Steam and Gas Power Systems
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Module No # 01
Lecture No # 03
Performance of Rankine Cycle

I welcome you all in this course of steam and gas power systems today we will discuss the performance of Rankine cycle.

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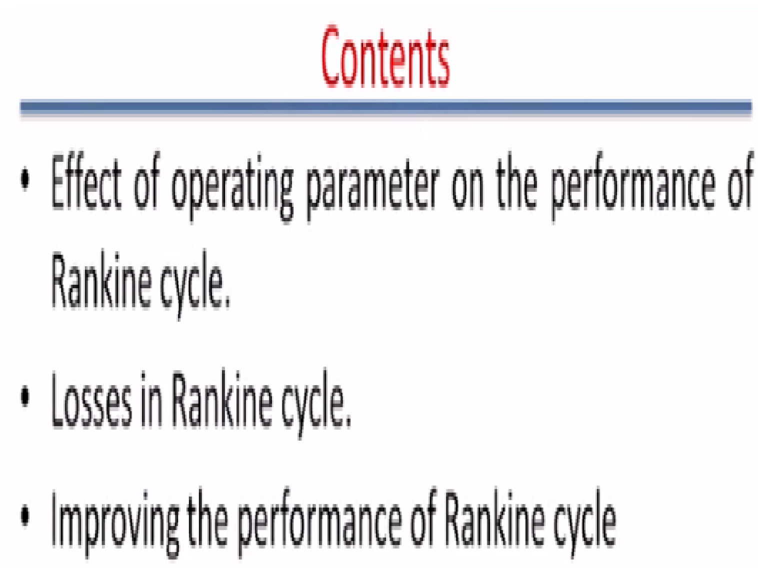

In today's lecture we will cover effect of operating parameters on the performance of rankine cycle losses in rankine cycle improving the performance of rankine cycle how we can improve the performance of rankine cycle?

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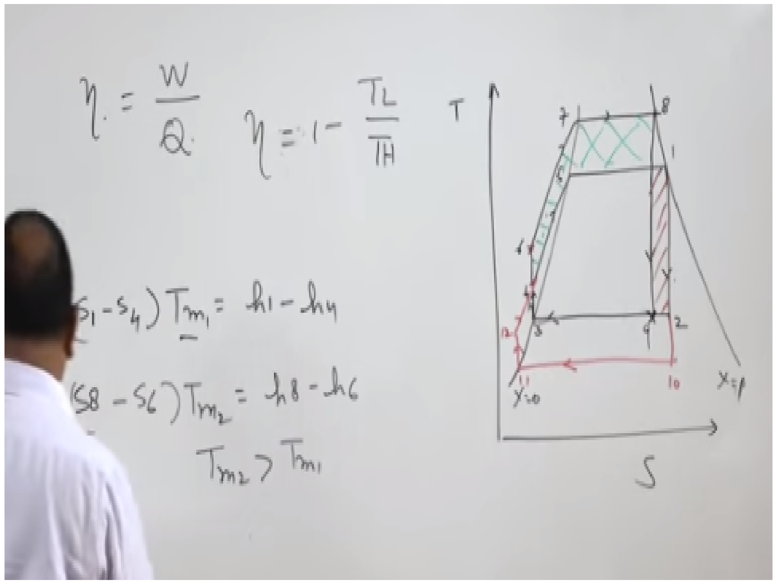

Now in a rankine cycle as you know there are four processes if you draw the rankine cycle on the temperature entropy diagram this is saturation line for the liquid this is saturated line for saturated vapor X = 0, X = 1 quality is 1 and this is state 1 expansion in turbine state 2 then complete condensation of the liquid vapor liquid in the condenser in complete condensation of vapor of condenser is state 3 then increasing pressure it is a vertical line 3 to 4 in a pump and then 4 to 5 and 5 to 1.

This process takes place inside a boiler and process 1 to 2 in a turbine and 2 to 3 in a condenser and 3 to 4 in a pump in process 3 to 4 pressure is increased. Now in this case suppose I increase the pressure of the boiler instead of going up to four this process is extended up to let us say 6 and this high pressure again the heat is added and then we get is state 7 and state 8 and after eight expansion takes place.

So this is one cycle 3 to 4 but instead of going to 3 to 4 we go to 3 to 6 and this is how we have done that the pressure of the boiler is increased and we are getting straight eight the pressure at state 8 is higher than the pressure at state 1 in this process we are moving this much of work by increasing the pressure and at the same time we are greening this much of work what is the net effect?

Net effect may be increase in output and if we go for high pressure this may decrease the output as well that is one thing another thing is efficiency of the cycle. Now efficiency of the cycle is work output divided by heat edit it is possible that the work output is increased but efficiency will be reduced in order to judge the efficiency increase in efficiency or decrease in efficiency we will try to find mean temperature of heat edition.

Mean temperature of heat edition is in first cycle it is S1 - S3 multiplied by TM = H1 - or S4 sorry S0, S4 H1 - H4. So from here we can get the value of mean temperature of heat addition now if you compare this mean temperature of heat edition with the mean temperature of heat addition at S8 - S6 multiplied by TM this is TM2 this is TM1 = H8 - H6.

Now if you compare this mean temperature heat addition you will find that this TM2 is larger than TM1 right. So mean temperature of heat addition is important here because if you look at the carnet cycle it is 1 - sorry this is = 1 - TN by TH right heat of the source and heat of the sink sorry temperature of the source temperature of the thing. So if we keep on increasing the temperature of mean temperature heat addition efficiency of the system or efficiency of the cycle will increase.

So here in this case when we increase the pressure of heat addition in the boiler the efficiency of the cycle increases at the same time the quality of the vapor this is coming out the turbine it keeps on reducing that is also a major issue we will discuss it later on and here in this case the heat rejected in condenser is also reduced that is one case. Another case is instead of increasing pressure if you reduce the pressure inside the condenser instead of increasing the pressure in the boiler.

If you reduce the pressure inside a condenser if you reduce the pressure inside a condenser then instead getting state 2 we will be getting state ten and then we can condense the entire gas and then pressure can be increased and we will be getting this process so 10, 11, 12 then 12 to 4 then this cycle will be completed I can redraw this because many curves are creating confusion. So here there is one original cycle X = 0, X = 1 that is one original cycle state 1, state 2, state 3 and state 4.

Now I am reducing the pressure in a steam condenser so pressure is reduced we are getting state 5 this is state 5. So now state 6 then condensed up to here and state 1, state 2, state 3 and state 4. Now the vapor is condensed up to state 7 and then pressurized to state 8 and then state 4 so now here the pressure is reduced but the moment the pressure in the condenser is reduced we get additional work this much work and some adding heating to be done from state 1 to state 4 right.

But if you again if you refer this equation when the TL is reduced the efficiency of the cycle is increased. So efficiency of the cycle can be increased either by increasing pressure as inlet of the turbine or the boiler pressure or reducing pressure inside the condenser the moment we reduce the condenser the output of the turbine increases because outer of the turbine is now in the modified cases H1 - H6 earlier it was H1 - H2.

So enthalpy at state 6 to enthalpy at state 2 so that is why we are getting more output the and the area of diagram has also increased when we reduce the pressure inside the condenser. Now the point is to what extent we can extent the pressure in the condenser can we go up to the vacuum. We cannot go up to the vacuum because theoretically we can go close to the vacuum not up to the vacuum close to the vacuum.

But in the actual practice it is very difficult to attain very low pressure because it is advisable because in the condenser we use normal water in the condenser for condensing the safety.

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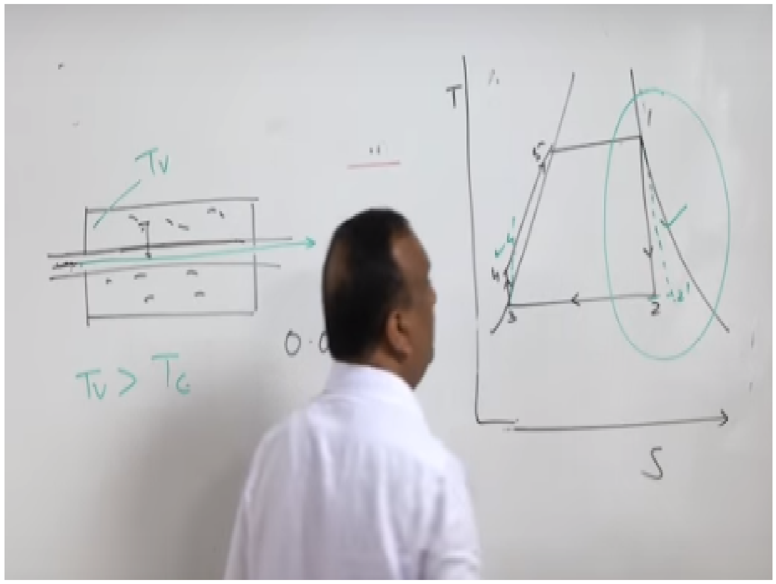

So it is a most of the cases it is a shallon cube of heat exchanger we have a inside tube we have a cooling water and shallon is filled with the wet steam and this wet steam when it is comes into the cold tubes or cold wall of this tubes cold walls of this tubes it gives heat to the flowing water inside this tube this water this is flowing inside this tube or cooling water and that heat is taken away. So definitely the temperature of the vapor should be greater than temperature of the cooling water otherwise the vapor will not condense.

So we have to maintain saturation pressure of the vapor so that such a in such a manner or which we have to choose the saturation pressure of the vapor in such a manner that the corresponding saturation temperature is high than the temperature of cooling otherwise condensation will not take place. So in previous numerical also you have seen that approximately the 0.04 bar pressure the temperature was approximately 28 degree centigrade.

But if we go further below this the temperature will reduce to 20 degree centigrade or 15 degree centigrade but you will not find cooling water at this temperature. So there is a restriction on using the pressure of the condenser at the same time when you increase the pressure in the boiler, the boiler has to be no burst right that will increase the fixed cost of the boiler as well fixed cost of the equipment's as well.

Now losses in rankine cycle because there are physical processes and in actual practice are ideal process is difficult to realize. So there has to be losses in all the processes some of the losses we can discuss here for example this is state 1, 2, 3, 4 and 5 say expansion is a vertical line or a isentropic expansion but in actual practice it is not isentropic expansion some friction losses and other losses are there so this line is no longer a vertical line it is an inclined line it means during expansion there is a change in entropy right.

In compression also the real process is not a vertical line it is an inclined line because there is a loss due to friction other things and there is in increase in entropy. Pressure loss in piping also takes place by piping and paints and pressure loss during flow of steam from pump to the boiler that also takes place during condensation also there is a pressure loss but the main loss is which we take into account or which we normally discuss is losses in the turbine and to some extent that losses in the pumps because the energy consumed by the pump is itself if you not seen.

If you compare the power down load by the turbine right so main losses are confined to the losses in power developed by the turbine now the thing is how to improve the performance of rankine cycle improving performance means to get more output with a given output or you increase the how to increase the efficiency of a rankine cycle.

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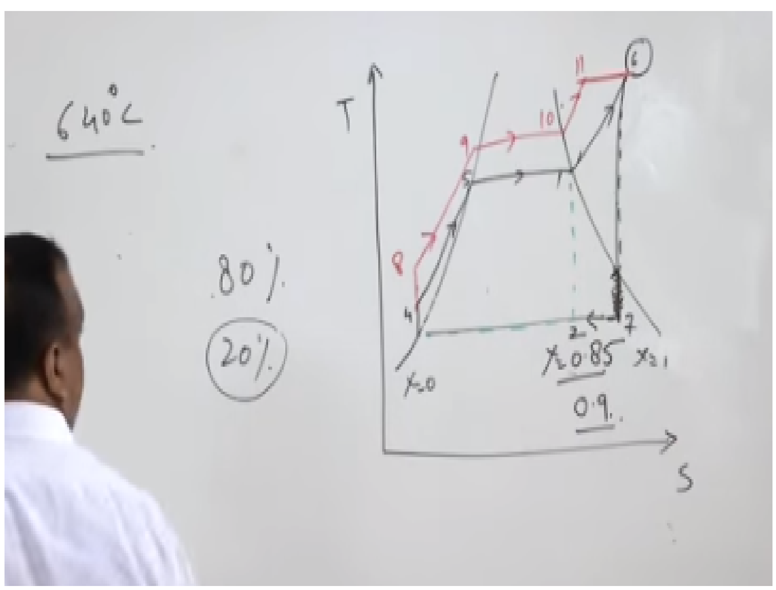

So in order to increase the efficiency of the rankine cycle one process is super heating of paper now if we show on temperature entropy diagram super heating of vapor. So the liquid which is entering the boiler it is 1, 2, 3, 4, 4 to 5 two files sensible heating the then 5 to 1 state 3 here we are getting saturated steam. So instead of expanding the Sistine from this point we can super heat this system up to state six and then expansion can take place six can get seven.

So instead of expanding steam at the point the city is superheating the moment we are superheating the speed steam the moment we are super heating this team the mean temperature if heat addition increases. So when there is an increase in mean temperature of heat addition the efficiency of the cycle will increase and of course by super heating we get more output but super heating is P.

So we are getting benefited by both the both ends one side we are one hand we are getting higher output on the other side the efficiency of the cycle has increased but the issue is again to what extent we can go here can we go 1000 degree centigrade or 2000 degree centigrade to what extent we can go here state temperature and state 6.

So temperature of the state 6 in turbines is restricted to 64 degree centigrade normally because if we go beyond that it will have effect on the performance of the turbine because this is the metallurgical limit of the turbine material so metallurgical changes can takes place so it is always advisable not to go beyond 640 degree centigrade temperature.

Otherwise in the turbine itself some metallurgical changes will take place now the issue is how further we can improve the efficiency of the system. Second thing is here is when during expansion when (()) (15:32) of the part of the vapor takes place when part of the vapor suppose here at the exit X = 0.8 suppose it means out rate of the turbine consists of 8 % vapor and 20 % liquid.

This liquid is in the form of droplets and droplets are moving with very high velocity at the exit of the turbine the velocity is high right and the steam is not steam is not still out of the turbine. So here also in this case in this portion or in this part of the expansion the velocity is quite high and with this high velocity this (()) (16:14) is striking the turbine blades as I said earlier the density of liquid is much much higher than the density of the vapor may be 1000 times 50 depending on the pressure.

1000 times, 500 times or 2000 times so the moment of the droplet is into that proportion. So momentum is high of this high momentum droplets when they strike the blades the erosion of the blades takes place. So in turbines while designing a turbine this quality is restricted to .85 and it is preferred it should be .9. In any case it should not be less than .85 so there is another restriction here we cannot reduce the condenser pressure here there is a restriction now how to improve the performance.

Another way of improving the performance is to increase the pressure that we have already discussed if we increase the pressure and we can go up to this temperature both the temperatures are same. So this is 5 this is state 1, 6 to 7 and this is 8, 9, 10, 11. So at state 11 the temperature is same as state 6 right but here in this case the efficiency will be more because mean temperature of heat addition is higher though we are having the same temperature at both the state 6 and 11.

Another way of improving the performance can be reheating of steam reheating means steam is expanded right here or I will draw a rather it will create. So reheat cycle is I will explain you a reheat cycle reheat cycle is in this cycle the expansion takes place in number of stages.

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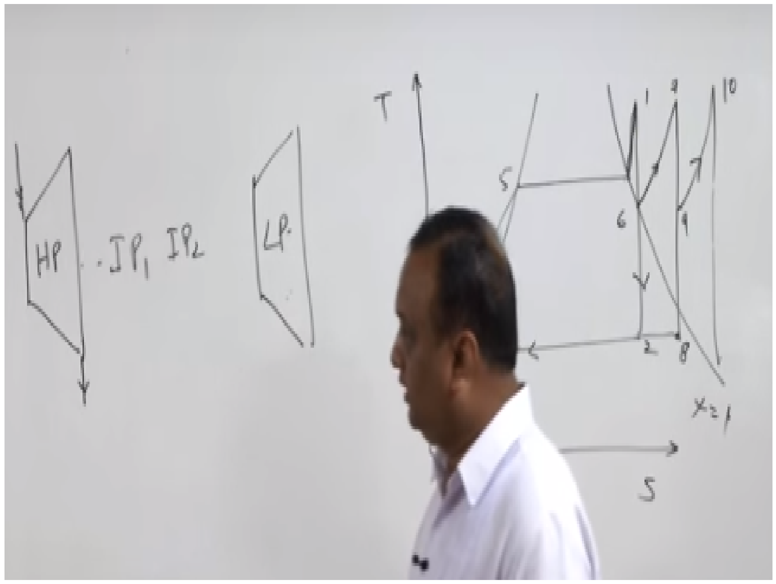

This is original cycle so 1, 2, 3, 4, 5 now reheat cycle what we do before this or at this point may be a let us say is 6 we reheat we take out the fluid and reheat it up to seven and then expand it this is 8. So this is how we can improve the quality of the vapor which is coming out the turbine. Now in this case the reheat cycle additional heat heating has been done in process 6 to 7 and you can see more heat is taken away by the condenser.

And at the same time the area of this diagram has increased so definitely output will increase so this process then 6 to 7 then 9 to 10. They can take place in reheat us and expansion processes or power develop in the turbine can take place in different number of stages. Now let us say this is one turbine this is high pressure turbine this is low pressure turbine and you can have intermediate pressure turbine also IP1 and IP2 or IP3 and number of turbines.

But by visual inspection you can easily judge which one is high pressure turbine in which we it means low pressure turbine because in high pressure turbine the size of the high pressure is turbine is the smallest. It is the smallest turbine because the specific value of vapor at high pressure is low as a pressure reduces the specific volume of the vapor increases as the specific volume of the vapor increases size of the turbine increases.

So definitely for high pressure you will get turbine of smaller size and for the lowest pressure you will get the turbine of the turbine of (()) (20:57). Now another method of improving the performance is the regeneration in the process of regeneration I will discuss the regeneration in subsequent lectures but here I will give you an idea.

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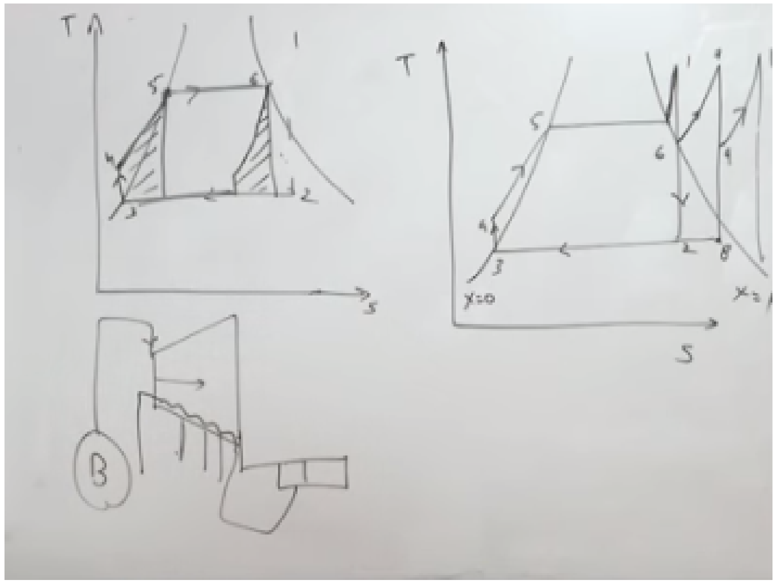

In rankine cycle temperature this is entropy suppose this is rankine cycle so 1, 2, 4, 5and this is 6 this feed water instead of heating this feed water in a in in boiler if we can circulate this feed water in the casing of the turbine. So it can get heat from the casing of turbine and at this .5 the water the saturated water will enter the boiler and this can be done by simply just taking turbine after the turbine the condensation condenser condensation and after the condensation the water is circulated in the casing of the turbine.

And after the exit of the casing of the turbine it will go to the boiler and from boiler to the turbine. So one bore root has been made now here after compression when the water enters the turbine there are certain assumptions that temperature of the steam inside the casing is infinite is similarly are higher than temperature of the water right. So and the perfect heat transfer takes place between the between steam in the water and all these conditions are realized in that case suppose let us take saturation case.

Instead of so because the heat is taken away from the steam instead of being the vertical line this process will become like this to certain extent right and this heating this will be removed because heating will be taking place inside the boiler and if you look at the energy wise the area of this is going to be the area of this. This area is going to be this area right so now here we are heating at this temperature rejecting heat at this temperature right the efficiency of the cycle will become the efficiency of the carnet cycle.

This is all imaginary things have not but the idea is very good just heating the water with the help of steam which is flowing in the direction. But in actual practice what is being done this steam part of the steam is extracted and heating of feed water is done. Instead of circulating this steam in the turbine casing at different stages the steam is trapped because this steam consist of very high energy and this steam of high energy steam or this steam is used for increasing the this for doing the sensible heating of the feed water okay.

We will take up one numerical in numerical solving and we will discuss this in details now after this we will discuss in numerical short that is about the reheating cycle. So in reheating cycle we will take the same numerical as we did in previous lecture.

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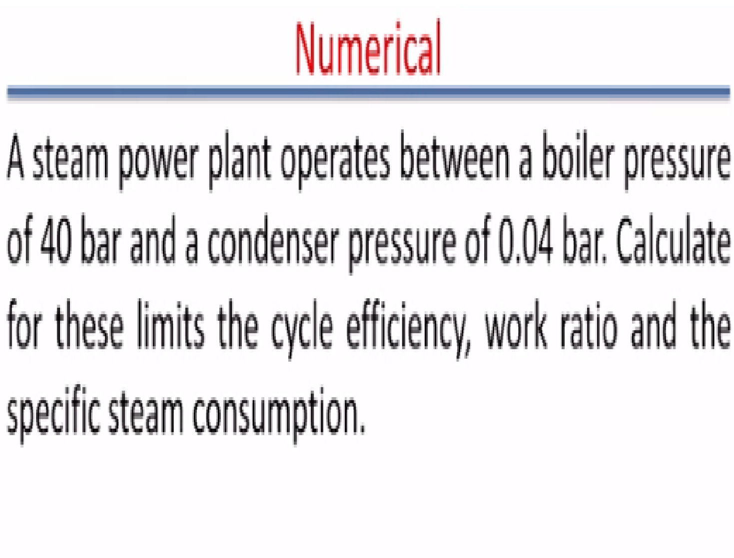

A steam power plant operates between a boiler pressure 40 bar and condenser pressure of 0.04 bar calculate of this limits cycle efficiency where we show that is alright but suppose instead of expanding the steam in the condenser directly to the condenser.

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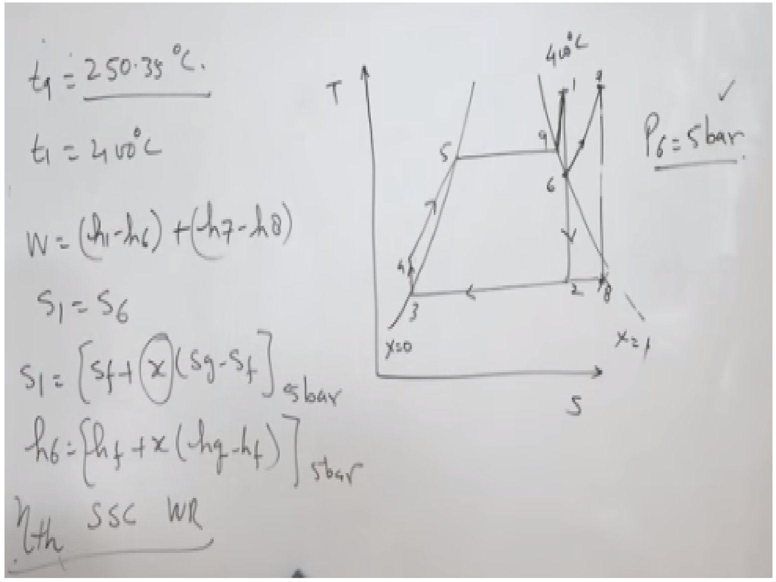

The steam is expanded up to 5 bar this P6 is 5 bar and then again it is reheated up to this temperature T1 is T7 and this temperature is how much let us say this is it is not given here let us assume it to be 400 degree centigrade taken. Let us assume this saturation temperature at this 40 bar was s let us say T5 was not T5 six seven eight let us say this is nine. So T9 was 250.35 degree centigrade and T1 is 400 degree centigrade pressure is 40 bar.

So for this purpose if you look at this steam table in the steam table superheated steam is given there right.

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kPa	C	vf	vfg	vg	uf	ufg	ug	hf	hfg	hg	sf	sfg	sg
4	28.96	0.001004	34.79	34.791	121.38	2293.12	2414.5	121.39	2432.31	2553.7	0.42239	8.05101	8.4734
100	99.606	0.001043	1.692857	1.6939	417.4	2088.2	2505.6	417.5	2257.4	2674.9	1.3028	6.056	7.3588
500	151.83	0.001093	0.373718	0.37481	639.54	1921.16	2560.7	640.09	2108.01	2748.1	1.8604	4.9603	6.8207
4000	250.35	0.001253	0.048523	0.04978	1082.5	1519.2	2601.7	1087.5	1713.3	2800.8	2.7968	3.2728	6.0696

		500 kPa		
C	v	u	h	s
151.83	0.37481	2560.7	2748.1	6.8207
200	0.42503	2643.3	2855.8	7.061
250	0.47443	2723.8	2961	7.2724
300	0.52261	2803.2	3064.6	7.4614
350	0.57015	2883	3168.1	7.6346
400	0.6173	2963.7	3272.3	7.7955
450	0.66421	3045.6	3377.7	7.9465
500	0.71094	3129	3484.5	8.0892
600	0.80409	3300.4	3702.5	8.3543

So you can see this steam table and find out from steam table directly you can find out enthalpy at state 1 right it is expanded to 5 bar. State 6 it is again reheated to state seven and then again now here how much heat is added here H9 - H4 right and H7 - H6 sorry H1 - H4. H1 - H4 H1 you can take from the steam table H4 you can always calculate H3 is known and then the pump work add pump work you will get H4.

So H1 - H4 + H7 - H6 enthalpy at divided so this is the heat given to the system. Now work output work output is H1 - H6 + H7 - H8 so work output is H1 - H6 + H7 - H6 how to find H6? Now again we will use the same technique S1 = S6 now S1 we can directly take from the steam table S6 will find if the value of entropy at 6 is I mean saturation and enthalpy is greater than this it means this steam is wet right.

So in that case the S1 = SF + X SG - SF at whatever the pressure is 5 bar pressure right from here we will get the value of X. Again we will put the value of X then we will get 6 = HF + X HG - HF at 5 bar. Once we know the enthalpy at 6 enthalpy at 7 we can take from superheated table.

Superheated table we will get the enthalpy at 6 similarly we will find the enthalpy at 8 right 1 we have enthalpies at all salient points we can easily calculate the thermal efficiency if specific steam consumption and work section right this is the end of this lecture and in the next class we will start with the binary vapor cycle.