Thermal Engineering Basic and Applied

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Lecture – 18
Multi-fluid Cycle and Analysis

I welcome you all to the session of Applied Thermal Engineering and the topic of our today's discussion is the Multi Fluid Cycle and its analysis. So, if we try to recall, in this module of the course, we have discussed about steam power cycles. Starting with the Carnot cycle we have discussed several other cycles which are used in real applications. Importantly, in all these cycles, we have seen that the working fluid is water or steam. So, we have identified that there are two parts in the cycle, one is the high temperature part, another is the low temperature part and the working fluid changes its phase from the low temperature part to the high temperature part.

Now, in the last class we have discussed about the desirable properties of the working fluid which will be used in the stream power cycle. And we have discussed that though water is predominantly used as the working fluid, but it is not considered as the ideal fluid. In fact, water has a few drawbacks and if we need to consider water as the ideal working fluid, all these shortcomings need to be eliminated and one way of considering this aspect is the use of binary cycle or the combined fluid cycle. So, the necessity of the combined cycle arises from the fact that we would like to use water as the working substance or working fluid despite knowing its few drawbacks, but our objective should be to eliminate all these drawbacks and in doing so we need to consider the multi fluid cycle or the binary cycle.

So, now if we try to write down the desirable properties of the working fluid;

1) High critical temperature at a reasonably low pressure.
2) Low triple point temperature that is the freezing temperature should be below the room temperature.

3) High enthalpy of vaporization or high heat of vaporization.
4) It should not have low condensation pressure. Rather vapor pressure should be relatively nearly closer to the atmospheric at a desirable condensation temperature.

High heat of vaporization means we should look at this particular property and if we can ensure the weight of the fluid in the cycle will be minimum. So, low condenser pressure is not allowed.

5) In addition to this we had discussed that it should be non-corrosive, chemically stable, easily available and non-toxic.

In addition to these properties the most important point which should be discussed today is that it should have ability to wet the metal surface to increase heat transfer.

Now, why I am discussing this part again today? High critical temperature at a reasonable low pressure is very important. It is very difficult to have all these properties in water. If we try to recall that when we are getting steam in the boiler, the rise in temperature of steam is accompanied with the rise in pressure. So, we should look for the working fluid which has high critical temperature at a reasonably low pressure. So, that means, we can increase the temperature without increasing the pressure.

As I told you for steam, rise in temperature is accompanied with a rise in pressure, so if we use steam water mixture as the working fluid, then the critical temperature is 374°C and pressure is 225 bar. So, try to understand that if we use water as the working fluid and when that water is getting converted into steam in the boiler, then even at the critical temperature, pressure is very high. So, if pressure is very high then you also need to look at three different issues that are design, operation and control. So, these three important issues like design, operation and control are the factors for which we should look for a fluid which will be having high critical temperature at a reasonable low pressure right.

Why you need to have high critical temperature? From the combustion, we will be getting energy and that energy should be transferred to the working fluid. And now if the critical temperature is very high, then it is highly possible to have phase change. When working fluid will be changing its phase that process can be maintained even at a high temperature. So, we are trying to mimic or get closer to the Carnot cycle.

Next I have mentioned that freezing temperature should be well below the atmospheric temperature. And by high heat of vaporization we can ensure that the weight of the working fluid should be minimum and finally, low condenser pressure is not allowed that we have discussed in the previous class. So if we use water as the working fluid, it is very unlikely to have all these properties at a time. Despite the fact that we will not be getting all these properties in water, we need to use water because it is used predominantly as it has a few advantages feature. But if you would like to use it essentially to increase the efficiency of the plant then we need to go for the binary cycle.

So, the concept of binary cycle is coming from this particular fact. Now let us look into this aspect. So we can draw the schematic of a steam power plant highlighting the boiler, turbine, pump and condenser. The process 1-2-3-4 has also been marked with $Q_{out}, W_{out}, Q_{in}, W_{in}$. Here all the processes are executed in a cyclic manner.

And we can also draw the equivalent form of this cyclic processes as shown in the slide. There we have also marked Q_H, T_H, T_L, Q_L & W_{net}. This is what we have learned in our basic thermodynamic course. So, you know that $W_{out} - W_{in} = W_{net}$, that is the network we are getting from the cyclic process. I am trying to represent the all these processes through this heat engine. So, essentially this is the engine which is operating between 2 temperature thermal reservoirs, one is at high temperature & another is at low temperature and we are getting continuous work output. So, essentially this representation is a very simplest form of this system.

$$\text{So thermal efficiency of this heat engine}, \eta_{th} = 1 - \frac{T_L}{T_H}$$

$$\text{For Reversible cycle, } \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

We can see that if we increase the temperature that is T_H so that means, temperature at which heat is added should be maximum. Also this temperature of sink to which heat is rejected should be minimum. So, either by reducing T_L or by increasing T_H we can ensure that the efficiency of the cycle will be maximum. Now if we go back to the simple form of this steam power cycle and its equivalent representation that is shown in the slide, our objective should be to get maximum T_H. I mean the temperature at which heat is added to the working fluid should be maximum. And the temperature at which it is rejected that also should be minimum. It is not always possible to reduce temperature because it is dictated by the temperature of the coolant which is available near the plant. So, what we can do is we can try our best to keep this T_H as maximum as possible.

And if you would like to do so then we need high critical temperature at a reasonably low pressure that means the working fluid should be chosen in such a way that the critical temperature should be very high. So, that we can increase the maximum temperature at which the substance will change its phase will be high. So the latent heat transfer or phase change heat transfer will be more efficient. I mean we can achieve high thermal efficiency.

Problem with water is that a rise in temperature is accompanied with a rise in pressure and that eventually creates problem from the perspective of the design, operation as well as control of the plant. So, that is why water alone cannot be used as the working fluid, if we need to achieve high thermal efficiency and it is because of this reason the concept of binary or the combined fluid cycle is there.

Combined fluid or binary vapor cycle

So, you know that different working fluids are having different attractive features, but not all of the features. I mean if we consider water and oil then these fluids are having different attractive feature in them, but not all. So, the properties or attractive feature of water is are absent in oil. In a similar way the attractive features of oil may absent when we look at water as the working fluid. So, this is very important. And in such a case two vapour cycles operating on two working fluid are put together, one is at high temperature and another is at low temperature. So, that means our objective is to get the attractive features of two different fluids and if you would like to get those, we need to consider two vapor cycles, each of them will be operating on different working fluid and if we combine them together. One working fluid will be at a high temperature, and another is at a low temperature and this total arrangement is known as the combine fluid cycle.

So water will be used as one working fluid definitely for the low temperature part of the cycle. I mean there are two different cycles, water will be used as the working fluid for the low temperature cycle while we also need to select another fluid which will be used as the working fluid for the high temperature part of the cycle. Now next question is which fluid should be selected to act as the working fluid for the high temperature part of the cycle. In this context it is seen that mercury is used as the working fluid for the high temperature cycle.

Although mercury does not have all the desirable properties which you have talked about in the beginning of today's class, yet mercury is used because of its few distinctive features. We shall discuss all those. So, the combined cycle that we are going to discuss today is known as mercury water combined vapour cycles. So, let us draw the schematic depiction that will help us to understand this very quickly. There are two different parts to be drawn. One is this Hg cycle which is high the temperature part and it is connected to electric generator. So, there is also a mercury generator and we need to supply heat in this mercury. So, basically this is combined fluid cycle and till now we have drawn only the mercury cycle. So, remaining low temperature cycle is water or steam water cycle.

So, we are supplying water and that water is getting converted into steam and that steam will be allowed to pass through the super heater and then it will be taken to another turbine from there we will be getting W_{out}. After doing work that steam will be collected in a condenser as usual, where heat will be rejected and then the collected condensate will be pumped back to the steam generator. So there is a steam generator and pump 2. So you can understand that this is water cycle or steam cycle. There is a steam turbine and a mercury turbine.

So, it is very easy to understand that there are two different cycles and two different fluids are used. Our objective is to increase the efficiency of this cycle. So heat is supplied to this mercury because mercury is having high critical temperature at a reasonably low pressure. So, we can increase the critical temperature and the isothermal heat transfer from this external source to mercury is very high. And then mercury vapour will be allowed to go through the mercury turbine. And this turbine is connected to this generator. Now, after doing some work that mercury should be again collected in this device which is given name as the steam generator, I also can call it mercury condenser. That means here mercury is allowed to make reduce the temperature by supplying water and that water will be converted into steam. That steam is taken through the superheater. We shall discuss about this later. For the timing you keep in mind that this is again a device through in which steam is allowed to pass essentially to increase its temperature before it enters into the turbine.

So, whatever steam is generated in this steam generator is in contact with the water. So, essentially the steam that we are getting is saturated steam. So, to increase the quality of the steam we need to superheat the steam and that is why it is passed through the superheater. This is what I have schematically shown. We shall discuss this part again when we shall be discussing about boiler.

Then that superheated steam is taken to the steam turbine and it does work and we are getting W_{out}. After doing work, the steam is collected in condenser wherein it reject heat of Q_{out} and that condensate is pumped back to the steam generator. In this way you can understand that this is also a cyclic process and all the process in the cycle are also cyclic, I mean executed in cyclic manner.

Now again we try to represent the entire system of this complex circuit in equivalent form as shown in the slide. We can understand that we are supplying heat from a heat source which is now having temperature T_H and eventually heat is rejected to another reservoir that is the heat sink which is having temperature T_L. And out of this heat transfer to the device and from where heat is rejected we are getting W_{net}. So, net work we are getting and that is in a cyclic manner. Had this cycle not been here I mean if we consider only the low temperature cycle and do not consider this high temperature cycle, I mean if the high temperature cycle is not integrated with this low temperature cycle, then we had seen from our previous classes that T_H should be maintained at a limit. And we cannot increase T_H beyond a particular limit and that is the critical temperature of water.

And we had seen that even at critical temperature, the pressure is very high and even for the super critical boiler or super critical plant, the design, operation and control, these three aspects are very difficult. So, we can see that by dragging this particular cycle to the lower temperature cycle or by integrating this high temperature cycle with this low temperature cycle with different working fluid, we are going to achieve or we are going to exploit a few distinctive features of mercury. So we can maintain T_H as maximum as possible so that the overall efficiency of the cycle can be increased. So, this is the concept of binary cycle.

So the Idea is if we use water alone as the working fluid, then we cannot increase T_H beyond a particular limit. If we cannot increase the limit, then we cannot increase thermal efficiency beyond a particular value. But we need to use water as it is predominantly used and also it is having a few distinctive features. And it is because of these properties, water is used. So, we are keeping the provision of using water in one part of the cycle where temperature is less, but at the same time we need to have high thermal efficiency. And that is why this high temperature cycle is added. So, these two cycles added and as a result of this, the efficiency of the plant will increase.

It is basically you know that though mercury does not have all these desirable properties, but we are still using it. So, definitely this fluid must be having a few advantageous features and that is why it is used. But we also need to keep in mind that the use of mercury is not very easy. So, we shall discuss the merits and demerits of this particular fluid which is used in this high temperature cycle.

Before going to conclude, we would like to draw the T-s diagram, because we also need to know the analysis part as entire objective is to look for the efficiency of the plant. So, we need to have the analytical expression of the thermal efficiency and from there, we shall see that integration of this particular cycle to the steam water cycle improves the efficiency. And that we will see from that particular analytical expression.

But before completing I would like to draw the T-s diagram. There is the low temperature part and high temperature part. So to distinguish them, in the T-s diagram drawn in the slide, we have used different colour. And you can understand the critical temperature of mercury is very high, so, this yellow color is used to represent the mercury cycle in the T-s diagram. If we give name, then 1-2-3-4 represents the high temperature cycle and 5-6-7-8 is for low temperature cycle. So, what we can see from the T-s diagram.

So there is this is low temperature cycle, and high temperature cycle having working fluids, steam water and mercury respectively. What we can see that heat which is rejected during condensation of mercury in the mercury condenser, which is also known as steam generator for this particular cycle that is low temperature cycle. Then heat is gained by the water and getting this heat from the condensed mercury, water is converted into steam and that steam is allowed to pass through the turbine and it does work, from there we are getting work output. So this is the overall concept of the combined and binary fluid cycle.

The Idea is that by using one such fluid, we can use maximum temperature at which heat is added that is T_H. So we can increase overall efficiency. You can see that overall efficiency or the thermal efficiency

$$\eta_{th} = 1 - \frac{T_L}{T_H}$$

So, you know we have very precise control over T_L because that is fixed by the temperature at which heat is rejected to the sink. And that basically depends on the temperature of coolant, which is available near the plant. But we can increase T_H and to do so, we have discussed about this combined fluid cycle. So, with this I stop here today and we shall continue our next topic in the next class.