Energy Conservation and Waste Heat Recovery

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Lecture – 16
Recapitulation of Common Power Cycles

Welcome back. If you recall, we were discussing for quite a few lectures. We have gone through different principles of thermodynamics, first law, second law, energy balance and then, second law efficiency. All these are very useful concept and they are having practical implications when we analyze the cycles which are engineering cycles for either power generation or for production of low temperature, we will see how these principles can be guiding principles for designing a good cycle, for designing some sort of a system which can derive maximum out of the available energy.

So, first I would like to start with power cycle because the power cycles have got lot of potentials for producing waste heat. So, if we study power cycles very well, then probably we can modify the cycle, so that waste heat production can be reduced. That is one aspect of it. Another that let us say there is production of waste heat generation of waste heat. With the help of a suitable power cycle, we can convert that waste heat into useful work into mechanical work or electrical work. So, that is also very important. So, for these two aspects, we need to study or we need to have a recap of the power cycles very quickly particularly relating it to the thermodynamic principles which we have learned for the last few lectures.

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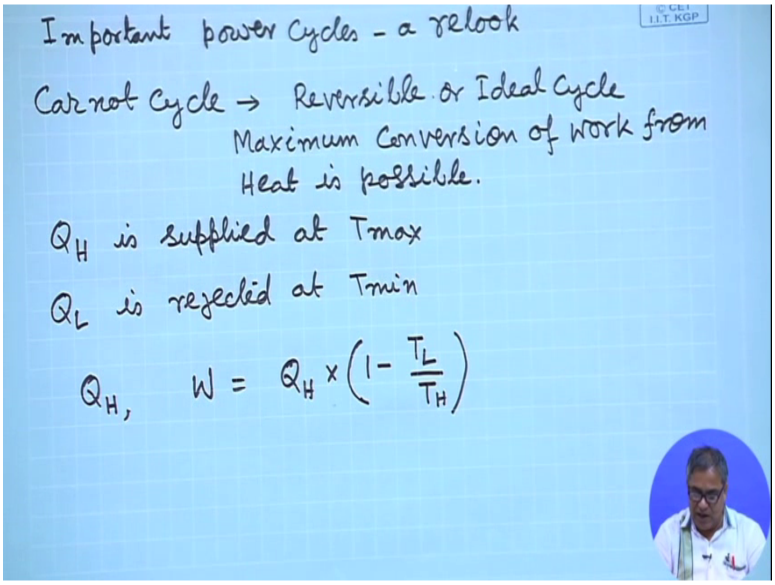

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Important power Cycles - a relook

Carnot Cycle → Reversible or Ideal Cycle
Maximum Conversion of work from Heat is possible.

Q_H is supplied at T_{max}

Q_L is rejected at T_{min}

$$Q_H, \quad W = Q_H \times \left(1 - \frac{T_L}{T_H}\right)$$

So, as the topic of the present lecture or corner stone of the present lecture is important, a relook power cycle means we are taking thermal energy and converting it into mechanical work.

So, whenever we talk about power cycle, immediately the name comes to our mind is the Carnot cycle. So, Carnot cycle is a reversible cycle and if two temperatures, that means T max and T min are given, then the maximum amount of conversion from thermal energy to useful work is possible with the help of a Carnot cycle. So, reversible or ideal cycle maximum conversion of work from heat is possible.

So, that is why it is so very important. It needs to be kept in mind that Carnot cycle is not the only reversible cycle. There are many reversible cycle, then why do we talk so much regarding Carnot cycle because in Carnot cycle the entire thermal energy is supplied to the cycle. All of the thermal energy which has to be supplied to the cycle is supplied to the cycle at the maximum cycle temperature.

So, if I write Q H is supplied at T max and Q L is rejected at T min, so the heat which has to be rejected that is also rejected at the minimum cycle temperature. So, that is the specialty of a Carnot cycle and that is why it is giving the best performance, but we have to keep it in mind that there are other reversible cycles also. Other reversible cycles are equally important. Why? It is because of course we will not have this scope to discuss it in details in any thermodynamics, any book of thermodynamics. These things are discussed at length that practical realization of Carnot cycle is very difficult.

So, that is why we have to think of other reversible cycles which are different from the operation of Carnot cycle, but which can be practically implied, employed or those can be taken as ideal cycles for many of the practical cycles. So, with this in mind let us proceed.

Now, again the efficiency of Carnot cycle that is given by if Q H amount of heat is taken, then the maximum work can be done by a Carnot cycle and that is given by for Q H, this is given by W is equal to Q H into I am writing first law efficiency 1 minus T L by T H. This is the efficiency and the efficiency of a Carnot cycle can be increased either by increasing the maximum temperature of the cycle or by minimizing, lowering the minimum temperature of the cycle.

So, if I have to derive maximum amount of work from a Carnot cycle, so either I have to increase the highest cycle temperature or I have to decrease the lowest cycle temperature. So, whether we use Carnot cycle or not, this can be used as a guideline for designing or selecting a cycle, all right.

Now, what is T L and T H? T L is where the heat can be dumped and for all practical purposes, it is the temperature of the environment or ambient. Now, from place to place this may vary, but this is more or less fixed. We do not have much of a flexibility in selecting P L, that is the temperature of the surroundings T H from where we derive the heat or we extract the heat. Now, that will depend on the source. So, this will have one value. If we use let us say a low grade coal if we use some sort of a nuclear reactor, T H will have a different value. If we use a high grade fuel let say oil, we may have another value which is different from the first two. So, it is always our lookout that we will try to increase T H and lower T L which of course is limited by the temperature of the environment

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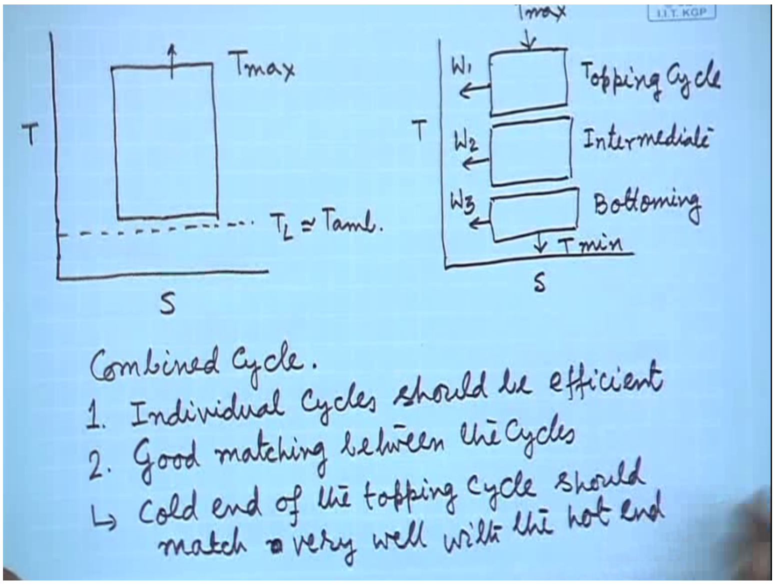

Combined Cycle.
1. Individual Cycles should be efficient
2. Good matching between the Cycles
↳ Cold end of the topping cycle should match very well with the hot end

So, let say this is a thermodynamic plane. Let us say we have taken some coordinates which are T and S. So, a Carnot cycle like this that will be very useful. So, here what we are having is T L that is your T ambient closed to T ambient and then, this T max I want to increase this side, there is a limitation. So, I want to increase T max.

Now, in many cases there are sources where T max could be high, but the problem is in practical cycle. We have to have some sort of a working through it, some sort of a working principle. So, for a very large temperature difference T max is very large, T L is low with a single cycle. We cannot have efficient conversion of thermal energy. So, what we can do conceptually, then one can do like this we can take a number of cycles I have shown three cycles over here notionally.

So, what is done is, the topmost cycle which is called topping cycle generally it is called topping cycle, then we have got some intermediate cycle and then, we have got a bottoming cycle. Now, the topmost cycle that will take thermal energy from a source from T max will take it, will convert part of it into work. Let us say this is W1, then it will reject heat which will be taken by the intermediate cycle. It will convert part of it into work, that is W2 and then, it will reject heat which will be accepted, taken by the bottoming cycle and it will create some amount of work which is W3 and then, ultimately heat will be dumped to T min, the minimum temperature.

So, this is the arrangement. If we can do this, then we are coming close to a cycle combining all these things which is having a very large T max and low T min and at the same time, the practical difficulty of having a single cycle which will operate from T max to T min that we have avoided. So, this is called combined cycle. So, combined cycle is a very useful concept. It is practically viable and we are having many examples of combined cycle where we can have much higher efficiency. So, it is good from the point of view of energy conservation and at the same time one can take or one can look into the combined cycle, the concept of combined cycle as a waste heat recovery device. Why? It is because the heat which is rejected from the topping cycle is taken by is utilized by, is recovered by the bottoming cycle or by the intermediate cycle. So, this is also a heat recovery device.

So, that is why we like to spend some time on combined cycle, but if we have to do combined cycle or if we have to have a good combined cycle, then what is the requirement? There are two requirements. Generally I have shown for example three cycles, but the application of two cycles; one of them is a topping cycle and another is a bottoming cycle. That is very common.

So, what we need to have a good combined cycle. Individual cycles should be efficient. Each individual cycle should be very efficient and then, good matching between the cycles. What does it mean? It means cold end of the topping cycle should match very well with the hot end of the bottoming cycle.

So, let me read it once again. Combined cycle if we have to have a very good combined cycle, then individual cycles should be very efficient and then, there should be a good matching. So, this is thermal matching. We will see it in details as we proceed. So, there should be a good match between the cold end of the topping cycle and the hot end of the bottoming cycle.

So, let us say if we take this figure. So, this is the cold end of the cycle at the top and this is the hot end of the cycle at below. So, they should match properly. What I mean by matching that I mean that we will elaborate as we proceed. So, with this let me start with a common power cycle that is vapor power cycle.

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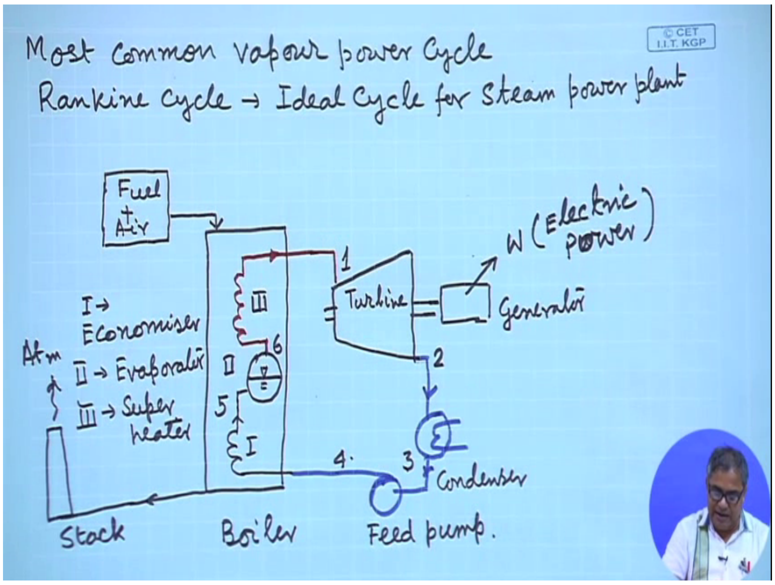

Most common vapour power Cycle

Rankine cycle → Ideal Cycle for Steam power plant

Most common vapor power cycle that is your Rankine cycle, ideal cycle for steam power plant; so, first we like to discuss the most common vapor power cycle that is Rankine cycle which is ideal cycle for steam power plant. Both fossil fuel and nuclear power can be used as the source as the thermal reservoir for steam power plant. Even it is possible to have steam power plant with some renewables. So, this is very important and a large portion of the world power that is generated by steam power plant.

So, this is very important in general for conversion of energy, for generation of power. This is also important because the potential of waste heat recovery which is related to steam power cycle. So, let us first start with a schematic diagram of the steam power plant. So, steam power plant will have a boiler. So, this is what I have drawn. This is the boiler and the boiler will have thermal energy due to combustion of fuel plus air. So, hot gas and of course, radiation heat that is responsible for supplying the thermal energy, from there we get the supply of thermal energy and then, a liquid that is sent to the boiler, this liquid initially it is in the sub cooled range or sub cooled region. Then, it gets into vapor stage and then, from there we get saturated vapor which is converted into superheated steam for most of the practical cycles and then, this steam has got the capacity to do certain amount of work.

So, in the boiler I have shown three parts; I, II and III and there I will write somewhere one is called economizer, 2 is evaporator and 3 is super heater. So, superheated steam we get all right and then, this gas comes out and then, it goes to a chimney or stack. This is atmosphere. So, this is stack. Then, what is happening from this side is, this superheated vapor or steam which is also at a high pressure that goes into a turbine and in the turbine, it expands.

So, when it expands, it rotates the turbine shaft through which generation of electricity is possible. So, we get electric power and then, what happens to this steam at the end of the boiler, this steam is at low temperature and low pressure. So, this steam is now condensed and the condensate which is in liquid condition, but at low pressure. So, that is pumped with the help of a pump to send it again to the boiler.

So, the additional components let us write this is turbine, this is generator, this is condenser and this is feed pump. Boiler is fed with this pump. So, this is called feed pump and we can put some numbers over here. If we put the numbers let us start from the turbine. So, if we put 1 over here, this denotes the state of the working fluid at the entry of the turbine. 2 denotes the state of the working fluid at the exit of the turbine, 3 denotes this state after the working fluid is condensed, 4 after the pump raises the pressure of the condensate or liquid water, 5 is the state when liquid water is heated in the single phase condition. Its temperature is increased and it reaches almost the saturation state and then, 6 is the condition of the working fluid when it is evaporated.

So, now the working fluid is in the vapor state and then, this vapor is taken and its temperature is further increased, that is it goes into the superheated region and that is your condition 1. So, at that condition, it goes to the turbine. So, this is how we will have the physical working or physical change of state of the working fluid and this cycle will continue now.

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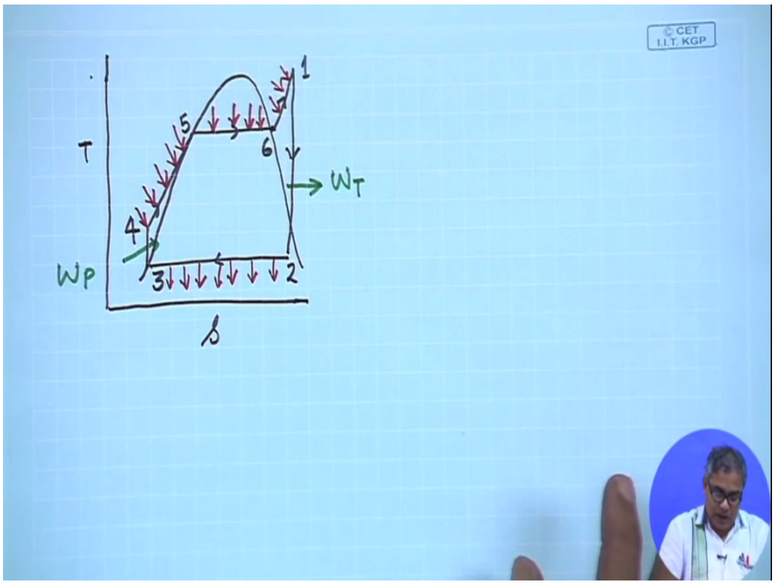

If we represent it on a thermodynamic plane, the convenient plane is your T S plane. Generally we do analysis based on per unit mass. So, I have written S and temperature.

So, this is the two phase dome because during the working of Rankine cycle, the working fluid is partially it is liquid at some part of the cycle it is liquid. Somewhere it is a mixture of liquid and vapor and somewhere it is vapor. So, we will have this kind of a figure. So, 1 2 to turbine 2 to 2 to 3, that is within the condenser and it is condensed and it has gone to the saturated liquid. Condition 3 to 4 is the pump where there is an increase in pressure, 4 to 5 temperature is increased for the liquid water, 5 to 6 evaporation process. So, at 6 we are having saturated vapor and 6 to 1, this is super heating.

So, what we can show now, this is the heat addition to the Rankine cycle in the boiler, this is the heat rejection by the Rankine cycle to the cooling water in the condenser. Here we need to supply some work W pump that we need to supply and from here. We will get W turbine that is the work done by the cycle. So, this is an ideal Rankine cycle or this is reversible, internally reversible Rankine cycle and this is the basis of all steam power plant.

Now, I like to stop over here and in the next class, in the next lecture I like to see or we would see what will be the efficiency of such a cycle and then, we will see what are the points where we are having loss of energy, how energy conversion can be made more efficient and then, how the cycle can be modified to have better efficiency that also you will try to find out.

Thank you.