Chemical Engineering Thermodynamics
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Indian Institute of Technology Kanpur
Lecture - 17
Power cycles and examples

Welcome back. In today's lecture I am going to cover power cycles. This will be the last lecture on series of the Second Law of Thermodynamics which we are trying to revise, related to the Engineering Thermodynamic aspects of the course.

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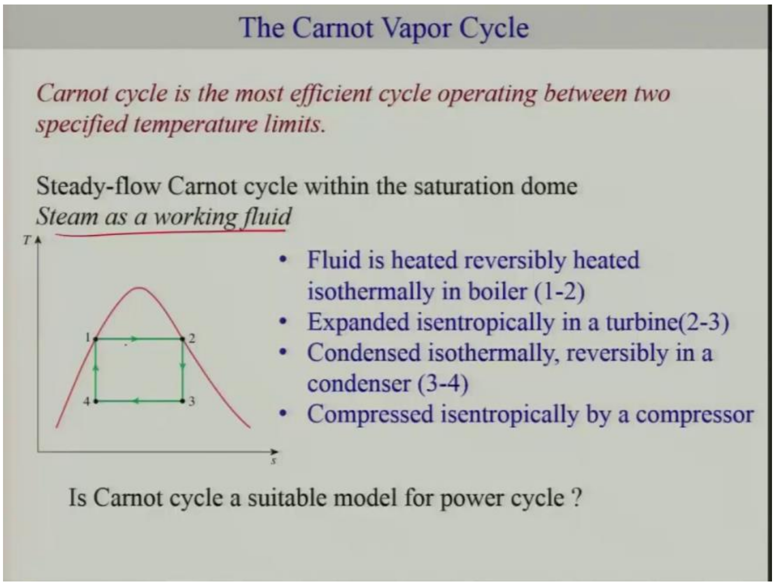

The Carnot Vapor Cycle

Carnot cycle is the most efficient cycle operating between two specified temperature limits.

Steady-flow Carnot cycle within the saturation dome

Steam as a working fluid

- Fluid is heated reversibly heated isothermally in boiler (1-2)
- Expanded isentropically in a turbine(2-3)
- Condensed isothermally, reversibly in a condenser (3-4)
- Compressed isentropically by a compressor

Is Carnot cycle a suitable model for power cycle ?

So, we have discussed earlier about the Carnot cycle which apparently is the most efficient cycle between two specified thermodynamic limits but here we have tried to use something of that order of gases.

But if you consider the working fluid where there is a phase transition along the process then one can consider again this Carnot cycle within dome of the phase transition. So, this is typically the diagram of T and s, and this would be your Carnot cycle considering your isothermal and adiabatic processes. So, this is a case for the steam as the working fluid.

Now, this has an issue, particularly if you consider this as the specific cycle where you have this liquid to gas vaporization then you have expansion and then again some kind of condensation and you have compression as isentropic. So if you consider this thing the question is that, is it a suitable model for power cycle that is a cycle which generates power? So that could be what typically we consider in a steam-based power plant, okay.

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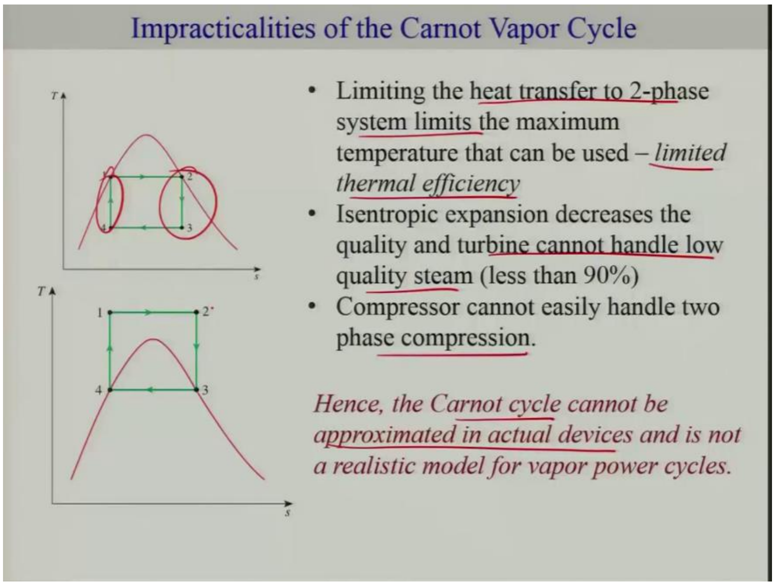

Impracticalities of the Carnot Vapor Cycle

- Limiting the heat transfer to 2-phase system limits the maximum temperature that can be used – *limited thermal efficiency*
- Isentropic expansion decreases the quality and turbine cannot handle low quality steam (less than 90%)
- Compressor cannot easily handle two phase compression.

Hence, the Carnot cycle cannot be approximated in actual devices and is not a realistic model for vapor power cycles.

So there are impracticality associated with considering such a Carnot cycle, we call it Carnot Vapor cycle, the reason is that it limits, when you consider these 2 points here that means the phase transition or the latent heat along this transition is equivalent to the heat which you can get or that means it limits the heat transfer because this will be your simply delta h. Now that is clearly one of the limits. So that means you, it has a limited thermal efficiency because of these constraints. Other issue is that the turbine cannot handle low quality steams, okay.

The second is the compressor cannot easily handle two phase compression which is the case here. Though the Carnot cycle we talked about is the most efficient cycle but when it comes to the power cycles the Carnot cycle cannot be approximated in actual device and certainly not realistic model in this case, okay. So you cannot just have 4 processes of isothermal and adiabatic form in the way we have learned as far as that is concerned.

So what we do? We try to modify bit of that and that is we can do that, we can play with, bring 1 to 2 process at very high end to avoid this phase transitions we can play with that, okay.

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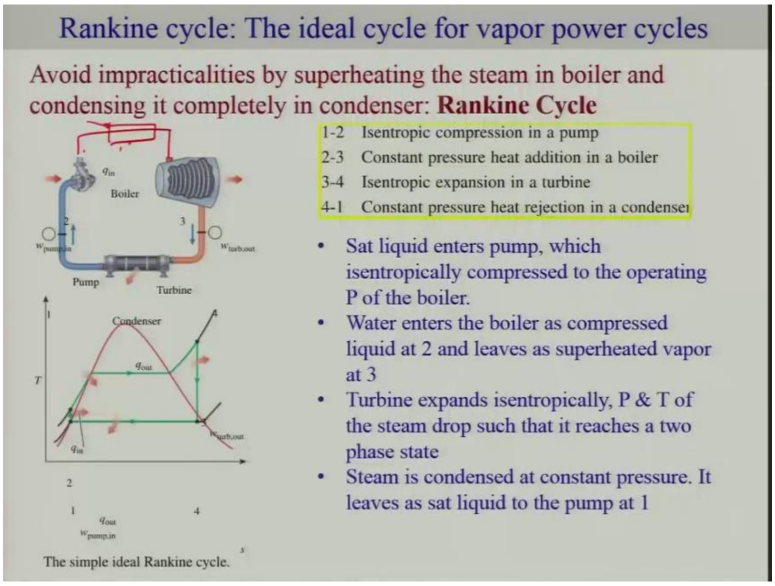

Rankine cycle: The ideal cycle for vapor power cycles

Avoid impracticalities by superheating the steam in boiler and condensing it completely in condenser: **Rankine Cycle**

1-2 Isentropic compression in a pump
2-3 Constant pressure heat addition in a boiler
3-4 Isentropic expansion in a turbine
4-1 Constant pressure heat rejection in a condenser

- Sat liquid enters pump, which isentropically compressed to the operating P of the boiler.
- Water enters the boiler as compressed liquid at 2 and leaves as superheated vapor at 3
- Turbine expands isentropically, P & T of the steam drop such that it reaches a two phase state
- Steam is condensed at constant pressure. It leaves as sat liquid to the pump at 1

The simple ideal Rankine cycle.

But the better one is cycles designed as Rankine cycle which is the ideal cycle for vapor power cycles, okay. So here what we have is we have a system. So this should be this, okay and there is a boiler here, okay which brings in the q in. So this represents the Rankine cycle set of devices and processes. So, so we do not want to do the solution which we have offered.

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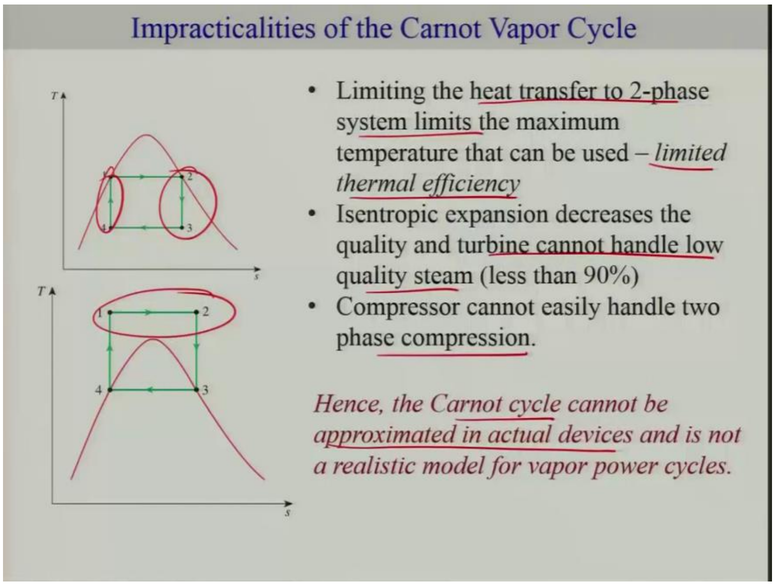

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Hence, the Carnot cycle cannot be approximated in actual devices and is not a realistic model for vapor power cycles.

And possibly heating to super heating that means you are operating at much, much higher pressure for the boiler which can cost a lot of money.

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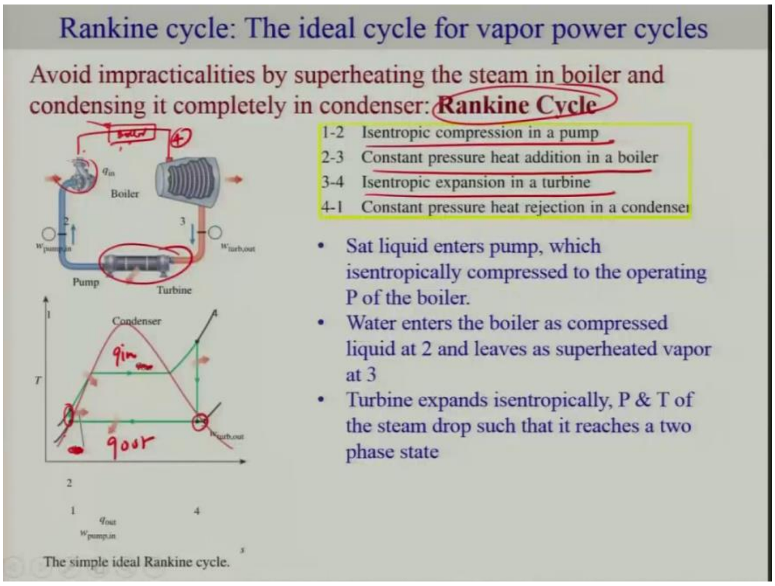

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The simple ideal Rankine cycle.

And basically it could be inefficient process in the end. So here what is done is differently, so if we look at the system here, the set of processes so let us look at, start with the pump here, okay. So here, the saturated liquid enters the pump so the corresponding 2 is somewhere here. So this is your 2 here, okay so this is the 2 part, this is the 1 to 2 is your basically pump here, so the numbers have got messed up but let me try to explain this.

So this is the point because saturated liquid enters the pump, okay. The pump is this, so this is the saturated liquid line; so this is the saturated liquid line, this is the saturated vapor line. From here it went to the higher pressure line. This is the higher pressure line, okay and this is the pressure of the boiler also. So this goes to the boiler at that pressure and then that heat is being supplied to the boiler which is your q in, okay so it appears little bit shift in these values so this must be q in, okay and this one is basically your q out, okay.

So q in is being provided here. So this goes to the superheated region and that is where the 4 is here and this is where it is basically given to the turbine where this fluid expands, the steam basically expands and what you get is something this point which has a very close to the saturation line, okay. And then it gets condensed to the saturated liquid part here okay so this is the complete cycle. So this is what we call it Rankine cycle.

This is something which you have already went through in the last, in your Engineering Thermodynamics class. If not, we will try to do some examples on it. So if you look at this 1 to 2, is an isentropic compression in the pump. Pumps operate at a constant entropy, okay so this is the pump, constant entropy then constant pressure heat addition in the boiler. So heat is at a constant pressure. This is the boiler.

Then isentropic expansion in the turbine, so turbine here gets expanded, the gas here gets expanded; the steam here gets expanded in the turbine and the constant pressure heat rejection in the condenser. So this is the constant pressure. So that is what you look at it, okay. So this is a complete cycle here. This is an ideal Rankine cycle relevant for your steam engines, okay.

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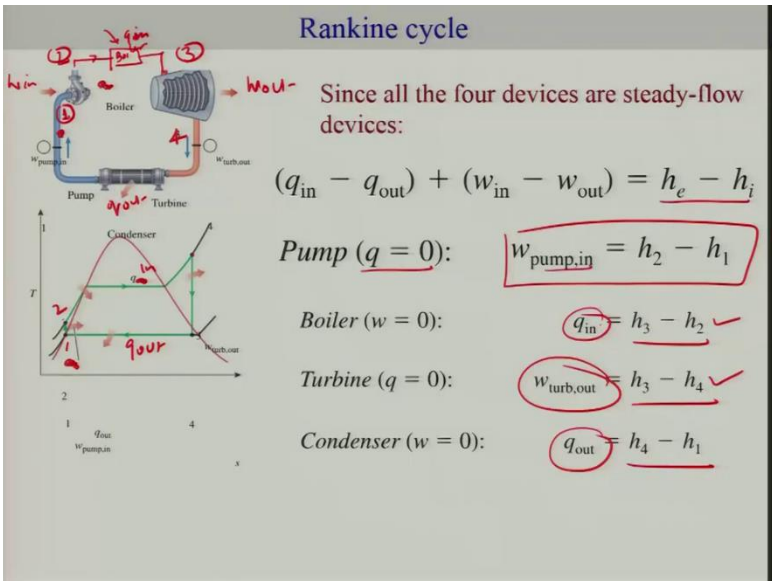

Rankine cycle

Since all the four devices are steady-flow devices:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \underline{h_e - h_i}$$

$$\text{Pump } (\underline{q = 0}): \quad \boxed{w_{\underline{pump,in}} = h_2 - h_1}$$

$$\text{Boiler } (w = 0): \quad q_{in} = \underline{h_3 - h_2} \checkmark$$

$$\text{Turbine } (q = 0): \quad w_{turb,out} = \underline{h_3 - h_4} \checkmark$$

$$\text{Condenser } (w = 0): \quad q_{out} = \underline{h_4 - h_1}$$

So one can now apply energy balances on each of the devices. Again this is something missed out here. So this is a boiler, okay. So this is the boiler, okay and this is heat being provided, q in okay and this is your q out. So, if you apply energy balance then essentially it will be something like this, because of the fact that this is a flow system.

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

So the fluid keeps flowing and hence you have to look into delta h here. So for the case of pump, the q is 0. It is adiabatic, that is why we consider this isentropic process.

$$Pump\ (q = 0){:}\, w_{pump,in} = h_2 - h_1$$

For the case of boiler the work is 0 and hence, I am going to consider the q in okay, q out is of course we consider 0.

$$Boiler\ (w = 0){:}\;\; q_{in} = h_3 - h_2$$

$$Turbine\ (q = 0):\quad w_{turb,out} = h_3 - h_4$$

$$Condenser\ (w = 0): q_{out} = h_4 - h_1$$

So that is the right-hand side part. The left-hand side of course, if you look at the turbine, it is q in, the turbine is the w out and boiler is q in and condenser is q out.

So this is a basic energy balance. If you put it down there it should be okay. So this, you can ignore, because there is some change in the or shift in the values which was put in here because of the compatibility issues, okay anyway so I hope you will understand, so again let me just revise just to make sure we are on the same page. So you have a pump, you have boiler, you have a turbine, you have a condenser.

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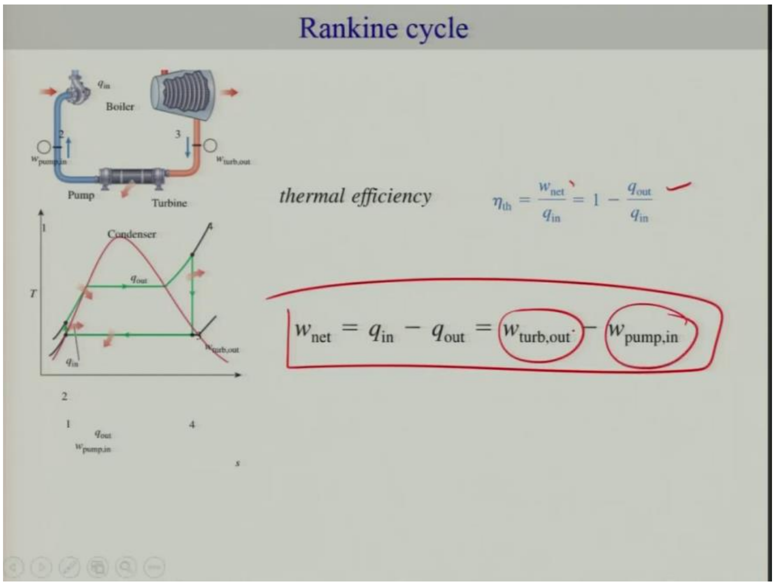

Rankine cycle

thermal efficiency $\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

Now, in order to find the thermal efficiency we know that w net divided by q in is the efficiency and this is something which we know that. We can use the total energy balance of the system.

$$thermal\ efficiency, \qquad \eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

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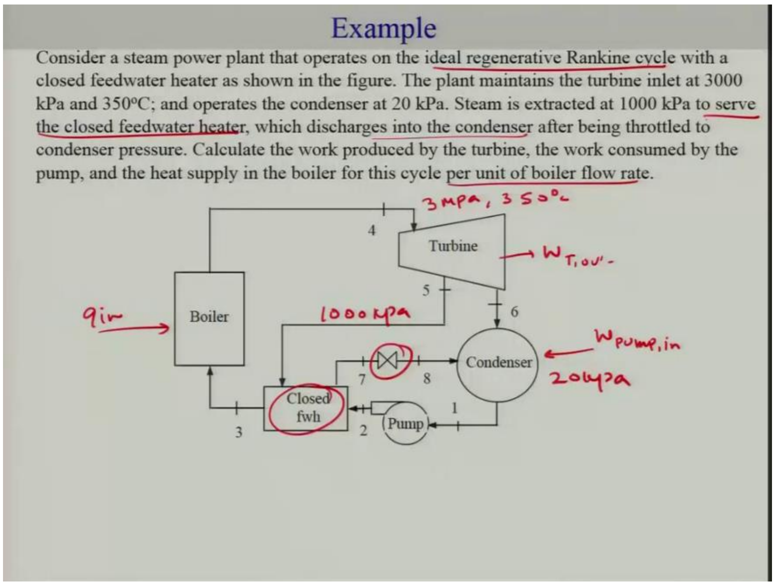

Example

Consider a steam power plant that operates on the ideal regenerative Rankine cycle with a closed feedwater heater as shown in the figure. The plant maintains the turbine inlet at 3000 kPa and 350°C; and operates the condenser at 20 kPa. Steam is extracted at 1000 kPa to serve the closed feedwater heater, which discharges into the condenser after being throttled to condenser pressure. Calculate the work produced by the turbine, the work consumed by the pump, and the heat supply in the boiler for this cycle per unit of boiler flow rate.

So that is something based on simple energy balance. So let us now try to solve a problem which is the usual regenerative ideal Rankine cycle problem which is considered, so this is little complicated, not the straight problem, but I thought this is a good problem where you can consider all aspect of what we do in such kind of power cycle analysis. So, this is a steam power plant that operates on the ideal regenerative Rankine cycle.

Now, with the closed feedwater heater, okay as shown in the figure. The plant maintains the turbine inlet, okay. So, it maintains the turbine inlet. Turbine inlet is 4 at 3 mega Pascal right or 300 kilo Pascal and 350 degree Celsius and it operates the condenser at 20 kilo Pascal. Steam is extracted at 1000 kilo Pascal so to serve the closed feedback feedwater heater. So, this is the feedwater heater.

So, it is at this, which discharged into the condenser after, discharged okay so this comes here in the closed water heater which is nothing but the heat exchanger kind of thing, okay where it is here but it goes up there and then is put back into the condenser. But then if you look at it there is a valve here which basically is nothing but expansion valve. So it is throttled, okay to the condenser pressure. So the pressure remains same, but here the pressure gets changed to that of the condenser, okay.

So calculate the work produced by the turbine, the work consumed by the pump and the heat supplied in the boiler for this cycle. Basically you have to do all analysis of it. So have to find w T out, you have to find condenser pump in, okay and you have to find the q in also, okay for this cycle per unit of the boiler flow rate. So assuming some, you know simple flow rate, we will be considering that, okay.

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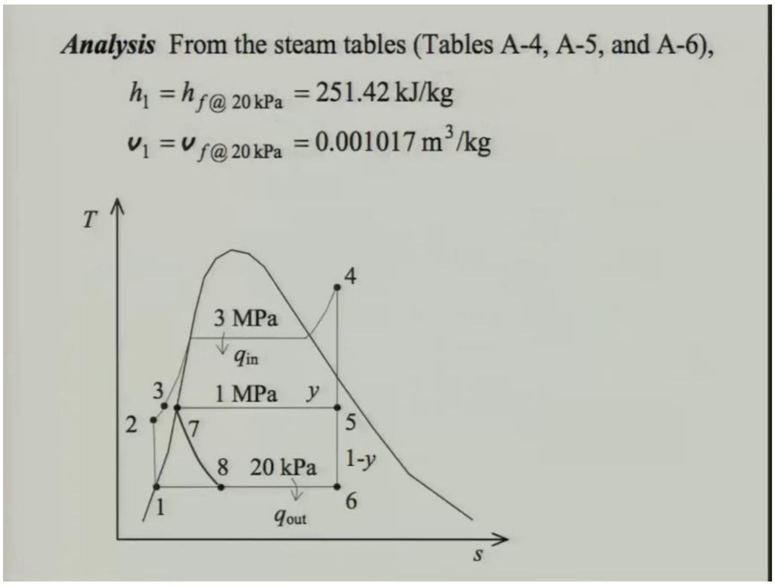

Analysis From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,20\,\text{kPa}} = 251.42\ \text{kJ/kg}$$

$$v_1 = v_{f@\,20\,\text{kPa}} = 0.001017\ \text{m}^3/\text{kg}$$

So let us look at it very carefully. So what we have is, if you look at it I have drawn directly this, we can start with simple phase diagram T s diagram and this is your basically binodal curve, saturated line vapor and then we just consider from this 1 which is nothing but here, okay. This is the saturated liquid inlet to the pump and then the second steam goes to the closed feedwater heater.

So here, if you look at it, this is 1 and this is the adiabatic process that is what we are assuming it for the pumps. So it is isotropically pressurized, okay at 2. 2 is basically the pressure at which the boiler works, okay 3 mega Pascal, okay. So from here what we are doing is you know, it goes to 3 and the 3 it happens here.

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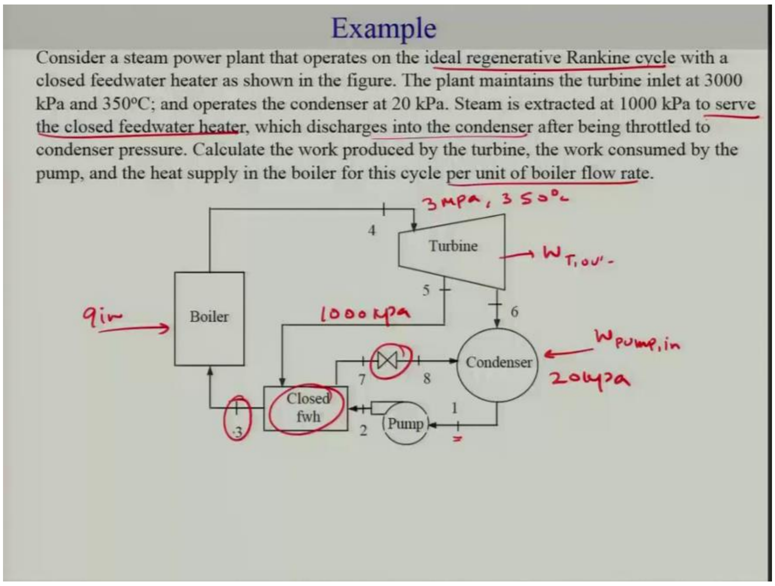

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So 1, 2 and 3 is here. 3 is at the boiler pressure. So essentially C is somewhere here, okay.

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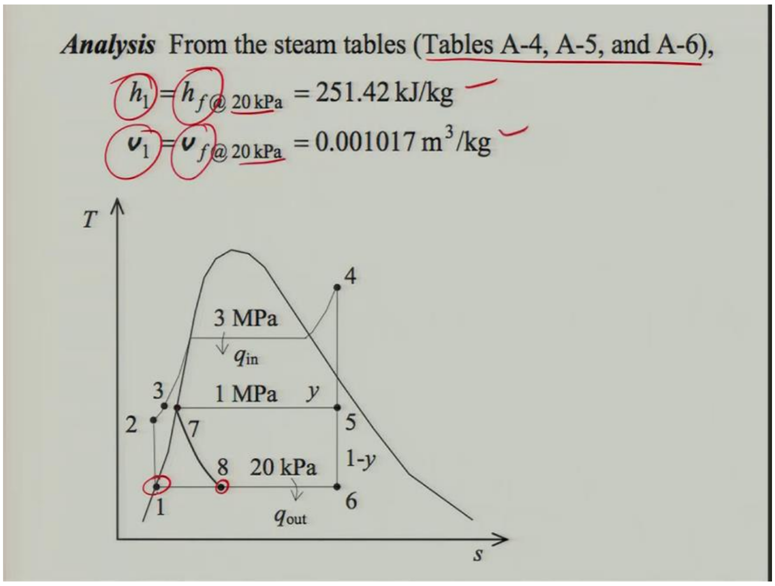

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But it would be also at 1 mega Pascal the pressure which is maintained because of this, okay. So this turbine goes here and this is the pressure we are getting from the feedwater heater, okay. So this is your mega Pascal out here. So from here, 1 to 2, 2 to 3 it goes to 4, superheated region and then at 5 because it has extract certain amount of the steam at 1 mega Pascal, okay.

So this 5 is being mixed with basically, if you look at it, not mixed, 5 is taken out and then essentially it is, 5 is here, okay so 5 is here and then it goes to, if you look at 7, so 5 to 7 is there. That is where it basically throttles, 5 to 7 here. So in this process the steam basically loses the energy, okay because it is here what we are getting is saturated system and then in the closed water heater it goes to the, this point which is saturated liquid and then it throttles so it essentially goes to the, it expands and from 7 to 8 it drops down the pressure, okay.

So we have drawn this line but essentially we do not know. So from 7 to 8 somewhere this is on this 20 kilo Pascal saturation line, okay. That is your 8 here, and that goes to the condenser and then 6 and 8 gets mixed and what we get is 1. Okay 6 and 8 get mixed and what you get is 1. So this is the complete cycle. This is little complicated but something worth discussing this kind of problem which is more common.

So let us now start, try to solve this problem. So one we know from the saturated liquid part. So from the table, now this table I have taken from the book but you can take it from any steam tables, and so this is just the illustrative numbers. We should not change much from this steam table to steam table. So this is, h 1 is nothing but the fluid enthalpy at 20 kilo Pascal which we know. Similarly, the specific volume would also be the specific volume of the fluid at 20 kilo Pascal which is this. So this is the information of 1 state which we know.

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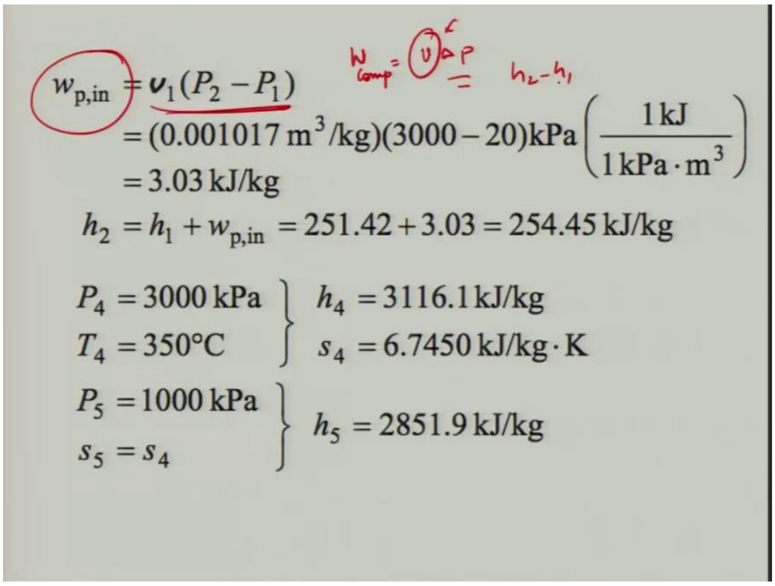

$W_{comp} = \boxed{v}\,\Delta P \qquad h_2 - h_1$

$$w_{p,in} = \underline{v_1(P_2 - P_1)}$$
$$= (0.001017\ \mathrm{m^3/kg})(3000 - 20)\mathrm{kPa}\left(\frac{1\ \mathrm{kJ}}{1\ \mathrm{kPa \cdot m^3}}\right)$$
$$= 3.03\ \mathrm{kJ/kg}$$
$$h_2 = h_1 + w_{p,in} = 251.42 + 3.03 = 254.45\ \mathrm{kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 3000\ \mathrm{kPa} \\ T_4 = 350^\circ\mathrm{C} \end{array}\right\} \begin{array}{l} h_4 = 3116.1\ \mathrm{kJ/kg} \\ s_4 = 6.7450\ \mathrm{kJ/kg \cdot K} \end{array}$$

$$\left.\begin{array}{l} P_5 = 1000\ \mathrm{kPa} \\ s_5 = s_4 \end{array}\right\} h_5 = 2851.9\ \mathrm{kJ/kg}$$

Now in order to find w p in, okay we can use directly the h 2 minus, the delta h, but we also know that for the case of the compressor work, it is nothing but the volume v d p also, okay. So this is something which we know for such a compressor work, okay. Considering that the v, because it is a fluid, is a constant, then simply we can write it as this. Okay so that comes out to be w p in minus P 1. But this is also same as h 2 minus h 1, okay. So then, with this we can find out precisely h 2.

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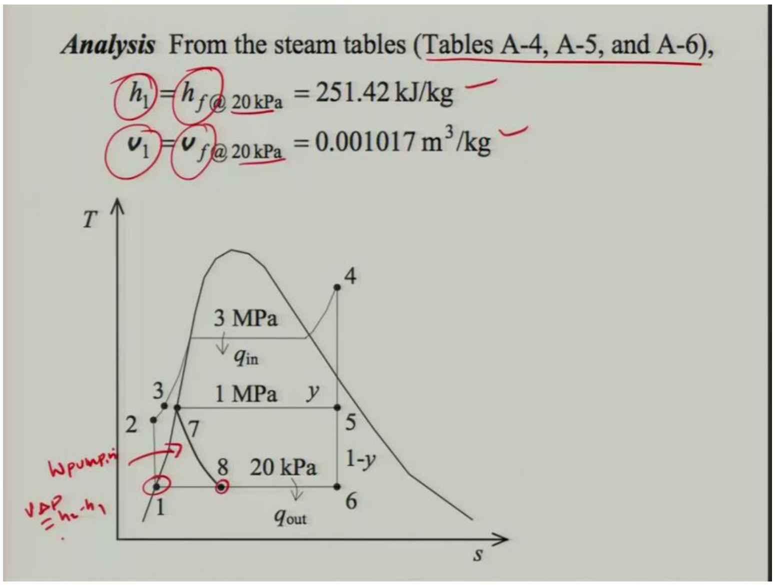

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Because otherwise we do not know the h 2. So using the information of the pressure, now we know the amount of the work which is being done here, w pump in, okay so this would be your v delta p, this is also h 2 minus h 1. So from here we obtain the value of h 2 and that is this.

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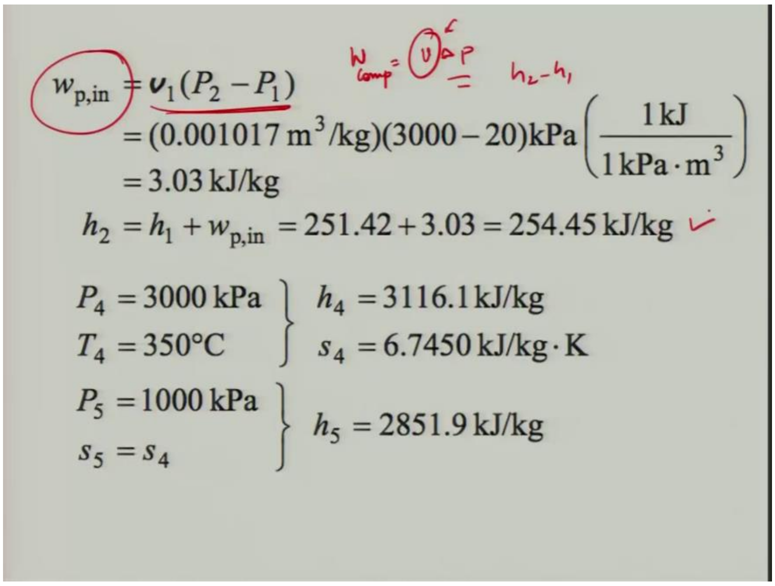

$$W_{comp} = v\Delta P = h_2 - h_1$$

$$\begin{aligned} w_{p,in} &= v_1(P_2 - P_1) \\ &= (0.001017\ \text{m}^3/\text{kg})(3000-20)\text{kPa}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 3.03\ \text{kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,in} = 251.42 + 3.03 = 254.45\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_4 &= 3000\ \text{kPa} \\ T_4 &= 350°\text{C} \end{aligned}\right\} \quad \begin{aligned} h_4 &= 3116.1\ \text{kJ/kg} \\ s_4 &= 6.7450\ \text{kJ/kg}\cdot\text{K} \end{aligned}$$

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$$w_{p,in} = v_1(P_2 - P_1)$$

So, we calculate this and obtain the value of h 2. Okay so now the question is like.

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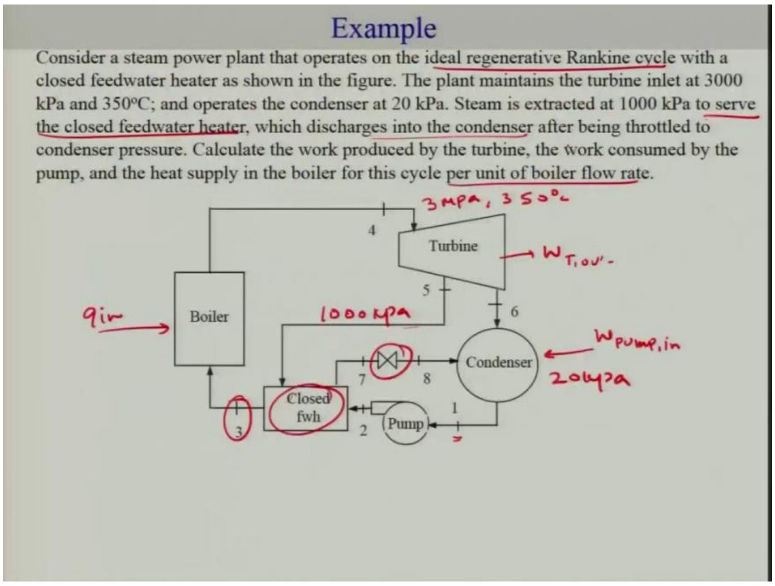

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From here essentially we want to find out the work consumed by the pump that already we have done that. We need to find out the heat supply in the boiler. That means we need to obtain many more things actually.

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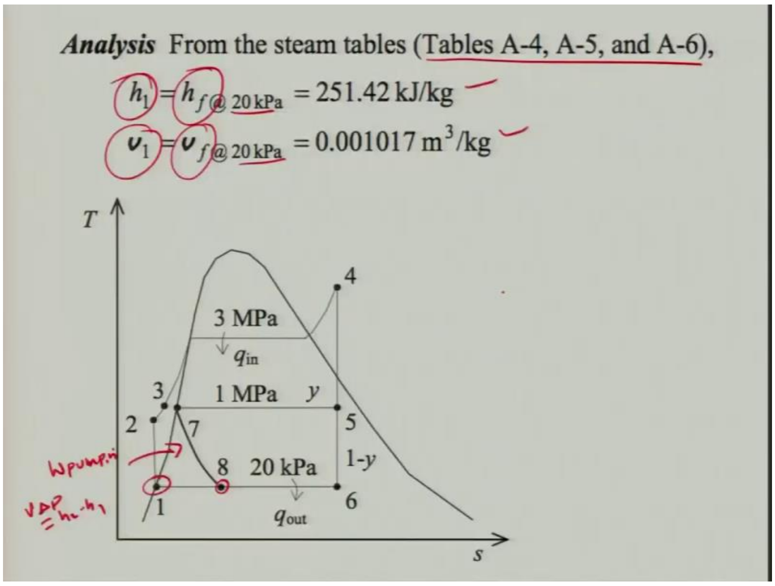

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So let us go systematically.

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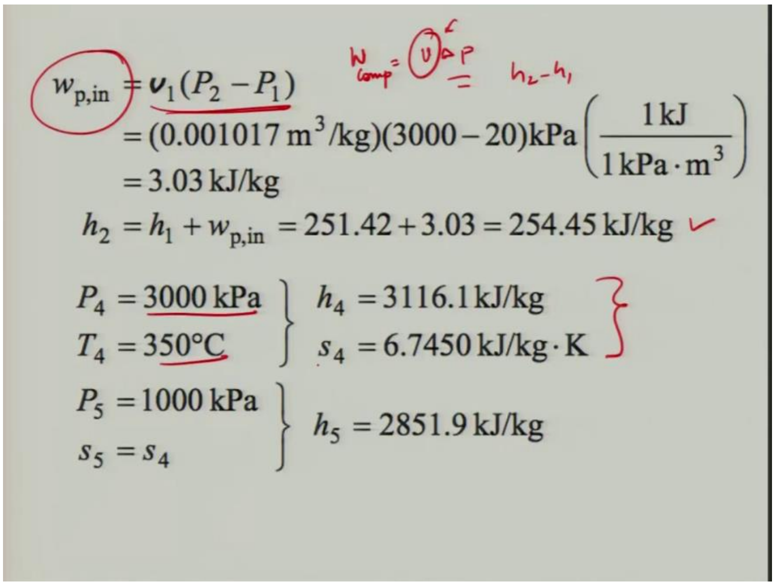

$$W_{comp} = v\Delta P = h_2 - h_1$$

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Let us find out the states of the 4 and 5 first before we try to solve the heat supplied to the turbine, heat supplied to the boiler and other part of the questions. So we know the state 4. So state 4 is basically at 3 mega Pascal and 350 degree Celsius, okay. So for that we have h 4 information from the table and from s 4, and as well as the entropy part.

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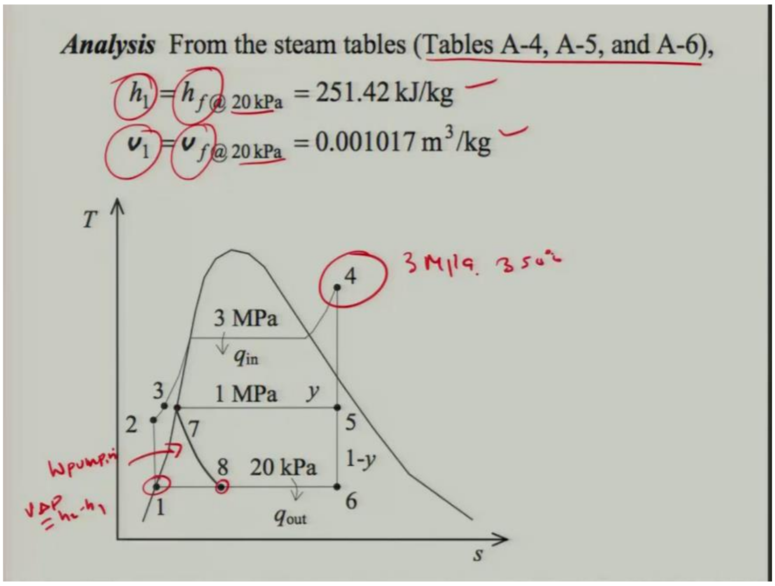

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So the 4 is 300 mega Pascal, okay and 350 degree Celsius. So this is directly from the thing.

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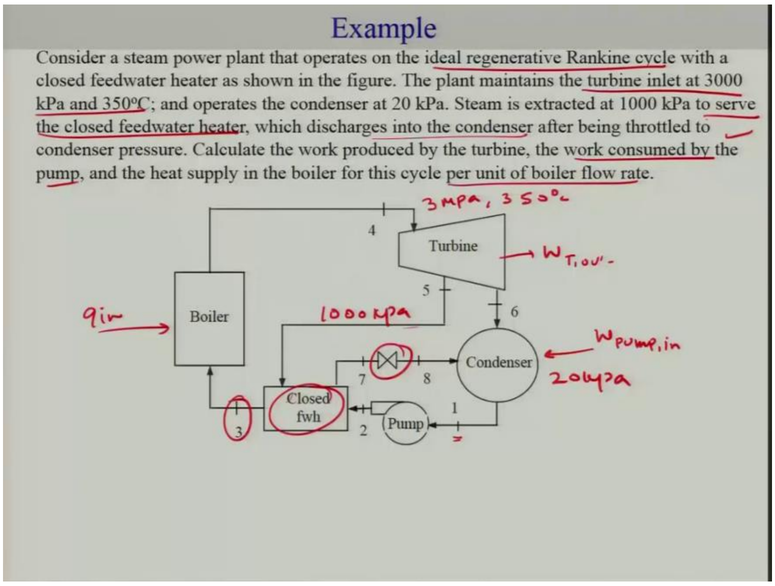

Example

Consider a steam power plant that operates on the ideal regenerative Rankine cycle with a closed feedwater heater as shown in the figure. The plant maintains the turbine inlet at 3000 kPa and 350°C; and operates the condenser at 20 kPa. Steam is extracted at 1000 kPa to serve the closed feedwater heater, which discharges into the condenser after being throttled to condenser pressure. Calculate the work produced by the turbine, the work consumed by the pump, and the heat supply in the boiler for this cycle per unit of boiler flow rate.

The plant maintains the turbine inlet at 3 mega Pascal and 350 degree Celsius.

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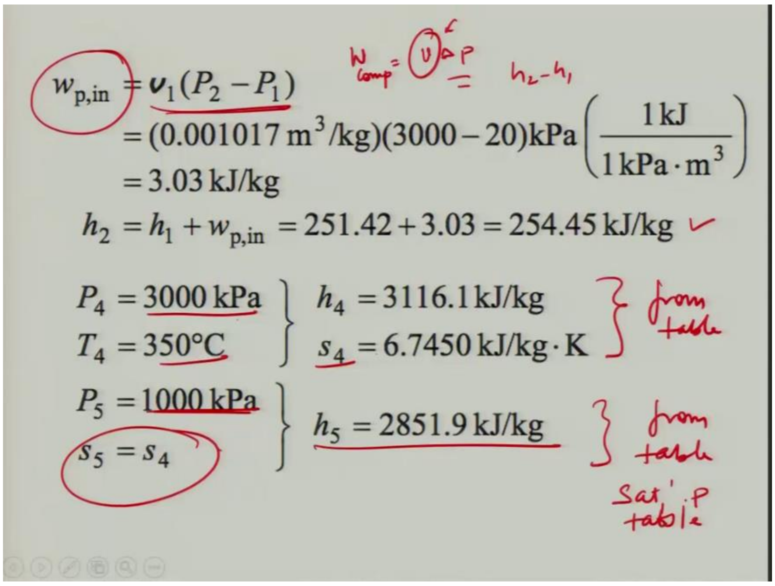

$$W_{comp} = v\Delta P = h_2 - h_1$$

$$w_{p,in} = v_1(P_2 - P_1)$$
$$= (0.001017\ \mathrm{m^3/kg})(3000-20)\mathrm{kPa}\left(\frac{1\ \mathrm{kJ}}{1\ \mathrm{kPa\cdot m^3}}\right)$$
$$= 3.03\ \mathrm{kJ/kg}$$
$$h_2 = h_1 + w_{p,in} = 251.42 + 3.03 = 254.45\ \mathrm{kJ/kg}$$

$$\left.\begin{aligned} P_4 &= 3000\ \mathrm{kPa} \\ T_4 &= 350°\mathrm{C} \end{aligned}\right\} \quad \begin{aligned} h_4 &= 3116.1\ \mathrm{kJ/kg} \\ s_4 &= 6.7450\ \mathrm{kJ/kg\cdot K} \end{aligned} \Big\} \text{ from table}$$

$$\left.\begin{aligned} P_5 &= 1000\ \mathrm{kPa} \\ s_5 &= s_4 \end{aligned}\right\} \quad h_5 = 2851.9\ \mathrm{kJ/kg} \Big\} \text{ from table}$$

Sat' P table

So that information is used here to obtain the enthalpy and entropy from table. Okay so here we are going to get, use the superheated table at 3 mega Pascal and corresponding to 350 we obtain this. Now, what is state 5? State 5 is at 1 mega Pascal but since it is isentropic process, because it is taken out from the turbine, S 5 is going to be S 4. So you have now P 5 which is 1 mega Pascal and then you look at this s 4 and from the table, now it is going to be saturated table, okay.

So from this saturated table, pressure table you can find out what is the appropriate enthalpy for h 5? So you may have to do some interpolation again from table, okay but in this case, saturated pressure table, okay. So you have the information of 5.

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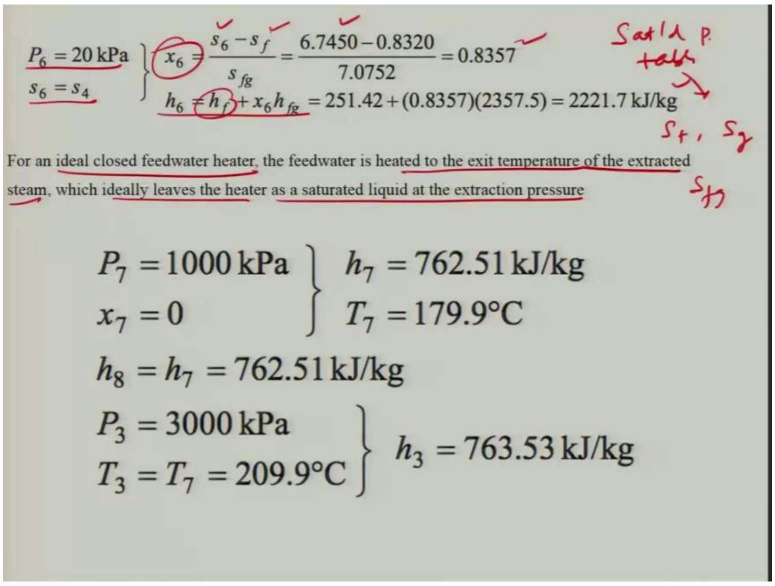

$$\left.\begin{array}{l} P_6 = 20\,\text{kPa} \\ s_6 = s_4 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{6.7450 - 0.8320}{7.0752} = 0.8357 \\ h_6 = h_f + x_6 h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7\,\text{kJ/kg} \end{array}$$

Sat'd P. table

s_f, s_g

s_{fg}

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure

$$\left.\begin{array}{l} P_7 = 1000\,\text{kPa} \\ x_7 = 0 \end{array}\right\} \begin{array}{l} h_7 = 762.51\,\text{kJ/kg} \\ T_7 = 179.9^\circ\text{C} \end{array}$$

$$h_8 = h_7 = 762.51\,\text{kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 3000\,\text{kPa} \\ T_3 = T_7 = 209.9^\circ\text{C} \end{array}\right\} h_3 = 763.53\,\text{kJ/kg}$$

Now similarly, you also can obtain information for state 6. P 6 is 20 kilo Pascal, we know and as well as we know that it is also an isentropic process because it is further down the line in the pressure so with lower value of x, so from here we can find out also the quality. So you can actually get h 6 directly. So a typical exercise would be something like this. You know s 6 because S 6 is nothing but s 4, okay and you know the saturation pressure table, okay.

$$x_6 = \frac{s_6 - s_f}{s_{fg}}$$

$$h_6 = h_f + x_6 h_{fg}$$

So similar way actually we have done this also, okay. Now we have the information of 5, we have the information of 6. What about 7?

For an ideal closed feedwater heater, the feedwater is heated to exit temperature of the extracted steam, okay which ideally means the heater has the saturated liquid at the extraction pressure. So this is the ideal closed feedwater heater. So this is something which we have to consider in this particular problem, that P 7, okay which is this here, P 7 which is this here, this 7.

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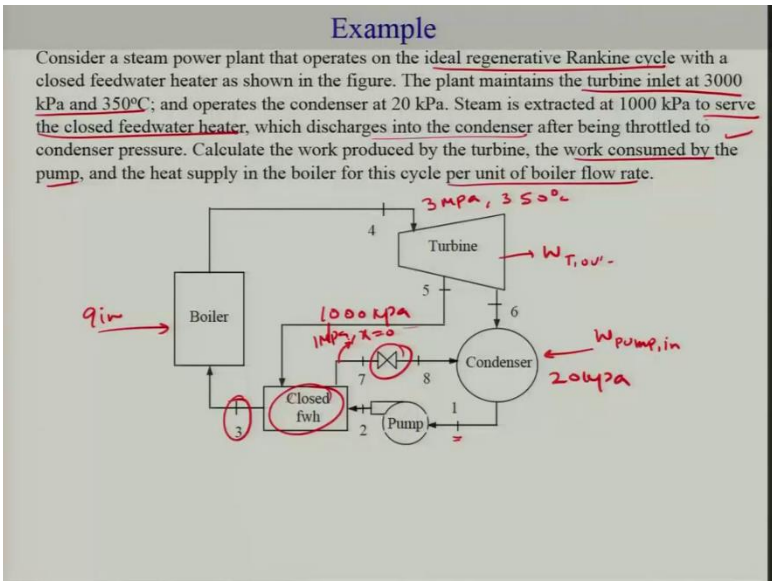

Example

Consider a steam power plant that operates on the ideal regenerative Rankine cycle with a closed feedwater heater as shown in the figure. The plant maintains the turbine inlet at 3000 kPa and 350ºC; and operates the condenser at 20 kPa. Steam is extracted at 1000 kPa to serve the closed feedwater heater, which discharges into the condenser after being throttled to condenser pressure. Calculate the work produced by the turbine, the work consumed by the pump, and the heat supply in the boiler for this cycle per unit of boiler flow rate.

This is the steam which is extracted and the one which is here, this will be of course saturated liquid with x close to 1 but when it exits from the closed feedwater heat the pressure is still going to be 1 mega Pascal, but the quality of this should be 0 because it would be saturated liquid. That is what the ideal feedwater heater is this.

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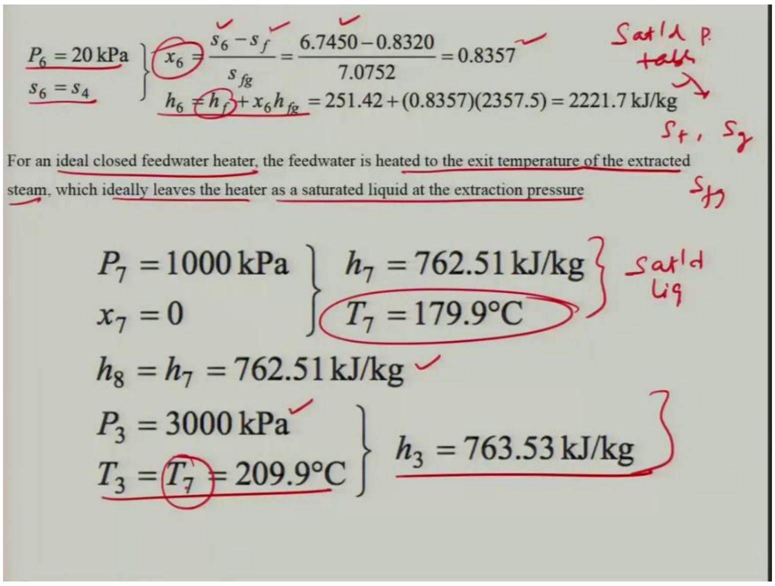

$$\left.\begin{aligned} P_6 &= 20\ \text{kPa} \\ s_6 &= s_4 \end{aligned}\right\} \begin{aligned} x_6 &= \frac{s_6 - s_f}{s_{fg}} = \frac{6.7450 - 0.8320}{7.0752} = 0.8357 \\ h_6 &= h_f + x_6 h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7\ \text{kJ/kg} \end{aligned}$$

Sat'd P. table

s_f, s_g

s_{fg}

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure

$$\left.\begin{aligned} P_7 &= 1000\ \text{kPa} \\ x_7 &= 0 \end{aligned}\right\} \left.\begin{aligned} h_7 &= 762.51\ \text{kJ/kg} \\ T_7 &= 179.9°\text{C} \end{aligned}\right\}$$

Sat'd liq

$$h_8 = h_7 = 762.51\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 3000\ \text{kPa} \\ T_3 &= T_7 = 209.9°\text{C} \end{aligned}\right\} h_3 = 763.53\ \text{kJ/kg}$$

That is what we consider here. So if you consider this then this is nothing, going to be saturated liquid, okay and the temperature corresponding to that would be this 179.9 degree Celsius. So this is something which we have done that. So from here 5 to 7 we have shown this as on the saturated liquid because this is the ideal feedwater heater, okay. So now, with this information we know the 7 but what about 8? Now, from 7 to 8, that means we are using the expansion here.

So here is throttle, using the throttling valve, so 7 to 8 occur, we know that this process would be at constant enthalpy. So h 7 is equal to, same as, h 7 is basically equal to h 8. So you have this information here, okay and what remains now is basically the P 3 which we have not talked about.

Now P 3 is going to be same as that of, P 3 will be on the same temperature as that of 7. So P 3 should be 3 mega Pascal and T 3 should be same as T 7. So there is a typo here but this should be same as T 7 and based on this information you can obtain s 3, okay. So now you have basically the information of, all the information of the state.

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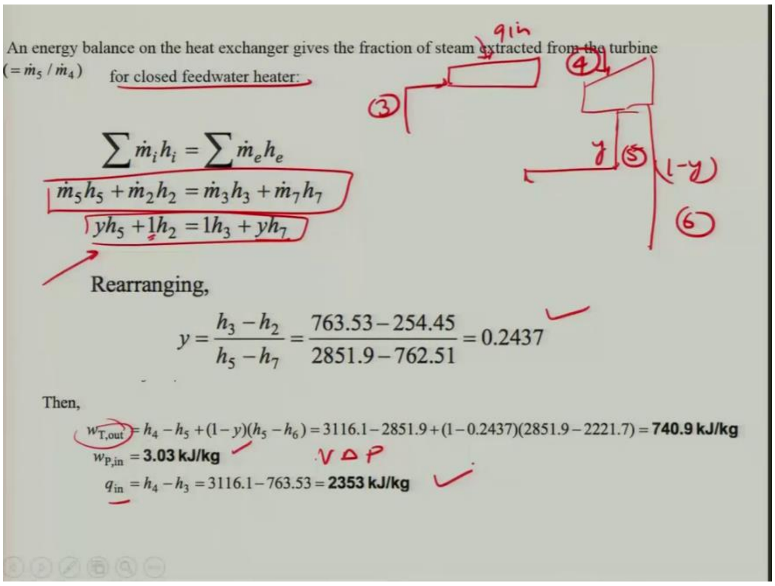

An energy balance on the heat exchanger gives the fraction of steam extracted from the turbine $(=\dot{m}_5/\dot{m}_4)$ for closed feedwater heater:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_5 h_5 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7$$

$$y h_5 + 1 h_2 = 1 h_3 + y h_7$$

Rearranging,

$$y = \frac{h_3 - h_2}{h_5 - h_7} = \frac{763.53 - 254.45}{2851.9 - 762.51} = 0.2437$$

Then,

$$w_{T,out} = h_4 - h_5 + (1-y)(h_5 - h_6) = 3116.1 - 2851.9 + (1 - 0.2437)(2851.9 - 2221.7) = \mathbf{740.9\ kJ/kg}$$

$$w_{P,in} = \mathbf{3.03\ kJ/kg}$$

$$q_{in} = h_4 - h_3 = 3116.1 - 763.53 = \mathbf{2353\ kJ/kg}$$

And you can now start doing bit of analysis. So one of the things which you can do is to, to apply energy balance over the heat exchanger that is feedwater heater. So we know that for the basic energy balance is going to be:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_5 h_5 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7$$

$$y h_5 + 1 h_2 = 1 h_3 + y h_7$$

$$\textit{Rearranging,} \qquad y = \frac{h_3 - h_2}{h_5 - h_7} = 0.2437$$

$$Then, \quad w_{T,out} = h_4 - h_5 + (1-y)(h_5 - h_6)$$

$$w_{P,in} = v\Delta P$$

$$q_{in} = h_4 - h_3$$

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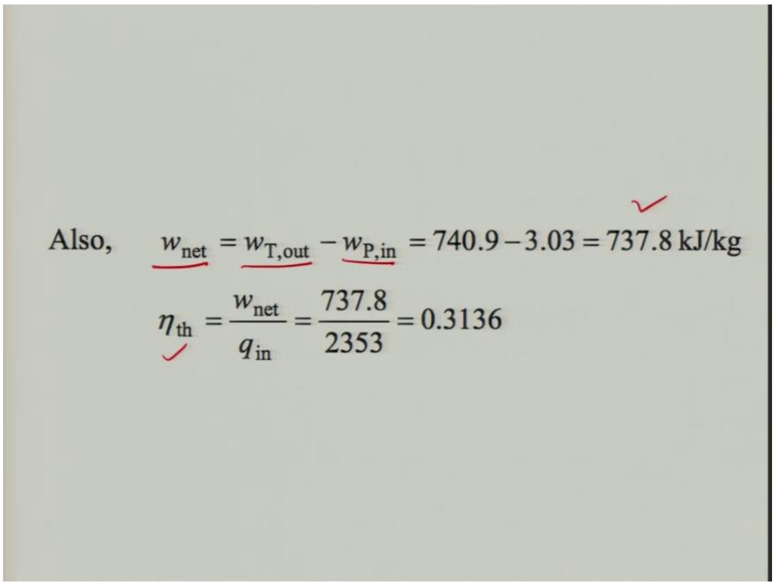

Also, $\underline{w_{\text{net}}} = \underline{w_{\text{T,out}}} - \underline{w_{\text{P,in}}} = 740.9 - 3.03 = 737.8 \text{ kJ/kg}$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{737.8}{2353} = 0.3136$$

Now you can obtain the w net which is w turbine out minus w p net and then you obtain this value and from here you can get the efficiency of this particular ideal regenerative Rankine cycle.

$$w_{net} = w_{T,out} - w_{P,in}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 0.3136$$

So that is a very, of course cumbersome but it is a careful exercise. One has to make sure that you have the information, right states of the properties of the exit and inlet conditions for different devices. And make use of the steam to find out the relevant, you know questions.

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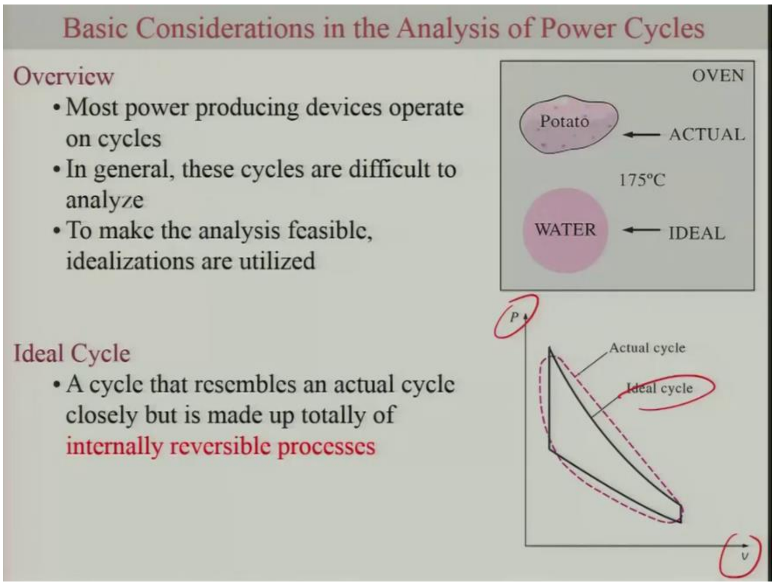

Basic Considerations in the Analysis of Power Cycles

Overview

- Most power producing devices operate on cycles
- In general, these cycles are difficult to analyze
- To make the analysis feasible, idealizations are utilized

Ideal Cycle

- A cycle that resembles an actual cycle closely but is made up totally of internally reversible processes

So I will just quickly go through this consideration of analysis of power cycle which we often make use of it. Most of the cases, it is not going to be a straightforward, many times we use ideal cycles just the way we have done in ideal regenerative cycle. Usually in ideal cycle we will be assuming to be internally reversible processes. So for example, if you consider a pressure versus volume the actual cycle may be in the dashed line but the ideal cycle will be in this way, right. So this is the approximation we often use in order to solve the problem, okay.

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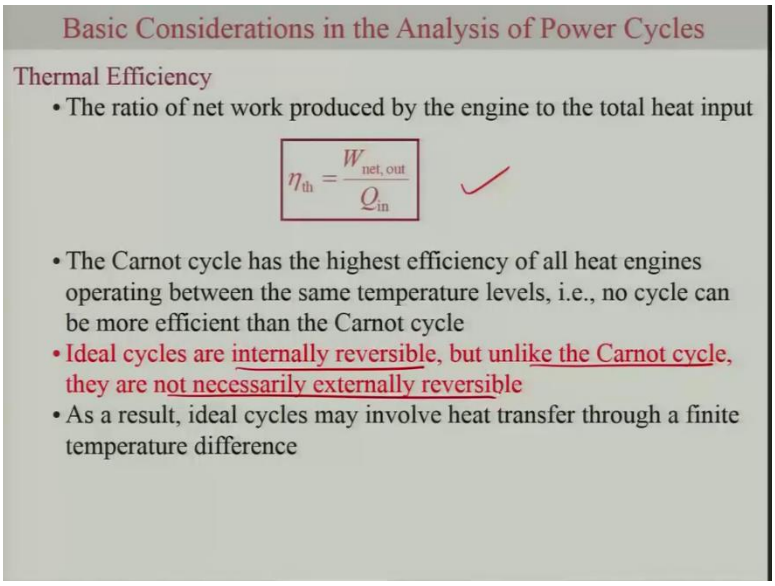

Basic Considerations in the Analysis of Power Cycles

Thermal Efficiency

- The ratio of net work produced by the engine to the total heat input

$$\boxed{\eta_{th} = \frac{W_{net,out}}{Q_{in}}}$$

- The Carnot cycle has the highest efficiency of all heat engines operating between the same temperature levels, i.e., no cycle can be more efficient than the Carnot cycle
- Ideal cycles are internally reversible, but unlike the Carnot cycle, they are not necessarily externally reversible
- As a result, ideal cycles may involve heat transfer through a finite temperature difference

$$Thermal\ Efficiency, \qquad \eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

So which essentially means that all our calculations which usually will have a higher efficiency and the actual may be much, much, much lower. So I can skip this part. We already know the ideal cycles are internally reversible, but unlike the Carnot cycle, Carnot cycle is totally reversible that means it is also externally reversible. The ideal cycles are not necessarily externally reversible. So that is something which we can remember that, okay.

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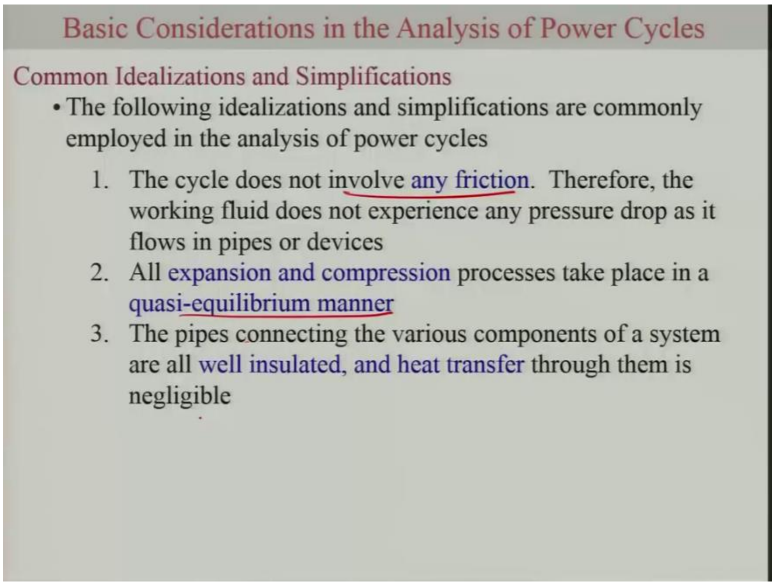

Basic Considerations in the Analysis of Power Cycles

Common Idealizations and Simplifications

- The following idealizations and simplifications are commonly employed in the analysis of power cycles
  1. The cycle does not involve any friction. Therefore, the working fluid does not experience any pressure drop as it flows in pipes or devices
  2. All expansion and compression processes take place in a quasi-equilibrium manner
  3. The pipes connecting the various components of a system are all well insulated, and heat transfer through them is negligible

So what are the common idealizations and simplifications in ideal cycle or power cycle? So we assume that the cycle does not involve any friction therefore the working fluid does not experience any pressure drop as it flows in pipes or devices. All expansion and compression processes take place in a quasi-equilibrium manner, okay. So in a sense we are considering internal reversible process. And the pipes connecting the various components of the system are all well-insulated and heat transfer through them is negligible, okay.

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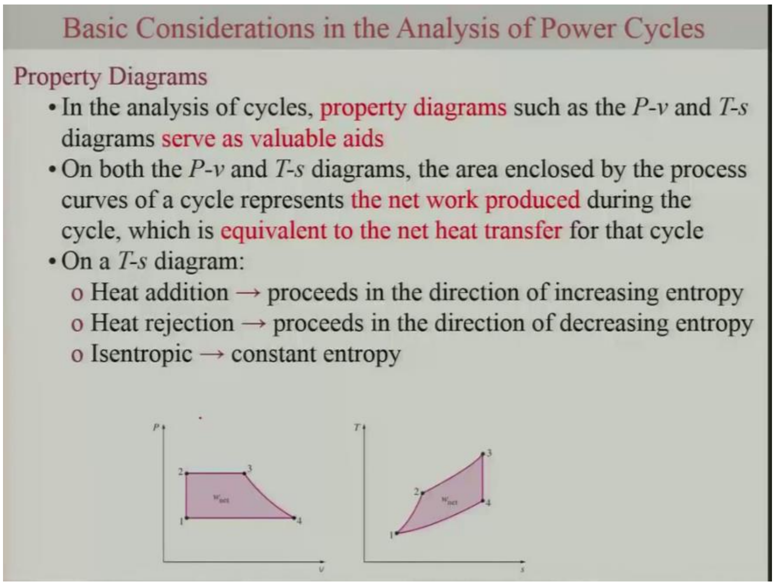

Basic Considerations in the Analysis of Power Cycles

Property Diagrams

- In the analysis of cycles, property diagrams such as the P-v and T-s diagrams serve as valuable aids
- On both the P-v and T-s diagrams, the area enclosed by the process curves of a cycle represents the net work produced during the cycle, which is equivalent to the net heat transfer for that cycle
- On a T-s diagram:
  - o Heat addition → proceeds in the direction of increasing entropy
  - o Heat rejection → proceeds in the direction of decreasing entropy
  - o Isentropic → constant entropy

So that is something we use it as an approximation. Many times we use property diagram which serves very valuable aid. For example, if you consider this P v then this process here, the cycle here, the area under this curve is nothing but w net, okay and similarly for T s also it shows that. So essentially it is because very valuable to just diagrammatically just find out what is the net work done, okay and which would be of course be equivalent to the net heat transfer in a, for a cycle okay so that becomes a very valuable exercise.

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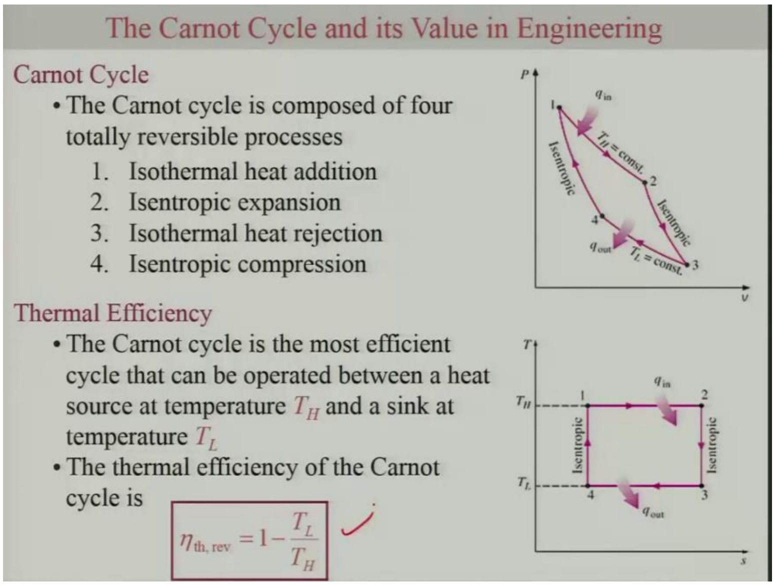

The Carnot Cycle and its Value in Engineering

Carnot Cycle

- The Carnot cycle is composed of four totally reversible processes
  1. Isothermal heat addition
  2. Isentropic expansion
  3. Isothermal heat rejection
  4. Isentropic compression

Thermal Efficiency

- The Carnot cycle is the most efficient cycle that can be operated between a heat source at temperature T_H and a sink at temperature T_L
- The thermal efficiency of the Carnot cycle is

$$\boxed{\eta_{\text{th, rev}} = 1 - \frac{T_L}{T_H}}$$

So as we have already discussed Carnot cycle is a valuable tool for analysis and gives a limit as far as efficiencies are concerned, and this we know that it can be written in this way.

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

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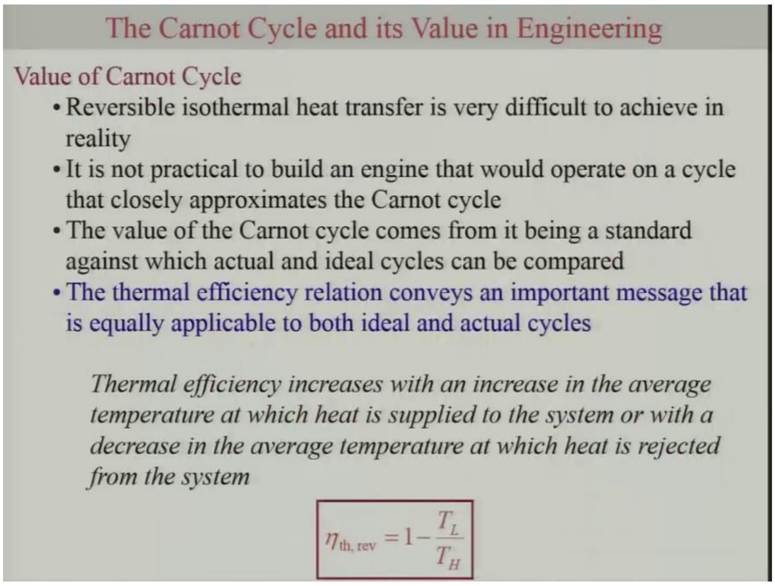

The Carnot Cycle and its Value in Engineering

Value of Carnot Cycle

- Reversible isothermal heat transfer is very difficult to achieve in reality
- It is not practical to build an engine that would operate on a cycle that closely approximates the Carnot cycle
- The value of the Carnot cycle comes from it being a standard against which actual and ideal cycles can be compared
- The thermal efficiency relation conveys an important message that is equally applicable to both ideal and actual cycles

Thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system

$$\boxed{\eta_{\text{th, rev}} = 1 - \frac{T_L}{T_H}}$$

For given two limits of the temperatures or the sources, okay.

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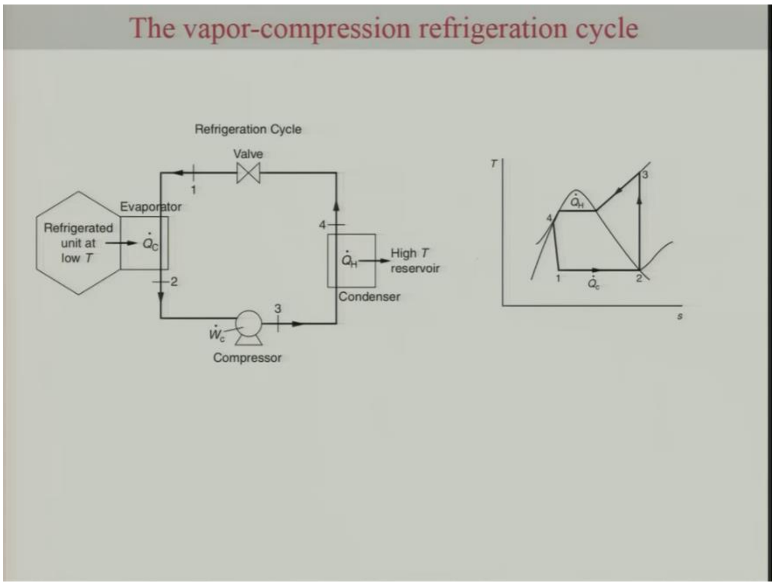
The vapor-compression refrigeration cycle



Okay so now we have this, we have done this exercise for Rankine cycle, now we can prove the similar exercise for refrigerator cycle, okay which is a reverse of what as far as the cycle is concerned. So here of course we are not going to use boiler. We will be having the evaporator, okay and we will not use turbine, we will be using a valve, okay.

So this is a typical refrigerator cycle, okay so this is the refrigerator unit which we would like to maintain at a temperature and this is evaporator which takes out the heat, okay and then it is passed to a compressor and this is the compressor basically pumps this particular fluid, working fluid to very high pressure, pressure of the condenser which finally condenses to a saturated liquid, okay and from there we get a expansion valve, brings to the, basically saturated liquid vapor state.

So if you look at it, this is the one which is saturated liquid vapor state and is evaporated further, it gets saturated vapor and pumped more to a higher temperature which is 3 and then it condenses to 4, okay.

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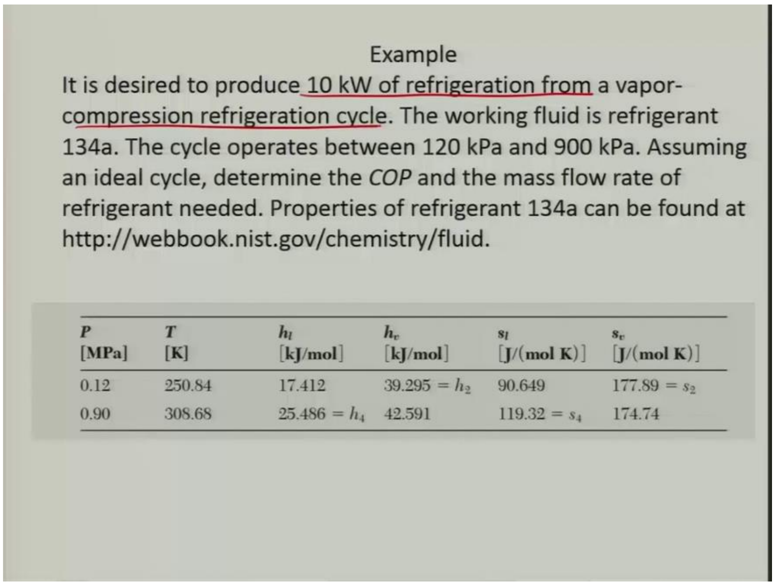

Example

It is desired to produce 10 kW of refrigeration from a vapor-compression refrigeration cycle. The working fluid is refrigerant 134a. The cycle operates between 120 kPa and 900 kPa. Assuming an ideal cycle, determine the *COP* and the mass flow rate of refrigerant needed. Properties of refrigerant 134a can be found at http://webbook.nist.gov/chemistry/fluid.

P [MPa]	T [K]	h_l [kJ/mol]	h_v [kJ/mol]	s_l [J/(mol K)]	s_v [J/(mol K)]
0.12	250.84	17.412	$39.295 = h_2$	90.649	$177.89 = s_2$
0.90	308.68	$25.486 = h_4$	42.591	$119.32 = s_4$	174.74

So let us now solve this problem based on this understanding. This is the desired, so this is example of refrigeration cycle. So it is desired to produce 10 kilo Watt of refrigeration from a vapor compression refrigeration cycle.

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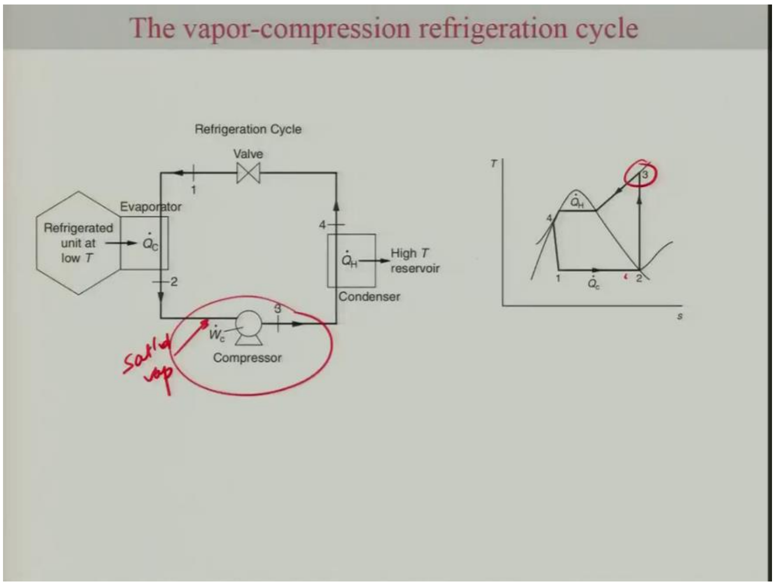

The vapor-compression refrigeration cycle

So what we have just shown is nothing but vapor compression refrigeration cycle, why vapor compression? Because this is kind of saturation vapor, okay and this is basically compressed here so and then this is condenser so this whole process entirely depends on from going from 2 to 3 so that we can extract, so this is one of the key element in the process and hence the name is formed.

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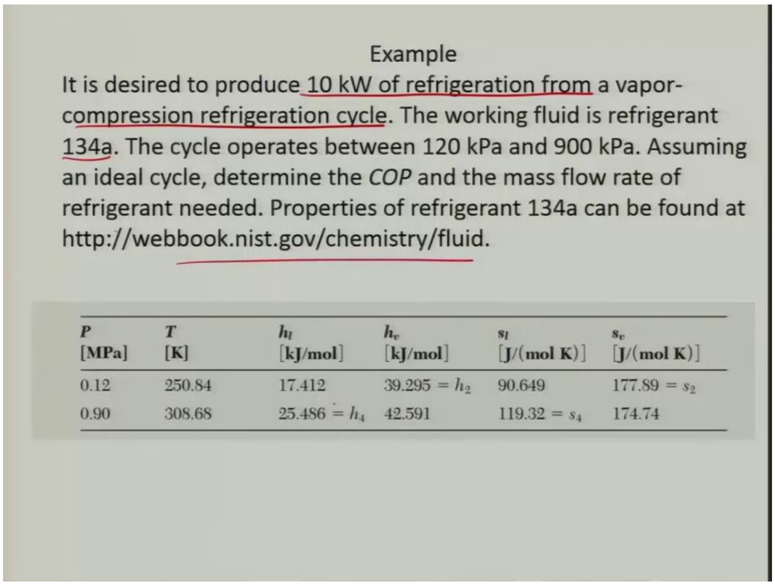

Example

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0.90	308.68	$25.486 = h_4$	42.591	$119.32 = s_4$	174.74

Okay, so let us go back to the question. It is desired to produce 10 kilo Watt of refrigeration from a vapor compression refrigeration cycle. So the working fluid is refrigerant 134a, the cycle operates between 120 kilo Pascal and 900 kilo Pascal.

Assuming an ideal cycle, determine the coefficient of performance and the mass flow rate of refrigerant needed. The property of the refrigerant is given here which we have taken from the web of book of NIST which is a very valuable resource for thermodynamic data. Okay so the couple of things which we have already made this here, so if you look at it, the pressure 0.12, this is something which is the working fluid.

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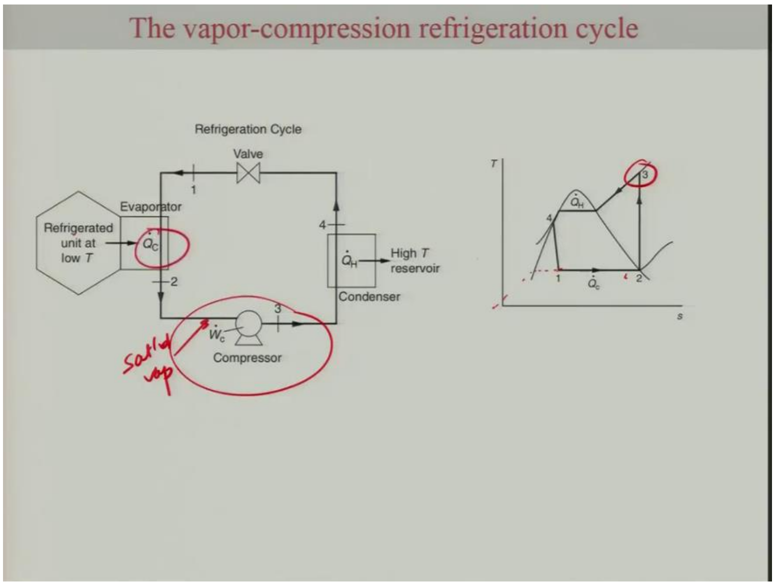

The vapor-compression refrigeration cycle

Now pressure, if you look at it, the pressure here is going to be less. This is going to be, 3 to 4 is going to be much higher. So these are 2 different limits of the pressure. So let us look at it. This is 0.12 and 0.9. The cycle operates between two pressures, okay. So it is like this, this one and then this, okay. So these are another pressure. So these are 2 different limits of the pressure, 1 and 2.

So now we need to find out COP so in order to get COP we need to obtain the condenser heat associated with, that means we need to also, we need to find QC and we need to find the work which we have done. So this is the desired output and this is a required input, okay so that is your coefficient of performance and hence we need to find these two variables.

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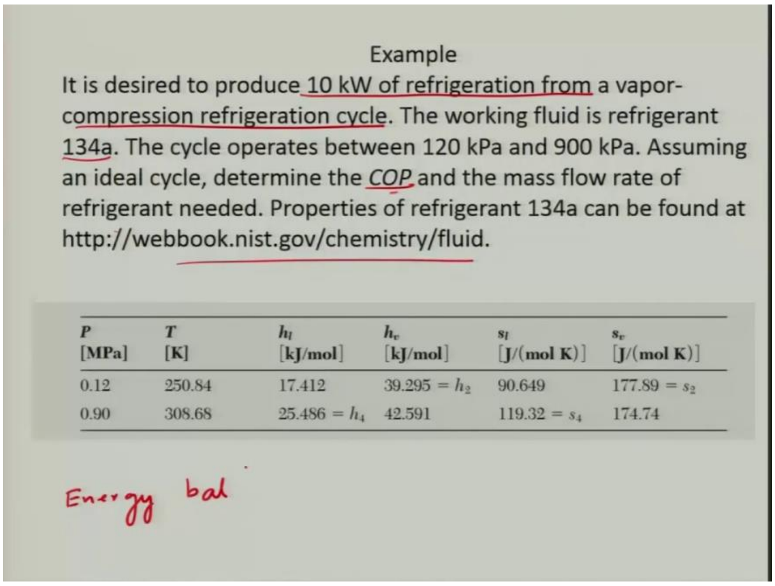

Example

It is desired to produce 10 kW of refrigeration from a vapor-compression refrigeration cycle. The working fluid is refrigerant 134a. The cycle operates between 120 kPa and 900 kPa. Assuming an ideal cycle, determine the COP and the mass flow rate of refrigerant needed. Properties of refrigerant 134a can be found at http://webbook.nist.gov/chemistry/fluid.

P [MPa]	T [K]	h_l [kJ/mol]	h_v [kJ/mol]	s_l [J/(mol K)]	s_v [J/(mol K)]
0.12	250.84	17.412	$39.295 = h_2$	90.649	$177.89 = s_2$
0.90	308.68	$25.486 = h_4$	42.591	$119.32 = s_4$	174.74

Energy bal.

So let us look at the energy balance first. So we will do the energy balance on evaporator.

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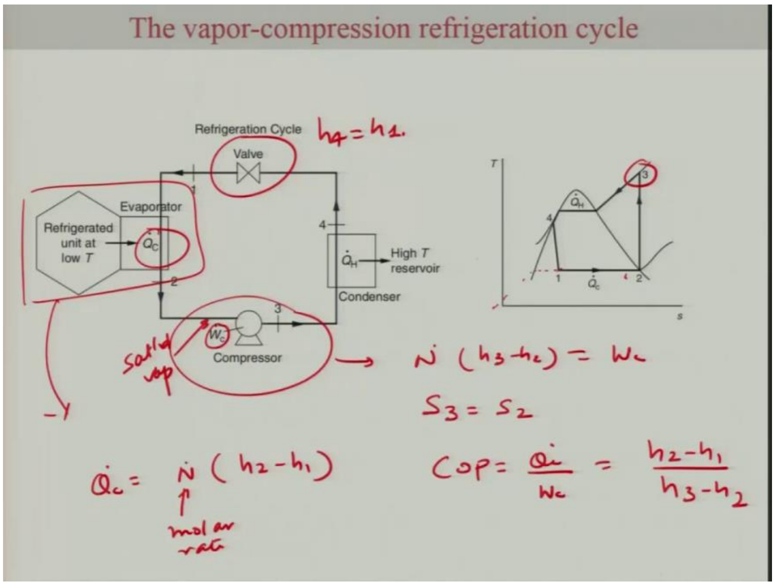

The vapor-compression refrigeration cycle

$h_4 = h_1$

$\dot{N}(h_3 - h_2) = W_c$

$S_3 = S_2$

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

molar rate

$COP = \frac{\dot{Q}_c}{W_c} = \frac{h_2 - h_1}{h_3 - h_2}$

So if you do energy balance here, so this is going to be:

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

$$\dot{N}(h_3 - h_2) = W_c$$

$$s_3 = s_2$$

$$COP = \frac{\dot{Q}_c}{W_c} = \frac{h_2 - h_1}{h_3 - h_2}; \quad h_4 = h_1$$

So basically this is our expression to find it out, okay. So, now the question is how do you get h, this variable so let us look at it. What we have?

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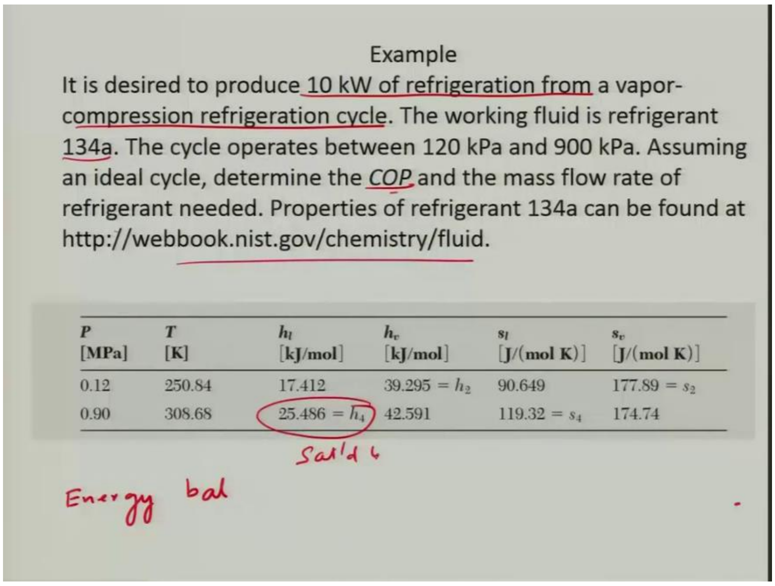

Example

It is desired to produce 10 kW of refrigeration from a vapor-compression refrigeration cycle. The working fluid is refrigerant 134a. The cycle operates between 120 kPa and 900 kPa. Assuming an ideal cycle, determine the COP and the mass flow rate of refrigerant needed. Properties of refrigerant 134a can be found at http://webbook.nist.gov/chemistry/fluid.

P [MPa]	*T* [K]	h_l [kJ/mol]	h_v [kJ/mol]	s_l [J/(mol K)]	s_v [J/(mol K)]
0.12	250.84	17.412	$39.295 = h_2$	90.649	$177.89 = s_2$
0.90	308.68	$\boxed{25.486 = h_4}$	42.591	$119.32 = s_4$	174.74

Sat'd l

Energy bal

0.9 mega Pascal, the saturated, saturated liquid enthalpy is h 4.

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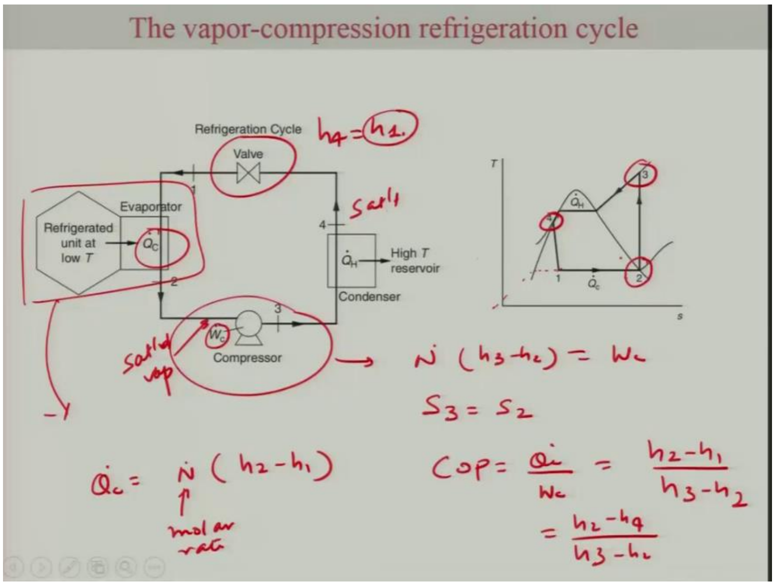
The vapor-compression refrigeration cycle



$h_4 = \boxed{h_1}$

$\dot{N}\,(h_3 - h_2) = W_c$

$S_3 = S_2$

$\dot{Q}_c = \dot{N}\,(h_2 - h_1)$

molar rate

$COP = \frac{\dot{Q}_c}{W_c} = \frac{h_2 - h_1}{h_3 - h_2}$

$= \frac{h_2 - h_4}{h_3 - h_2}$

And that should be saturated liquid enthalpy. This is what it is. This must be same as h 1. So essentially I can write this h 2 minus h 4, h 3 minus h 2 what about h 2? h 2 is saturated vapor at 0.12.

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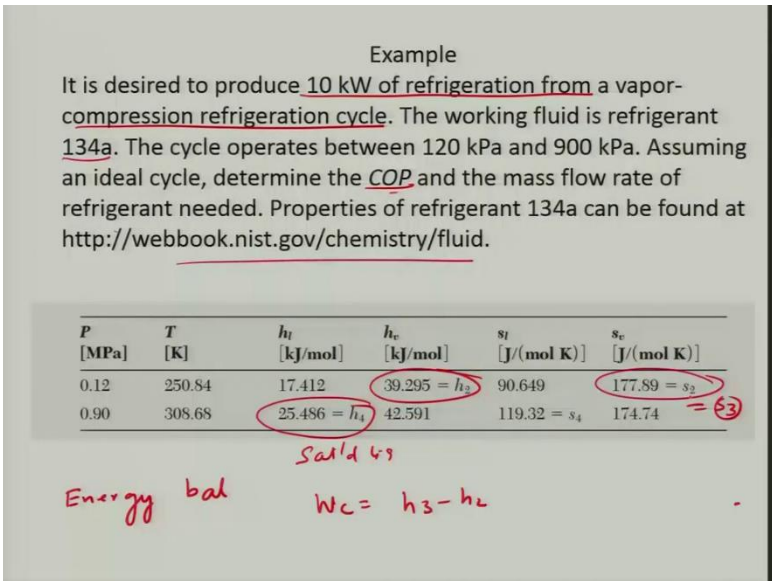

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Sat'd liq

Energy bal

$W_c = h_3 - h_2$

So that is also given to us, saturated vapor at 0.12 that is h 2 so essentially I know this. So I have the value of Q C. So this is something, I know this, I know this. So I have the value of Q C. What about W C? So in order to calculate W C, so W C is what I do not know at this point. So W C is nothing but h 3 minus h 2. Okay h 2 we know so how do we calculate h 3?

So h 3 is here. So h 3 is nothing but at 0.9 mega Pascal, okay, 0.93 mega Pascal and this is the entropy is same. So essentially S 3 and S 2 entropy is same. S 2 is given here, so S 2 entropy is this, okay. This condition is information is given. So this must be same as S 3.

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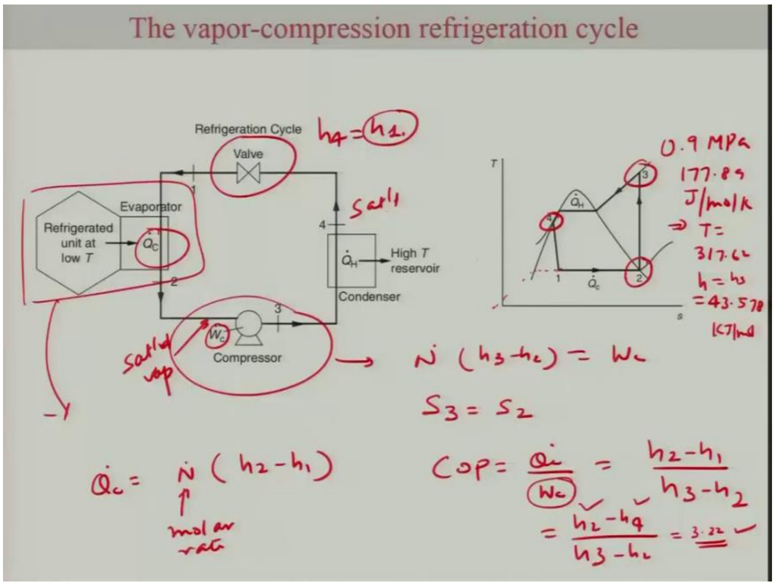

The vapor-compression refrigeration cycle

$h_4 = h_1$

0.9 MPa
177.89 J/mol K
⇒ T = 317.62
h = h3
= 43.578 KJ/mol

$\dot{N}(h_3 - h_2) = W_c$

$S_3 = S_2$

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

molar rate

$COP = \frac{\dot{Q}_c}{W_c} = \frac{h_2 - h_1}{h_3 - h_2} = \frac{h_2 - h_4}{h_3 - h_2} = 3.22$

So if you look at the steam table so at 177.89 Joules per mole Kelvin, this is your entropy. So if you look at it the corresponding temperature we can get, that is going to be 176.2 from the superheated steam pressure table you obtain the temperature and as well as you obtain the h of that, that is 43.578, okay, so this is your kilo Joules per mole, okay. So from here this is nothing but h 3. So you plug in here this information in C O P, okay because now you obtain the C O P easily by knowing all this value.

So if you plug in this, you can find out this is going to be 3.22 okay. So that is the information. Based on this that we have just calculated from vigorous analysis, okay. So what we have done is very straightforward. You had a table which is given to you. And you know the state, final states of 1 and 2, 3, 4. And then we made use of the information such as the isentropic for, it is isentropic process and enthalpy is going to be constant for the case of valve.

For the case of the compressor, it is going to be isentropic process and hence you know these conditions and you applied that and you obtained the value of Q C and W C, and subsequently you know C O P from this exercise. Okay, so I think this exercise will illustrate the use of the learning which we have done in last few lectures. And with this we will be closing the Second Law applications and then we will move to a new set of lectures from next week onward. So I will see you in the next week.