

Clean Coal Technology
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Week-11
Lecture-52

Hi, I am Professor Barun Kumar Nandi, welcoming you to the NPTEL online certification course on clean coal technology. We are in module 11, discussing coal-based power generation. In this module, we will discuss different aspects of coal-based power generation, including the Rankine cycle, gas turbine, combined cycle, and IGCC. So, let us start lecture 2 on coal-based power generation.

This is the schematic of the major units of a thermal power plant, which operates on the Rankine cycle principle, also known as the steam turbine cycle-based power generation. In this cycle, this is the unit where coal is actually burned. In our previous lecture, I discussed coal preparation, how coal is crushed, how it is transported, crushed, and further ground in the different coal handling units or CHP units of the plant. After the CHP units, the CHP units prepare the coal particles as per the required size or fineness based on the fluidized bed combustion as well as the pulverized coal combustion. In fluidized bed combustion, this fuel or coal will be of a bigger size, around 2 mm to 10 mm, whereas in pulverized coal combustion, this fuel or coal will be 75 microns or smaller. So, this fuel, as well as coal, is sent to the boiler. Here, these coal particles will burn, and there will also be primary air, which will transport the coal particles from the pulverizer to this unit. So, in this boiler, coal burning occurs. This is the representative or schematic of the boiler where coal is burned. After the coal burning, the flue gas and fly ash particles will pass through different types of ESP, cyclone, and other units as required to maintain environmental pollution levels under control. These will then go to the stack, where the flue gas is released. In between, there will be different units such as cyclone separators, ESP, SOX removal units, flue gas desulfurization units, and others as required. So, if we take the coal and air here, it will burn, and the generated heat will be transferring this steam through these tubes. So here, the boiler tubes are present. These boiler tubes have different names depending on the temperature in the boiler region. The overall purpose of these boiler tubes is to collect heat from the combustor and convert it into steam. The liquid water enters here as H₂O in the liquid phase at a temperature around atmospheric conditions or just preheating conditions, maybe 60 or 70 degrees Celsius, so it will enter here. It will then flow

through these boiler tubes, where it will be converted into steam. After the steam is produced, it will go to the turbine. In an actual plant, this turbine can have different types, such as low-pressure turbine, high-pressure turbine, intermediate-pressure turbine, with some type of reheating, regeneration, and other aspects. Overall, it will go to the turbine. In the turbine, it will release energy to the turbine blades, causing them to rotate. As rotation occurs, it will produce electricity or induce electricity in the electrical coils placed inside the electric generator. This output electricity will go to the final electricity dispatch section, where it will be further stepped up as per the grid requirements.

The purpose of the turbine is to take high-pressure, high-temperature steam as input, which forces the turbine to rotate. Electricity is then induced in the electric generator. The exhaust steam, whatever remains, will go to the condenser, where it releases excess heat not used by the turbine. In the condenser, it condenses back into liquid. To return it to atmospheric conditions, it will be recycled and reused here. As a result, water will be used in this cycle. The water initially exists in the liquid phase, then transitions to the vapor phase in the boiler. It then releases heat in the turbine blades and condenses back. These are the major units. The water goes to the feedwater pump, which compresses or pressurizes it so that high-pressure water enters the boiler. This is the overall design of the Rankine cycle.

On the scientist named Rankine, and whatever the exhaust heat is there, that will go to the cooling tower, which will cool the water and release the remaining amount of heat, and the water will recycle back through this unit. That's why this cooling tower will also be there, which will actually release the exhaust heat that is not being used by this turbine. So overall, this entire circuit operates theoretically around 42% energy efficiency. In actuality, this energy efficiency might be 35 to 40%, but theoretically, it is about 42%. If all the other units operate at good efficiency, we can get 42%. If there is some efficiency lack, in exact terms, it will be maybe less than 42%, like 40% or 37%, 38%, and others. So overall, the Rankine cycle efficiency is around 42%. Whereas modern plants improve it by changing the steam pressure and temperature to higher levels to make it 44% or 46%, which is also achievable. So overall, the Rankine cycle's efficiency is 42%. That means the remaining 58% of energy is not used and is discharged either through the stack as high-heat flue gas or through the cooling tower, as well as the efficiency loss in different equipment.

Now, if we see what the exact purpose of these turbine blades is, like in this turbine and in this generator, what actually happens, how it produces electricity. So, if we see the power

generation, it is basically the interaction between the electrical coils and the magnetic field. As we have read in our electrical technology books, electrical coils are there, and the magnetic field is there inside the turbine blades. The generator is the location where electrical coils are placed, and in between, the shaft is there. So, this shaft will rotate, and the turbine blades will be installed there. So, all this steam will enter here in these turbine blades, and these turbine blades will rotate in this direction. As a result, the shaft connecting to with this, it will also rotate, and this shaft will initially be induced with magnets, and these electrical coils will also be there. As a result, this shaft, which has some magnetic properties as well as electrical coils, will have variation in the magnetic field, which will induce electricity as per Fleming's rule. So, whatever is there that it has electrical coils and magnetic field and electricity is induced in the magnetic field if that is the principle of electrical engineering that if any magnet is rotated nearby some electrical coils and there will be electricity will be induced to this electrical coil. So, we need a turbine in the turbine we fix some magnet. So, this magnet will rotate as the turbine rotate. Whenever the steam is entered there, it will force this turbine to rotate in this direction. As a result, it is connecting shaft which at this point, the shaft will have the magnets. So, this magnet will also rotate and as a result, in this electrical coil, electricity will be induced. and we consider electricity as output. So, whatever you need is that we need to create a rotational movement. For any electricity generation through such principle, we need to create rotational movement of the shaft that is we can generate by any fluid we can use any type of fluid that will release this kinetic energy at the turbine blades. So, for electricity generation we need any fluid which will have higher amount of kinetic energy that will be released by the turbine blades. Turbine blade will rotate that will induce electricity in these electrical cables through this magnet and this fluid should have higher amount of kinetic energy. The requirement of this fluid is that fluid should have higher amount of kinetic energy. That's why it should be at high pressure, high temperature, steam or other. So that will be released at the turbine blades and which will convert that kinetic energy to the rotational energy initially. Then electric will transfer as the electromagnetic energy and finally as the electricity will be induced.

In case of steam turbine, this is the heat is transferred or energy is transferred through this high temperature steam. So, purpose of produce steam is that to transfer the energy from the coal as the kinetic energy to the turbine blades through the steam turbine and then it will produce the electricity. So, this Steam turbine-based plants works on this principle is that energy available in the coal that will be released as the heat energy. Water will accept this heat energy.

It will be converted to steam. As a result, steam will have a high temperature and high pressure and that will release the energy at the turbine blades. And the turbine blade will rotate. It will induce electricity. So, this entire thing is governed by the Fleming's left-hand rule where the interaction between the electrical coil magnetic field and electricity induced is varying magnetic field. So, in the turbine magnets rotate electricity generates in the electricity cables and we get the electricity output. So overall by this route coal is burned it will produce steam, steam will release the energy over the turbine plates turbine blade will rotate and it will induce electricity in the electrical cables or coils and this way we will get the electricity output. Typically if we see the power plant they needs to operate at constant capacity say 500 megawatt any thermal power plant it is always preferable that thermal power plants operate at is constant capacity of whatever is designed it may be 500 megawatt it may be 200 megawatt or it may be 1000 megawatt it should operate as per its constant capacity because whenever coal is burned or coal is charged to the boiler it will produce steam and it will induce electricity. So once coal is charged to the boiler whatever energy or chemical energy is available in the coal that will be released and we cannot store it to the any other location. So it will produce electricity and now this coal burning we can control to minor level to changing the temperature or what we changing the flow rate of the coal but we cannot allow the temperature of the boiler to fall very much significantly so minor control in the variation of coal feed rate can be done but it is not possible that coal feed rate should be stopped for few hours or few minutes for any particular day whenever some electricity demand is not there because if temperature of the boiler is false below certain temperature coal combustion rate will be very low and it will release lots of unburned carbon and others and also, an increase in temperature will be very difficult. So, in any condition, boiler temperature cannot be reduced to a certain level. That's why the power plant should operate at its constant capacity, for which it has been actually designed. Suppose it is a 500-megawatt power plant. So, whatever the coal feed rate is there, that will be constantly charged and constantly burned in the boiler.

Minor control, like reducing 500 to 450 megawatts or up to 400 megawatts, is possible. But 500 megawatts cannot be reduced to 250 megawatts by changing the coal feed rate. If the coal feed rate is changed, the boiler will not be able to maintain the desired temperature, and there will be a lot of issues in the coal combustion. And in such a case, whenever we want to step up with the 500 megawatts, it will take a lot of time to get back to its own capacity, so it is always desirable that these power plants operate at their constant capacity, for which they have been designed.

So, based on the design, plants need constant steam quality. If the quality of the steam is not as desired, like this steam, it will always have parameters like steam temperature and pressure. So, all these steam temperatures, pressure, and their mass flow rate will be constant and cannot be changed very significantly. For high-pressure steam, as per the steam table data or humidity chart data, as we know, if the temperature of the steam is excessive or if the temperature of the steam falls, it will condense back to the liquid phase. So, if it is in the liquid phase and that steam is released to the turbine blades, the turbine blades will get damaged. So, to maintain the quality of steam so that it will always be in the vapor phase, measuring the condition of steam temperature and pressure is very important. We cannot certainly, changing the steam temperature and pressure will severely damage the turbine blades. So, as per the design, the plant needs to maintain the desired steam quality for which it has been designed. Suppose this turbine is designed for 560-degree centigrade steam and 200 bar. Now, if the pressure of the steam falls, some of the water will condense back or return to the liquid phase. Similarly, if the temperature changes, it will again alter the steam quality. So, any change in this condition will affect the amount of heat transferred to the turbine blades. If there is any change in temperature or pressure, steam will condense back to the liquid phase as per the steam table data. Steam is used as the operating fluid. If we consider the role of steam or water, it acts as the operating fluid which effectively transports energy from the combustor to the turbine. The overall role of water or steam is to carry or receive heat at the combustor, water gets heated, and the heat is released over the turbine blades. The purpose of using steam or water is to act as an operating fluid that transports heat from the boiler to the turbine. It is the medium used to transport energy from the combustor to the turbine. Steam quality, such as mass flow rate, temperature, and pressure, must be maintained by the boiler. If any boiler cannot maintain the desired temperature and pressure of the steam, the turbine blades will get damaged and will not produce the desired electricity output. For efficient operation, the boiler or combustor must release the required amount of heat by burning coal. If coal does not burn properly or if the heat release does not meet the steam requirement, the plant cannot operate.

So, the boiler should always burn coal at the desirable heat release rate. It cannot fall to a significant level. Coal must be burned properly with the required heat release rate, such as kilocalories per minute. Whatever the heat requirement for the steam is, coal burning should release that amount of heat consistently. So, the GCV of the coal is important.

If we see here, to maintain the desirable heat release rate, that kilocalorie per minute we have to maintain so that the steam quality as per the required temperature and pressure is maintained.

So, here we get the impact of the GCV. If we see the GCV, it represents the kilocalorie per kg of coal. Like how much energy is available per unit mass of coal, but here we need to know how much kilocalorie is releasing per minute. Or per unit time. So here, the rate of reaction, the rate of combustion, is important. Gross calorific value has a role, but much more important is whether this calorific value is released within the desirable time or not. If coal is burning very slowly, then it will not be able to maintain the desirable heat release rate. So, slow combustion will not be able to maintain the desirable heat release rate. If coal is burning at a very slow rate, it will may not be able to maintain the desirable heat release rate as per the boiler design. So, coal should have both good GCV as well as a desirable coal combustion rate. So, here coal means that only GCV is not important. GCV is important, but also its rate of combustion is important. If it is not able to maintain the desirable heat release rate, in such a case, steam quality will not be maintained, and in such a case, power plant output will not be good.

So, if we go to the back side, to maintain the desirable heat release rate, the pulverizer must grind the coal up to 75 microns within the desirable time. That means if we want to maintain the desirable temperature inside the boiler, the coal feed rate must be constant. So, the pulverizer or coal grinder or coal grinder. Meal that should be able to maintain the desirable coal grinding or coal feed rate, so that the desired mass of coal is sent to the boiler. So here the importance of HGI plays a role. If coal is very hard or it is very soft, in such a case, the hard coal will not be able to maintain the desirable coal grinding because hard coal will take a lot of time or much more time for grinding. In such a case, if we use very hard coal or its coal has a very low value, in such a case, the pulverizer will not be able to maintain the desirable coal output. After the grinding and here the role of primary air is that primary air flow rate must be designed to transport the coal particle with desired density and size. The primary air flow rate is controlled to some compressor or air blower is there. It is designed in such a way that it will transport all the whole particle of less than 75 micron with desirable particle density so that they can easily be transported as per requirement to the combustor or the boiler. if coal GCV varies then combustion rate will also vary and it will be must be as per the design. So, whenever we see the boiler design is there it should be designed based on the GCV of coal as well as the coal combustion rate of the coal as well as based on the grinding index or HGI value of the coal. So, all this plays an important role during the design of boiler. So, whenever any boiler is designed they need the data of GCV as well as the rate of reaction or rate of combustion at what rate combustion will occur so that they can change the desirable amount of coal filtrate

and that coal filtrate must be maintained by this pulverizer. So, they should also get the coal of desired HGI value so that entire pulverizer unit can be able to supply the desired coal particle with the desired mass flow rate, desired fineness within the desired time limit. Now if we see how these entire calculations are made in case of thermal power plant, suppose any power plant is operating at 500 megawatts so 500 megawatt is at the output level that is 500 megawatts to the electricity output at the final stage it is the 500 megawatt and one megawatt the conversion factor is made. So that how much megawatt is equivalent to how much kilocalorie per hour or kilocalorie per second. So, this energy output calculation is made so if I go to the previous slide like in this slide so here requirement is the 500 megawatts so to produce these 500 megawatts how much energy or heat is to be used here that is in the calorie per hour that has to be calculated. So based on this we can see is that that one megawatt corresponds to this amount of kilocalorie per hour. So based on this value and plant will have overall efficiency for the ranking cycle so if we see in this plot these corresponding to this amount of kilocalorie per minute. Now in this cycle, overall it has some efficiency factor their plant will operate around 42 percent or 40 percent or some efficiency factor is there, so that efficiency factor is there which is called the Rankine cycle efficiency factor say it is operating at 40 percent efficiency so this is the 500 megawatt is output power and if the plant is operating with the 40 percent efficiency so heat must be released from the coal with the capacity of 500 megawatt by 0.40 in kilo calorie per kg we have to calculate so this amount of heat is required and this plant is operating at 40 percent efficiency so coal must be burned or coal must release heat with this capacity of 500 megawatt by 0.4 factor so this much amount of energy to be released like 500 megawatt by 0.4 means it will be around 1200 megawatt so this amount of heat must be released in the boiler now if coal has the GCV of 5000 kilocalories per kg. We can get how much mass of coal has to be burned inside the boiler or what is the coal feed rate to be used. So, this entirely depends on the individual level of the efficiency factor. So, here we have used the 40% efficiency only for the ranking cycle.

So, actually, there can be other types of efficiency factors, such as the turbine having an individual efficiency of maybe 90%, and the boiler having its own efficiency based on the heat exchanger design. The heat exchanger will also have some heat transfer efficiency, so all these efficiency factors will play a major role. The final estimation of the coal feed rate is done based on the amount of heat to be released and the GCV of that coal, determining how much coal feed rate should be charged into the boiler. Typically, in the case of fluidized bed power plants, this temperature ranges from 850 to 980 degrees centigrade. Since the fluidized bed combustor

emits inferior quality coal, their temperature typically ranges from 850 to 900 degrees centigrade. In such cases, ash fusion does not occur, and the steam quality is not as high as that of pulverized coal. In the case of pulverized coal, the steam quality is 560 degrees at 200 bars, or similar, where the temperature will not reach that extent. An advantage is that if we opt for an FBC-based unit, it can accept high-sulfur coal. If the coal has a higher sulfur content or exceeds the permissible limit, it must be used in an FBC-based unit. Ash fusion temperature is particularly important in the design of a pulverized boiler. If ash fusion occurs, the boiler must be designed to handle fused or molten ash accordingly. Typically, the maximum temperature is determined based on the ash fusion temperature of the coal.

If the ash fusion temperature of the coal is 1300 degrees centigrade, the boiler is operated just below 1300 degrees to avoid ash fusion, ensuring the ash is released in a solid, powdered state rather than a liquid phase. During the design of a pulverized boiler or any boiler, the ash fusion temperature is a critical factor. Nowadays, various types of power plants are available. Typically, a Rankine cycle-based power plant has an efficiency of around 42 percent, meaning 58 percent of energy is wasted. Efforts are made to improve this efficiency to 42-44 or even 46 percent. A mere 2% increase in efficiency can lead to a significant rise in power output and better environmental pollution control. Coal will be utilized much more efficiently even with a 1% or 2% increase in efficiency. This can be achieved by leveraging the metallurgical limits of the boiler tubes and turbine blades.

If we use high-pressure and high-temperature steam, the boiler tube material and turbine blade material must be able to withstand that type of high temperature and high pressure. That's why it is typically known as the metallurgical limit of the boiler. Whether the boiler is able to handle such high-pressure and high-temperature conditions. So, depending on improvements in the metallurgical sector, improvements in steel manufacturing units, and others, nowadays ultra-super thermal plants are being installed where the materials used in the design of boiler tubes as well as the turbine, they can withstand extremely high temperatures as well as high pressure.

So, these are based on the maximum steam temperature and pressure used in the plant. Mostly, that is based on the metallurgical limit of the boiler. Whether this boiler tube will be able to withstand high temperature, high pressure, and corrosive conditions, etc. This is based on this. That metallurgical limit, if we are using higher-quality materials in the metal in this design, we can go for high temperature. So, the difference between super thermal, ultra-super thermal, and all is that they are using much better-quality materials in their design of turbine blades and

others. Thus, they can operate the plant at much higher temperature and high pressure, as a result, the efficiency of the plant is increased.

Now, another important factor is that auxiliary power is also required for the plant operation. If we see any power plant operating or their efficiency, their output is 500 megawatts. Now, out of these 500 megawatts, some amount of electricity is also consumed to run the plant. Like to run the coal handling section, they need electricity to operate the crusher. ESP also needs electricity to operate to capture the dust particles and others.

So, all this electricity consumption is known as the auxiliary power consumption. That means out of these 500 megawatts, maybe 10 megawatt or 12 megawatt is consumed inside the plant itself for operating different type of equipment, which is known as the auxiliary power consumption. If this auxiliary power consumption is on the higher side, then entire plant profitability will be on the lower side so this is the auxiliary power is required for smooth operation of plant to run different equipments which needs electricity to run the motors and etc. running different equipment before the plant generates its own electricity even if we see that plant will produce electricity only after cold combustion and running of turbine but before this coal combustion coal must be grinded crushed etc. they must be transported to the boiler conveyor belt must be operates so for actual starting of the plant before that plan player needs some amount of electricity so any thermal power plant cannot operate by its own it must have another source of electricity through grid connectivity, That is very much important that if we have connected to the grids that all the power plants are connected in one network. So if one power plant is under shutdown or it under maintenance, so they can get required amount of electricity from the other power plant that's why this grid connectivity is very much important nowadays the we have the power grid corporation which maintains these grids to connect all the thermal power plants as well as the other types of power plants in an one grid so that if any one plant is out of Operation under maintenance or any other condition. So still that power plant receives some amount of electricity for their day-to-day operation or even their starting of electricity production.

So that grid connectivity is very much important. So isolated plant cannot operate smoothly because they are needs electricity to run these plants. and electricity if we see the electricity consumption pattern there is always some peak demand lean demand sudden demand etc. they are very much important if we see the electricity demand in our daily life Typically in the evening hours electricity consumption is very high where the both domestic load as well as the

industrial load or commercial load is there. That is the typically called the peak demand time whether it is the after midnight of 12 a.m. or 3 a.m., 6 a.m. In such cases, domestic load is also less, industrial load is also less, and commercial load is also less. So, that is typically called the lean time. Similarly, in some cases, if there is a function, sports event, or other activity on particular days or at particular times, there can be a sudden increase in electricity demand—an additional demand of 200 megawatts or 400 megawatts for only 2 hours or 4 hours due to specific activities. That is known as sudden demand. So, all these demands. They vary day-wise and also season-wise. For example, in the winter season, peak demand is less because ACs and other equipment are not operating. But in the summer, many ACs and cooling equipment operate, so there is higher peak demand. Even on the same day, if there is rain.

Electricity demand reduces significantly within a few hours. So, that causes sudden changes in electricity demand. So, all these are very important. That's why it must be connected to the grid so that any change in electricity load—any increase or decrease in demand—can be easily managed by this grid connectivity. Now, if we want all power plants to be connected to the grid. So, all power plants must produce electricity of the same quality. Only then can they be connected to the same network. That's why, in the case of electricity, frequency is very important. In electricity, we can change voltage or amperage using different types of transformers, such as step-up and step-down transformers, but we cannot change the frequency of the electricity output. So, for any thermal power plant, they should operate with a fixed or constant electricity output as per the grid's requirements. Typically, for Indian conditions, this is 50 hertz. Any minor change from 50 hertz will cause the entire grid to trip—meaning the entire grid will stop operating if the frequency is just below 50 hertz. That's why 50 hertz must be maintained with 100% accuracy. A variation of plus or minus one percent may cause the entire grid to fail. So, any thermal power plant must operate accordingly.

And particularly, care must be taken about the frequency of the electricity output. If any thermal power plant is not able to maintain its frequency, it will not be able to connect to the grid. And for each plant, the charged electricity cannot be accepted by the grid. So, this entire frequency management is typically done by this system. Turbine blades, whatever the electrical formula is there, depending on the rotational speed of the turbine, this frequency is calculated. So, if turbine blades cannot operate at the desired speed or desired RPM, they will not be able to produce the desired frequency of the electricity. So, the turbine must operate at the desired speed. It can have the desired amount of energy, which can be different. The power plant may operate at 500 megawatts or 400 megawatts, but the output must be at a constant frequency of

50 hertz. So that the turbine can operate at a constant speed, and to operate this turbine at a constant speed, there is some different type of gear assembly and other arrangements. So that at the generator endpoint, there is no change in the RPM or speed of this turbine. So that the electricity frequency is always maintained as per the requirement, and that is the major role of how this coal combustion plays here. If coal combustion is not of the desired quality or if the fuel is not able to maintain the desired heat release rate, in such a case, the turbine will not be able to rotate at the desired speed or desired RPM. In such a case, electricity output will be there, but that will not be at 50 hertz. In such a case, the plant cannot operate. So overall, if we see in the case of a thermal power plant, coal combustion is the most important part, and fuel quality is the most important part. They should be able to release the desired amount of heat within the desired time rate so that the turbine can rotate and they can produce electricity.

Thank you.