POWER PLANT SYSTEM ENGINEERING

Lec 3: Thermodynamic Analysis of Vapor Power Cycle

Dear learners, greetings from IIT, Guwahati. We are in this MOOCs course Power Plant System Engineering. Today, we are going to start the module 2 and in this module we will discuss about Vapour Power Systems part 1. So, in the first lecture of this module, I will try to explain the following topics. First is vapor power plants, its basic introductions. Next point would be the performance indicators for vapor power plants.

Here we will try to see for a plant design, what are the critical thermodynamic parameters that needs to be evaluated first. Then we will move on to thermodynamic analysis. Here we will mainly focus on the steady flow energy equations which can be applied for a simple vapor power plant system. Then we will try to revisit our basic thermodynamic aspects that talks about Carnot cycle and in fact, Carnot engine is one of the fundamental cycle in which we can get the information of net work output for a given heat input.

In other words, it justifies this fact that it is possible to extract work output from a low grade energy source which is in heat form. But unfortunately, there are certain limitations Carnot cycles cannot be implemented in practice. So, why we cannot implement Carnot cycles, we will be discussing about that topic. Then if Carnot cycle is not there, then what is the next alternative? So, for that we need to consider certain power plant design considerations, based on that we will propose a new cycle which is in line with the vapor power plant systems. So, this is the overall summary of the lecture.

Then let us start the basic introductions of vapor power plants. We all know that energy is the basic need for society and in fact, in 21st century there is an immense growth of power that needs in every sectors across this globe. In fact, there are some main areas of application is that if you want to extract power, then the possible choices that we can have is through internal combustion engines or gas turbines power plants or third category would be vapor power plant systems. So, in our basic thermodynamics course that is applied thermodynamics course, we have mostly dealt with internal combustion engine and gas turbine plants. Of course, to some extent we will also discussed about the steam power systems and in this module we will exhaustively discussed about this vapor power plant systems.

Now, the main basic difference between this IC engine or gas turbine plants with respect to vapor power plant is that, in IC engines or gas turbine systems, the main working fluid always remains in the gas phase. So, for example, either you see internal combustion engines where we think about only air or air fuel mixture or even in gas turbines air is the basic ingredient which is sucked into the intake systems of a compressors and in this entire cycle the working fluid is always remains in the gas phase. Although its pressure temperatures keeps on changing, but the working fluid remains in the gas phase. But in a vapor power systems we dealt with the working fluid which continuously changes its thermodynamic states. So, in other words what we say that the working fluid is alternatively vaporized and then condensed.

So, for that thing we need a large volume of working fluid or large quantity of working fluid so, for which water is the unanimous choice. Now, while looking at these vapor power systems if you want to convert the water to steam then we require some heat from a reservoirs. So, regardless of what working fluid we use, the choice of heat transfer is mainly decided by the user. So, this can be a conventional fossil power based systems like coal, other choice could be in a nuclear mode or it can be in any other oil or nowadays the renewable form of energy also comes into pictures. So, the choice of heat transfer mode to the working fluid it can be a biomass, solar or geothermal.

But whateverheat source you decide it all precisely depends its availability at that locations. So, here we are going to demonstrate a schematic diagram of a vapor power plant systems that talks about the complete picture. So, what we see here in this figure is that we have a boiler, we have a turbine, we have a condenser, we have a pump this is the main constituents which comes under the segment N and beyond this N, we have another segment that how this boiler gets heat from the outer source. So, that segment is N. So, that means, M transfer the supply of energy to the working fluid.

So, it could be a fossil fuel, it could be a nuclear, it could be a solar, it could be geothermal unit. Geothermal unit mainly talks about inside the earth the temperature medium is very high. So, we can think about extracting energy from the underground earth materials and that can be pumped as a hot water and steam through the heat exchangers. So, other option could be a solar thermal based vapor power plant where boiler is integrated with a solar power systems. Other option is that we can think of a nuclear power plant where boiler is integrated with a nuclear reactor.

So, this choice of the energy or heat energy supplying to the systems is mainly based on the users. The second category which is in the N, which means that it is the energy conversion mechanisms. That means, when heat is being supplied we are trying to find out a mechanism through which we can get work. So, this has something as resemblance that the working fluid is being circulated in this circuit which involves N and that takes heat from this boiler and which can quantify it as a Q_1. And if you look at this Carnot cycle which sees that we have a source, we have a sink and the source and sink are operated at certain temperature T_1 and T_2 and this is connected through an engines involving working fluid.

So, in this process the engine takes Q_1 amount of heat and rejects Q_2 amount of heat to this sink and side by side it produces net work W_{net}. So, if this is the case then if you can imagine this particular cycle which is N which replicates as a engine. So, in this process heat is being supplied to this segment N and heat is being taken out in this condenser. So, this we can say as Q_2 and this Q_1 is being heat supplied by the fossil fuel into this system N and through this process this turbine delivers W_{net}. So, this is a direct resemblance that how a vapour power cycle concept comes from the Carnot engines.

Now apart from this we have another segment called O that means, when the turbine gives power output, then it has to be integrated for generating the electric power. So, there is an electric generator or alternator. Other part is P which is this segment. Now in order to run this system N, we require continuous supply of working fluid that supply we are getting it through a feed water pump and in fact, it takes water either from a sump or it can be taken from a cooling tower. So, it all depends how you supply working fluid to this subsystem N.

So, this is how the entire vapour power plant system consists of, but our main focus would be in the section N or subsystem N. So, we will not deal with how this heat source comes. So, we will simply say that it is a fossil based power plant system when water is getting heated and we will say that water is being supplied either from a river or from a sump and or it can be recirculating water from a cooling tower. And the other part is that in terms of power generation we will not think about the electric power we will just talk about only mechanical power which is the net work output. Now let us try to understand what is this W_{net}.

So, in this Carnot cycle we says that net work output that gets out of the systems. Now here, I am just explaining that how that net work comes into pictures. So, normally when a engine is operated we say that the ideal component would be a turbine that produces net work output, but again there are some additional devices which needs to be integrated in this thermal circuit that also consumes power. So, in this case in a vapor power system is a simply a pump. So, the net work is normally decided by turbine work minus pump work.

So, this picture shows about how the concept is justified. So, second point that I need to emphasize what is the actual cycle and what is the Carnot cycle. So, what does this mean if you look at two engines one is a reversible engine or other is any arbitrary engine X and they operate between two temperatures upper temperature T_h or source temperature T_h and lower temperature is sink T_L and both operate in the same temperature limit. And in this process the reversible engine produces work output as W_R and any other engines arbitrary engine it produces work output is W_X. So, obviously, since it is a reversible engines we can say it is a Carnot engine and its efficiency is decided by this Carnot efficiency which is $\eta_c = 1 - \frac{T_l}{T_h} = \frac{T_h - T_l}{T_h}$.

And if you look at the other engines for which the net work is normally decided by this W_X. But what the next figure talks about that we can think of a system or instead of talking about this heat and we will simply remove the source and connect these things through this manner. So, in that way what we will have is that some work is being utilized to run this reversible engines. So, basically what we are seeing is that if you remove this reversible engine by a pump so, obviously, it will take some work input which is W_R and it operates from same source T_h and they take both Q_1 heat input for both of them. And if you imagine that we do not have this reversible engines and instead of that to produce this net work we also require some additional components that is W_{pump}. So, so instead of W_R, I will put it as W_p so, that the net work we can imagine to be W_X - W_p. So, the net work now comes down as the actual work minus the pump work. So, here this actual work refers to our turbine work. So, what it trying to say is that not all engines are reversible. So, for any irreversible engines the efficiency will be always less than the cannot efficiency.

So, this is in the same concept. So, the basic summary that we get out of this exercise that all real processes are irreversible and this irreversibility reduces the cycle efficiency. Now, using this concept we will move further to find out different performance indicators for a vapor power systems. The first performance indicator is nothing, but the efficiency ratio. Now, again we revisit the same Carnot cycles which we call this engine is being operated through a cyclic device and it takes Q_H amount of heat and rejects Q_L amount of heat. But how this QH is coming, QH is coming from the fuel air mixture which is being supplied at a source segment and side by side it gives the combustion products. So, what we are trying to look at is that there are two efficiency that is coming up one is the Carnot efficiency other is with actual engines efficiency. So, when I write this Carnot efficiency which is thermal efficiency for a Carnot engines that is $\eta_{ti} = 1 - \frac{T_l}{T_h}$. Now, if you talk about the actual engines. So, that is nothing, but the $\eta_{ta} = 1 - \frac{Q_l}{Q_h} = \frac{W_{net}}{Q_{in}}$.

So, one parameter that can be popped is because due to irreversibility in the medium or in other words if there are irreversibilities in this systems, then our efficiency cannot approach to this Carnot efficiency. So, for that reasons we define this efficiency as actual efficiency. Now, looking at these two efficiency, Carnot efficiency will talk about the upper limit and actual efficiency will talk about the system operating while calculating irreversibility in the medium. So, ratio between these two we define it as a efficiency ratio. This is something similar to the second law efficiency what we understood in the first level thermodynamics course. Then moving into next parameter which is work ratio. As I mentioned earlier, this net work consists of two parts one is turbine work, other is the pump work. So, difference between these two we call this as a net work, but gross work which is defined by the turbine work. So, work ratio is defined by net work to the gross work. $\text{WR} = \frac{W_{net}}{W_t} = \frac{W_t - W_p}{W_t}$

So, many books also instead of talking about work ratio they talk about back work ratio. Back work ratio means it is not in the form of net work it is in the form of pump work. So, basically pump work is the additional input that we were going to give this engine to produce the turbine power. So, back work ratio is normally defined by pump work to the turbine work, but however, our attention will be mainly focused on the work ratio. The next performance indicator is the steam consumption rate. So, to quantify this we call this as a specific steam consumption or heat rate. So, what does this mean? So, when you say work ratio, normally it defines the size of the systems and it talks about what should be the size of turbine, what should be the size of compressors and which involves the capital cost. But once we have installed turbines, compressor and other units, but we need a continuous supply of working fluid. Normally the continuous supply of working fluid is decided by the fact that how much steam is being fed to the turbine to produce certain work output or in other words when you are talking about steam flow rate that can be quantified as also heat rate. So, these two parameter talks about the running cost of a plant.

So, for that reasons we define this parameter as follows that the direct indication of vapour power plant is given through specific steam consumptions; it is nothing but the mass flow rate of steam per unit power output. And in analogous to this, we also call as heat rate which is the amount of energy added by heat transfer to the cycle to produce a unit of work output that means, in kilowatt hour. So, if you compare the SSC, specific steam consumption and heat rate will have a direct relations, but it has a inverse relation with respect to efficiency. So, many a times if you bring back the definition in mathematical form we say specific steam consumption SSC $= \frac{1}{W_{net}}\left(\frac{\text{kg}}{\text{kWs}}\right)$. But this number is typically very low. So, a more appropriate way of looking is to define the steam specific steam consumptions in terms of kg per kilowatt hour because kilowatt hour is a unanimous choice in terms of recognizing the power. So, for that reasons the SSC is $\frac{3600}{W_{net}}\left(\frac{\text{kg}}{\text{kWh}}\right)$. So, this 3600 term comes when you convert hour to second. Now once you know this steam consumption rate, then the corresponding correlated parameter would be heat rate which is nothing, but the amount of energy is being supplied for 1 kilowatt power. So, $HR = \frac{Q_{in}(\text{kJ})}{1(\text{kWh})} \Rightarrow HR\alpha \frac{1}{\eta_t}$.

Now moving further, we will talk of more details on thermodynamic analysis and this thermodynamic analysis is mainly dealt with the steady flow calculations. We all know precisely that steady flow energy equations is one of the fundamental equations that was taught in the level 1 thermodynamics course and we are going to use those steady flow calculations for a vapour power systems. If you take a vapour power cycles and we try to understand that cycle through steady flow energy equations, then certain characteristics features that we can highlight here. First the working fluid is a condensable vapor which is in liquid phase during one part of the cycles. So, working fluid at some part of the cycles remains in a liquid phase and we can condense it and this liquid is obtained through condensation. The cycle consists of the components like boiler, turbine, condenser and feed pump. Boiler supplies heat energy to the working fluid, turbine produces work output, condenser condenses the steam to water, feed pump supplies the working fluid of required volume. And each component consists of a open system, they are connected in series we will see that how they are connected. The working fluid passes through each component and changes its phase. The working fluid enters and leaves the system in the same state that means, it enters in liquid state and also leaves the systems in the liquid state.

We will see how it happens. The work and heat transfer in various processes of the cycle is calculated through steady flow energy equation and equation and it is calculated based on unit mass. The changes in the kinetic and potential energy of the fluid at the entry and each component is neglected and all the processes are assumed to be reversible. So, it is an ideal cycle. The component as well as the system analysis can be done through steady flow energy equation and the first law of thermodynamics. Let us understand how this steady flow energy equations are obtained.

So, we see here that the components like boiler, turbine, condenser and pumps in the circuit. Heat is being given by a boiler, work is being produced by a turbine, pump supplies the necessary pressure difference between condenser to boiler and steam that leaves from the turbine it gets condensed in the condenser. So, we can see here that the working fluid enters to the systems that is state 1, it is in the liquid state and when heat is added it changes its phase. So, it becomes steam. So, it enters to the turbine and after coming back again when it enters to the condenser, it releases its heat and gets condensed and comes back to a water medium.

So, it means that it enters and leaves with same state that is in the liquid state. There are two options possible one is we can think about this working fluid continuously supplied in a cyclic manner. Other option is that in many a times since the working fluid is water we do not circulate it. In one way that it comes out from the condenser and goes to the atmosphere rather you take fresh water from the atmospheres. So, the state a' and a, we have introduced here, but their thermodynamic conditions may be little bit difference, but any case they enter in same state.

But what is main difference is that same system which was a closed system it is now viewed as a open system because the circuit breaks here. But however, if you do the steady flow energy calculations it really did not alter the main energy equations. Now, if you recall the main steady flow energy equations by involving heat transfer, mass transfer and enthalpy difference, kinetic energy changes, potential energy changes. What we assume is that since it is a power producing device, we will neglect the changes in the kinetic energy and changes in the potential energy. So, these two terms gets neglected in comparison with this enthalpy term because contribution of these two is very less as compared to this enthalpy difference.

So, the main equations boils down to $\dot{Q} + \dot{W} = \dot{m}\left[(h_2 - h_1) + \frac{1}{2}(C_2^2 - C_1^2) + g(z_2 - z_1)\right] = \dot{m}(h_2 - h_1)$. Now, this equation is being applied for boiler which supplies heat, turbine which produces power; Boiler: $\dot{Q}_{1-2} = \dot{m}(h_2 - h_1)$; Turbine: $\dot{W}_{2-3} = \dot{m}(h_3 - h_2)$. Again in the condenser its again a heat rejection process, feed pump also is the enthalpy difference. Now, if you sum it up one fundamental thing that arrives here that cyclic work transfer and cyclic heat transfers are same. Now, again if same system is viewed as a open systems that means, fluid enters at a state a and leaves at state a', here also will we have the same thing, but by assuming this difference to be small, this also talks about the same information that $\sum \delta Q + \sum \delta W = 0$.

So, this is all about the thermodynamic analysis where we did not bring the efficiency parameter into this picture. Now, we will move on to the fact that when you think about a Carnot cycle; why we say always repeat the word Carnot cycle because the first basic important information that Carnot cycle gives is that thermodynamically if you want to extract heat from a low grade energy that is in the heat form to a work form, then we must reject the heat and this sense was visualized by looking at the components which can act as a boiler. Now, instead of the turbine because the turbine was the recent development, but initially in the Carnot cycle, it was imagined to be an expander which produces the power, condenser which releases the heat, boiler it takes the heat, compressorwhich feeds this working fluid to the boiler. And same thing if you want to draw plot in a T-s diagram, ideally speaking, if you look at the working fluid there is a dome and in this dome you can say this is the critical point and this side is liquid and in between the dome we have liquid plus vapor and outside the dome it is the vapor. So, the circuit starts with point 1, where heat is being added through a boiler that is process 1-2 and process 2-3 is in the expander.

So, here Q_{12} is added and here W_{23} is getting produced and heat rejection process that is from 3 to 4 in a condenser. So, you say Q_{34} and compressor takes W_{41}. So, based on this we can recalculate these equations where $\dot{m}$ is the mass flow rate of the working fluid. $\dot{Q}_{1-2} = \dot{m}(h_2 - h_1)\dot{W}_{2-3} = \dot{m}(h_3 - h_2)\dot{Q}_{3-4} = \dot{m}(h_4 - h_3)\dot{W}_{4-1} = \dot{m}(h_1 - h_4)$.

Then, although thermodynamically it is possible and we can draw this in the T-s diagram, but unfortunately if you look at the close realistic way of applying this concept, it is not advisable to operate a vapor power system on a Carnot cycle. The main difficulties are as follows first thing is highest possible temperatures. The highest possible temperature of the working fluid is decided based on the metallurgical strength of the turbine blades or in a expander. Lowest temperature that is in the condenser side, it is mainly dealt with the water availability in the atmosphere or river which is in the range of 15 to 25 degree centigrades. Other option is that for a sufficient sucking of water or supplying water, we need to have a temperature difference of 10 to 15 degree kelvins. So, in other words it says that the condensing temperature ideally should be in the range of 25 to 30 degree centigrades with an average condenser pressure of 0.04 bar which means, if you want to try to plot them; take a data and try to calculate them, what we says is that when you see efficiency and if you say that precisely working pressure for a boiler is 30 bar and condenser pressure of 0.04 bar, we can see that your efficiency increases with condenser pressure or temperature which means the efficiency increases with decrease in the condenser pressure. So, the efficiency increases with decrease in the condenser temperature, but again efficiency increases with increase in the boiler pressure.

So, these two things are contradicting to each other, side by side if you talk about the steam consumption rate, specific steam consumption, it increases if your boiler pressure increases. So, a proper overlap or matching has to be done to precisely say that what should be the upper limit of boiler pressure and what is the lower limit of condenser pressure and more or less it boils down the range between 30 to 35 bar for boiler and 0.04-0.05 bar for condenser to have a reasonable estimate. Another limitations that a Carnot cycle has is that it has the highest possible temperature is 374 degree centigrade and 221 bar that we can operate the Carnot cycle in the wet regions which is somewhere here. Even this Carnot cycle has work ratio of 0.07 which is not advisable and if you include this component irreversibility this number still falls down. In addition to that there are practical difficulties which is associated with respect to compressions when we deal with the liquid vapor mixture during the compression phase. That means, if you think about this compressing from 4 to 1 in this liquid vapor region because this is region is liquid plus vapor, then it is a difficulty for compressor because liquids and vapors are two different states and they form actually non homogeneous mixture. And moreover if you look at the power input from 4 to 1 and power output from 2 to 3, more or less this is a rectangle and more or less they have equal sides which means to get appreciable power output from the turbines we also expect that similar range of compression work needs to be there.

So, which is not a feasible options. So, for that reasons the Carnot cycle was ruled out and while ruling it out, what was the proposed is a Rankine cycle. So, what does it say that if you look at a comparison of T-s plot for a Carnot cycle and a Rankine cycle both operate at same temperature limits let us say Ta and Tb, looking at the limitations of Carnot cycle we have pushed this point 4 to the saturated liquid regions. So, now, 4 falls in this saturated liquid regions and what did you do hen you bring this state of 4 to 1 through a constant pressure heating that means, 4 to 5 process is the pump work and through this process you can clearly say the side 4-5 is less than the side 1-4’. So, in that way we reduce the pump work drastically, but while reducing the pump work obviously, then net work also gets increased that is one part. Second part through this process additionally what did you do if you look at the area under this diagram, the heat input is little bit increased, side by side for which the efficiency for Rankine cycle is less than the Carnot cycle, but if you talk in terms of work ratio your work output for Rankine cycle is higher than the Carnot cycles.

So, this gives a clear indications for a vapour power plant which precisely work on the work ratio enhancement rather than the efficiency. So, through this process what additionally you do is size of the plant becomes relatively smaller because you have reduced the pump work as compared to this Carnot cycles. So, based on these considerations we are now proposing a main concept of vapour power plant design considerations which talks about two things one is capital cost other is the running cost. So, one is the capital cost mainly is the function of size and complexity like what should be the size of boiler turbines pumps and all and this operating cost mainly depends on the overall efficiency and that operating cost mainly assessed through how much your steam is getting into the systems. So, the overall efficiency is a function of these two like source efficiency through the combustions which is obtained by amount of available energy which is transferred as heat to the working fluid other is the cycle efficiency which is the actual heat which is converted to the mechanical work.

So, these two things has to be coupled. Now, here I want to try to emphasize a case study which talks about the main design aspects of a vapour power plant systems. What does it mean is that so, here we are proposing two important parameters or indicators one is work ratio WR other is the efficiency and what were the user input? User input is the heat input Qin which comes into this power plant systems and what is the main need? We need to get out of is net work which is the difference between the turbine work and pump work. Now, we are proposing two situations one is an ideal cycle other is the actual cycle. So, actual cycle involves a component efficiency or we call as process inefficiency or irreversibility introduced into the cycle.

So, let us learn to find out the first focus on the ideal cycles. So, for the time being let us not think about actual cycles. So, ideal cycle we have two models one we can think of for a given work input of 150 and we are trying to get out of a number that Wnet is 49. So, that means, we have resources available of Qin is maybe 150 kilojoule and net work we are supposed to get as 49. So, through this process there are two possibilities that means to get this 49, I can think of turbine work as 125 and pump work is 76 difference is again 49. So, these are just a generic numbers. In another situations I will propose the turbine work is 50 and pump work is 1 in both cases your net work is 49. So, based on these numbers you can calculate the work ratio you will find the cycle 2 has work ratio of 0.98 and while the cycle 1 was work ratio of 0.392, but both of them have same efficiency. So, what is the main summary that we get? So, cycle 2 is a better approach because it gives higher work ratio for same efficiency.

And now if you propose the cycle 2 and same thing we recalculate here for actual cycle where the component efficiencies of turbines and compressor is introduced with a number of 0.9 then we can recalculate these numbers. Here also if you just decompose this ideal cycle to actual cycle same logic we will get, in one case we will have work ratio of 0.975 other case we will have work ratio of 0.25. So, obviously, cycle 2 is also a better approach. Now comparing this two, if you try to compare cycle 2 for ideal and actual, when there is a minimal pump work the work ratio is not much affected. So, of course, there is a little bit of difference in the efficiency, but with small difference in the efficiency work ratio is mostly unaffected. So, that is the reasons the ideal choice for a power plant consideration is to have minimal pump work and which can give a very good overall efficiency and work ratio.

So, with this background and topic now we are going to solve a numerical problem. So, whatever we have understood in this lecture if you want to quantify in a thermodynamic cycle and let us see how we are going to do that. So, one particular numerical problems that we are going to look at is that a power plants operates with upper pressure of 35 bar which is on boiler and lower pressure condenser is 0.04 bar and it operates in a Carnot cycle. So, we need to find out work heat transfer cycle efficiency work ratio and all. So, this is the similar problem that I have given in the case study, but here we will look into a realistic case actually by using the steady flow energy equation, how we can find out all these numbers.

So, before you start the problems, we should recall that we must have a thorough knowledge of the steam table because we have to take most of the data for water and steam medium. So, first we will understand that what this Carnot cycle is all about in a T-s diagram. So, we plot this in a Carnot cycle. So, state 1-2 is the boiler, 2-3 is the turbine, 3-4 is condenser and 4 -1 is pump. And we say that this saturation pressure corresponding to this, we say it is a 35 bar and this is 0.04 bar and corresponding temperatures we can say this is the T saturated at 35 bar and T saturated at 0.04 bar. So, let us recall that from the steam table you refer saturated pressure table. So, we can say at 35 bar, T saturated will be 516 Kelvin and second one is condenser pressure that is 0.04 bar, so, here T saturated will be 29 degree centigrade. Now, let us find out what is the state point we require, information of h_1, h_2, h_3 and h_4. So, for this we have to get the data from the steam table.

$$@35\ bar: h_1 = 1049.8\frac{kJ}{kg} = h_f\ ; h_2 = 2803.4\frac{kJ}{kg} = h_g\ ; s_1 = 2.7253\frac{kJ}{kg-K};\ s_2 = 6.1253\frac{kJ}{kg-K}$$

Across the turbine and pump, $s_1 = s_4\ \&\ s_2 = s_3$

$$@0.04\ bar: s_{4f} = s_{3f} = 0.4226\frac{kJ}{kg-K};\ s_{4g} = s_{3g} = 8.4746\frac{kJ}{kg-K}$$

As state 3 and 4 is in wet region,

$$s_3 = s_{3f} + x_3 s_{3fg} = s_2; x_3 = \frac{6.1253 - 0.4226}{8.4746 - 0.4226} = 0.67;$$

$$s_4 = s_{4f} + x_4 s_{4fg} = s_1; x_4 = 0.27;$$

$$h_3 = h_{3f} + x_3 h_{3fg} = 1832.9\frac{kJ}{kg}\ ;\ h_4 = h_{4f} + x_4 h_{4fg} = 811.15\ kJ/kg$$

$$w_t = h_2 - h_3 = 970.5\ kJ/kg$$

$$w_c = h_1 - h_4 = 238.65\ kJ/kg$$

$$Q_{in} = h_2 - h_1 = 1753.6\ kJ/kg$$

$$Q_{out} = h_3 - h_4 = 1021.75\ kJ/kg$$

$$\eta = \frac{w_{net}}{Q_{in}} = 0.417; WR = \frac{W_{net}}{W_t} = 0.778; SSC = \frac{3600}{W_{net}} = 4.92\ kg/kWh$$

So, basically we draw this Carnot cycle we found out its cardinal points. Then from this data we evaluate the parameters like efficiency work ratio and SSC is steam consumptions. So, this particular problem does not have process inefficiency into account. So, the next problems we are trying to incorporate the process inefficiency as in terms by recognizing it as isentropic efficiency for compression and expansion process. So, the calculations remains same. Now when you include this, how this cycle should look like? The cycle should look like in the manner that instead of a rectangle; so, the expansion process goes in this manner and the compression process goes in this manner. So, we say actual process as $1' - 2 - 3' - 4$ and in between we have 3 and 1. So, 1-2-3-4 is the actual Carnot process and without involving the component efficiency and here with real process is $1' - 2 - 3' - 4$.

So, for that we have to still rely on the same data which is $h_1 = 1049.8\frac{kJ}{kg}\ ; h_2 =$

$2803.4\frac{kJ}{kg}$; $h_3 = 1832.9\frac{kJ}{kg}$; $h_4 = 811.15\frac{kJ}{kg}$. So, this was obtained in the last problem from the steam table based on 35 bar and 0.054 bar. So, now we are going to put component efficiency for the compressor and turbines. So, for that things we have to recalculate turbine work.

$$w_{23'} = \eta_t(h_2 - h_3) = 728\ kJ/kg$$

$$w_{41'} = \frac{h_1 - h_4}{\eta_c} = 318.2\frac{kJ}{kg}$$

$$Q_{in} = h_2 - h_{1'} = h_2 - (w_{41'} + h_4) = 1129.35\frac{kJ}{kg}$$

$$\eta = \frac{W_{net}}{Qin} = 0.24; WR = \frac{W_{net}}{W_t} = 0.56; SSC = \frac{3600}{W_{net}} = 8.78\ kg/kWh$$

So, if you see our previous data the efficiency was 0.417, work ratio was 0.778 and SSC was 4.92 kg per kilowatt hour. So, this implies process inefficiency have effects as drop in cycle efficiency, drop in work ratio and increase in specific fuel consumption. So, ideally speaking that we should keep this process inefficiency or in terms of irreversibility to as minimal as possible. So, with this I conclude this lecture. Thank you for your attention.