Engineering Thermodynamics
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Module 07
Lecture No 49
Ideal Regenerative Rankine Cycle, Cogeneration, Combined Gas Vapor Cycle

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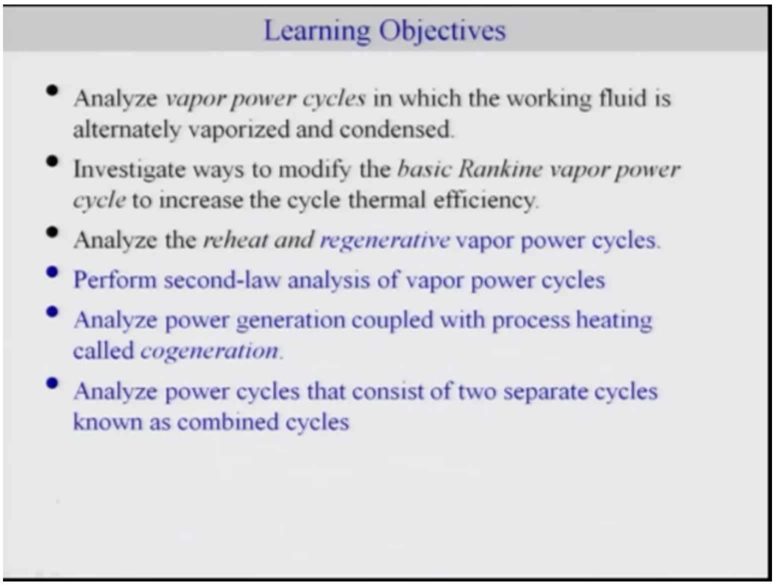

Okay welcome back, in the last lecture, we started a new topic on vapor power cycles and we realized that Carnot cycle is not an efficient if you want to have working fluid with vaporization and condensation as a part of a cycle and thus we introduced basic Rankine cycle so that was what we considered in the last lecture where we considered Rankine cycle where the stream was heated to superheated condition okay and then we talked about different ways to increase the efficiency of Rankine cycle by using reheat and the importance of high temperature when it enters the boiler.

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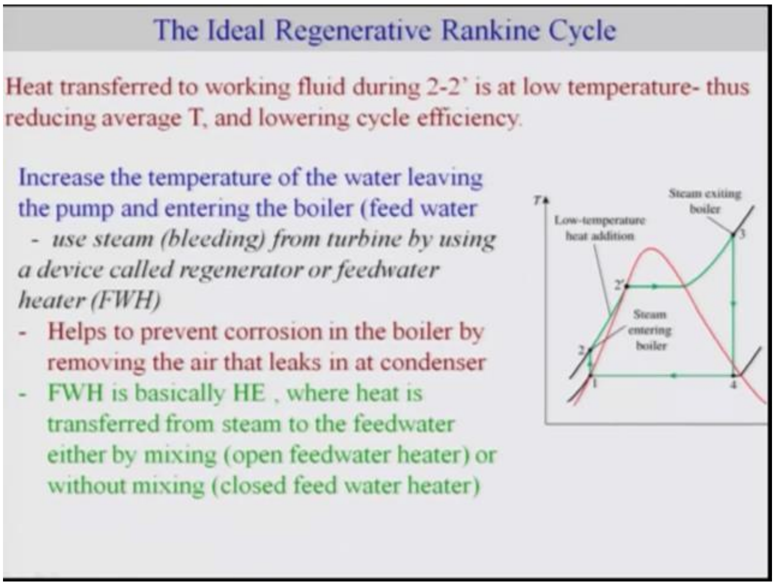

Let us relook at how the Rankine works, so if we look at it, it enters saturated liquid enters the pump okay at 1 and the pump increases the pressure of the saturated liquid such that it reaches where the boiler provides heat and it goes up till superheated condition and this at this condition it enters the turbine which isentropically expands to reach a 2 phase system that is at 4 and here it enters the condenser and the condenser is such that we obtain saturated liquid. So that means this is nothing but at condenser pressure, this is your boiler pressure okay.

Now, what you should notice here that that this part is at low temperature okay, so though it is at a constant pressure but this part is certainly at low temperature and thus the average is low and we have discussed this aspect in the last lecture that if average temperature is low then the cycle efficiency would be low, so we need to increase the average temperature at which the boiler works okay and that is why the reheat was used as one of the solution.

So what is the alternative way to increase this particular temperature is to take out some stream from the turbine and mix it in order to increase the temperature and this is something we call it using a device okay and that we are going to call as a regenerator or feed water heater so what it uses is stream from the turbine okay, so we will talk about it, we will discuss this process. So one of the key advantages of this is of course you are using some part of the heat from the turbine, you are using some part of the stream itself in order to increase the stream temperature, which enters the boiler but more importantly also it helps to prevent the corrosion in the boiler okay by removing the air that leaks it at condenser okay.

So what are the different forms of feed water heater which is nothing but heat exchanger, you can have a direct mixing which we call it a open feed water heater or closed mixing or without mixing or closed feed water heater which is without mixing okay. So let me just first describe this open feed water heater. This is overall process for we call it regenerative Rankine cycle where we are going to use open feed water here.

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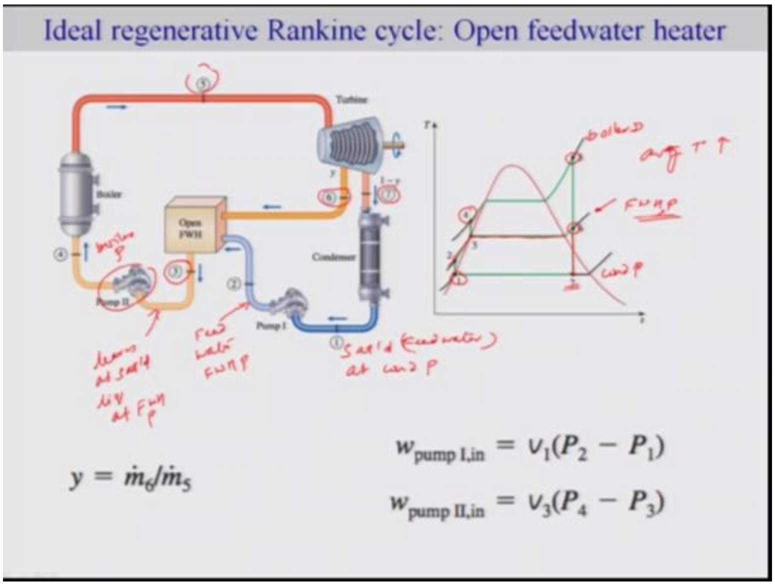

So let us look at the complete process here so at 5, the stream is at the boiler pressure, it enters the turbine okay so this is 5, this was the original point as for without the open feed water so what we are going to do is, we will take out certain stream at an intimated pressure which is 6 okay and let the rest of the stream expand isentropically okay, so it goes here until it reaches the 2 phase system at condenser pressure okay.

And this 7 condenser reaches the saturated liquid and then this particular pump increases the pressure till 2 okay, now we are going to mix this 6 and 2 so 6 and 2 are at the same pressure okay. If you look at it, this is at the same pressure, so it mixes and it goes up till 6 that means along this isochore or constant pressure line, it goes up till this point such that this is saturated liquid okay. So this is your of course your saturated liquid at condenser pressure, this is we also can call this as a feed water okay and this is a feed water at FWH pressure okay and this mixes and what you get is this as a saturated liquid at FWH pressure, so the pressure is now high at this pressure, so this would be your FWH pressure okay.

And then second pump is used in order to increase the pressure of this fluid from 3 to 4 so that means from this pressure to this boiler pressure okay the second pump is used to increase the here where it is now at boiler pressure. Now while doing this, we can also see that the temperature is 4 I high compared to if we have used without the open FWH at 2 okay and thus the average T is now much higher okay. So what would be the, we can analyze this regenerative Rankine cycle with all the energy and mass balance and we can come up with the work required for pump 1 and 2 and as well as the heat out okay and then so we can write down the general expression without going into details of the derivation.

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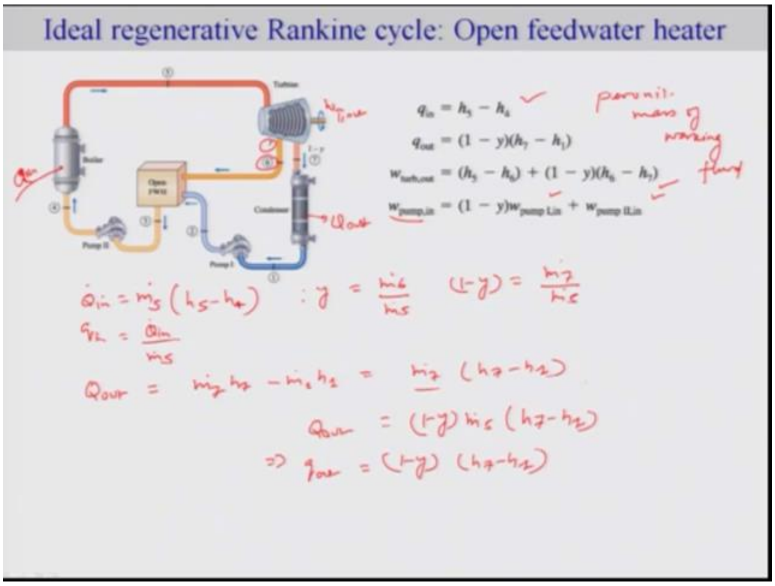

As we know that of course the work for this flow system is nothing but V into delta P. This is V1, pump 1 is V1 times P2 - P1 and for the case of the pump 2 work in required is V3 times P4 - P3 okay. Now we can also evaluate the heat supplied to the boiler okay, so Q in here is going to simply the change in enthalpy that will be your H5 - H4. What about Q out? So now this Q in is nothing but your per unit mass of working fluid so here the working fluid here we can consider this M dot 5, so if you want to find out total Q, Qin dot is going to be M5 dot H5 - H4 okay considering Y as M6 by M5. This is the stream extracted at intimated pressure okay so per unit mass of working fluid Q in is nothing but your Q total in okay divided by M dot 5 okay.

Similarly we can find Q out at condenser okay I can also write this in terms of capital Q in and Q out is your M dot H7 - M dot 1 H1 or in other word as M dot 7 is same as M dot 1 and what about M dot 7, M dot 7 here is nothing but 1 - Y times M dot 5, H7 - H1 so this is a fraction of 5 which goes to 6 and the rest of them goes to 7 stream so thus 1 - Y is going to be M7 by M5 okay. So this is your Q out thus your Q out as a per unit mass of working fluid 1 - Y as 7 - H1 and similarly you can also evaluate the work for the turbine out so that your T out okay and the total work done by the pump okay, so you can this derive this, obviously these expressions.

Okay so what we have discussed is open feed water heater. Now we can analyze the closed feed water heater so the difference between the open feed water is the stream physically makes with each other and then you have to operate at same pressure and that is why the extract is stream from the turbine and as well as the stream from the condenser where the pump is used to bring it to the same pressure in order to mix it but now for the closed feed water, there is no necessity of mixing it physically and thus we can have different pressures also that means the streams can operate at different pressure

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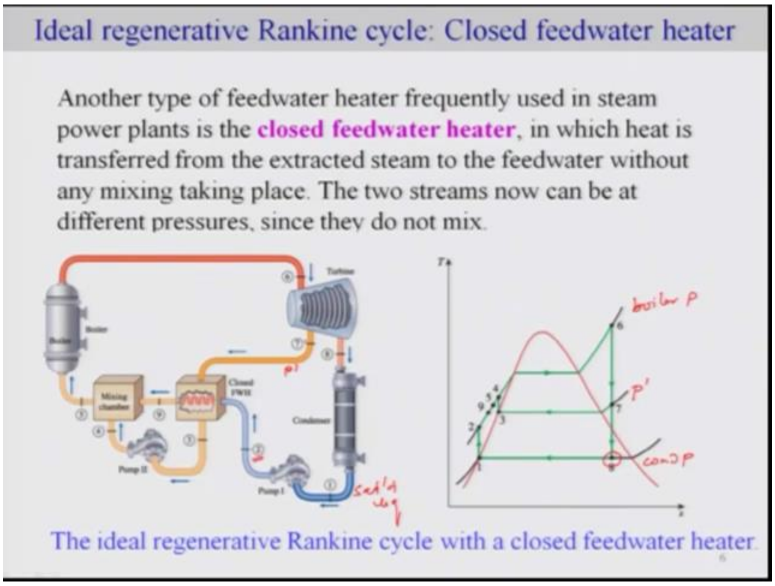

So let us look at how it can be done and particularly how does it look on TS diagram, so the process is the same so for example, so you can you can consider 6 which is your working fluid and here, this which is your stream which undergoes some part of it is extracted as 7 okay and this is at a different pressure so you can see this is at pressure that you know P dash, okay. Now rest of the 8 isentropically expands until it reaches the condenser pressure okay and of course the 1 is at saturated liquid okay, so the pump 2 is used to get to this pressure and this pressure is the same pressure as the boiler now okay. Note that earlier we have to make sure that the first pump outlet is at the pressure of the extracted intermediate stream okay so you can look at it again okay this was exactly this like the second pump to pressure here was same as that of the pressure of the extracted stream.

Whereas, here now you can see that the second stream is at the pressure of the boiler okay and the reason will be very clear. Because this pressure need not be same at the pressure at this which is nothing but your boiler pressure okay, it is like constant pressure we want to keep it here. Now this stream 7 exchanges energy without mixing and undergo condensation such that your 3 is at saturated okay liquid okay that is 3 is here. So while doing so, the 2 at this constant pressure goes to 9, that is 9 is at higher temperature or at the same pressure though, okay and then this particular liquid that means your 3 is being pumped such that this is at the same pressure of your feed water and that means it is pumped here such that it reaches at this on the same isobar okay at the same pressure and thus your 4 and 9 are at the same pressure.

Now it is being mixed so this is your mixing chamber okay so it is being mixed. Of course that average temperature would be less, so final stream will have lesser temperature than 4 which is your 5, 5 is the stream at this temperature goes to the boiler okay and it should be noted that 4, 9, 5 all have same pressure so it is constant pressure mixing okay and that is why the 5 is there. So now you can clearly see that so this region here is the region which will be supplied by Q so this will be your Q in, this region which is the yellow one because this would be the region. By using this closed feed water heater, we have also raised the average temperature from what is observed at 25 okay without mixing here, which can exchange heat at different pressure but of course also, here we are having a physical mixing.

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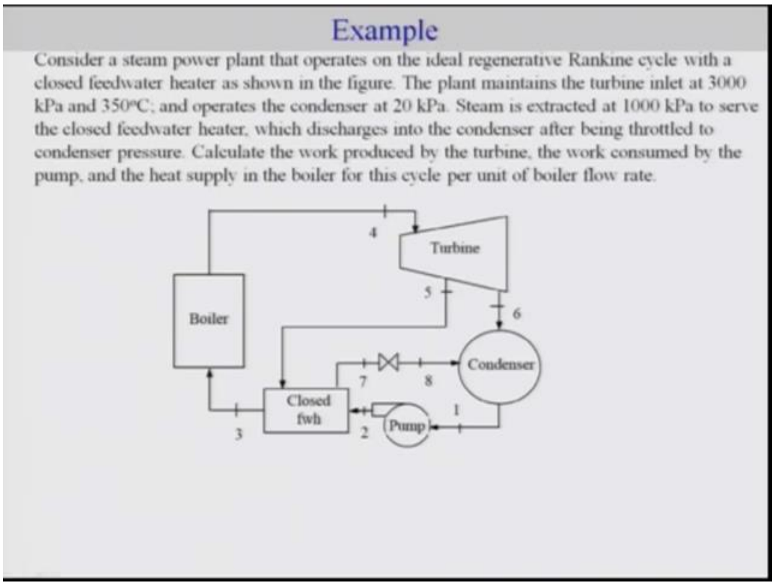

So this is the different way of increasing the heat or temperature of the fluid before entering the boiler okay and that is regenerative Rankine cycle okay. Now based on this an understanding, you can solve the problems by applying the basic mass balance and an energy balance here and this is an example which you can attempt at your leisure so with an example with a closed feed water heater.

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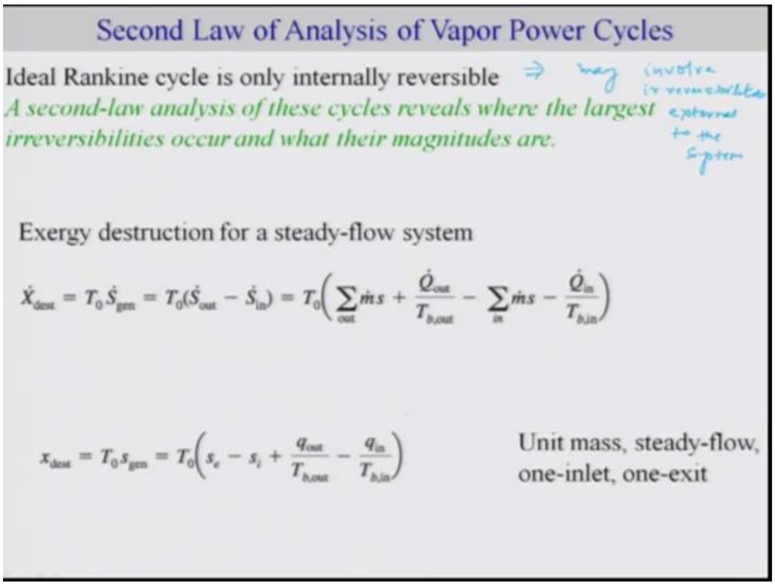

Now we will try to understand the need for second law analysis of the vapor power cycle as we have discussed the Carnot cycle, Carnot cycle is nothing but totally reversible cycle so that means there is no irreversibility associated with it. On the other hand, the ideal Rankine cycle is internal reversible which essentially means there is irreversibility associated outside the system, so this may involve reversibilities external to the system, okay.

And thus it will be very useful to make use of second law of thermodynamics analysis in order to find the largest irreversibility of the system so this is why we may like to use the fundamental understanding of exergy so I am trying to now here summarize simple expression and this case for the case of power, vapor power cycle, we will be making use of the steady flow system and this is an expression of exergy destruction which is nothing but your T 0 multiplied by generation and that can be written as simply the change in the entropy for the steady flow system S out - S in.

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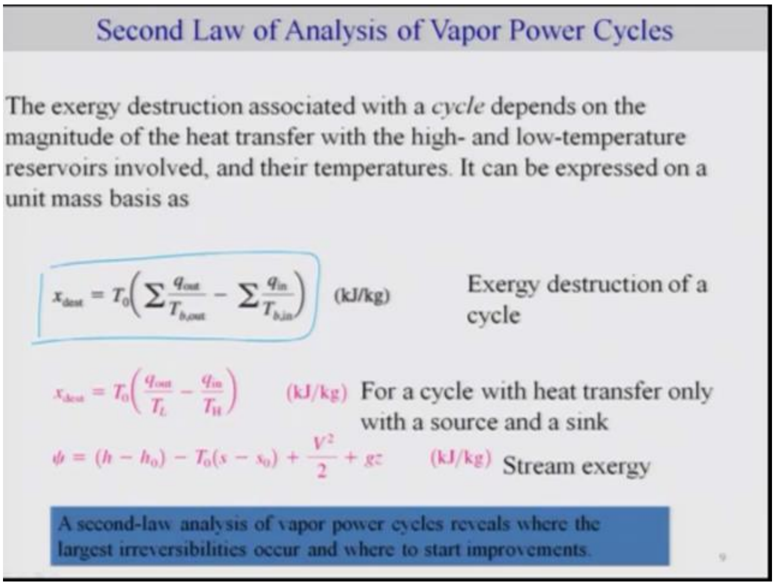

Now S out can be written in terms of the contribution due to the mass flow and temperature, heat transfer and similarly for the in. One can also write this expression in terms of unit mass, so this is already we have gone through in our earlier lectures. Now the exergy destruction on the of course heat transfer so we consider for cycle so this was for a given flow system. Now if you consider for cycle, this would be the expression for the cycle where we are considering the heat transfer for the out and as well as for the in where TB is nothing but the temperature at the boundary of the system.

For the cycle with the only one particular source in the sink you will have only 1 term, Q out by TL and Q in by TH okay, so assuming this is sink and this is your source and this is your of course the extreme exergy which we can make use of it. Now, one can do such a problem and analyze it, but the idea behind using of second law is to find out the largest irreversibility and that is where we can also find out to how to improve our process for the problem at hand okay, so by finding out the highest irreversibility, you possibly can come up with the new design which can minimize this such irreversibility.

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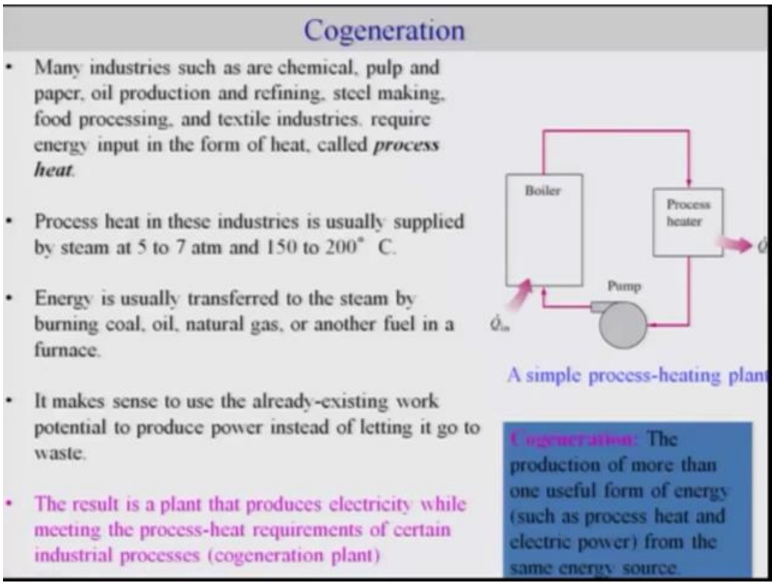

Now we will talk about co generation, now again many industries such that in a chemical pulp and paper and all production and refinery, you need a large amount of energy in terms of input or in terms of heat and this particular type of energy, we call it a process heat okay. And these are typically required or typically supplied by a stream at 5 to 7 angstrom and 150 to 200 degree Celsius okay. So what happens in that such a large industry does make us of let us say a power plant then it automatically, it is generating certain work okay and it is throwing some part of heat let us say from the condenser.

Now some part of that heat can be used for as an input to other requirements okay and this what we call it as a process heat okay where you do not throw all the condenser heat okay to environment but make use of it by transferring to some other you know process requirement. So that is why it make sense to use the already existing work potential to produce power instead of letting it go to waste okay and this kind of combined effort okay or plant is called cogeneration plant okay where while you produce electricity okay you also make use of process heat for certain industrial application okay so this is an example here. This is a complete process heating plant, a very simple one. The boiler directly heats let us say the stream and this heat generated is used in some process heater okay so this Q p is nothing but your process heat okay.

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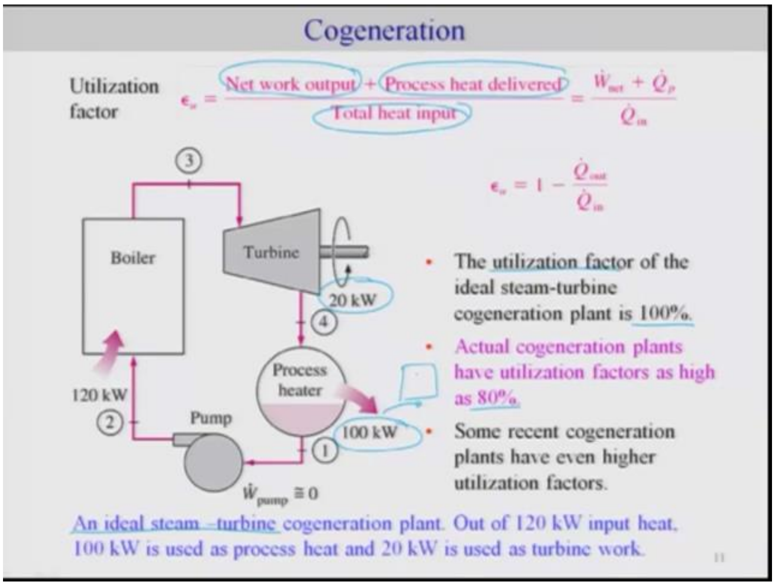

So let us discuss a bit of that, so let us say you have stream turbine plant and then we are trying to combine this idea and this is an example of stream turbine cogeneration plant so where, out of 120 kilowatt which has been used to provide the heat to the boiler, some part of course using turbine is being produced as the work that is 20 kilowatt and the rest of them is used as a process heat of 120 kilowatt okay.

So this is like a condenser so otherwise if we do not use it, it will be wasted so now we are trying to use this 100 kilowatt goes to the other process plant. So this how do we describe this kind of a plant and what is a typical efficiency in order to make use of this such kind of cogeneration plant, we do not use efficiency, we rather use utilization because the issue is, how to utilize the energies here. So the term utilization factor is used where we say the net work output okay + the process heat delivered divided by total heat input and thus Wnet + Q p divided by Qin so in case of ideal stream turbine, the utilization is 100% where we are trying to use this to some other part of the plant okay, so we are trying to use this for some part of the plant.

Okay so thus your utilization factor could be 100 but actual cogeneration plants have around 80% utilization. Now the problem in this is that it is not very practical because it cannot adjust to the load. Sometimes you may need a process heat, sometimes you do not need, sometimes you want to generate completely turbine work, so you need to have some adjustable load in between so you can manipulate this you know to process heat okay depending on the requirement.

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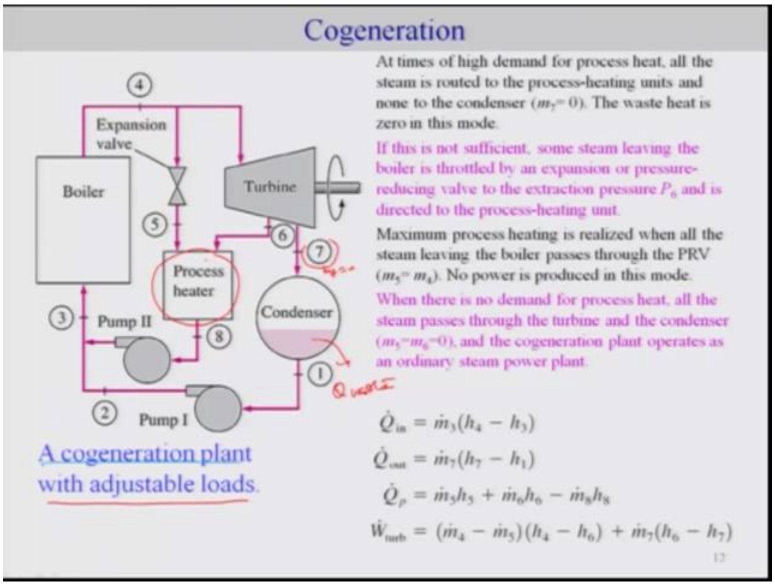

It is more prudent to have a cogeneration plant with adjustable load and hence this is an example here while from the boiler, some stream is taken out, goes to expansion valve and goes to the process heater hence the rest of them goes to the turbine and here itself we make use of 7, which directly goes to condenser and of course the heat is lost so this could be waste okay and some goes to the process heater okay.

So you can and then of course it goes to the pump which has different pressures at 8 and 1. Now you can clearly see that how this can be very useful. For example at very high demand or process heat okay you directly pass this completely to your process heater which means you make this M7 to be 0 okay. In the case of if you make this completely goes let us say here which means you do not have any turbine work output and you pass this stream 4 directly to the process then this will lead to the maximum process heating okay.

That means in such case M5 is = M4 no power is produced is in this mode. So you can manipulate this now, for example, if you do not need your process heat then you make this M5 and M6 to be 0 which is your other possibility and then in that case, the cogeneration plant will work like simple and ordinary stream power plant. So this is the summary of the energy balance which we can come up with where the of course, the Q in is here and Q out is this okay. Q p is your heat through the process heater and W turbine is of course this okay, one can come up to this expression completely by doing simple mass and energy balance.

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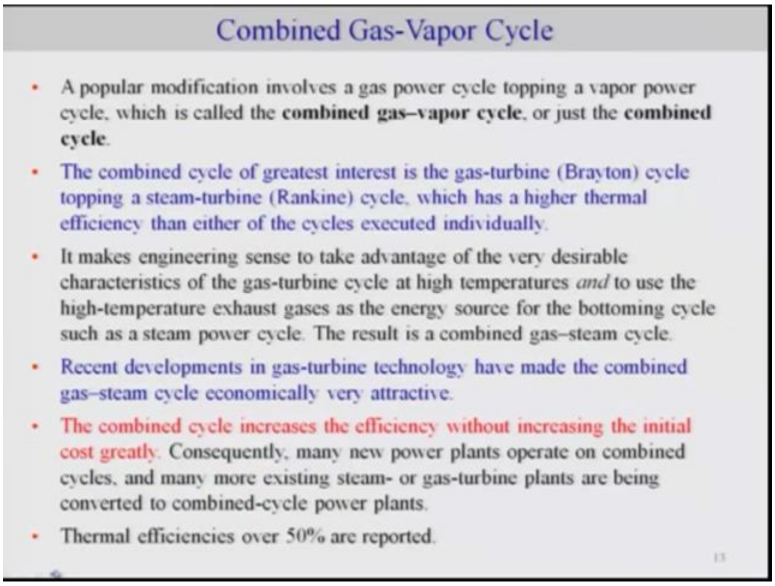

Now, of course as we require more efficient plants, it is necessary to come up with the new design and one of the design is called combined gas vapor cycle okay and the idea was to make use of high temperature Brayton cycle which is your gas turbine cycle and here you make use of the exhaust of the gas turbine as a energy source to heat up the stream okay.

So this is the idea of combining your gas vapor cycle where the gas turbine exhaust is used to heat up the energy that means instead of having a specific boiler or heat exchanger, you make a use of the exhaust gas as kind of the in the heat exchanger okay and this particular way of combining this or combined cycle apparently has more efficiency compared to the individual these 2 cycle okay and the recent gas turbine technology combining with the gas, combining with the stream apparently has the efficiency more than 60% okay, so some of these has become very popular and highly efficient.

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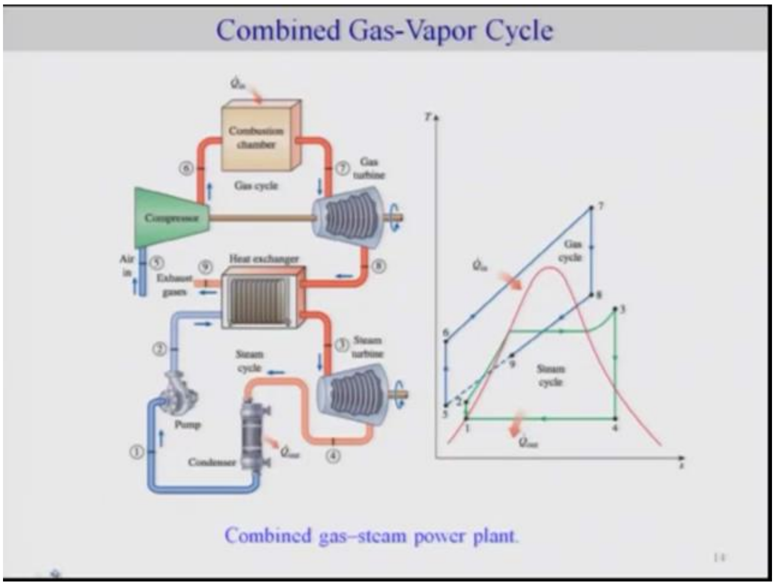

So this is an example so this is your gas turbine that is Brayton cycle and this is your simple your Rankine cycle okay. So clearly instead of boiler, we are using heat exchanger where the exhaust gas from the turbine which is used to heat up the liquid to a super critical vapor okay so that means from 2 to this is kind of taking heat from the your exhaust gas. Now note that on the TS diagram this is for the stream okay or the vapor or for water okay so this particular phase diagram is for the water okay and this blue one is basically for the gas okay.

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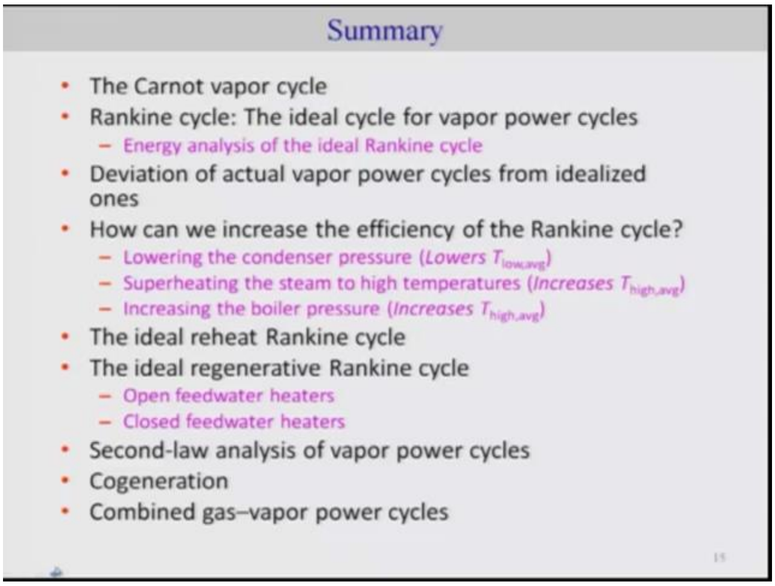

Of course it does not have any vapor liquid within this condition but you have this TS diagram on top of that, it looks like this okay. So this is an example of combined gas vapor cycle and one can do analysis also of this based on the simple mass energy balance as well as one can do a second law analysis for such a process so let me now end now this particular topic okay. We have gone through a series of different possible cycles for vapor power cycles where we started with our Rankine and we talked about the deviation from the ideal cycle.

We also looked into different ways to improve its efficiency by lowering the condenser pressure, superheating the stream increasing the boiling pressure, so we talked about reheat as well as the regenerative Rankine cycle and though we have not done very rigorous analysis of second law, but something which you can do on your own to analyze this second law or exergy analysis of the vapor power cycle and we also discussed the importance of co generation and finally today high efficient combined gas vapor power cycle was discussed okay, so that will be the end of the lecture and we will start a new topic next time so we will see you in the next lecture.