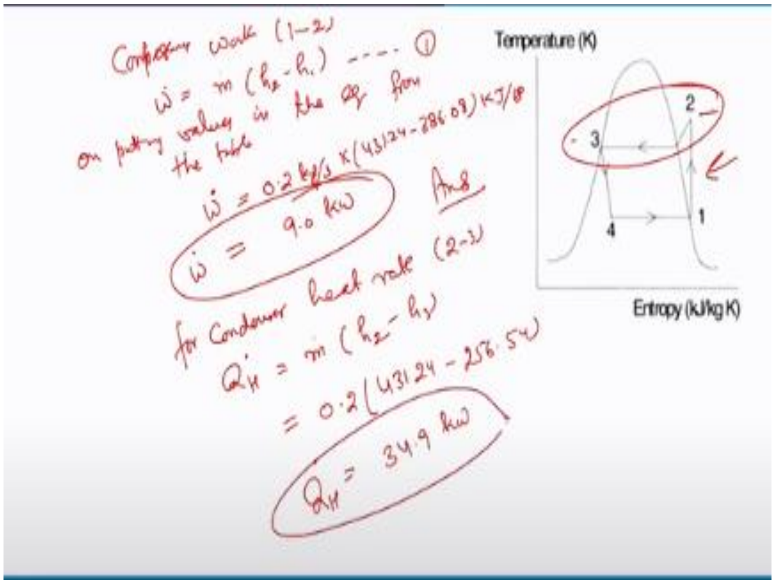

Compressor work (1–2)

$\dot{W} = \dot{m}(h_2 - h_1)$ ---- ①

on putting values in the eq from the table

$\dot{W} = 0.2\ \text{kg/s} \times (431.24 - 286.08)\ \text{kJ/kg}$

$\dot{W} = 9.0\ \text{kW}$ Ans

for Condenser heat rate (2–3)

$\dot{Q}_H = \dot{m}(h_2 - h_3)$

$= 0.2(431.24 - 256.54)$

$Q_H = 34.9\ \text{kW}$

So let us solve this particular problem now here this is the compressor work so if we take from station 1 to 2 so W = m h 2 - h 1 that is equation number 1. Now if we put on putting the values in the equation from the table w = 0.2 into 431.24 – 386.08 kilojoule per kilogram. So, if we calculate it comes out to be 9.0 kilowatts so work rate is 9.0 kilowatt. Now if that is from stage 1 to stage 2 now for the condenser heat rate and that is stage 2 to 3, we can write Q H = m h 2 – h 3.

So, 0.2 which is given in the problem into 431.24 – 256.54 so Q H is comes out to be 34.9 kilowatt.

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The compressor work (1-2)

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

On putting values in this equation from the table we have,

$$\dot{W} = 0.2\frac{kg}{s} \times (431.23 - 386.08)KJ/kg$$

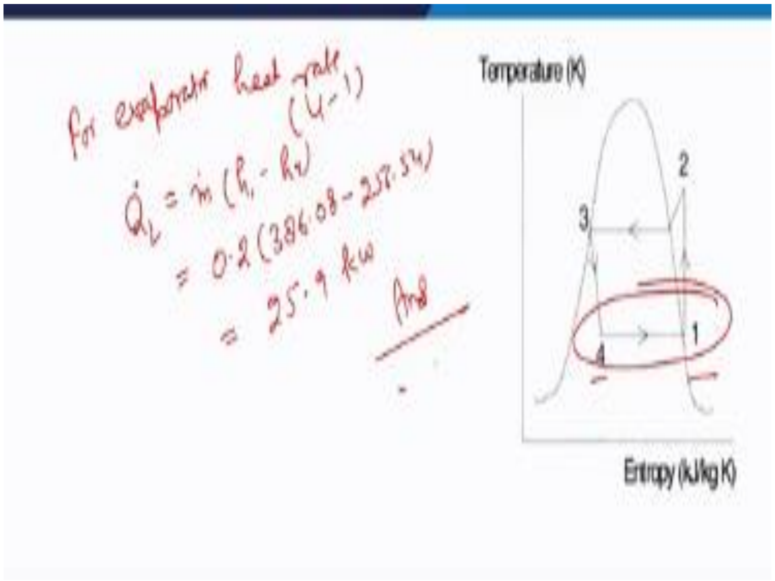
$$\dot{W} = 9.0\ kW$$

For condenser heat rate (2-3)

$$\dot{Q}_H = \dot{m}(h_2 - h_3)$$

$$\dot{Q}_H = 0.2(431.23 - 256.54))$$

$$\dot{Q}_H = 34.9\ kW$$



for evaporator heat rate (4-1)

$\dot{Q}_L = \dot{m}(h_1 - h_4)$

$= 0.2(386.08 - 256.54)$

$= 25.9\ kW$

Ans

Next stage is for evaporator heat rate that is 4 to station 1 to station 4 to station 1. So, this is Q L = m h 1 – h 4 so it is 0.2 into 386.08 – 256.54 and that is comes out to be 25.9 kilowatt.

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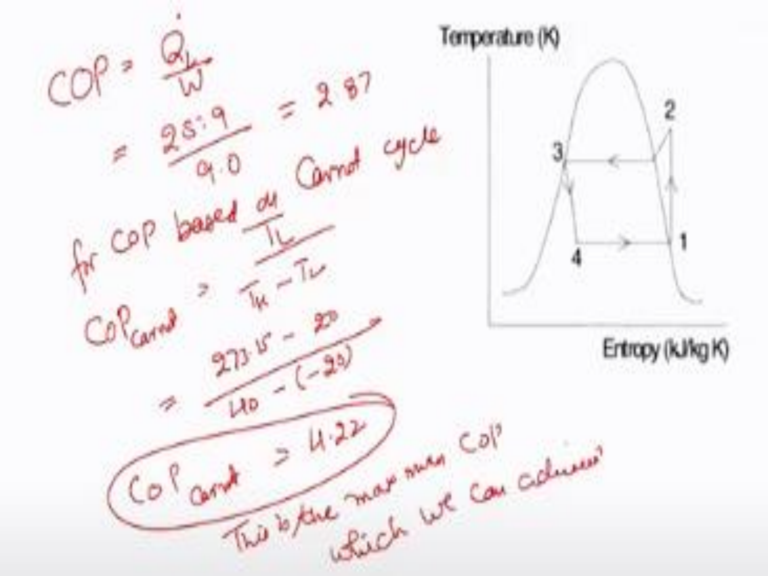
For evaporator heat rate (4-1)

$$\dot{Q}_L = \dot{m}(h_1 - h_4)$$

$$\dot{Q}_L = 0.2(386.08 - 256.54)$$

$$\dot{Q}_L = 25.9\ kW$$



$COP = \frac{\dot{Q}_L}{W}$

$= \frac{25.9}{9.0} = 2.87$

for COP based on Carnot cycle

$COP_{carnot} = \frac{T_L}{T_H - T_L}$

$= \frac{273.15 - 20}{40 - (-20)}$

$\boxed{COP_{carnot} = 4.22}$

This is the max max COP which we can achieve

So, the next stage is to calculate the coefficient of performance so as you know that the coefficient of performance cop that is Q L over W. So, if we write this is we have already calculated that is comes out that was 25.9 divided by 9 and it is 2.87. So, for COP based on Carnot cycle so is equal to T L upon T H – T L and that is 273.15 - 20 upon 40 - and – 20 so the COP Carnot is 4.22 now this is the maximum cop which we can achieve.

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The Coefficient of performance (COP)

$$\boldsymbol{COP = \frac{\dot{Q}_L}{\dot{W}}}$$

$$\boldsymbol{COP = \frac{25.9}{9.0} = 2.87}$$

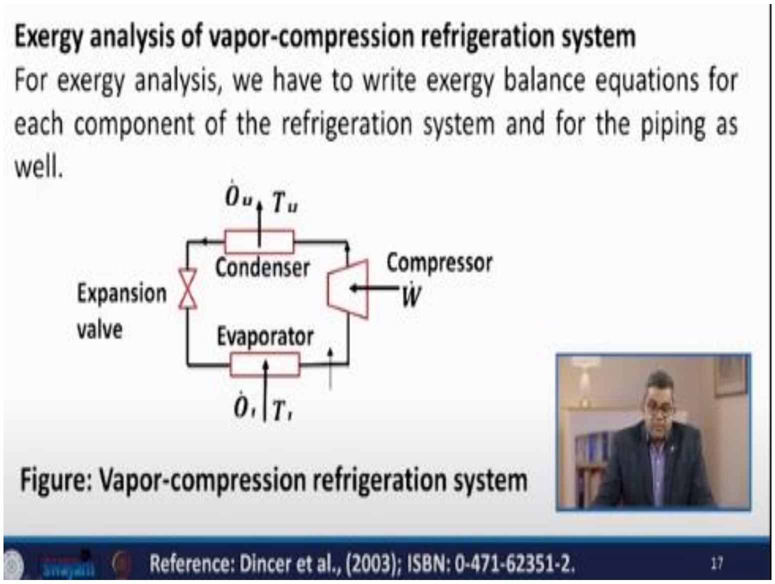
For COP based on Carnot cycle

$$\boldsymbol{COP = \frac{T_L}{T_H - T_L}}$$

$$\boldsymbol{COP = \frac{273.15 - 20}{40 - (-20)}}$$

$$\boldsymbol{COP = 4.22}$$

This is the maximum COP.



Exergy analysis of vapor-compression refrigeration system

For exergy analysis, we have to write exergy balance equations for each component of the refrigeration system and for the piping as well.

Figure: Vapor-compression refrigeration system

Reference: Dincer et al., (2003); ISBN: 0-471-62351-2.

Now let us talk about the exergy analysis of vapor compression refrigeration system. Now for exergy analysis we have to write exergy balance equation for each component of the refrigeration system and for the piping as well. Now here you see that again we are coming back to our vapor compression refrigeration system again the compressor condenser expansion valve and evaporator all these things are here.

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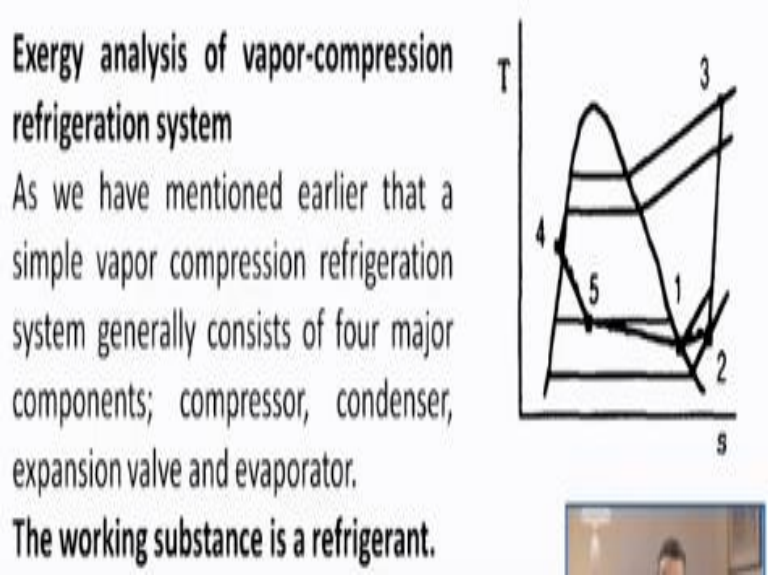

Exergy analysis of vapor-compression refrigeration system

As we have mentioned earlier that a simple vapor compression refrigeration system generally consists of four major components; compressor, condenser, expansion valve and evaporator.

The working substance is a refrigerant.

Now see when we perform the exergy analysis of vapor compression refrigeration system. Here you see that we have already mentioned that a simple vapor compression refrigeration system generally consists of four major operations. One is the compression that is attributed by the compressor, condensation that is with respect to the condenser, expansion through the expansion valve and evaporation through the evaporator now the working substance is a refrigerant.

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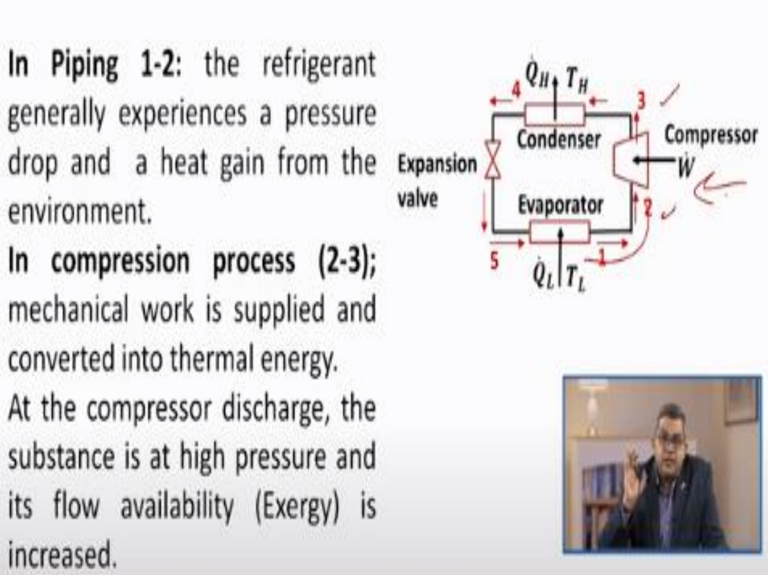

In Piping 1-2: the refrigerant generally experiences a pressure drop and a heat gain from the environment.

In compression process (2-3); mechanical work is supplied and converted into thermal energy.

At the compressor discharge, the substance is at high pressure and its flow availability (Exergy) is increased.

Now in piping from 1 to 2 the refrigerant generally experiences a pressure drop and heat gain from the environment. So, in the compression process of from station 2 to station 3 the mechanical work is supplied and converted into the thermal energy. So, at the compressor discharge the substance is at high pressure and its low availability that is exergy is increased.

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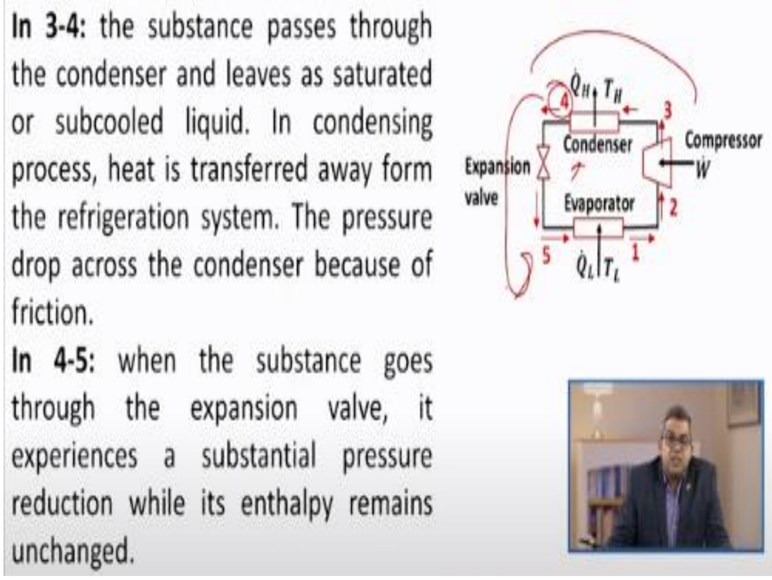

In 3-4: the substance passes through the condenser and leaves as saturated or subcooled liquid. In condensing process, heat is transferred away form the refrigeration system. The pressure drop across the condenser because of friction.

In 4-5: when the substance goes through the expansion valve, it experiences a substantial pressure reduction while its enthalpy remains unchanged.

Now if we go to station 3 to 4 the substance passes through the condenser this is the condenser now condenser and leaves as saturated or sub cooled liquid. Now in condensing process heat is transferred away or extracted away from the refrigeration system the pressure drops across the condenser because of the friction. Now if we go from station 4 to station 5 when the substance goes through the expansion valve it experiences a substantial pressure reduction while its enthalpy remains unchanged.

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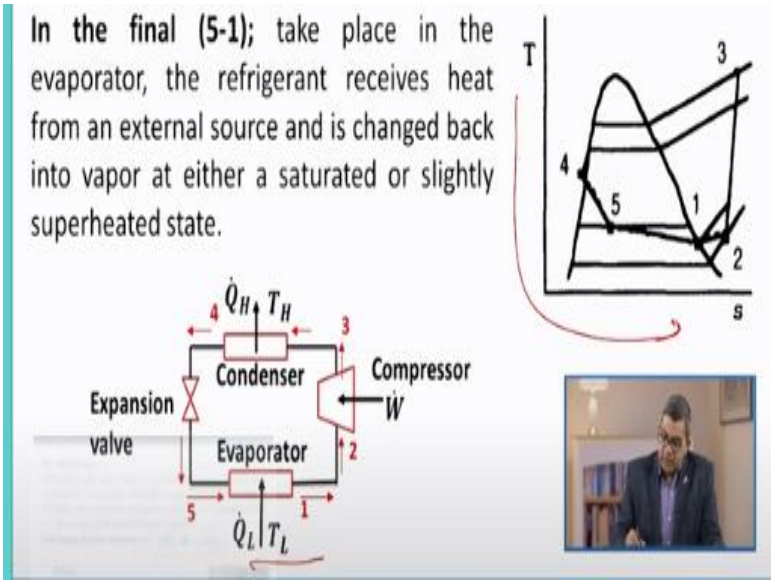

In the final (5-1); take place in the evaporator, the refrigerant receives heat from an external source and is changed back into vapor at either a saturated or slightly superheated state.

So, when we talk about the final system that is from station 5 to station 1. It takes place in evaporator and the refrigerant receives heat from an external source and is changed back into vapor at either a saturated or slightly superheated state. So, this reflects with respect to this T S diagram.

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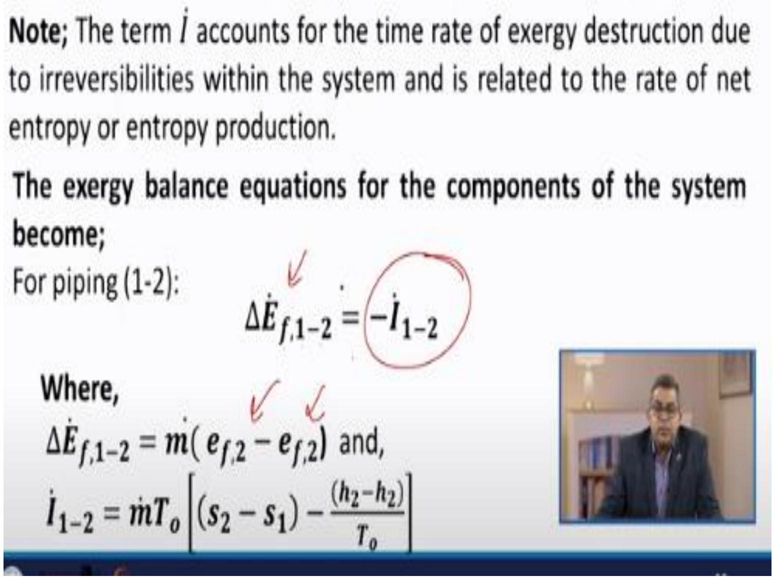

Note; The term $\dot{I}$ accounts for the time rate of exergy destruction due to irreversibilities within the system and is related to the rate of net entropy or entropy production.

The exergy balance equations for the components of the system become;

For piping (1-2):

$$\Delta\dot{E}_{f,1-2} = -\dot{I}_{1-2}$$

Where,

$$\Delta\dot{E}_{f,1-2} = \dot{m}(e_{f,2} - e_{f,2}) \text{ and,}$$

$$\dot{I}_{1-2} = \dot{m}T_0\left[(s_2 - s_1) - \frac{(h_2 - h_2)}{T_0}\right]$$

Now the term i accounts for the time rate of exergy destruction due to irreversibility's within the system and related to the rate of net entropy or entropy production. So, the exergy balance equation for the component of the system this becomes for piping between station 1 to 2 that it is delta E f 1 to 2 and it is - I 1 to 2. Now where delta E f 1 to 2 = m e f 2 - e and i 1 2 that is m T naught into S 2 - S 1 - h 2 - h 2 upon T naught.

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The exergy balance equations for the components of the system become;

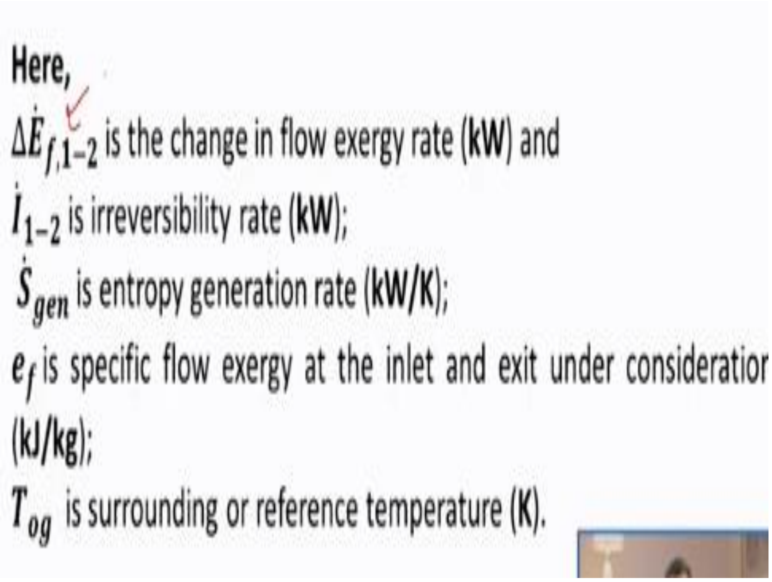
For piping (1-2):

$$\Delta\dot{E}_{f,1-2} \dot{=} -\dot{I}_{1-2}$$

Where,

$$\Delta\dot{E}_{f,1-2} = \dot{m}(\, e_{f,2} - e_{f,2}) \text{ and,}$$

$$\dot{I}_{1-2} = \dot{m}T_o\left[(s_2 - s_1) - \frac{(h_2 - h_2)}{T_o}\right]$$



Here,

$\Delta\dot{E}_{f,1-2}$ is the change in flow exergy rate (kW) and

$\dot{I}_{1-2}$ is irreversibility rate (kW);

$\dot{S}_{gen}$ is entropy generation rate (kW/K);

e_f is specific flow exergy at the inlet and exit under consideratio

(kJ/kg);

T_{og} is surrounding or reference temperature (K).

Now here this delta f 1 to 2 is the change in the flow exergy rate and it is having the unit of kilowatt and I 1 to 2 is the irreversibility rate from station 1 to 2 it again it is having the unit of kilowatt. And s gen is the entropy generation rate and that is kilo watt per kelvin. And e f is the specific flow f stands for flow so e f is the specific flow exergy in at the inlet and exit under the consideration.

And the unit of this e f is kilo joule per kilogram and T naught g is the surrounding or reference temperature and that is again having the unit of kelvin.

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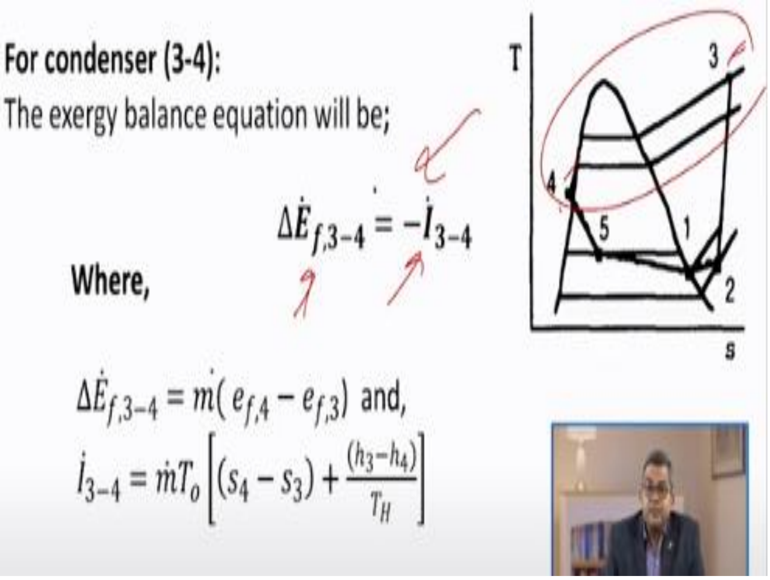


For condenser (3-4):

The exergy balance equation will be;

$$\Delta \dot{E}_{f,3-4} = -\dot{I}_{3-4}$$

Where,

$\Delta \dot{E}_{f,3-4} = \dot{m}(e_{f,4} - e_{f,3})$ and,

$\dot{I}_{3-4} = \dot{m}T_o\left[(s_4 - s_3) + \frac{(h_3-h_4)}{T_H}\right]$

Now let us talk about the compression from stage 2 to 3 now the exergy balance equation we can write as delta E f 2 to 3 that is equal to W - I 2 to 3 where delta f 1 to 2 2 = m e f 3 that is station 3 - E f 2 and I 2 to 3 = m T naught into S 3 - S 2 and W = m h 3 - h 2. Now if we take the condenser aspect from station 3 to 4 the exergy balance equation is represented as delta E f 3 to 4 = -I 3 to 4.

Now where delta E f 3 = m into E f 4 - E f 3 and I 3 to 4 = m T naught into S 4 - S 3 that is S 4 - S 3 in entropy station 4 - entropy station 3 + enthalpy at station 3 - h 4 that is enthalpy at station 4 upon T H.

(Refer Slide Time: 21:15)

For compressor (2-3):

The exergy balance equation will be;

$$\Delta \dot{E}_{f,2-3} = \dot{W} - \dot{I}_{2-3}$$

Where,

$\Delta \dot{E}_{f,1-2} = \dot{m}(e_{f,3} - e_{f,2})$ **and,**

$\dot{I}_{2-3} = \dot{m}T_o(s_3 - s_2)$ **and** $\dot{W} = \dot{m}(h_3 - h_2)$

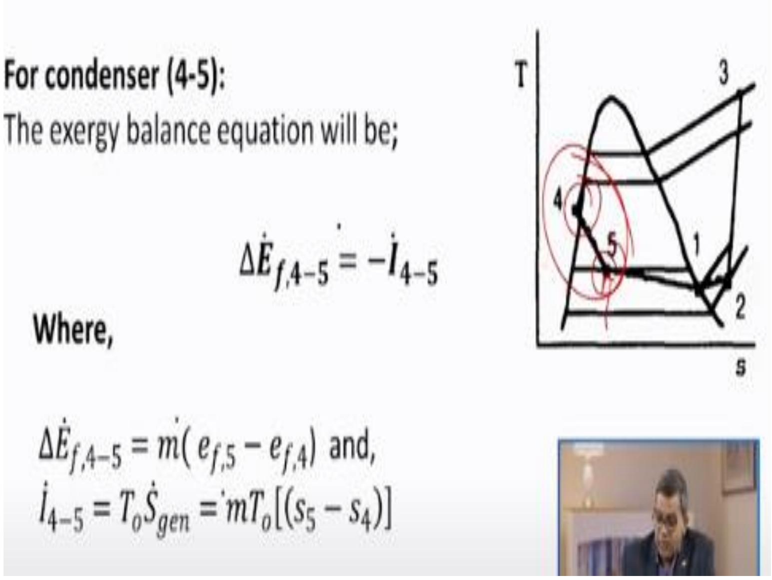
For condenser (3-4):

The exergy balance equation will be;

$$\Delta\dot{E}_{f,3-4} = -\dot{I}_{3-4}$$

Where,

$\Delta\dot{E}_{f,3-4} = \dot{m}(e_{f,4} - e_{f,3})$ **and,** $\dot{I}_{3-4} = \dot{m}T_o\left[(s_4 - s_3) + \frac{(h_3 - h_4)}{T_H}\right]$



For condenser (4-5):

The exergy balance equation will be;

$$\Delta\dot{E}_{f,4-5} = -\dot{I}_{4-5}$$

Where,

$\Delta\dot{E}_{f,4-5} = \dot{m}(e_{f,5} - e_{f,4})$ and,

$\dot{I}_{4-5} = T_0\dot{S}_{gen} = \dot{m}T_0[(s_5 - s_4)]$

Now if we talk about for the condenser between; 4 to 5 the exergy balance equation it will be delta f 4 to 5 = - i 4 to 5 where delta e f 4 to 5 = m e f at the station 5 - e f at station 4. And i 4 to 5 is t naught s gen and that is equal to m t naught s 5 that is entropy at station 5 - entropy at station 4 so these are the equations.

(Refer Slide Time: 21:57)

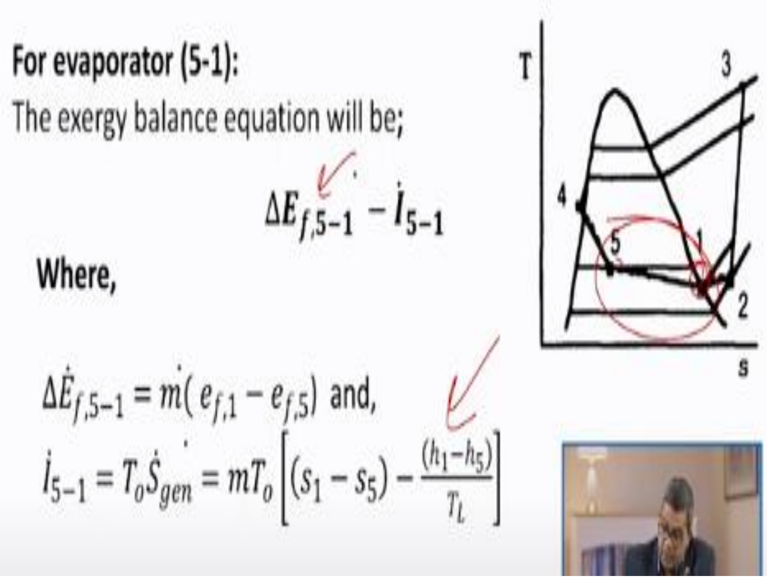
For condenser (4-5):

$$\Delta\dot{E}_{f,4-5} = -\dot{I}_{4-5}$$

Where,

$\Delta\dot{E}_{f,4-5} = \dot{m}(e_{f,5} - e_{f,4})$ **and,**

$$\dot{I}_{4-5} = T_o\dot{S}_{gen} = \dot{m}T_o[(s_5 - s_4)]$$



For evaporator (5-1):

The exergy balance equation will be;

$$\Delta E_{f,5-1} - \dot{I}_{5-1}$$

Where,

$$\Delta\dot{E}_{f,5-1} = \dot{m}(e_{f,1} - e_{f,5}) \text{ and,}$$

$$\dot{I}_{5-1} = T_0\dot{S}_{gen} = mT_0\left[(s_1 - s_5) - \frac{(h_1 - h_5)}{T_L}\right]$$

Now if we talk about the evaporator side that is station 5 to 1 the exergy balance equation 1 can write as delta e f 5 to 1 – I 5 to 1. Where delta E f 5 to 1 = m e f 1 - e f 5 and i 5 - 1 = t s 0 = m T naught S 1 - S 5 and that is the entropy at station 1 and station 5 respectively - h 1 - h 5 that is enthalpy at station 1 and station 5 respectively upon T L.

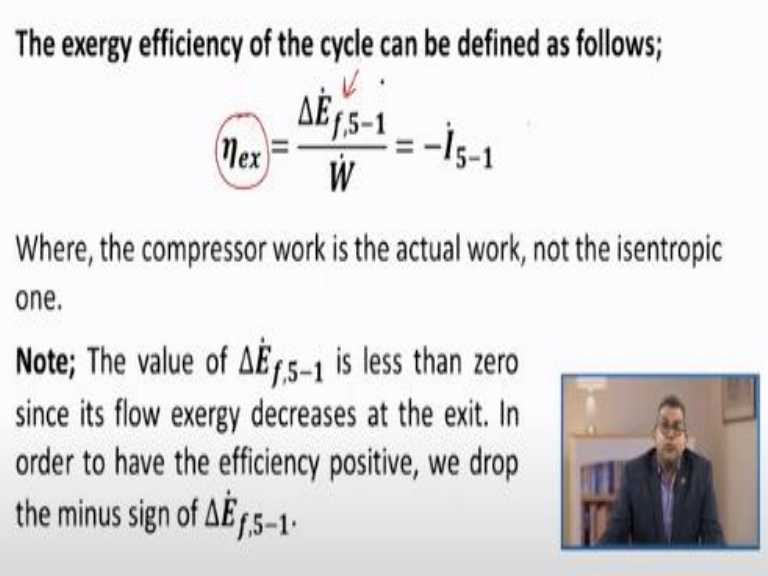
(Refer Slide Time: 22:44)

For evaporator (5-1):

$$\Delta \boldsymbol{E}_{f,5-1}\dot{} - \dot{\boldsymbol{I}}_{5-1}$$

Where,

$\Delta\dot{\boldsymbol{E}}_{f,5-1} = \dot{\boldsymbol{m}}(\,\boldsymbol{e}_{f,1} - \boldsymbol{e}_{f,5})$ **and,** $\dot{\boldsymbol{I}}_{5-1} = \boldsymbol{T}_o\dot{\boldsymbol{S}}_{gen}\dot{} = \boldsymbol{m}\boldsymbol{T}_o\left[(\boldsymbol{s}_1 - \boldsymbol{s}_5) - \frac{(\boldsymbol{h}_1 - \boldsymbol{h}_5)}{\boldsymbol{T}_L}\right]$



The exergy efficiency of the cycle can be defined as follows;

$$\eta_{ex} = \frac{\Delta \dot{E}_{f,5-1}}{\dot{W}} = -\dot{I}_{5-1}$$

Where, the compressor work is the actual work, not the isentropic one.

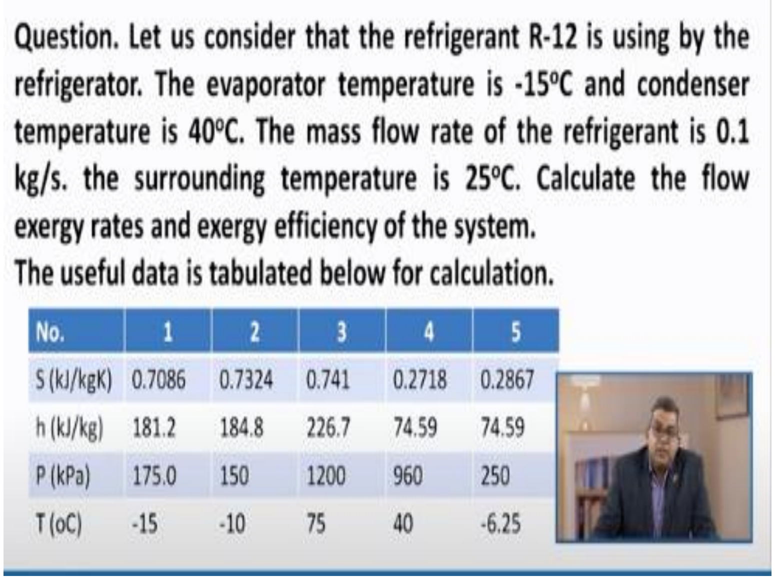
Note; The value of $\Delta \dot{E}_{f,5-1}$ is less than zero since its flow exergy decreases at the exit. In order to have the efficiency positive, we drop the minus sign of $\Delta \dot{E}_{f,5-1}$.

So, the exergy efficiency of the cycle this can be defined as eta exergy delta E f 5 to 1 upon w and its equal to - I 5 to 1 where the compressor work is the actual work and not the isentropic one. So, the value of delta E f 5 to 1 is less than 0 since its flow exergy decreases at the exit and in order to have the efficiency positive, we drop the minus sign for this delta E f 5 to 1.

(Refer Slide Time: 23:21)

The exergy efficiency of the cycle can be defined as follows;

$$\boldsymbol{\eta_{ex} = \frac{\Delta \dot{E}_{f,5-1}}{\dot{W}} = -\dot{I}_{5-1}}$$



Question. Let us consider that the refrigerant R-12 is using by the refrigerator. The evaporator temperature is -15°C and condenser temperature is 40°C. The mass flow rate of the refrigerant is 0.1 kg/s. the surrounding temperature is 25°C. Calculate the flow exergy rates and exergy efficiency of the system.

The useful data is tabulated below for calculation.

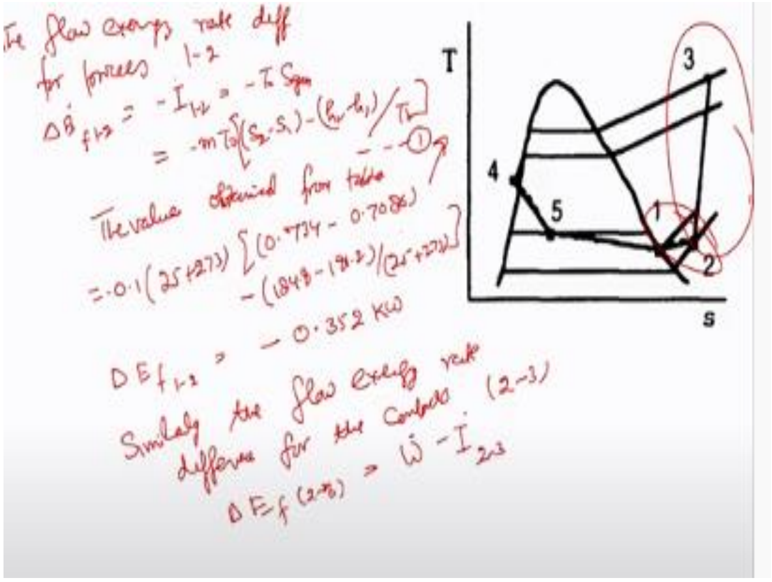
No.	1	2	3	4	5
S (kJ/kgK)	0.7086	0.7324	0.741	0.2718	0.2867
h (kJ/kg)	181.2	184.8	226.7	74.59	74.59
P (kPa)	175.0	150	1200	960	250
T (oC)	-15	-10	75	40	-6.25

Now it is time to have another numerical problem now here let us consider that a refrigerant R 1 2 is using by the refrigerator and the evaporator temperature is -15 degree Celsius and condensing temperature is 40 degrees Celsius. The mass flow rate of the refrigerant is 0.1 kilogram per second the surrounding temperature is 25 degrees Celsius. So, you need to calculate the flow exergy rates and exergy efficiency of the system.

We have given some useful data in the tabulated form for different stages like 1, 2, 3, 4 and 5 and the entropy in kilojoule per kilogram kelvin. Now you see again the same aspect we have applied the if you see that enthalpy kilojoule per kilogram and the stage 4 and stage 5, they are having the isenthalpic operation and they are having the enthalpy of 74.59 each. Apart from this stage 1 is having the enthalpy of 181.2 and stage 2 and 3 they are having the enthalpy of 184.8 and 226.7 respectively.

Similarly, if you talk about the pressure which is represented in kilopascal so all the stage 1, 2, 3, 4 and 5 they are having 175, 150, 1200, 960 and 250 respectively. Now if we see that the temperature profiling that is temperature is represented in degree Celsius. So, stage 1 is having the temperature of -15-degree Celsius stage 2 is having the temperature of -10 and stage 3, 75 and stage 4 is having 40-degree Celsius temperature and stage 5 is having -6.25-degree Celsius temperature.

(Refer Slide Time: 25:24)



The flow exergy rate diff for process 1-2

$$\Delta \dot{E}_{f1-2} = -\dot{I}_{1-2} = -T_0 S_{gen}$$

$$= -\dot{m} T_0 \left[(s_2 - s_1) - (h_2 - h_1)/T_L\right] \text{ --- ①}$$

The value obtained from table

$$= -0.1(25+273)\left[(0.7734 - 0.7086) - (184.8 - 181.2)/(25+273)\right]$$

$$\Delta E_{f1-2} = -0.352 \text{ kW}$$

Similarly the flow exergy rate difference for the compressor (2-3)

$$\Delta E_{f(2-3)} = \dot{W} - \dot{I}_{2-3}$$

So let us solve this problem now the flow exergy rate difference for process 1 to 2 so delta E = - I 1 to 2 and that is T naught. And this is m T naught S 2 - S 1 - h 2 - s 1 upon t naught that is equation number 1. So, we are having the values obtained from table and if you substitute the value in this particular equation we get - 0.1 into 25 + 273 into 0.734 - 0.7086 - 184.8 - 181.2 divided by 25 + 273.

So, delta E f from station 1 to 2 is comes out to be -0.352 kilowatt. Now similarly the flow exergy rate difference for the compressor that is from 2 to 3 so delta E f from 2 to 3 that is as per the discussion 2 to 3.

(Refer Slide Time: 27:34)

The exergy balance equations for the components of the system become;

For piping (1-2):

$$\Delta \dot{E}_{f,1-2} = -\dot{I}_{1-2}$$

Where,

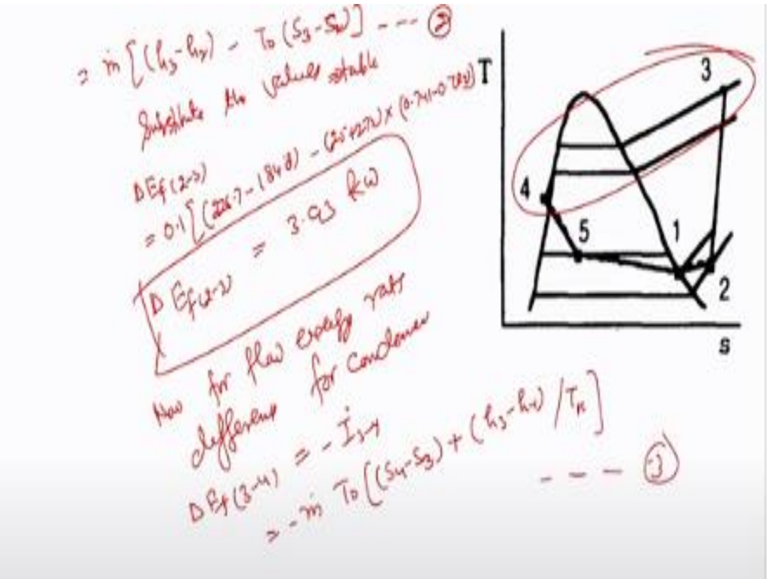
$\Delta \dot{E}_{f,1-2} = \dot{m}(e_{f,2} - e_{f,2})$ and,

$$\dot{I}_{1-2} = \dot{m}T_o\left[(s_2 - s_1) - \frac{(h_2 - h_1)}{T_o}\right]$$

The values obtained from the table

$$\Delta \dot{E}_{f,1-2} = 0.1 \times (25 + 273)\left[(0.734 - 0.7086) - \frac{(184.8 - 181.2)}{(25 + 273)}\right]$$

$$\Delta \dot{E}_{f,1-2} = -0.352\ kW$$


$= \dot{m}[(h_3 - h_2) - T_0(S_3 - S_2)]$ --- ②

Substitute the values of table

$\Delta E_{f(2-3)} = 0.1[(226.7 - 184.8) - (25+273) \times (0.741 - 0.7324)]$

$\Delta E_{f(2-3)} = 3.93$ kW

Now for flow exergy rate difference for condenser

$\Delta E_{f(3-4)} = -\dot{I}_{3-4}$

$= -\dot{m}\, T_0[(S_4 - S_3) + (h_3 - h_4)/T_H]$ --- ③

Now here if we expand this mathematical relation so it comes out to be h 3 - h 2 - T naught S 3 - S 2 that is equation number 2. So, if we substitute the values which is given in the table so we have delta e f from 2 to 3 that is 0.1 into 226.7 - 184.8 - 25 + 273 into 741 - 0.7324 so it comes out to be e f 2 to 3, 3.93 kilowatt. Now for flow exergy rate difference for condenser that is E f 3 to 4 = -I 3 to 4 and that is - m T naught S 4 S 3 + h 3 and that is equation number 3.

(Refer Slide Time: 29:21)

Similarly the flow exergy rate difference for the compressor

$$\Delta \dot{E}_{f,2-3} \overset{\cdot}{=} \dot{W} - \dot{I}_{2-3}$$

Where,

$\Delta \dot{E}_{f,1-2} = \dot{m}(e_{f,3} - e_{f,2})$ and,

$\dot{I}_{2-3} = \dot{m}T_o(s_3 - s_2)$ **and** $\dot{W} = \dot{m}(h_3 - h_2)$

$$\Delta \dot{E}_{f,2-3} = \dot{m}(h_3 - \dot{h}_2) - \dot{m}T_o(s_3 - s_2)$$

$$\Delta \dot{E}_{f,2-3} = 0.1(226.7 - 184.8) - 0.1(25 + 273)(0.741 - 0.7324)$$

$$\Delta \dot{E}_{f,2-3} = 3.93\ kW$$

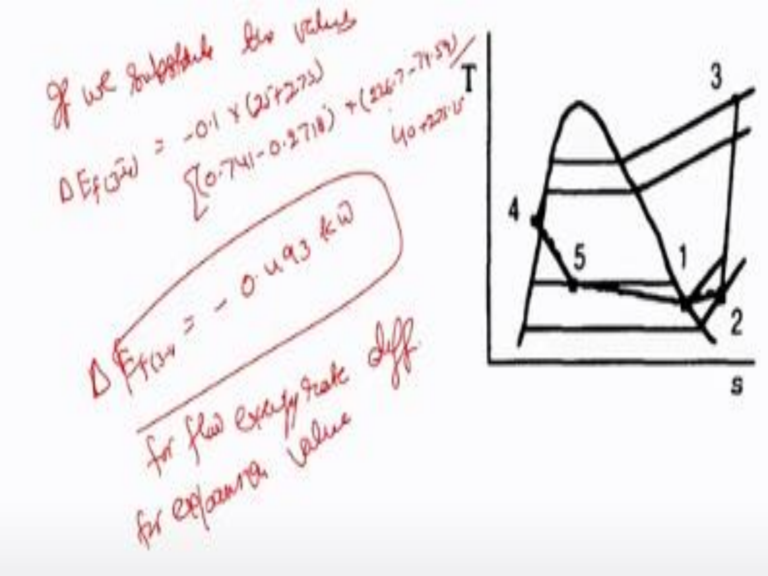
Similarly the flow exergy rate difference for the condenser

$$\Delta \dot{E}_{f,3-4} \overset{\cdot}{=} -\dot{I}_{3-4}$$

Where,

$\Delta \dot{E}_{f,3-4} = \dot{m}(\,e_{f,4} - e_{f,3})$ *and,*

$$\Delta \dot{E}_{f,3-4} = I_{3-4} = \dot{m}T_o\left[(s_4 - s_3) + \frac{(h_3 - h_4)}{T_H}\right]$$



If we substitute the values

$\Delta E_{f(3-4)} = -0.1 \times (25+273) \left[(0.741-0.2718) + \frac{(226.7-74.59)}{40+273.15}\right]$

$\boxed{\Delta E_{f(3-4)} = -0.493\ kW}$

for flow exergy rate diff
for expansion value

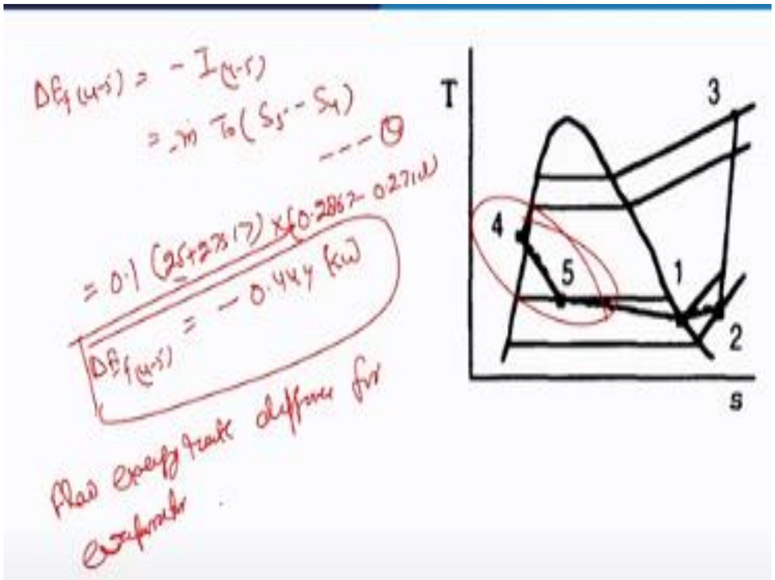
So, if we substitute the values from the table so it comes out to be e f 3 to 4 and that is -0.1 into 25 + 273 multiplied by 0.741 - 0.2718 + 226.7 – 74.59 divided by 40 + 273.15. So, delta E f 3 to 4 comes out to be - 0.493 kilo watt now for flow exergy rate difference for expansion valve.

(Refer Slide Time: 30:36)

On substituting the values in the above equation, we have

$$\Delta \dot{E}_{f,3-4} = I_{3-4} = -0.1 \times (25 + 273)\left[(0.741 - 0.2718) + \frac{(226.7 - 74.59)}{(40 + 273.15)}\right]$$

$$\Delta \dot{E}_{f,3-4} = I_{3-4} = -0.493\ kW$$



$\Delta E_{f(4-5)} = -I_{(4-5)}$

$= -\dot{m} T_0 (S_5 - S_4)$ ---④

$= 0.1 (25+273.17) \times (0.2867 - 0.2718)$

$\boxed{\Delta E_{f(4-5)} = -0.444 \text{ kW}}$

Flow exergy rate differs for evaporator.

So, this is between this one so delta E f 4 to 5 = - I 4 to 5 and that is - m T naught S 5 - S 4 and that is equation number 4. So, if you substitute the value then it comes out to be 0.1 into 25 + 273.17 into 0.2867 - 0.2718 and delta E f 4 to 5 = -0.444 watt.

(Refer Slide Time: 31:43)

For condenser (4-5):

The exergy balance equation will be;

$$\Delta \dot{E}_{f,4-5} = -\dot{I}_{4-5}$$

Where,

$\Delta \dot{E}_{f,4-5} = \dot{m}(e_{f,5} - e_{f,4})$ **and,**

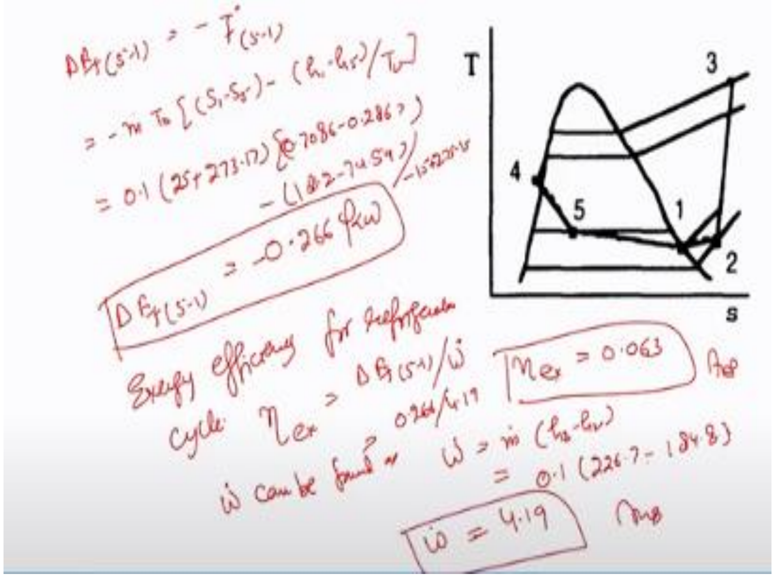
$$\dot{I}_{4-5} = T_o \dot{S}_{gen} = \dot{m} T_o [(s_5 - s_4)]$$

On substituting the values, we have;

$$\Delta \dot{E}_{f,4-5} = T_o \dot{S}_{gen} = \dot{m} T_o [(s_5 - s_4)]$$

$$\Delta \dot{E}_{f,4-5} = T_o \dot{S}_{gen} = 0.1 \times (25 + 273.15)[(0.2867 - 0.2718)]$$

$$\Delta \dot{E}_{f,4-5} = -0.444 \; kW$$



$\Delta E_{f(5-1)} = -\dot{I}_{(5-1)}$

$= -\dot{m}\, T_0 \left[(s_1 - s_5) - (h_1 - h_5)/T_L \right]$

$= 0.1\,(25 + 273.17)\{(0.7086 - 0.2867) - (182 - 74.59)/(-15+273.15)\}$

$\boxed{\Delta E_{f(5-1)} = -0.266 \text{ kW}}$

Exergy efficiency for refrigeration cycle: $\eta_{ex} = \Delta E_{f(5-1)}/\dot{W}$ $= 0.266/4.19$ $\boxed{\eta_{ex} = 0.063}$ Ans

$\dot{W}$ can be found as $\dot{W} = \dot{m}\,(h_3 - h_2)$ $= 0.1\,(226.7 - 184.8)$

$\boxed{\dot{W} = 4.19}$ Ans

So, the flow exergy rate difference for evaporator can be written as delta E f 5 to 1, 5 to 1 and that is T naught S 1 - S 5 - h 1 - h 5 upon t l and that is 0.1, 25 + 273.17 into 0.7086 - 0.2867 all these values are given in the question itself. So, 181.2 - 74.59 divided by - 15 + 273.15 so delta E f from 5 to 1 it comes out to be - 0.266 kilowatt. So, the exergy efficiency for refrigeration cycle is given by exergy delta E f 5 to 1 w and that is 0.266 upon 4.19.

So, this is 0.063 now we can be found out as w = m h 3 – h 2 and that is 0.1 into 226.7 - 184.8 so w = 4.19 and that is the answer. So, in this particular lecture we had discussed about the energy analysis and exergy analysis with reference to the vapor compression refrigeration cycle.

(Refer Slide Time: 34:04)

For evaporator (5-1):

The exergy balance equation will be;

$$\Delta \boldsymbol{E}_{f,5-1}^{\cdot} - \dot{\boldsymbol{I}}_{5-1}$$

Where,

$\Delta\dot{E}_{f,5-1} = \dot{m}(\, e_{f,1} - e_{f,5})$ and,

$$\dot{I}_{5-1} = T_o\dot{S}_{gen}^{\cdot} = mT_o\left[(s_1 - s_5) - \frac{(h_1 - h_5)}{T_L}\right]$$

$$\Delta\dot{E}_{f,5-1} = \mathbf{0.1 \times (25 + 273.15)\left[(0.7086 - 0.2867) - \frac{181.2 - 74.59}{-15 + 273.15}\right]}$$

$$\Delta\dot{E}_{f,5-1} = -0.266\ kW$$

The exergy efficiency of the cycle can be defined as follows;

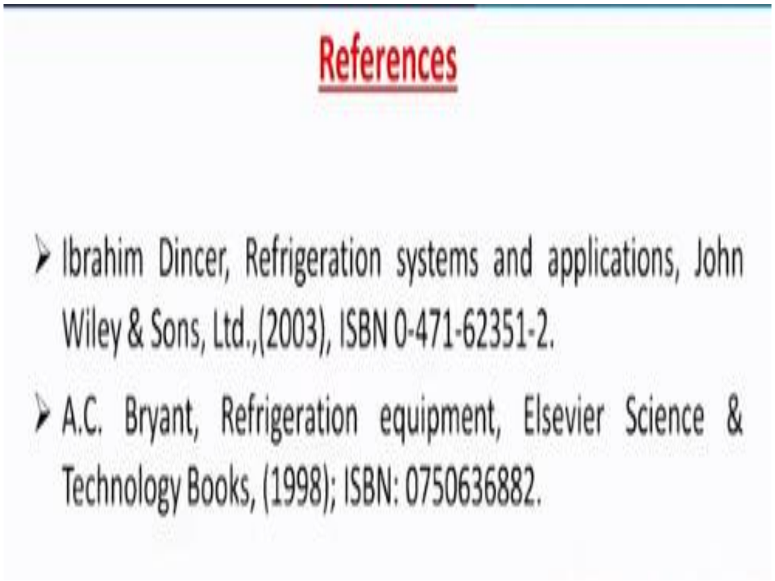
$$\boldsymbol{\eta_{ex} = \frac{\Delta\dot{E}_{f,5-1}}{\dot{W}} = -\dot{I}_{5-1}}$$

$$\boldsymbol{\eta_{ex} = \frac{0.266}{4.19} = 0.063}$$

Where, work can be found by

$$\boldsymbol{\dot{W} = \dot{m}(h_3 - h_2)}$$

$$\boldsymbol{\dot{W} = 0.1(266.7 - 184.8) = 4.19}$$



References

- Ibrahim Dincer, Refrigeration systems and applications, John Wiley & Sons, Ltd.,(2003), ISBN 0-471-62351-2.
- A.C. Bryant, Refrigeration equipment, Elsevier Science & Technology Books, (1998); ISBN: 0750636882.

So, for convenience we have listed references and if anyone wishes to go in detail about this vapor compression representation cycle, they can utilize these references for their convenience thank you very much.