POWER PLANT SYSTEM ENGINEERING

Lec 6: Exergy Analysis of Vapor Power Cycles

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering module 2, Vapor Power System part 1. Now, in this lecture number 4, we are going to explore the following topics. First one is vapor cycle exergy analysis. Till this point of time, we have analyzed exhaustively the Rankine cycle. Now, in order to study the performance of the cycle, we want to do the exergy analysis component wise.

So, important components for Rankine cycle we can think of are, Boiler - this can model as a heat exchanger unit, then we have other components like turbines, pumps and condensers. So, for these components, we will try to explore what are the expressions for exergy and in a Rankine cycle, how you are going to evaluate the complete exergy analysis. Now, apart from this, this will almost complete this vapor cycle analysis thermodynamically, but we will try to explore other vapors of power cycle that operate on Rankine cycles, but with certain differences.

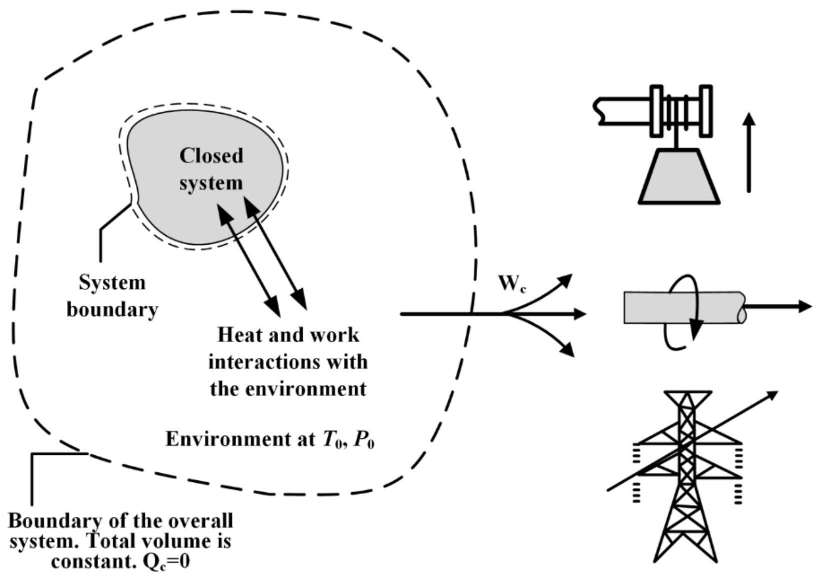
First one is working fluid and organic cycle. So, basically in our analysis so far, we have told that working fluid is water and steam, but there are thermodynamic cycles, where working fluids can be changed through some organic substances. So, we call them as organic cycles based on Rankine cycles. Then we have other vapor power cycles. Here also we can have a multiple working fluids like one case we can have water and in other situation we can have some other fluids like some organic fluids.

Then we have the steam cycle that is operated for nuclear power plants. So, Rankine cycle is almost a very common for nuclear power plant applications where it supplies steam for the coolant of the nuclear power plant. Then we have low temperature cycles. There are certain situations like where there is a possibility of exploring energy from low temperature environment. For example, we can think of solar radiation getting absorbed in a pond and such a things we can say solar pond.

There are some geothermal fluids which is underground water at high temperature. So, if you explore geothermal energy which uses water as one such working fluid, then we can use the temperature of water as one of the medium or a source of boiler. Then subsequently we have to use some other working fluids that operates in the low temperature cycles that means, we can think of various refrigerants. The other concept that goes is co-generations. So, this, but this is a concept where we think of integrating two or more power generation systems for variety of applications.

One such instance could be the combination of a gas turbine plant and steam power plant. Other may be some kind of extraction, steam extraction plant which can be utilized for various heating systems. So, such models they work on co-generation systems. So, we will try to touch upon the basics of these other vapor power cycles. Now, let us go to our first topic which is vapor cycle exergy analysis.

So, before you go for this exergy analysis for steam power systems, let us try to understand what the concept of exergy is. So, exergy in thermodynamic viewpoint is considered as one of the property like energy, but it has a different meaning. So, when you say energy in thermodynamic viewpoint, we say either it is available in the form of heat or work. And in second law analysis says that heat cannot be completely converted to work form which means there is a certain potential that heat can be converted to certain extent. And on top of that when you integrate these systems with environment, then we need to view this system as well as environment together.



Now, system can be considered as the best potential of work when it reaches the final thermodynamic conditions which is certainly at the dead state. So, if you look at this particular systems, if you say there is a closed system and if this system has certain boundary we say it as a system boundary and this system can interact with the environment and the environment condition is at pressure p_0 and temperature T_0 . And through these things the system and environment can be considered to work together in which heat and work interaction is possible. Now, if you take the system and surrounding together and bring it as a combined system and the system and surrounding work together to produce the energy in the form of work. So, we say that the work potential of the combined system that is W_c and that can be viewed as a rotation of a shaft or raising a weight or it can be considered as electric energy.

So, basically speaking we are considering the system and the surrounding together and try to find out the work potential of the combined system. And for how long this work potential or work delivery can be possible- when the system finally reaches to the dead state or environment. So, the potential to develop the work is known as the exergy and other way we can view that if a dead state can reach to the system state, then we regard this minimum theoretical work as its work potential to bring the dead state to a given state. So, this view or this concept leads to the fact of finding the work potential of a given system. So, there are more details also available in the basic thermodynamic course, but here the system is brought to the dead state and we view this as a combined system and try to find out what is the work potential.

So, if you say the total energy of the combined system is E consisting of internal energy U, potential energy PE , and kinetic energy KE,

Work transfer for combined system, $E = U + PE + KE$

Work Potential $W_c = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + KE + PE - T_0\sigma_c; \sigma_c = \Delta S_c$

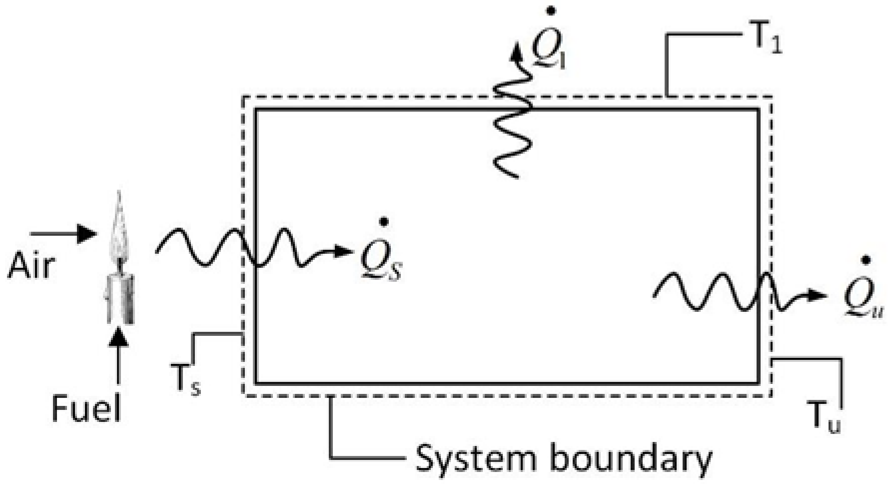
So, basically if you take this as a work potential and exergy is termed as the maximum work potential, then obviously, the final term becomes 0. So, you can find out the exergy of a system, subsequently when we find the exergy per unit mass we say it specific exergy. So, this is the working formula to find out the exergy of a system by considering system and surrounding together.

Exergy: $E = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + KE + PE$

Specific exergy: $e = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + \left(\frac{V^2}{2}\right) + gz$

Now, here p_0 & T_0 stands for the conditions of environment and in all our dead state situations we say, $p_0 = 1$ bar and $T_0 = 25$°C. So, this is the dead state conditions in which we are going to work upon. So, that means, whatever work potential has to be calculated till this final pressure and temperature where the system reaches to the dead state.

Then moving further we need to quantify the exergy by a parameter something called as exergetic efficiency. This is something similar to the efficiency which is defined in the Carnot cycle, but here, a little bit of difference is available that we need to find out.



So, let us try to understand that we have a system consisting of its boundary and it is receiving some heat $\dot{Q}_s$ and by receiving this heat, system does some useful work in the form of $\dot{Q}_u$ and heat which is going to be lost is known $\dot{Q}_1$. So, basically speaking

$\dot{Q}_s = \dot{Q}_u + \dot{Q}_1$. Where $\dot{Q}_1$ is considered for loss and $\dot{Q}_u$ is considered as the energy utilization. Now when you calculate the efficiency of this particular systems, it is nothing, but the ratio of $\dot{Q}_u$ & $\dot{Q}_s$ that means, the ratio energy which is being utilized & heat energy which is being supplied. So, this is what we known as efficiency of this system, but if you want to find out the exegetic efficiency then we need to find out what is this work potential for this $\dot{Q}_u$ .because this $\dot{Q}_u$ has not been taken into account of the surrounding conditions which is $p_0 = 1$ bar and $T_0 = 25$°C.

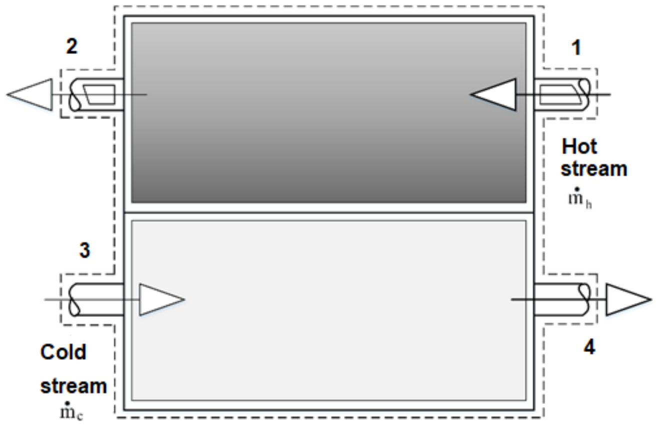
Exergetic efficiency: $\varepsilon = \dfrac{\left(1-\frac{T_0}{T_u}\right)\dot{Q}_u}{\left(1-\frac{T_0}{T_s}\right)\dot{Q}_s} = \eta\dfrac{\left(1-\frac{T_0}{T_u}\right)}{\left(1-\frac{T_0}{T_s}\right)}$

Efficiency: $\eta = \dfrac{\dot{Q}_u}{\dot{Q}_s} \Rightarrow \varepsilon < 1$

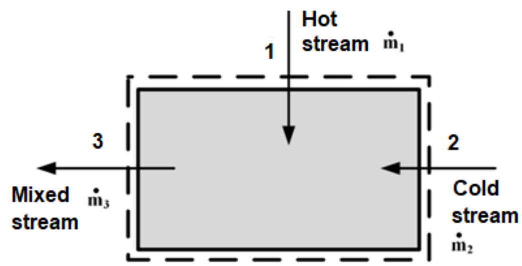
So, considering this as a dead state condition we can find out the work potential for this $\dot{Q}_u$ through our expressions using from the Carnot cycle. So, work potential for this $\dot{Q}_u$ will be $\left(1-\frac{T_0}{T_u}\right)$. Similarly, work potential for $\dot{Q}_s$, we can write it as $\left(1-\frac{T_0}{T_s}\right)$ and this is nothing, but we get the expressions from the Carnot efficiency. So, now this exegetic efficiency can now be rewritten as $\eta \frac{\left(1-\frac{T_0}{T_u}\right)}{\left(1-\frac{T_0}{T_s}\right)}$ and obviously, since efficiency is always less than 1 the exegetic efficiency will also be less than 1. So, this is how you calculate the exegetic efficiency.

Now, in our term when you take into account a vapor power system, we are now going to work on this exegetic efficiency. So, the components involved here are turbines, pumps, then heat exchanger, condensers. So, all these things are involved and they are considered as the steady flow devices. So, our main role for this discussion would be to find out, how you are going to define the exegetic efficiency for different components. So, we can say that there is a decrease in the flow exergy for turbines from inlet to exit of the turbines and there is an increase in the flow exergy from inlet to exit of the compressors and pumps. Obviously, we are going for pumps only; there is increase in the exergy.

We say that heat exchanger are typically analogous for a boiler, where hot steam supply the exergy to the cold stream as well as the exergy is also destroyed. So, basically in a boiler what happens, heat is being supplied to the system through some certain processes like the combustion of products. Thereby some exergy is being carried into the system and some exergy is being carried out by the system. So, we are going to model that way.



Counter flow heat exchanger



Now, here when you talk about the heat exchanger unit there are two possibilities one being - the fluids mixed together. Like if you say one particular counter flow arrangement, we have a hot stream that is coming in and which is going out as a cold stream and another channel we have a cold stream which is entering and it is going out. So, through this process the cold fluid is receiving heat from this hot fluid and of course, they do not mix with each other and their flow rates are also different. That means, cold stream has a different flow rate and hot stream has a different flow rate.

But in second type of arrangement there can be possibilities that hot stream is coming and cold stream is coming and they go as a mixed stream that means, both the fluids are mixing together. So, here we can say mass balance as addition of m_1 and m_2 gives the m_3. So, accordingly the term for the exergetic efficiency for different components can be found out. So, here you start with an expression specific exergy and this specific exergy term we have to apply it for different components.

Specific exergy: $e = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + \left(\frac{V^2}{2}\right) + gz$

And if you apply for the turbines we can find out what is the exergy flow coming into this and what is the exergy going out of the turbines. So, that is the actual work output per unit mass which we are getting from the turbine.

Exergetic turbine efficiency: $\varepsilon_t = \dfrac{\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)}{\left(e_{f1} - e_{f2}\right)}$

So, this ratio gives the exergetic efficiency for turbines.

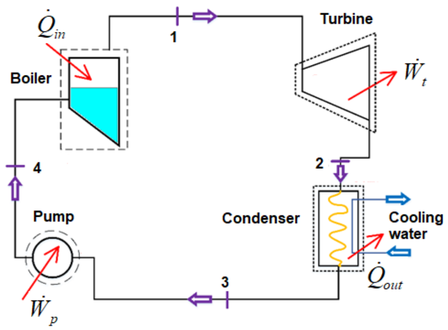
Exergetic pump efficiency: $\varepsilon_p = \dfrac{\left(e_{f2} - e_{f1}\right)}{\left(\frac{-\dot{W}_{cv}}{\dot{m}}\right)}$

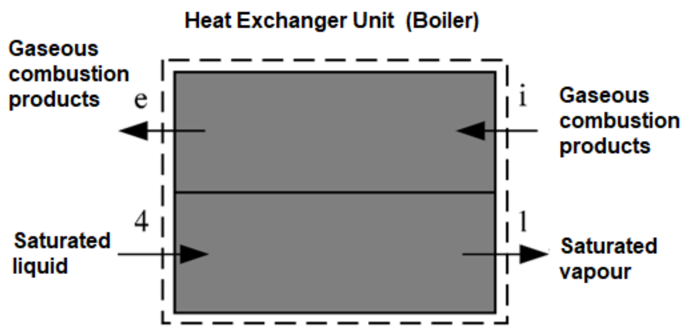
For pump the expression is completely reversed because the pump requires work as an input.

Heat exchangers without mixing: $\varepsilon_{he} = \dfrac{\dot{m}_c\left(e_{f4} - e_{f3}\right)}{\dot{m}_h\left(e_{f1} - e_{f2}\right)}$

Direct contact heat exchangers: $\varepsilon_{hem} = \dfrac{\dot{m}_2\left(e_{f3} - e_{f2}\right)}{\dot{m}_1\left(e_{f1} - e_{f3}\right)}$

Now, for heat exchangers the expressions are defined through the heat carried by the working fluid of hot stream and heat being rejected to the cold stream. Here the expressions are slightly changed based on this mass balance. So, these are the working formula for exergy analysis and in our subsequent discussions, we will see how these formulas can be used to solve some problems.





Then let us start with the first unit like in our exergy analysis if you say, it is a heat exchanger unit, in our prospective of vapor power systems it is considered as a boiler. So, in our analysis we simply said that heat is being fed to the boiler, but how this heat is being fed? To have certain insight into this particular philosophy, we model this as a heat exchanger unit. And in fact, heat comes from fuel like by burning coal or some other fluids like petrol, diesels in IC engines. By burning these we get the gaseous products of combustion, its temperature is very high and that enters to the boiler unit. And of course, this operates at boiler pressure and when it enters, it gives the heat to the working fluid for this vapor power cycle.

And this is nothing, but your liquid water which enters in a counter flow arrangement in the manner shown in picture. So, here if you look at the boiler, the working fluid that is water enters at state 4 and it goes at state 1. So, from 4 to 1 its enthalpy changes and it receives heat from the gaseous products of combustion. So, when you talk about the heat exchanger unit this is how we need to find out what is the exergy that is being carried out by these gaseous products and typically in case of absence of data, this products of combustion can be modeled in a more appropriate manner by using air. And this is being carried into these system and in other side of the story is that the heat exergy is carried out by the water from this heat exchanger units. So, the net effect will give you the exergetic efficiency. And remember while talking this analysis we still assumes that dead state conditions, $p_0 = 1$ bar and $T_0 = 25°C$. And in similar way, we can calculate the exergy for each of the stream. And considering this heat exchanger unit, we can say that the combustion products can be modeled as air. If we model this as air and its mass flow rate is $\dot{m}_a$ and this mass flow rate is also conserved.

And side by side if you say steam is being modeled. So, stream that is entering $\dot{m}_4$ and steam that is leaving $\dot{m}_1$, are same and we say that, $\dot{m}_4 = \dot{m}_1 = \dot{m}$.

Heat exchanger unit (without mixing)

Steady state conservation of mass: $\dot{m}_i = \dot{m}_a(\text{air}); \dot{m}_4 = \dot{m}_1(\text{water})$

Energy rate balance for control volume:

$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_a(h_i - h_e) + \dot{m}(h_4 - h_1) \Rightarrow \frac{\dot{m}_a}{\dot{m}} = \frac{h_1 - h_4}{h_i - h_e}$$

Now, considering this we calculate,

Net rate of exergy carried into the heat exchanger by gaseous stream:

$\Delta\dot{E}_g = \dot{m}_a(e_{fi} - e_{fe}) = \dot{m}_a[(h_i - h_e) - T_0(s_i - s_e)]$. And this is the working formula for the specific exergy.

And similar way we can find the
Net rate of exergy carried out of the heat exchanger by water stream:

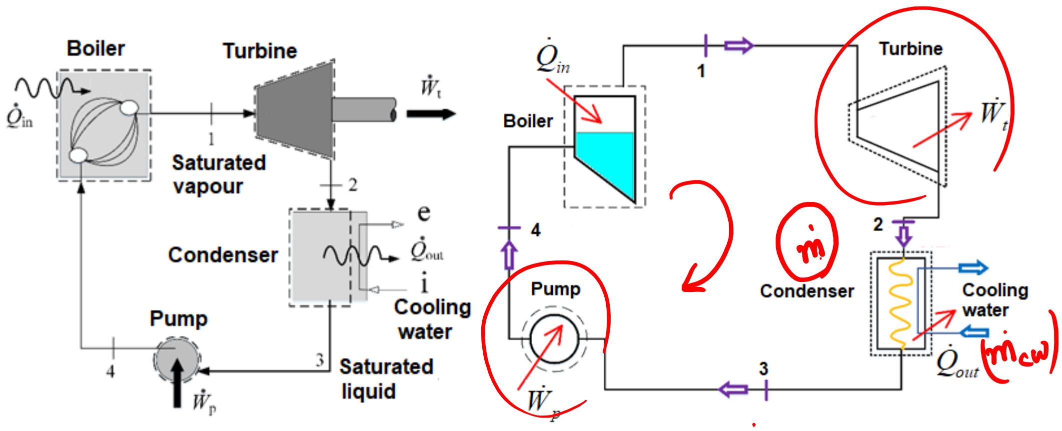
$$\Delta\dot{E}_w = \dot{m}(e_{f1} - e_{f4}) = \dot{m}[(h_1 - h_4) - T_0(s_1 - s_4)]$$

So, calculating both the parameters we can find out the rate of exergy destructions and subsequently exergetic efficiency for the heat exchanger.

Rate of exergy destruction for heat exchanger: $\dot{E}_d = \dot{m}_a(e_{fi} - e_{fe}) + \dot{m}(e_{f1} - e_{f4})$

Exergetic efficiency for heat exchanger: $\varepsilon_{he} = \dfrac{\dot{m}(e_{f1} - e_{f4})}{\dot{m}_a(e_{fi} - e_{fe})}$

And in our vapor power term, we say its exergetic efficiency for boiler.



And in similar way we can model it for other individual components like turbines, then pumps. So, both of them can be modeled in a similar manner. But for condenser we think that, this is similar to boiler, but with a little bit of difference. Here what happens the working fluid and enters to the condenser at state 2 and leaves state 3 and during this condensing process heat is being carried out by this cooling water. So, we say that $\dot{m}$ is the steam or fluid that is being circulated within this vapor power cycle and heat from this $\dot{m}$ fluid is being taken out by cooling water $\dot{m}_{cw}$, which is entering at some state and leaving at some other state. So, when you say in this model stream 1: a 2 phase liquid vapor mixture enters and the condensate is existing. Other stream can be separate cooling water is entering and exiting at known temperature and pressure. And again here also while modeling this, we assume that it is at dead state conditions, $p_0 = 1$ bar and $T_0 = 25$℃ .

The similar way we analyze it for boiler & we can find out the exegetic efficiency for condenser. But for pumps and all there are direct expressions for exergy destruction, which can be utilized, based on the thermodynamic data at the state points.

Rate of exergy destruction for turbine: $\dot{E}_{d,t} = T_0\dot{\sigma}_{cv,t} = \dot{m}T_0(s_2 - s_1)$

Rate of exergy destruction for pump: $\dot{E}_{d,p} = T_0\dot{\sigma}_{cv,p} = \dot{m}T_0(s_4 - s_3)$

Rate of exergy destruction in condenser: $\dot{E}_{d,c} = T_0\dot{\sigma}_{cv,c}$

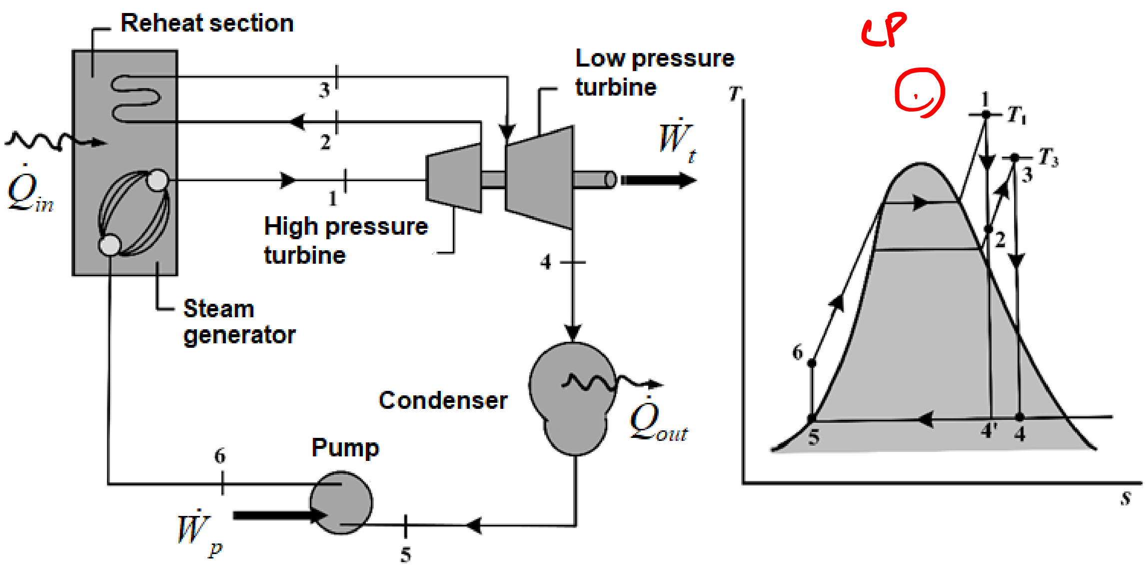
$$= T_0[\dot{m}(s_3 - s_2) + \dot{m}_{cw}(s_e - s_i)]$$

Exergetic efficiency for turbine: $\varepsilon_t = \frac{\left(\frac{\dot{W}_{cv,t}}{\dot{m}}\right)}{(e_{t1} - e_{t2})}$; $(e_{t1} - e_{t2}) = \left(\frac{\dot{W}_{cv,t}}{\dot{m}}\right) + \left(\frac{\dot{E}_{d,t}}{\dot{m}}\right)$

Exergetic efficiency for pump: $\varepsilon_p = \frac{(e_{p4} - e_{p3})}{-\left(\frac{\dot{W}_{cv,p}}{\dot{m}}\right)}$; $(e_{p4} - e_{p3}) = -\left(\frac{\dot{W}_{cv,p}}{\dot{m}}\right) - \left(\frac{\dot{E}_{d,p}}{\dot{m}}\right)$

Exergetic efficiency for condenser: $\varepsilon_c = \frac{\dot{m}(s_3 - s_2)}{\dot{m}_{cw}(s_e - s_i)}$

So, we will see how these formulas are being used in while solving the problems. So, this is all about the exergy analysis. Now, we will move on to other vapor power cycles.



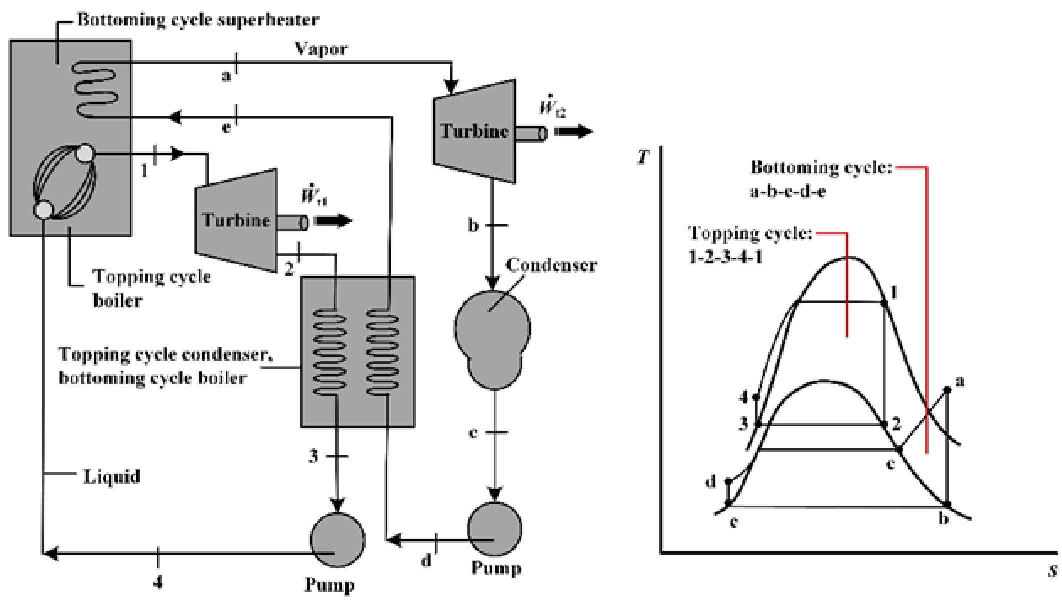
So, the first segment of this discussion is that we need to talk about working fluid and organic cycles. Organic cycle; means in a conventional system where water is the main working fluid in a Rankine cycle and there we use the concept like reheat, superheating and with these techniques there are certain limit, we can go up to. And that is restricted by the critical point that is the peak point of this dome. So, we can keep on increasing the temperature till we reach the critical point. But that critical point has also restrictions on the type of materials that are being used.

Now, to reach this critical point, many a times your working materials has certain metallurgical disadvantage or limitations. There will be thermal endurance of the materials for which we cannot go beyond this critical point. So, there the role of Rankine cycle is restricted. Although there is a thermodynamic possibility that we can go up, but the material restrictions does not allow to go for this. So, in such cases what we expect is that we explore some cycles and which are operated as supercritical cycles. That means, instead of going through these terms for example, if you go for critical pressure of water then you have to create an ambience of 22.1 MPa or higher to go directly from water to steam.

But there is a restriction that we cannot achieve this through this conventional materials. So, for that reasons if you want to go from liquid to steam directly without crossing this liquid vapour region then we have to think of the cycle which is being operated on supercritical cycle. But, to do that, the material poses some limitations and because of which we have to choose some working fluids for which this critical pressure can be less. That means, we can operate Rankine cycle in a supercritical manner that means, directly going from liquid to vapor without going through this liquid vapor region and for that reason, we have to change our working fluids.

And there are some substances, typically they fall under the category as organic substances. They are nothing, but the mixture of hydrocarbons/ refrigerants/ ammonia/ silicon oil. And such substance has the capability for going from liquid state to the vapor state directly without crossing this liquid vapor region and that too they can operate at relatively less critical pressure. And when they operate at relatively less critical pressures then of course, temperature goes down. So in this way the metallurgical difficulties of materials are being taken care of. And such cycles has many advantages because they have low boiling points and which allows this Rankine cycle to produce power even from low temperature sources such as industrial waste/ geothermal hot water/ fluids heated through the solar collectors, but they incur high cost per unit power as compared to conventional power plants, but the fuel cost is considerably lower. So, that gives rise to higher thermal efficiency. And of course, as less fuel is used so the supercritical plants have less environmental impact.

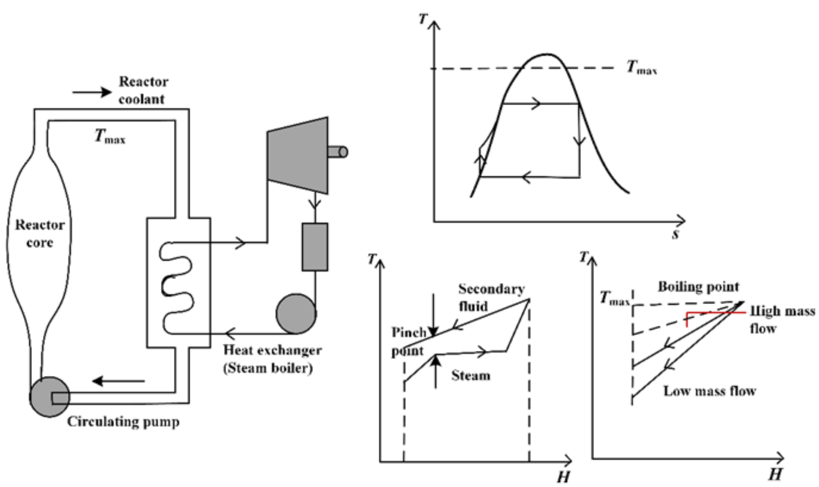
Then we will move on to another type of cycle that is binary vapor cycle. So, here the vapour power cycle has the concept that whether in a given cycle you can think of using more than one working fluid. That means, we try to decouple the system in such a way that two turbines can be used and for each turbine the working fluid will be different. For example, a decoupled arrangement is shown here and we call this as a binary vapor cycle. To understand the cycle first let us see what this means thermodynamically to us.



In fact, here we draw the two domes that is one dome for one working fluid, other dome for different working fluid on a single plot. So, you can see that one cycle, that is Rankine cycle, operates as a-b-c-d-a, called as Bottoming cycle and other one operates as1-2-3-4-1, called as topping cycle. And for both of them the common thing is boiler unit and condenser unit. So, for topping cycle the condensing unit that is state point from 2 to 3 will act as a boiler unit for the bottoming cycle that is a-b-c-d-a.

So, through this process, the working fluid from topping cycle rejects the heat and that is being taken by the bottoming cycle. So, considering this as a working model, thermodynamically we see that the power unit that comes as W_{12} one part and W_{ab} as second part. So, there are two power turbines. So, the thermodynamic model here looks like, we have a topping cycle and we have a bottoming cycle. So, the bottoming cycle works as a-b-c-d-a and the topping cycle condenser works as a bottoming cycle boiler; both of them have a same unit and two power units, $\dot{W}_{t1}$ and $\dot{W}_{t2}$ comes into picture.

And here other feature is that, both of them have a common steam generation unit and in one case we say we say it is a conventional well based arrangement, other case we say it is a superheater systems. That means, we can say the steam generation units consist of a boiler and a superheater unit. The superheater unit is for bottoming cycle and the conventional cycle work on a topping cycle. The advantage we get through this process is that the combined cycle has higher average temperature of heat additions and lower average temperature of heat rejections. And of course, thermal efficiency is greater from either cycles. That means, combined thermal efficiency is higher than that of either cycle. The next cycle that we normally use it for nuclear power plants.



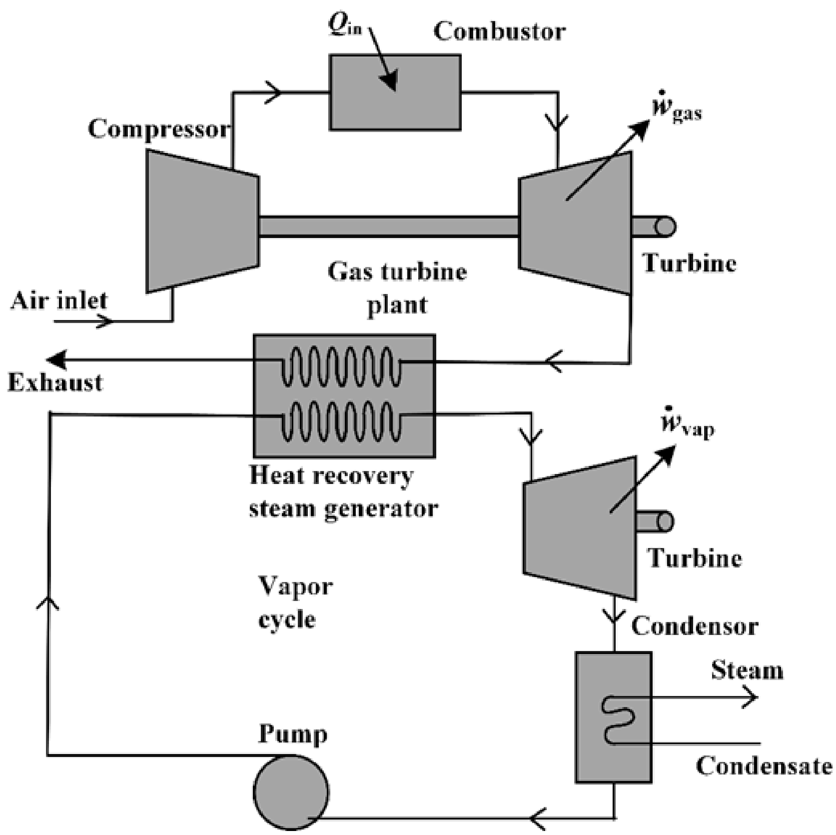
So, here in the schematic diagram, we have turbine, we have condenser, we have boiler. This works as a Rankine cycle using the common steam as similar to the steam power plant. So, basically the reactor coolant gives heat to this Rankine cycle and acts as a steam boiler to produce the power. That means, we have a primary fluid which is water and we have a secondary fluid which is circulated here. And the upper limit for this working fluid would be T_{max}. Now, we operate the Rankine cycle in a similar manner because this heat exchanger unit called as a steam boiler for this Rankine cycle using water. And for the secondary fluid; if you look at the temperature enthalpy diagram says that secondary fluid rejects the heat, so, its temperature falls down and it is being taken away by the steam. But one particular time we will have to see that what is the curve looks like.

So, there is a upper limit that the secondary fluid can work and there is temperature difference in the saturated liquid dome and that temperature difference is known as pinch point. So, we define a point which is called as a pinch point which is specified such that temperature of the secondary fluid is slightly higher than the saturated temperature of the steam. This is one aspect. And other aspect is that permissible maximum temperature; and that is restricted by the secondary fluid leaving temperature and which is below the critical temperature of the steam. That means, if you say the temperature of water critical point is here and this steam maximum operable temperature would be somewhere below than that. And of course, the slope of the line for the secondary fluid in the temperature enthalpy diagram can be changed by considering the mass flow rate. So, by increasing or decreasing the mass flow rate this line, slope of the line can be changed. And that again gives the judgment what should be the pinch point for the operational conditions.

Then there is another concept called as low temperature power cycles. So, normally low temperature power cycles use different waste energies/ renewable energies and which involves similar components like turbines, condenser and pump and there is a low temperature source. And this low temperature source could be a solar pond, where the solar radiations are absorbed; or could be hot water from a geothermal reservoir or could be considered as ocean thermal energy. The operating limits, normally for this kind of applications is between 20 ℃ to 90℃.

So, obviously, we cannot use water as a working fluid for this cycle. So, we have to think about some kind of refrigerants like R 134a is one of such cases. And this can operate in pressure ratios in the range of 32.4 bar to 5.72 bar. So, this particular number tells you that by considering different refrigerant in a power cycle one can think of Rankine cycle to operate in a low temperature power cycle.

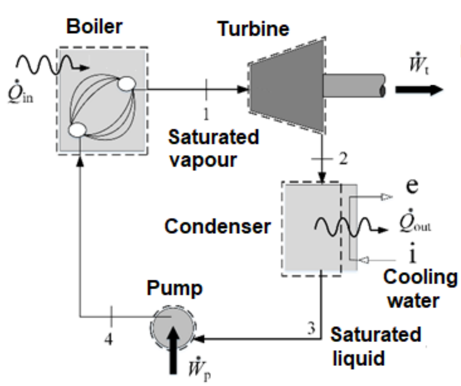
The last segment of this other vapor power cycle is on co-generations. Co-generation is a concept where we say that two or more power systems can be integrated together to have the need based applications. So, in this particular figure, it can be said that a gas turbine power plant is integrated with the vapour power cycle. So, that means, in a gas turbine power plant unit, whatever exhaust from the turbine is being utilized partially as a heat recovery steam generator unit.



There are two power sources that comes in; one is gaseous source from the gas power plant & other is from the vapor power plants. So, here we say it is steam or water and here the working fluid is air. So, this is one aspect where two power plants are combined. Other way of looking at is extraction plant. You all have come across the regenerative cycles where we see that some part of steam is being extracted at some different state or some states of the during the expansion phase in the turbine. So, what we do is that we can think of meeting different heating loads in a flexible manner by extracting steam at different segment of the power plants. We call such concept as an extraction plant. I mean it is application oriented for example, we can extract some of the steam from a turbine and try to use it for some heating unit. For example, heating of water is one of the essential requirement for a community. So, this particular concept also works in the mode of co-generations.

With this we complete our discussion on exergy analysis and different vapor power plants. Now, we will try to solve a numerical problems based on our discussion for a vapor power system.

Q1. In a Rankine cycle, the saturated vapor enters the turbine at 8MPa and saturated liquid leaves the condenser at 0.008MPa. The net power output of the cycle is 85 MW. The thermodynamic data are given in the following figure. Determine the following parameters for the heat exchanger unit: (a) net rate of exergy carried into the heat exchanger unit by the gas stream; (b) net rate of exergy carried away by the water stream; (c) rate of exergy destruction in the heat exchanger; (d) exergetic efficiency.



Data sheet

Mass flow rate of steam: 125 kg/s Mass flow rate of cooling water: 2500 kg/s

State 1: saturated vapour (8MPa; 2758 kJ/kg; 5.74 kJ/kg.K)

State 2: liquid vapour mixture (0.008MPa; 1939 kJ/kg; 6.2 kJ/kg.K)

State 3: saturated liquid (0.008MPa; 174 kJ/kg; 0.9 kJ/kg.K)

State 4: subcooled liquid (8MPa; 183 kJ/kg; 0.92 kJ/kg.K)

Cooling water

$\left(\text{At } T = 18^0\text{C, } s_i = 0.22\,\text{kJ/kg.K; } T = 38^0\text{C, } s_e = 0.5\,\text{kJ/kg.K}\right)$

Combustion products (may be modelled as 'air')

$\left(\text{At } T = 1177^0\text{C, } s_i = 3.4\,\text{kJ/kg.K; } T = 527^0\text{C, } s_e = 2.7\,\text{kJ/kg.K}\right)$

So, in the first problem, I have drawn the schematic figure and prepared a data sheet. What it means? We have a conventional vapor power systems operating water as a working fluid and it operates on a Rankine cycle and the cycle has components like boiler, turbine, condenser and pump. And in our previous discussion we have done the complete cycle analysis and for this complete cycle analysis based on the data given one can find out all possible points for the cycle.

That means, first we have to use the operating pressures and using the operating pressure, the condition of the steam at each component & steam table one can find out the thermodynamic states for each components. So, here the complete analysis has already been done. I mean in our previous lecture we solved similar problem. So, here I need to summarize that when a vapor power cycle operates at these following states.

State 1: Entry for the turbine

Saturated Vapor (Pressure = 8 MPa, enthalpy = 2758 kJ/kg, entropy= 5.74 kJ/kg.K)

State 2: Entry for condenser and exit for turbine

Liquid Vapor mixture (Pressure = 0.008 MPa, enthalpy = 1939 kJ/kg, entropy= 6.2 kJ/kg.K)

State 3: Entry for Pump

Saturated Liquid (Pressure = 0.008 MPa, enthalpy = 174kJ/kg, entropy= 0.9 kJ/kg.K)

State 4: Entry for Boiler

Almost pure liquid/ Subcooled liquid (Pressure = 8 MPa, enthalpy = 183 kJ/kg, entropy= 0.92 kJ/kg.K)

So, these values of pressure, enthalpy and entropy are given. Another additional information is that the net output for the power cycle, that is turbine work, $\dot{W_t} = 85$ MW.

Now while doing this analysis we see that we supply this $\dot{Q_{in}}$ to heat exchanger unit by using some combustion products and we will see that how this combustion products is modeled. So, we can think of this particular boiler unit as a heat exchanger unit in which the combustion products comes from inlet at state 1177 ℃ and goes out as at 527 ℃ and at 1 atmosphere.

Now what while doing so, this releases heat to the steam which is entering in a counter flow manner. Now here the water enters at state 4 as liquid and it goes as saturated vapor at a pressure of 8 MPa. So, this condition is at 1. So, here the main condition is that both the fluid do not mix with each other and this heat exchanger unit can be modeled. So, for that reason, first thing that we need to find out is that for this steam flow rate what is the requirement for the combustion products and here we can assume that it can be modeled as the data from air. This air data is stated below.

Combustion products (modeled as air)

At $T = 1177°C$, Entropy at inlet, $s_i = 3.4$kJ/kg.K, Entropy at exit, $s_e = 2.7$kJ/kg.K

So, a quick look of energy balance that gives that

$\dot{m}_a(h_\iota - h_e) + \dot{m}(h_4 - h_1) = 0$; $\dot{m}_a$ is for combustion product & $\dot{m}$ is for steam

$\Rightarrow \frac{\dot{m}_a}{\dot{m}_a} = \frac{h_1 - h_4}{h_i - h_e} = \frac{2758 - 183}{1457 - 805} = 3.95$

Since we know $\dot{m} = 125$ kg/s

So, mass of air requirement, $\dot{m}_a = 494$ kg/s.

We are now prepared for answering the first thing that is

a) Net rate of exergy carried into the heat exchange unit by the gaseous streams. So, $\dot{E}_{fa} = \dot{m}(e_{fi} - e_{fe}) = \dot{m}_a[(h_i - h_e) - T_0(s_i - s_e)]$

And since we can model this enthalpy for air. $h = c_p T$

Now, $h_i = c_p T_i = 1457$ kJ/kg

$h_e = c_p T_e = 805$ kJ/kg and s_i & s_e data is already given above.

So, $\dot{E}_{fa} = \dot{m}(e_{fi} - e_{fe}) = \dot{m}_a[(h_i - h_e) - T_0(s_i - s_e)]$

$\Rightarrow \quad \dot{E}_{fa} = 494[(1457 - 805) - 298(3.4 - 2.7)] = 219040$ kJ/s ≈ 219 MW.

And of course, this is being taken away by the steam.

So, next part is for the steam.

b) $\dot{E_{fw}} = \dot{m}\left(e_{fi} - e_{fe}\right) = \dot{m_a}[(h_1 - h_4) - T_0(s_1 - s_4)]$

$\Rightarrow \ E_{fw} = 125[(2758 - 183) - 298(5.74 - 0.92)]$ = 142375 kJ/s ≈ 142 MW

c) Rate of exergy destruction in the heat exchanger, $E_d = \dot{E_{fa}} - \dot{E_{fw}}$ = 77MW

d) Exergetic efficiency $\varepsilon_b = \frac{\dot{m}(e_{f1}-e_{f4})}{\dot{m_a}(e_{fi}-e_{fe})} = \frac{142}{219}$ ≈ 0.64 =64%

That means, boiler has used 64 % of the of exergetic efficiency.

Q2. For the Rankine cycle in Q1, Determine the exergy destruction for the turbine and pump.

Then we will move on to turbines and pumps.

For turbines we can directly write down Exergy destruction in the turbine

$(E_d)_t = \dot{m}T_0(s_2 - s_1) = 125 \times 298\ (6.2 - 5.74)$

$\Rightarrow (E_d)_t$ = 17135 kJ/s ≈ 17 MW

exergetic efficiency for turbine, $\varepsilon_t = \frac{\dot{W_{cycle}}}{\dot{W_{cycle}}+(E_d)_t} = \frac{85}{85+17}$ = 0.83 ≈ 83%

So, exergetic efficiency is 83% which is quite good.

Similarly for pump let's calculate. In the power plants the pumps normally takes the least energy or negligible energy. So, just for the sake of calculation if you just try to calculate,

Exergy destruction for the pump,

$(E_d)_p = \dot{m}T_0(s_4 - s_3) = 125 \times 298\ (0.92 - 0.9)$ ≈ 3.7kJ/s ≈ 0.003MW

This is quite low that means, pumps take least energy. Of course, you can say exergetic efficiency is almost nil/negligible.

Q3. In a Rankine cycle, for Q1, Determine the following parameters for the condenser unit: (a) net rate of exergy carried by the cooling water; (b) exergy destruction; (c) exergetic efficiency.

Then we will move on to last component that is condensing unit. If you look at this condensing unit there is a separate water stream, in which we have the steam, which is liquid plus vapor mixture that enters at state 2 and leaves at state 3 as saturated liquid. And here this is giving heat to the cooling water.

The data sheet for this cooling water-

Cooling water enters at 38 °Cand leaves at 18°C. The mass flow rate of this cooling water is given here as $\dot{m_{cw}}$ =2500 kg/s.

So, this analysis is modeled in similar way we did for boiler.

a) Net exergy carried by the cooling tower,

$$\dot{E_{fcw}} = \dot{m}_{cw}\left(e_{fe} - e_{fi}\right) = \dot{m_{cw}}[(h_e - h_i) - T_0(s_e - s_i)]$$

$$= 2500[4.2(38 - 18) - 298(0.5 - 0.22)] = 1400 \text{ kJ/s} \approx 1.4\text{MW}$$

b) Exergy destruction

$E_d = T_0\sigma_{cv}$; Where σ_{cv} is nothing, but control volume for the condenser unit.

$$E_d = T_0\sigma_{cv} = T_0[\ \dot{m}(s_3 - s_2) + \ m_{cw}(\dot{s_e} - s_\iota)$$

$$= 298[125(0.9 - 6.2) + 2500(0.5 - 0.22)] = 11175 \text{ kJ/s} \approx 11.175 \text{ MW}$$

c) Exergetic efficiency for the condenser

$$\varepsilon_c = \frac{T_0[\dot{m}(s_3 - s_2)]}{T_0[\dot{m_{cw}}(s_e - s_i)]} = \frac{197425}{208600} = 0.94 \approx 94\%$$

So you say exergetic efficiency for condensing unit is about 94%.

So, this gives you the combined effect of a vapor power system for this complete power cycle integrated with a dead state at p_0 and T_0, we can find out the exergetic efficiency of each component when they work together. So, with this I conclude. Thank you for your attention.