Thermal Engineering: Basic and Applied
Dr. Pranab K Mondal
Department of Mechanical Engineering
Indian Institute of Technology-Guwahati

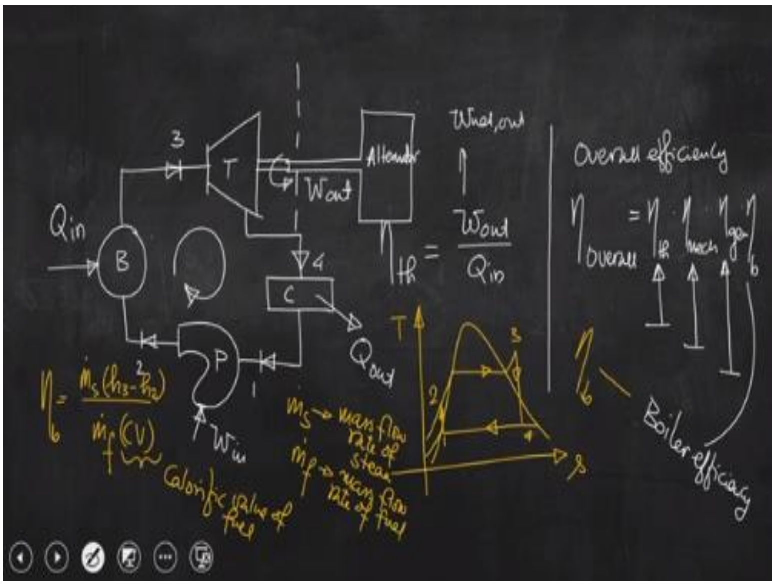
Lecture - 22
Types of Boiler, Different Cycles in Boiler Operation, Boiler Attachment

I welcome you all to this session of thermal engineering, basic and applied. Today we shall discuss about the boilers. In fact, we have discussed several cycles, which are used to describe all the processes in a steam power plant and we have seen that all these processes can be mapped in different thermodynamic planes. Mapping all these processes in thermodynamic planes in particular P-v and T-s plane, we could establish the thermal efficiency of the cycle.

Now we have seen that thermal efficiency of the cycle is not only the efficiency which dictates the overall efficiency of the plant. So if we try to find out what would be the overall efficiency of the plant, we also need to understand the performance of several other components along with several other efficiencies, which are also important to be looked at.

So now before I go to discuss about the classification of boilers, their working principle, let us first draw the schematic depiction of the plant. From there we shall try to understand why we need to specifically study about boilers.

(Refer Slide Time: 02:50)



So this is the simplest schematic depiction of the steam power cycle or plant drawn in the slide. And we can see from this depiction that there are four major components; boiler, turbine, condenser and pump. So this B is used to denote boiler. We have discussed about the description of this particular diagram. We have also discussed about thermal efficiency of the cycle. That is nothing but

$$\text{Thermal Efficiency}, \eta_{th} = \frac{W_{out}}{Q_{in}}$$

So you know this is the thermal efficiency and by knowing only this thermal efficiency, it is difficult to predict what would be the overall efficiency of the plant. So the overall efficiency of the plant,

$$\text{Overall Efficiency}, \eta_{overall} = \eta_{th}.\eta_{mech}.\eta_{gen}.\eta_{b}$$

So you can understand if we want to predict the overall efficiency of the plant, we also need to know three other efficiencies together with the thermal efficiency that we have already discussed. So you know this thermal efficiency which we have studied and we have worked out numerical problems as well. So this is the efficiency which comes into the picture accounting for the efficiency of the turbine or pump. Because, this is the amount of energy that we are going to add in the cycle and out of this input energy, we are also getting some amount of energy in the form of work and this is W_{out} but ideally it should be $W_{net,out}$. That means, this device is also taking or consuming some amount of work from this output work and as a result this $W_{net,out}$ is coming into the picture. So to take care of the efficiency of these two devices, this thermal efficiency is coming into the picture.

What about this mechanical efficiency? This is also another important efficiency that perhaps you have studied in the context of pumps. So you know that the energy which is being developed inside the turbine, that energy is not available at the shaft of the turbine. Some mechanical losses are there. Accounting for these mechanical losses, we also need to define one efficiency that is mechanical efficiency. So that means, when steam is flowing through the turbine, it does work on the rotating part of the turbine, so energy is produced, but that energy is not available at the shaft of the turbine, because of some mechanical losses. And that is why this mechanical efficiency is coming into the picture.

So we have talked about the thermal efficiency, we have now discussed about mechanical efficiency. Third is the efficiency of the generator. You know that the shaft of turbine is connected to the shaft of an alternator. From there you are getting electricity. So the work which is available at the turbine shaft that work is not going to produce equal amount of electricity because some losses will be there. Perhaps you have studied about this in electric motor. So windage loss will be there and bearing loss will be there. So accounting for all these losses, the generator efficiency is coming into the picture.

So we have discussed about thermal efficiency, mechanical efficiency and generator efficiency. But in addition to all these three efficiencies, we are also having another important efficiency that is boiler efficiency. So it is equally important to be looked at while we are trying to predict the overall efficiency of the plant. Why? Because when someone is designing several components, which should be placed in a thermal power plant, even after incorporating all these devices in a power plant, we also need to calculate the overall efficiency. So whoever is going to design the plant then, he or she must be considering the overall efficiency. If he or she needs to calculate overall efficiency, then in addition to all these three efficiencies, this boiler efficiency is very important to be looked at.

Now question is what is boiler efficiency? For that let us first draw the T-s diagram, then it will help us to understand exactly what we are going to discuss now. So we have drawn the T-s plane for the modified Rankine cycle where steam is superheated beyond the saturated state up to 3. So now if we look at the schematic diagram vis-a-vis the corresponding T-s diagram, what we can observe?

You know that we are supplying Q_{in}. So this is the amount of energy we are going to supply in the form of heat and that is coming by burning the combustion of coal in case of the coal fired boiler and in case of the diesel fired boiler, this energy will be coming from the combustion of diesel. So whatever the case may be, we are going to supply some amount of energy in the form of heat and at the cost of that input energy, we are getting some amount of energy recovery.

Why am I using the word recovery? Because you know the amount of energy that is being added to the boiler is not going to get converted to an equal amount of energy to increase the energy of the working substance which is allowed to go through the boiler. The amount of energy that is added to the boiler would be utilized to convert water into steam, there is no doubt about it. But there must be some amount of leakage of energy inside the boiler. So accounting for the heat loss from the boiler surface to the surroundings, all the energy which is supplied by either by burning coal or diesel or any other fuel, it is very difficult to have equivalent conversion.

Of course I would like to say conversion because this thermal energy is again going to increase the, total energy of the steam or I should say the internal energy of the steam. But there will be losses of heat while it is added to the boiler as some amount of heat will be transferred from the boiler surface to the surroundings, some amount of heat leakage will be there and as a result of which we will be getting some amount of energy recovery, but it is not equal to the energy which is added.

It is because of this reason, boiler efficiency η_b comes into picture. That means, whenever we are giving some energy inside the boiler, which is a mechanical device, the heat is transferred to the boiler and using that heat water is converted into steam.

So this process is not completely reversible process, so the amount of energy that we are going to give to the boiler will not be converted equally to increase the internal energy of the steam or working substance. As you have studied earlier that there is heat transfer due to finite temperature difference so naturally this process is highly irreversible. And as long as the process is irreversible, it is very difficult to achieve maximum efficiency or maximum exergetic efficiency. So this device will not run with the maximum exergetic efficiency. And that means, the energy will be recovered that is 100% true, but this recovery will not be full. So accounting for that, we have boiler efficiency. So you can understand now what boiler efficiency is.

$$\eta_b = \frac{\text{Output energy}}{\text{Input energy}}$$

So fuel is burned and out of the burning of the fuel (combustion), we are getting some amount of energy. And that energy is nothing but the product of mass flow rate of fuel and the calorific value of the fuel.

$$\text{Input energy} = \dot{m}_f(CV)$$

$$\dot{m}_f = \text{mass flow rate of the fuel}$$

$$(CV) = \text{calorific value of the fuel}$$

Now for the output energy, let us look at T-s diagram. In one of the previous classes we have discussed about that the process that is there inside the boiler is mapped in T-s plane and we know this process is constant pressure heating. So if we consider the constant pressure heat addition process is steady state steady flow process, then by ignoring the changes in kinetic and potential energy, (let me tell you once again, not ignoring the kinetic and potential energy rather ignoring the changes in kinetic and potential energy), it is possible to write that

$$\text{Amount of heat added to the working substance} = \dot{m}_s(h_3 - h_2)$$

So this is the amount of energy added to the working substance, if we apply the steady state steady flow equation to the process that is there in the boiler that is the constant pressure heat addition process and if we ignore the changes in kinetic and potential energies. This amount of energy which is added to the working substance is coming essentially from the energy which is being supplied to the boiler.

$$\eta_b = \frac{\text{Output energy}}{\text{Input energy}} = \frac{\dot{m}_s(h_3 - h_2)}{\dot{m}_f(CV)}$$

$$\dot{m}_s = \text{mass flow rate of the steam}$$

But, never these two quantities means output energy & input energy are equal. Otherwise, it will violate second law of thermodynamics. These two quantities will never be equal accounting for the process which is highly reversible because there is heat transfer due to finite temperature difference and also some amount of heat losses or heat leakage will be there inside the boiler.

$$\text{So}, \eta_b < 1$$

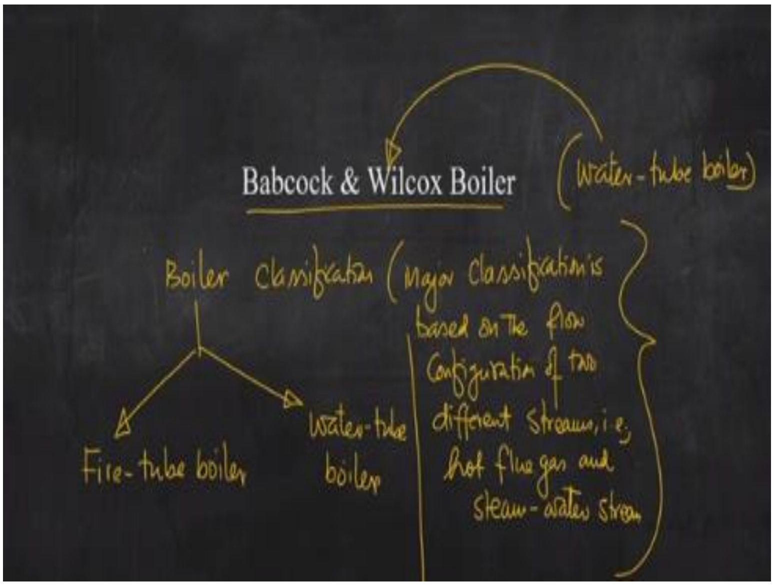
So this is what is known as boiler efficiency. So now we can understand that, this efficiency plays an important role towards the prediction of the overall efficiency of the plant. As I had mentioned few minutes back that $\dot{m}_s(h_3 - h_2)$ & $\dot{m}_f(CV)$ these two quantities are not equal. It is very difficult to achieve in practice where these two quantities will be equal. But our target should be to increase the quantity that is $\dot{m}_s(h_3 - h_2)$. We are trying that how closer this quantity will be equal to $\dot{m}_f(CV)$.

If we need to do so, we also need to know several processes, which are there inside the boiler; several components which are there inside the boiler. That means, we need to know the configuration of the boiler. And by this time, we have understood that this is the device which is again a heat interacting device, heat transfer takes place from one stream to the other stream. What are the two different streams? One stream is steam water and other stream is hot flue gas, which is high temperature products of combustion. So these two different streams are there inside the boiler and when these two different streams are flowing through the boiler, they exchange heat among themselves and we are getting steam from the water.

So that means, considering all these aspects we can understand that it is needed to look at several components which are there inside the boiler, several flow paths through which these two different streams flow from one part to the other part of the boiler and the mechanism by how we can maximize the quantity, that is $\dot{m}_s(h_3 - h_2)$.

So the the objective behind this particular module of this course is to describe the working principle of the boiler. But before that, we should understand several components of the boiler and their functionalities. At least we have understood that boiler is a heat exchanger. So inside the boiler, two different streams are allowed to flow and while they are flowing, they exchange heat and as a result of which we are getting steam from water.

(Refer Slide Time: 23:03)

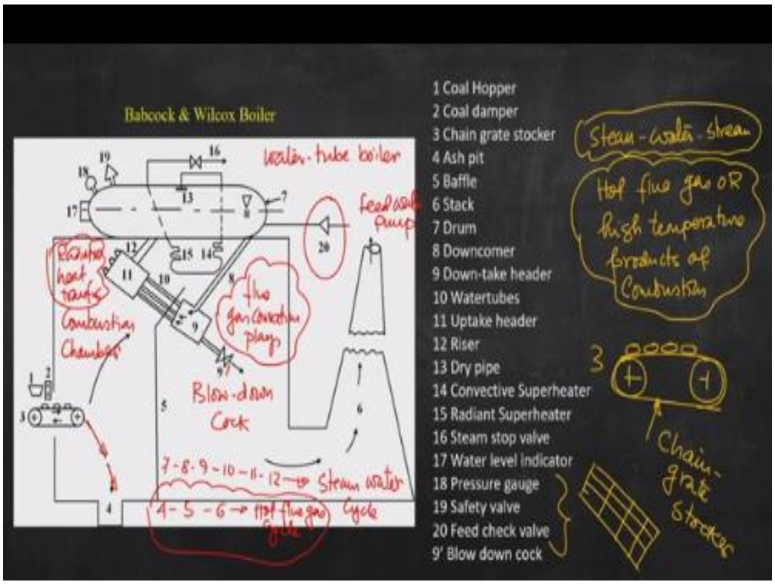


Today I will discuss about one particular type of boiler that is called Babcock and Wilcox boiler. Before that it is better to discuss about the classification. So Boiler is classified into two different categories. And major classification is based on the flow configuration of two different streams, which are hot flue gas and steam water stream. So the major classification is based on this particular aspect. Again little bit of fluid dynamics is coming into the picture, but there is no score to discuss about the hydrodynamics part of the boiler in this course. But at least we should know that flow configuration. So hydrodynamics will play an important role while designing the boiler essentially to achieve maximum performance of the boiler, but that is beyond the scope of this course. So based on this classification boilers can be placed into two categories, one is known as fire-tube boiler and other class is water-tube boiler.

So the Babcock Wilcox boiler that we are going to study today is essentially a water tube boiler. So based on the flow configuration of two different streams that is hot flue gas and steam water stream, it is possible to classify boiler into two different categories. One category is the water-tube boiler. Another category is known as fire-tube boiler.

So now you can understand from the name itself water-tube boiler indicates that water stream is allowed to pass through the tube. And you have studied about heat exchanger in your heat transfer course that this is a kind of cell and tube heat exchanger. So if one stream is allowed to flow through the tube, other stream will definitely pass through the cell that is over the tube.

(Refer Slide Time: 27:45)



Now let us come to the schematic depiction of this Babcock Wilcox boiler. The schematic depiction shown in the slide is the cross-sectional view of the boiler. There are several components and all components have been labeled. Not only that, I have also described all these components in the right panel of this slide. You can see that component are labeled 1 to 20 including 9'. So the components are coal hopper, coal damper, chain grate stocker, ash pit, baffle, stack, drum, downcomer, down-take header, watertubes, uptake header, riser, dry pipe, convective superheater, radiant superheater, steam stop valve, water level indicator, pressure gauge, safety valve, feed check valve.

So the pressure gauge, safety valve, feed check valve, these three are very important. I will discuss in one class that there are two important terminologies. One is known as accessories, other is mountings. So the pressure gauge, safety valve, feed check valve are common to all types of boiler. And lastly 9' is blow down cock.

So let us briefly discuss about all this. So first of all, we need to identify what are the two different streams. We know that there are two different streams and these two different streams will be allowed to flow through the boiler using different configuration. And that is how the classification of boiler has been done. Babcock Wilcox boiler is the water-tube boiler. So what are the two different streams here? One is water and other is hot flue gas or it is also known as high temperature products of combustion.

If we look at the components, from 1, 2, 3 and 4 we can understand, it is a coal fired boiler. So basically coal is placed initially at the coal hopper that is at 1. And that coal is now dumped at 3. So at 3, there are two different pulleys through which the chain grate stocker moves continuously. So coal is taken to coal hopper. From the hopper, coal is dumped on the chain grate stocker. So basically we are stocking coal over the chain grate. Chain grate stocker is a kind of perforated plates. Now as we are going to stock coal using coal hopper and damper on this chain grate stocker, this perforation is very important to have efficient combustion. We need to have oxygen, otherwise combustion will not sustain. So when that chain grate stocker is moving from 3 towards the inner end of the chain grate, entire combustion should be completed.

So that means, whoever is going to design this particular component of this boiler, he or she must be careful that whenever we are putting coal over here, the entire coal should be combusted within this short distance of chain grater. And that means the RPM of this chain grate stocker should be decided accordingly so that the entire coal would be combusted.

And after combustion, we will be getting residue, which is ash. So that ash will come into this ash pit in the direction as shown by the arrow in the schematic. So ash will be stored in 4 that is ash pit. So ash is coming as the residue and another thing is hot flue gas that is the high temperature products of combustion.

The high temperature products of combustion will flow upwards. It is designed to direct the flow of high temperature products of combustion towards the upper part of the boiler. Otherwise, the combustion products will flow in the horizontal direction, it will go through the chimney to the surroundings without doing the task, which is important in the context of this boiler operation. And that is why this baffle is given, labeled as 5. So the purpose of baffle is to provide a proper direction to the combustion products towards the upper part of the boiler and also to prevent the movement of the combustion products towards the stack without doing the necessary conversion of energy.

So now the high temperature products of combustion is moving towards the up. Then we are coming to discuss about 7 that is drum, it contains water. Water from drum passes through 8 that is downcomer and comes to 9 that is called down-take header. And from the down-take header, water passes through the tubes that is shown by 10. There are three different tubes which are shown over here, so water will move through the tubes. While moving through the tubes the conversion will start that means water will be converted to steam. In fact conversion of stream from water starts from 9 itself. Being lighter than water, steam will flow towards the uptake header that is 11 through water tubes.

So now when it is again moving through water tubes, all the water will be converted into steam. Since steam is lighter, it will be there in 11. You can understand that 11, 10 and 12, these three different parts are very close to the high temperature part of the combustion chamber.

Since 11, 12 and even 10, these three different parts of the boiler are very close to the high temperature part of the combustion chamber, wherein radiative heat transfer plays an important role. So there are two different modes of heat transfer, one is flue gas convection, other is radiative heat transfer. Since part 11 is very close to the combustion chamber, wherein the temperature is very high, so radiative heat transfer will play an important role because of high temperature difference. So the steam will move through the riser that is 12. As steam is lighter then it will go at the top and will be collected at 13.

Now 13 is dry pipe, 14 is the convective superheater and 15 is radiant superheater. In this T-s diagram we have tried to modify that is steam is to be superheated beyond the saturated line up to 3. So if we need to super heat then the steam should be allowed to flow through this convective superheater and radiant superheater. These two superheaters are connected in series that I will discuss later.

So you know that if the quality of the steam is not very high, then even allowing steam to flow through these two superheaters, it is very difficult to get superheated steam at 16. That is why the dry pipe is there at 13. The purpose of the dry pipe is to increase the dryness fraction of the steam before it enters into the superheater. Had this component not been there, steam will be directly taken to the radiative and convective separators, in that case, if the quality of the steam which is being produced inside the boiler is not very high, then even after allowing them through the superheater, it is very difficult to get superheated steam. So only to make ensure that we are getting superheated steam, the dry pipe is there.

And as I told you, the purpose of these two superheaters is to increase the quality of the steam and that is why they are placed almost in the middle of the boiler which is very close to the combustion chamber. 15 is the radiative superheater and radiative heat transfer plays an important role at very close to 11 and 15. While at the right part of the boiler that is part 8 and 9, flue gas convection takes place. So basically if we consider baffle as the dividing wall, then left side of this baffle that is the 11, 10 and 12 where radiative heat transfer becomes important and dominating. While at the right part of this baffle that is 8, 9 and 9'; in this zone of the boiler, flue gas convection plays an important role. So the flue gas convection is the dominating mode of heat transfer here.

We have understood that from 16 we take steam to the turbine. And 20 is feed check valve. Sometimes because of some losses we also need to supply water, which is called make up water to the boiler drum because some amount of water will be lost. This is done in order to compensate that water so that the water level does not fall below the below certain point. This feed check line is connected, so one is feed water pump is there and that feed water pump line is having feed check valve. The purpose of this feed check valve is not to allow the relatively high temperature water flow back to the pump. So the purpose of this feed check valve is to arrest back flow of hot water to the pump.

And 17 is the water level indicator. As I told you that we also need to maintain a constant level of water in the drum. If water level falls, steam will increase and steam pressure will increase, which may rupture the cell. Not only that, if water level falls, high temperature part of the boiler like 11, 12 will also be exposed to steam. And the temperature of all these parts will be very high and that may break the total system. So basically cell wall will rupture. That high temperature will lead to generation of thermal crack, which is not desirable. So 17 is given to always maintain a particular level of water in the drum.

18 is the pressure gauge. Definitely we always need to measure pressure for the purpose of the safety of the boiler. This is to know what is the pressure inside the boiler, whether pressure is increasing or not. If pressure increases drastically, then there must be provision like some safety valve, so by opening the safety valve pressure should be released, otherwise, it may start breaking down the entire system. So that is why the safety valve is there. So water level indicator, pressure gauge and safety valve, all these three components are provided essentially for the safety operation of the boiler.

I have already discussed about feed check valve. Last is blow down cock labeled as 9'. You know that water is coming from 8 to 9 then water passes through the tube. So normally the water which is supplied to the boiler is purified, but even after purification, some impurities may still be there. So that impurities may start sedimentation. Sometimes that need to be taken out from the system, otherwise it may reduce the heat transfer coefficient. So that is why this blow down cock is there to remove the impurities which are stored in the pipe as well as in section 9, so that heat transfer rate should not be affected.

So if we summarize, there is steam water cycle that is 7-8-9-10-11-12 and 4-5-6 is the hot flue gas cycle. These two streams are allowed to flow in such a way that it is possible to have maximum heat recovery from the high temperature products of combustion. I would like to discuss one important thing. Since water is allowed to pass through the tube, so by increasing the length of the tube, it is possible to have superheated steam. Because as I told you that steam conversion starts from 9 itself. So when steam is coming at 11, it is not in contact to the water. And that too 11, 10 and 12 these three parts are close to the high temperature zone of the combustion chamber. As a result of which though there is a small amount of water that water will be converted into steam. So allowing water through the tube, it is possible to have superheated steam at the exit of the boiler.

But for that, we need to increase the tube length drastically. Sometimes it becomes difficult considering the space requirement and that is why we are going to get good quality steam even at the exit of 12 but it is taken through the superheaters to ensure that the steam at the exit of the boiler will be super-heated.

Second point, since water is passing through the tube wherein steam is generated and steam pressure is very high. Steam is generated at a high pressure. Per kg of water supply 40 to 50 kg steam is generated. So for high pressure, tube is good enough to withstand that high pressure instead of cell. There is a case where water passes through the cell and flue gas passes through the tube, which is called as the fire tube boiler that we will discuss later. In that case, cell has to withstand that high pressure, so the flow configuration of steam should be able to withstand that high pressure. For that thickness of that particular component should be designed accordingly.

Steam is passing through small tube with very less diameter, so it can withstand high pressure. And this is why this water tube boiler or Babcock Wilcox boiler is suitable for high pressure system. So the only reason is steam is passing through the tube and tube can withstand high pressure easily, hence this type of boiler is much more suited for the high pressure operation.

So to summarize today's class, we had started our discussion from the basic of this particular cycle that is steam power cycle and we have discussed why boiler efficiency is so important. From there we have understood that it is essential to understand different streams, flow of different streams inside the boiler. That is because if we understand the flow path of different streams of the boiler, then we can also modify the design, as the entire objective should be to increase the boiler efficiency which in turn will increase the overall efficiency of the plant. So with this I stop here today and in the next class, we shall discuss about the fire tube boiler. Thank you.