Steam and Gas Power Systems
Prof. Ravi Kumar
Department of Mechanical and Industrial Engineering
Indian Institute of Technology - Roorkee

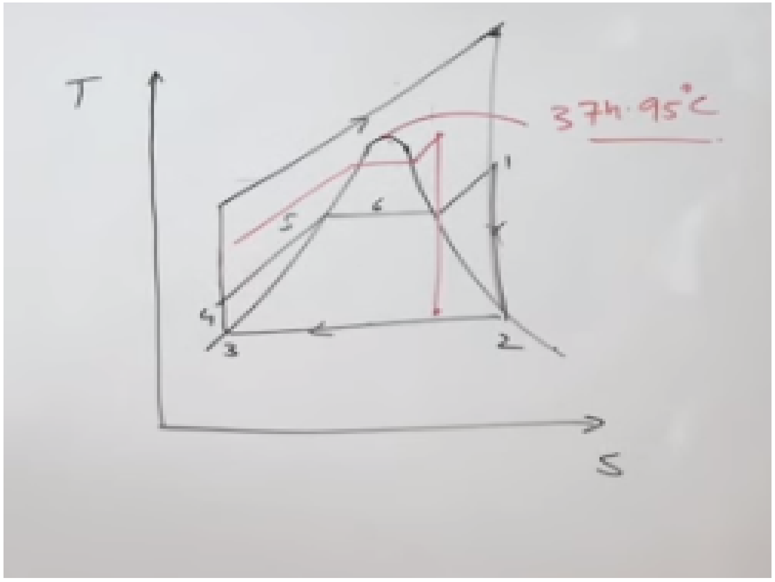
Module No # 01
Lecture No # 04
Binary vapor cycle and co-generation

I welcome you all in this course on steam and gas power systems and today we will discuss binary vapor cycle and co-generation.

(Refer Slide Time: 00:31)

In today's lecture we will be covering super critical rankine cycle binary vapor cycle and co-generation.

(Refer Slide Time: 00:41)



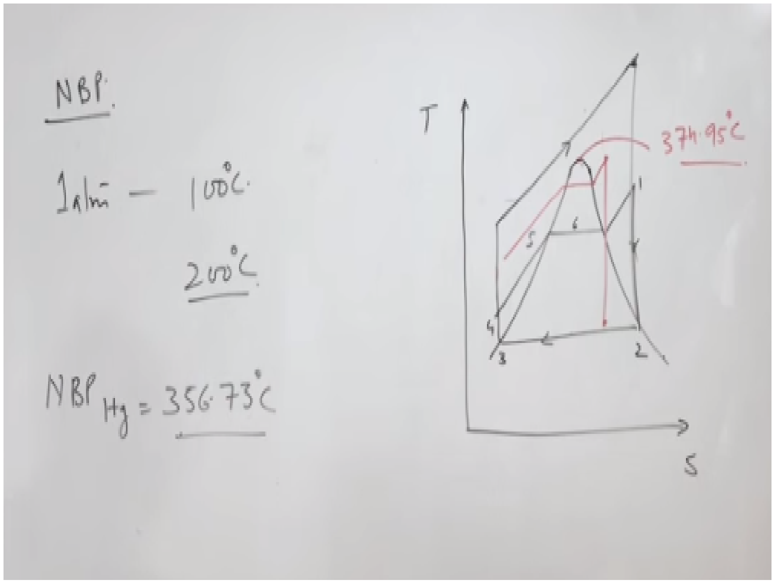
Now in the last lecture as we discussed that when we increase the pressure or boiler pressure of the cycle rankine cycle the efficiency of cycle improve so this is a typical superheated vapor rankine cycle 1, 2, 3, 4 and then 5 and 6 this is temperature and entropy. But if I want to improve the efficiency of the cycle I will have to increase the boiler pressure either boiler pressure or reduce the condenser pressure.

Now if I increase the boiler pressure the net temperature of heat addition will increase and I will get more output from the turbine in some of the cases in some of the thermal power plants the pressure is increased beyond the critical temperature. Critical temperature of steam is approximately 374.95 degree centigrade and this critical pressure is approximately 22 megapascal 21 bar and if the vapor is pressurized beyond this point I mean the heating table take place like this.

So the boiler will be operating beyond the critical point and the boil the system or the cycle becomes the super critical cycle. So super critical cycle the heat addition in the fluid takes place beyond the critical point rest of the process are same there is no change in rest of the processes only change is the pressure of heat addition in the work fluid.

Now after this super critical rankine cycle we will come to the binary vapor cycle when we say in super critical cycle. When we are operating at high pressure definitely the design of the boiler has to be very robust right and for the robust design I mean thicker plates we will have to be used and in overall cost of the plant is high right. Now instead of doing this if we replace the steam or water vapor by some other fluid right and with some other which has very high boiling point.

(Refer Slide Time: 03:28)



Now what is the normal boiling point is the boiling point of the fluid at one atmospheric pressure right. So at one atmospheric pressure the normal boiling point of the water is let us 100 degree centigrade. So we can we should go for fluid which has higher normal boiling point if suppose any fluid is having normal boiling point of 200 degree centigrade.

So will not have to go for a higher pressure the system can work on relatively lower pressure and the cost of the plant can be reduced and further the efficiency of the system will also increase. Now in the case of the binary vapor cycle the binary word has come because we are using two fluids one fluid is water one is water another can be either of these three but normally which is in practice it is mercury is used I will show you the thermo physical properties of the mercury.

(Refer Slide Time: 04:46)

Mercury NBP 356.73 °C

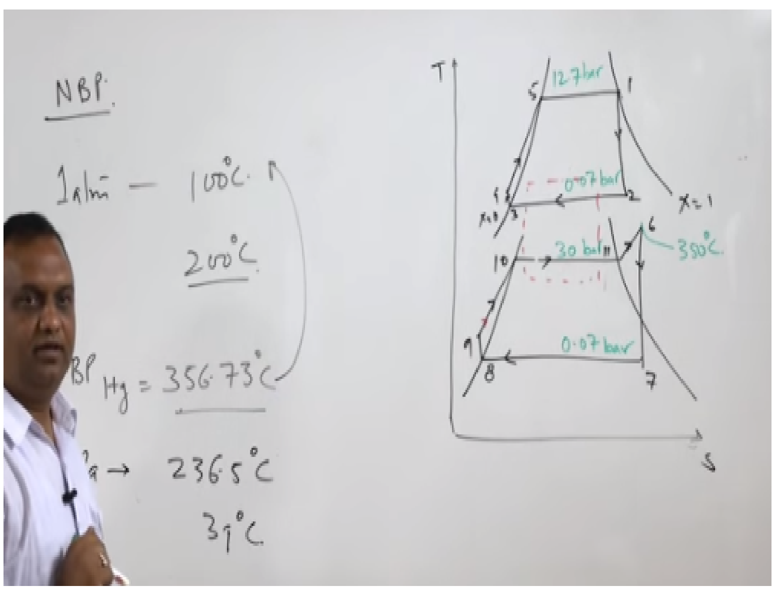
P, bar	t_s, °C	h_f, kJ/kg	h_g, kJ/kg	h_{fg}, kJ/kg
0.07	236.5	32.40	326.07	293.67
12.7	537.5	71.98	360.74	288.76

Water

P, bar	t_s, °C	h_f, kJ/kg	h_g, kJ/kg	h_{fg}, kJ/kg
0.07	39.0	163.35	2571.7	2408.3
12.7	190.5	809.82	2785.7	1975.9

The mercury has normal boiling point of 356 normal boiling point of mercury is 356.73 degree centigrade that is a normal boiling point of the mercury. So in binary vapor cycle what is exactly done then I will show you the schematic arrangement or arrangement on temperature entropy diagram.

(Refer Slide Time: 05:17)



There two cycles which are operating one is mercury cycle or let us say the superheated or saturated the making difference saturated that is one cycle. So one, two X = one, X = 0 temperature entropy. So 1, 2, 3, 4, 5 this is mercury cycle this is working on high temperature now another cycle which is steam cycle and this cycle is working at lower temperature because thermal boiling point of water is much less than the normal boiling point of this those 5 this is 6, 7, 8, 9, 10 in this level.

So arrangement is made that heat rejected during this process 2 to 3 it does not go wasted so the heat rejected in this process 2 to 3 is used for generating the steam in process 9,10, 11. So they are coupled so heat in rejected during process 2 to 3 does not get wasted whatever heat is rejected is it is taken away by the steam which is flowing in it.

So there is a heat exchanger the arrangement is like this from one side this vapor mercury vapor enters from the other side the high pressure water enters and heat exchange takes place and water is converted into this steam and this vapor of mercury gets condensed. So we have two cycles if you look at the thermo physical property of these two fluids they were interesting mercury at 0.07 pressure the temperature is 236.5 to 36.5 let us take temperature at 0.07 bar or 7 kilo pascal.

At 7 kilo pascal the mercury is 236.5 and water is 0.0739 degree centigrade. Even at 11.7 bar the water is that only 139.5 degree centigrade. Well mercury as 12.7 is 527.5 it is quite high. So mercury cycle even if it is working it here it is 12.7.

So if it is suppose it is working at 15 bar or 14 bar it will cross 600 degree centigrade temperature but the system will work relatively higher lower the pressure in comparison to the case of water at the same temperature. Now look at other properties height of the liquid that is enthalpy of the liquid that is 32.4 here163.35 right enthalpy of the vapor and enthalpy of the vapor here and healthy of the vapor is 2571.7.

Water is a unique fluid which has I mean very high latent heat in comparison to the other chemicals or other fluids available it is typically very high for water for other fluids for example refrigerants the latent heat of the order of 160 and 170 and 200 but for wanted the latent heat goes up to 2200 or 2300 kilo joules per KG. Here also we can see for mercury the enthalpy of the vapor is only 33 enthalpy of saturated vapor at 12 point bar is only 360.74 kilo joules per KG.

However in the case of water it is twenty seven two thousand seven hundred and eighty five point seven hundred per KG. So if you compare the thermo physical properties so as for as the energy is concerned what water it turns out to be much superior than mercury but the property of the mercury is the normal boiling point. The normal boiling point is 35.6 degree centigrade.

So if we take mercury if we start hitting the mercury will boil at a temperature of five 356.73 degree centigrade.

(Refer Slide Time: 10:09)

In a binary vapour cycle the mercury vapour entering the turbine is dry and saturated at 12.7 bar pressure. The condenser pressure of mercury cycle is 0.07 bar. The steam cycle operates between pressures of 30 bar and 0.07 bar and the steam is superheated to 350 °C. Find the efficiency of combined cycle.

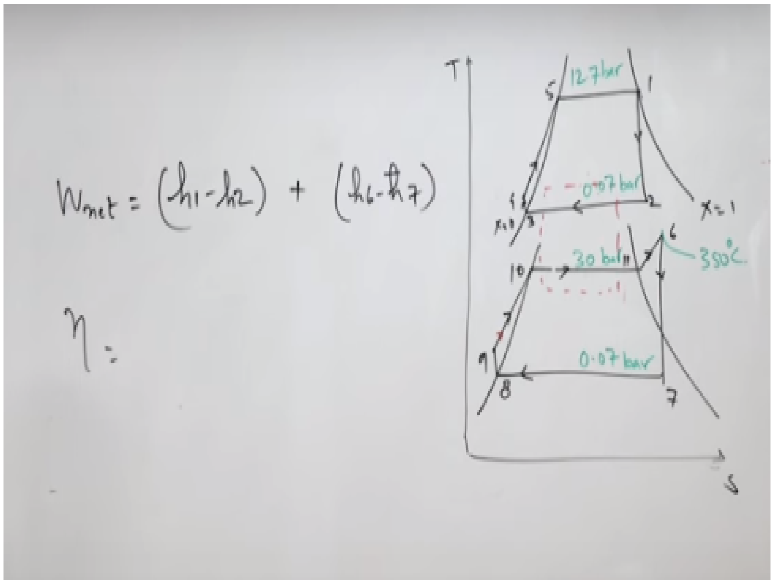
P, bar	t_s, °C	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/kg-K	s_g, kJ/kg-K
0.07	236.5	32.40	326.07	0.08548	0.66291
12.7	537.5	71.98	360.74	0.14580	0.50185

So now let us take one example solve try to solve a numerical in a binary value cycle the memory vapor entering the turbine is dry and saturated at 12.7 bar. So here will be putting the values it is 12 of 7 bar right and condenser pressure of company is 0.07 bar. The steam cycle operates between the pressure 30 bar this is thirty bar and the condenser pressure the steam cycle is also 0.07 bar and extremely is superheated to 350 degree centigrade.

So T6 is 350 degree centigrade right and if you compare the properties this properties of no properties of mercury is not here okay. So we will adopt the same process I can give you some numerical values we will adopt of the same process to find the out of the cycle I think they should not be any problem in finding out the output of the cycle if we have the thermo physical properties at the saturation points like at this point and this point and this point for mercury right.

As we have done in the previously we can here also we can find the efficiency of the cycle or output of the cycle. Similar manner we can find the output of this cycle as well right and the net output of the cycle.

(Refer Slide Time: 12:03)



Net output of the system is going to be net output of the system is going to be sorry net output net output of the system is going to be how much H1 - H2 + H6 – H7 per KG of respective fluid it is possible that here the mass flow rate here is different form the mass flow rate in the cycle. I am just taking per KG of circulating fluid and efficiency how much heat is added heat is added only in this process that is it.

Because beat addition in this process is through rejection of heat in the previous cycle right. If we do this sort of clubbing of or coupled cycle the efficiency of the system also improves. I will show you how the efficiency of the coupled cycle is improved.

(Refer Slide Time: 13:19)

$$\eta_1 = 1 - \frac{Q_2}{Q_1} \Rightarrow Q_2 = (1-\eta_1) Q_1$$

$$\eta_2 = 1 - \frac{Q_3}{Q_2} \qquad Q_3 = (1-\eta_2) Q_2$$

$$\eta_0 = 1 - \frac{Q_3}{Q_1} = 1 - \frac{Q_2 (1-\eta_2)}{Q_1}.$$

$$\eta_0 = 1 - \frac{(1-\eta_1)(1-\eta_2)\cancel{Q_1}}{\cancel{Q_1}}$$

$$(1-\eta_0) = (1-\eta_1)(1-\eta_2)$$

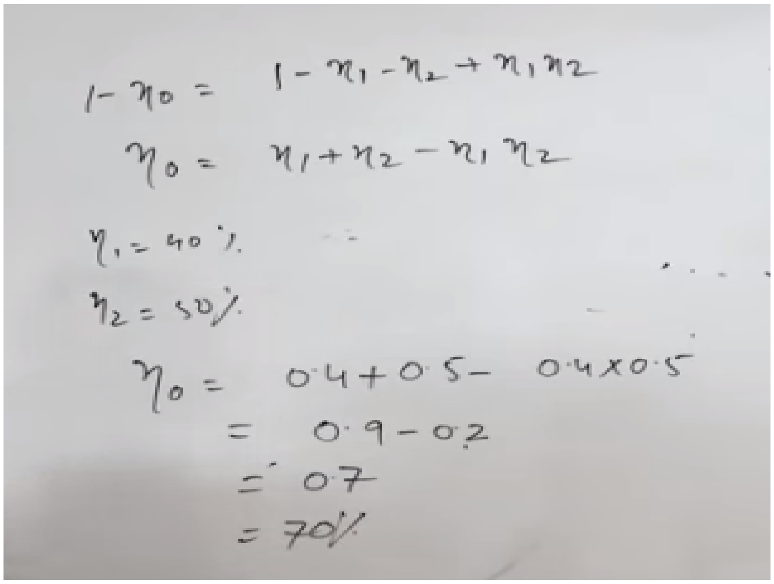
Let us take a carnet cycle I will start with carnet cycle let us take a carnet cycle one efficiency of one is 1 - Q2 by Q1. Q2 is this carnet cycle due this heat rejected Q1 is heat supplied so 1 by 1 - Q2 by Q1 will be the efficiency of the cycle now another cycle which is using this as source of rejected heat efficiency of two is going to be is it clear.

So here Q2 is going to be = 1- efficiency of 1 multiplied by Q1 right and here Q3 is going to be 1 - efficiency of 2 multiplied by Q2 now another cycle which is operating between 1 and 3. Now if you take this coupled cycle now the couple cycle efficiency overall efficiency of this coupled cycle is cycle working between one and three so it is Q3 by Q1 right = 1- Q2, 1- Q1.

Q2 again you can put = 1- here I will do hmmm so overall efficiency is going to be = 1 - efficiency of 1 divided by efficiency of 2 multiplied by efficiency of 2. This is Q2 and divided by Q1 and this is also Q1 this Q1 and Q1 will be cancelled out. So 1 - overall efficiency is = 1 - efficiency of one multiplied by 1 - efficiency of 2.

Now here coupling has been done and efficient and if you have N number of cycles then if we keep on going efficiency of 3 multiplied by 1 - efficiency of 5 and so on.

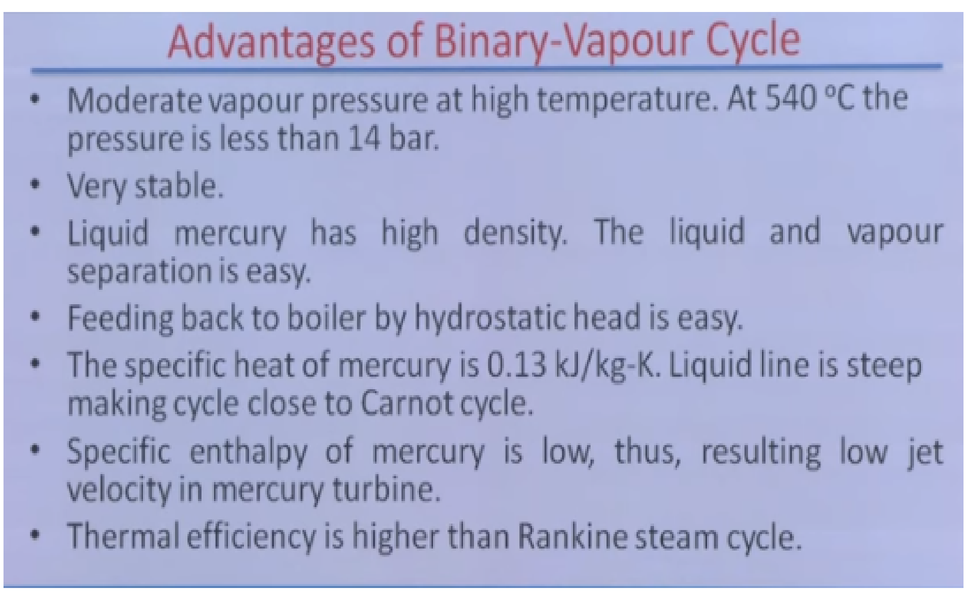
(Refer Slide Time: 16:01)



Now 1 - efficiency of O we can multiply this this is 1 - efficiency this is 1 - efficiency of 2 + efficiency of 1 efficiency of 2 if there are two cycles then we can say the overall efficiency is efficiency of 1+ efficiency of 2 -efficiency of one efficiency of 2 right. Now if we have take first efficiency is 40% another is 50%.

So first cycle couple cycle first cycle efficiency is 40% and this is 50%. So overall efficiency is going to be 0.4 + 0.5 – 0.4 into 0.5 that is going to be equal to 0.9 -0.2 = 0.7 or 70 %. So individual second efficiency was 40 % and 50 % but we have composed a cycle the efficiency as increased to 70%.

(Refer Slide Time: 17:35)



Now in addition to this now after this there are certain advantages of binary vapor cycle. In binary vapor cycle when mercury is used if we take the combination of mercury and water and mercury is used for high pressure cycle then in at high temperature the pressure of mercury is moderate. For example at 540 degree centigrade temperature the pressure of the mercury is less than 14 bar.

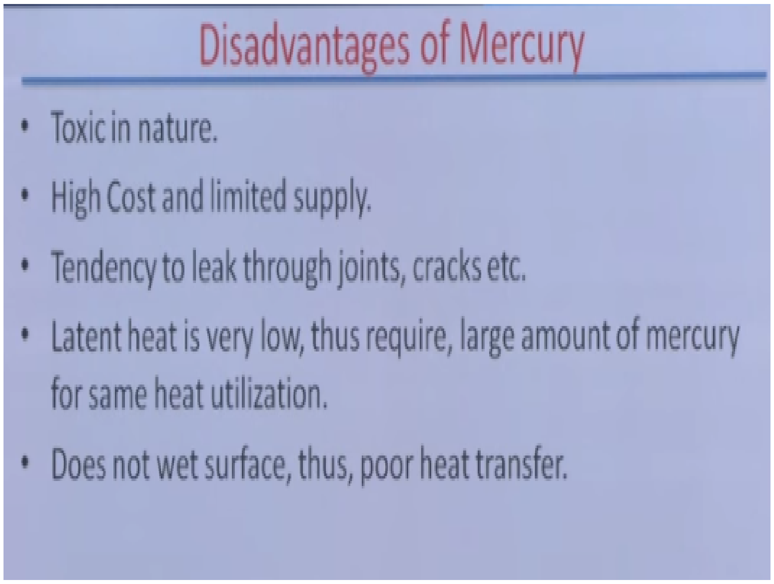
The mercury is stable at the high temperature there is another advantage of using mercury in the cycle. In addition to this liquid mercury has high density and therefore the separation of liquid and vapor in case of mercury is easier. The feedback to the boiler by hysteresis against the mercury can be fed to the boiler by hydrostatic head only the pump is not required in this case. If you want feed mercury in the boiler through hydrostatic pressure only the mercury can be fed because the density of the mercury is very high.

The mercury can be sent to the boiler at the hydrostatic head because the density of the mercury is high so pump can be eliminated pump which is used for increasing the pressure of the fluid which is coming from the condenser to the pressure of the boiler that pump can be eliminated and the mercury can be fed into the boiler through hydrostatic pressure or as the hydrostatic head. The specific state of the mercury is very low it is only 0.13 kilo joules per KG kelvin.

If you remember this specific heat of the water is 4.18 kilo joules per KG kelvin it is more than thirty times specific heat of the mercury. So in case of temperature entropy diagram or for mercury the liquid line is a steeper and which makes this mercury cycle closer to the carnet cycle. Another point is the favor of the mercury is that specific enthalpy of mercury is low thus it results in low jet velocity in mercury turbine and it is compensated by density of the mercury in this cycle.

In the cycle the mercury is used the thermal efficiency of the cycle is high it is higher than the right hand cycle running on the steam. So the thermal efficiency of the thermal cycle is higher than the thermal efficiency of the cycle working with steam as the working fluid.

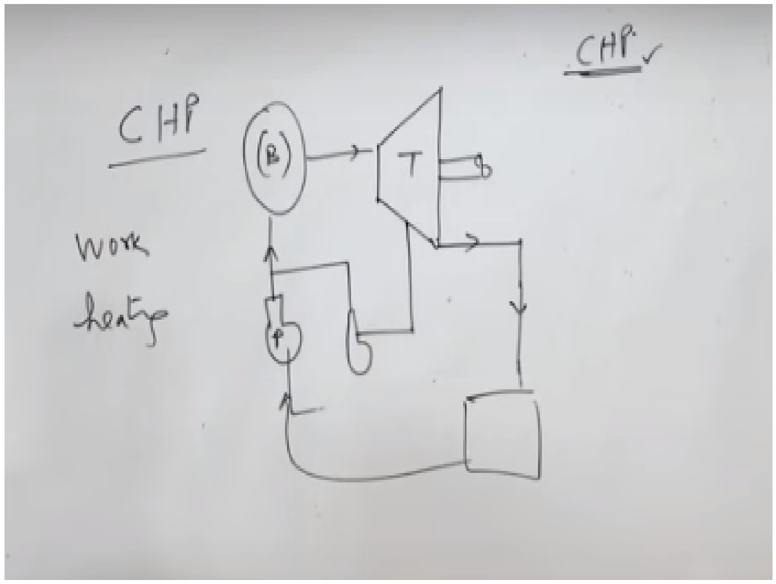
(Refer Slide Time: 20:12)



There are certain disadvantages of the use of mercury in binary cycle first of all mercury is toxic in nature. Secondly the cost of mercury is high and the supply of mercury is limited the mercury is pervasive. So tendency of mercury is leak through joints and cracks is very high. So the joints and the leaks the enter cracks have to properly leak through otherwise the mercury will leave through this joint and since it is toxic in nature in can cause the hazard.

The latent heat of mercury is very low so for generation of same amount of power high quantity of mercury is required the contact angle of mercury is high so it does not wet the surface therefore the heat transfer in the case of mercury is poor. So there are certain disadvantages of mercury using in a binary vapor cycle. So what is combined heat and power CHP it is known as CHP.

(Refer Slide Time: 21:29)



CHP combined heat and power in CHP processes in a single process the work is done I mean we extract the work shaft work from a turbine and from the same process the heating process heat process heat is also taken. So heating is done the work is done by the sample I will show you one such of one of the first cycles.

So it is sequential generation of two different forms of energy one is work another is heating and this heating is done it is sort of process heating in the different processes may be in the mechanical or chemical industries. One of such arrangement can be that you have a turbine now exit of the turbine is going to the condenser and condenser to the pump this is typical arrangement and pump to the boiler and boiler to the turbine this is a typical arrangement of a rankine cycle from turbine.

Turbine to condenser, condenser to pump and pump to boiler now in back pressure turbine what happens instead of using condenser. The steam coming out of the turbine is used for some process maybe sterilization or some chemical process. So steam is not condensed in condenser and the steam goes for the process it is known as back pressure turbine even in in some of the sugar mills you will find this type of back pressure turbine and there many industries where it is being used.

So the pressure so the steam coming out of the turbine does not go the condenser it goes to for some process and process heating is done. So from the same source to sequences of the processes we are getting from here we are getting the shaft output and after the shaft output we doing the heating also. So this is known CHP combined heating and power generation it is also possible that the process heat after the process the water is not usable.

So we can provide the fresh water or after the process the water can go to the pump and cycle is completed. Now another type of the CHP is extraction condensing I mean this process the condenser is there for the process heat the steam is extracted from a certain stage of the turbine during the expansion the steam is extracted at the particular pressure used for the process right and then after the process it is sent to the boiler through a different pump it is more of the same thing.

So this is known as the combined heating and the power system where power is generated at the same time process heating is also done or steam can be used for some other processes and this is also known as co-generation I end my lecture here in the next class we will be solving one numerical related with the rankine cycle.