Clean Coal Technology

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IIT ISM Dhanbad

Week-11

Lecture-55

Hi, I am Professor Barun Kumar Nandi, welcoming you to the NPTEL online certification course on clean coal technology. We are at module 11, discussing coal-based power generation. In this module, we have discussed an introduction to coal-based power generation and the Rankine cycle. In today's discussion, I will discuss gas turbines, combined cycles, and IGCC-based power generation. So, let us start lecture 5 on combined cycle power generation and IGCC. Now, we have seen in the case of the Rankine cycle that power is generated using steam, where steam is used as the working fluid for power generation.

In the case of a gas turbine, the power generation process is a little bit different. Here, a gas turbine generates power by burning fuel, which is very similar to that of the Rankine cycle. However, these hot gases or hot flue gases generated by the combustion of the fuel are used to rotate the turbine. So, the main difference with the Rankine cycle or steam turbine-based power generation is that in the case of a steam turbine, fuel is burned to produce steam, and the steam is used to rotate the turbine, which is why it is called a steam turbine. But in this case, the flue gas generated is used directly to rotate the turbine.

So, here, these hot gases are used to rotate the turbine, which is why it is called a gas turbine or GT cycle. So, this cycle is named after the scientist Brayton, and the Brayton cycle is used for power generation. If we look at the schematic, we can see how power is generated in this chamber. Here, fuel—which can be any gaseous fuel, liquid fuel, or even coal—is burned with compressed air, and this compressed air is supplied from another compressor where This 'C' means compressor. This air is initially compressed at high pressure.

So, this high-pressure air is sent to the combustor where combustor will burn the fuel. So, after burning this fuel that produced flue gas, it will also be in the high pressure. And its pressure will get increased significantly due to combustion gases. That from 1 mole of gases, 2 or 3 moles of product gases will be released. So, from that combustion gases, its pressure will further get increased and it will also be at the high temperature.

So this high temperature and high pressure flue gas is used to rotate the turbine known as this GT. so as the turbine is rotate the same shaft is connected with this compressor so whatever the electricity or rotational movement is produced by this turbine some part of this rotational energy is used to run this compressor so overall if we see the rotational energy produced by this gas turbine here that is used some part maybe 10 to 15 20 part 20% of that rotational energy is used to run this compressor. So initially compressor may need some initial power but once this cycle started then compressor will run from the output energy whatever is released here. And finally, the exhaust gases go out to the stack for release to the environment following the environmental guideline. And here the efficiency of the cycle is calculated based on this formula where RP is the pressure ratio and gamma is the specific heat ratio. Particularly here the efficiency of this GT cycle it is entirely depends on the heat transport capacity of the flue gas. Because here this flue gas is used to transport the energy from this combustor to the gas turbine. So, depending on the specific heat capacity how much heat it can carry, what is the input pressure and what is the output pressure, its efficiency varies. Typically, this gas turbine efficiency is on the lower side, around 20 to 25% efficiency, it can be obtained depending on the different types of fuel and others.

So overall, if we see the exact principle, initially air is compressed by rotor or compressor. and it is that compressed air is sent to the combustor where fuel is burned at high temperature and pressure of the flue gas is generated initially fuel will have some pressure but after the combustion the flue gas will be of much more higher pressure because for burning one mole of fuel we can get two mole three mole or four mole or higher number of moles of combustible gases as number of moles of product gas is higher so The partial pressure of individual gases will be on the higher side and overall pressure of the gas or flue gas is increased. So here flue gas is used to rotate the turbine which is again further connected with the generator to produce the electricity. So, flue gas will rotate to the turbine.

Turbine will be connected again to the electrical generator which will produce the electricity. Some part of the energy is consumed to rotate the compressor which is used to compress the primary air as we have seen in the first point. Here we can use any type of fuel, coal, liquid fuel or gaseous fuel. They all can be used here. And typically, the commercial units, whatever is ready-made available or very mostly widely used is that is based on either of the gaseous fuel or in the liquid fuel. Because this gaseous fuel or liquid fuel ignition is very easy. So, they can start within the very shortest span within two to three minutes or five minutes time. This gaseous fuel or liquid fuel-based gas turbine cycle can be started. And whether if we use the coal, it can take some much more time. Its efficiency can vary depending on the fuel—what type of fuel we are using, how much efficiency we can achieve at different temperature and pressure levels.

So, typically on the lower side, it can be 20 to 25%. On the higher side, it can reach 30 to 35% efficiency. So, overall, this efficiency is much lower than that of a Rankine cycle-based power plant. The main advantage of this type of gas turbine cycle is that it has very little installation time. This is a ready-made equipment that can be available anywhere. For small capacities, the entire gas turbine can be transported from one location to another. For bigger plants, this plant can be installed within a short span of time, like 3 to 6 months, whereas a large steam-based thermal power plant can take a minimum of 2 to 5 years for installation.

So, the major advantage of this gas turbine cycle is that it can be installed within a short span of time. The cost is a little bit lower because it has only three main pieces of equipment. In coal-based power plants, the coal handling section is required. But for liquid or gaseous fuel-based gas turbine cycles, the system can start within a very short span of time. So, mostly, this gas turbine is used to compensate for or maintain a certain increase in the load of the circuit. For example, during a particular event or time, if there is a sudden increase in power consumption in the grid—requiring an additional 20, 30, or 40 megawatts within 10 to 20 minutes—gas turbines are very efficient in such cases. They can go for quick start and stop. Whereas conventional coal-based thermal power plants cannot start very quickly. They require a minimum of 6 to 12 hours to ignite the coal, achieve the desired temperature and pressure in the turbine, and bring the entire circuit online. so typically coal-based power plants their startup time and shutdown time is longer minimum six hour or in the higher side 12 hours 18 hours is required to start and stop the plant whereas this gas turbine cycle they can be start within the five to ten minutes that's why they are very much famous or they have major advantages that they can go for quick start and quick stop so that in any sudden change in the load you can easily manage by operating the that is their major advantage. as they are mostly operate using the liquid fuel or gaseous fuel and so in such case operating cost is on significantly higher so overall if we see these gas turbines are mostly operated based on the liquid fuel or gaseous fuel because those fuel can be ignited or stopped very quickly within shorter span of time so in most of the cases these gas turbine cycles are operated using the gaseous fuel or the liquid fuel but it can be operated using the coal-based flue gas also. And if we go for the combined cycle power generation, in case of combined cycle power generation, here two or more power generation cycles are operated in series or in parallel to increase the overall efficiency of the plant. so, in case of combined cycle not any single cycle plant is operated it is operated in multiple cycle either two cycle or three cycles power generation is done so typical example is that we can operate one gas turbine cycle another steam turbine cycle or we can operate two gas turbine cycle working at two different temperature and pressure.

We can operate two steam turbine cycle working at high temperature, low temperature or it can be initially steaming turbine followed by the gas turbine. So, this type of cycle power generation is known as the combined cycle power generation where multiple cycle or at least two cycle power generations are used to increase the overall efficiency of the plant. Typically, the exhaust energy from one power generation cycle is used in the next power generation cycle. If we see in case of gas turbine cycle whatever the flue gas is released from the gas turbine still it may contain some higher amount of energy. Like that exhaust gas may be releasing at 300 or 400 degrees centigrade.

So, using that temperature we can produce some steam and we can operate one small steam turbine waste cycle. Similarly, from the steam turbine waste cycle, where we are producing the steam from the major units but the flue gas is going out that flue gas also can be used to operate one of the gas turbine cycle or initially coal can be burned to produce flue gas. This flue gas can be used to operate one gas turbine cycle and further exhaust flue gas can be used to operate one steam turbine cycle. So, typically, exhaust energy or excess energy or waste energy from one power generation cycle can be either from a GT (gas turbine) or from a steam turbine or ST cycle. They are used in the next power generation cycle to produce a higher quantity of power so that the overall power generation from the feed fuel is increased. For example, the first power generation GT cycle is operated, and electricity is generated. Further, exhaust flue gas is used to generate steam and produce electricity using the Rankine cycle, which may be based on steam as the operating fluid or other types of organic liquids or any other medium. Such a cycle is known as a gas turbine cycle followed by a steam turbine or Rankine cycle-based cycle. Similarly, it can have many other combinations as well.

The major advantage is that there is a significant increase in the overall plant output or efficiency. For example, if a gas turbine cycle produces 200 megawatts of electricity followed by a small steam turbine cycle producing 100 megawatts of electricity, we can get an overall output of 300 megawatts from these plants. However, if we operate only one gas turbine, we can get only 200 megawatts. So, overall, the major advantage of this combined cycle is that we can produce more electricity or power for the same amount of fuel or slightly higher amount of fuel, so that the overall plant capacity is increased, as well as the plant efficiency or fuel utilization efficiency. The disadvantage of such a cycle is that the plant operations become much more complex because one unit is dependent on the other. So, depending on the temperature and pressure of the gas turbine cycle, the Rankine cycle power efficiency may vary. If the gas turbine cycle is not working properly, the next Rankine cycle will not get suitable quality or quantity of energy to produce electricity. So, overall, it makes plant operations much more complex. too much units or much greater number of units to be controlled at the same time.

So as a result, overall plant complexity and its operation is getting very much difficult. And also, it increases the investment cost. Whenever we see overall plant cost, there is both steam turbine cycle will be there as well as gas turbine cycle will be there or there will be two gas turbine cycle up to different temperature and pressure or there can have two different Rankine cycle-based units operating at different temperature and pressure condition. So, overall, there will have significant amount of investment compared to single either gas turbine or steam turbine-based cycle. and similarly there can have dual cycle is also possible where inside the steam turbine there can have in one plant there can have two different steam turbine cycle is also there so they are almost similar in nature their dual cycle or combined cycle that means there will have two different power cycle can also be there are two individual steam turbine or two individual gas turbine or gas turbine followed by steam turbine or even inside the same unit gas turbine one at high temperature another at low temperature is possible. So overall there can have different combination of power cycle is possible to increase or improve the efficiency of the plant as well as to utilize much more quantity of exhaust energy from the fuel so that the environmental impact of utilizing fossil fuel is on the lower side. So, for example, if you see this is the gas turbine cycle where compressed air, this fuel burning is there and gas turbine cycle is operated. So here we can get one amount of electricity. Now exhaust from this unit, it goes to this main unit or furnace. Where this the flue gas released from this this unit is used to produce steam here and if required we can add some quantity of much more fuel burning that is called the supplementary heating like if the steam exhaust heat temperature is not significantly higher and it is not meeting the criteria for producing good quality steam so some smaller quantity of fuel can also be burned here to get the desired quality of flue gas here which can be used to run or to chain to an heat exchanger device where in this heat exchanger device water will enter here so water will be entering here it will produce steam and this flue gas will go out in this way so in this unit particularly this heat exchanger unit whatever the flue gas is there that will go in this way and whatever the steam or liquid is there that will go in this side so this unit will act as the boiler or the combustor unit which is as per of conventional steam turbine cycle. Difference is that here directly coal or directly fuel is not burned.

The steam is produced by heat exchanging with the exhaust flue gas. So, if exhaust flue gas going at 800 degree centigrade, it can easily maintain or create the steam condition as per required for the steam turbine base cycle and that steam is also goes to the steam turbine produce electricity at this point then for the cooling tower pump and everything other units is there so overall in this plant if we see we can get electricity output from this unit where that is the steam turbine base cycle and from this unit it is the gas turbine base cycle so this entire unit is for the gas turbine based cycle whereas this unit is for the steam turbine based cycle only two this unit are very common where they are heat transfer from one unit to other unit will takes place so overall by this combined cycle power generation we can get much higher quantity of heat compared to single steam turbine based cycle and same thing it can have some one type of topping cycle also again one the steam turbine cycle one heat at operating at high temperature there can have another steam turbine cycle operating at lower temperature so this is also possible or dual cycle is also possible where we can operate two different steam turbine cycle or Rankine cycle based cycle where this unit will operate at very high temperature and pressure. This unit will operate at much lower temperature but still produce some quantity of electricity. So overall if we see in case of combined cycle power generation like if we are using natural gas as a fuel we can get that gas turbine cycle may give efficiency or power output of 69 megawatt whether a steam turbine cycle can give power output of 78 megawatt. And the station service power gives the 2.1 megawatt. So overall heat input to this plant is 230 megawatt and heat input to the supplementary heating to maintain the desired quality for steam turbine is 79 megawatts. So overall this is the amount of heat input to the plant. If gas turbine cycle efficiency is 30%, energy in the exhaust gas is 159 megawatts. And overall, if you see the steam turbine cycle efficiency is 32.9%. And finally, we can get that overall efficiency of the plant is 46.9%. So, in this way, if we see, if we are operating one single cycle, it can have either an efficiency of 30% in the gas turbine or it can have 30%, 29 percent in the case of a steam turbine. So, if we combine both of these, as both the units are producing individual amounts of electricity, a much greater quantity of electricity is produced. Thus, the overall efficiency of the plant will increase significantly, around 46.9 percent or higher. from the same type of fuel. So, if we operate combined cycle power generation, typically the energy efficiency or energy utilization efficiency of the plant increases significantly. So, that same concept is also used in a much more advanced type of power plant, which is known as the integrated power plant. gasification combined cycle-based power plant, or well known as the IGCC. So, in the case of IGCC, a single plant is used where coal is initially used to fulfill multiple purposes. Here, coal is used as a fuel or as a fossil fuel, as well as for other purposes. So, using this coal, multiple plants will be operating based on this coal.

So, initially, coal is gasified based on the gasification principle. So, initially, coal is gasified, and we remove different types of pollutants. Now, if we see the major difference between coal combustion units and coal gasification units, it is that in the case of coal gasification units, we can easily remove pollutants like H2S and other gases using different types of chemicals and others. After we remove the pollutants, whatever gaseous fuel we obtain can be burned much more efficiently with less environmental impact than if we directly burn coal. Their environmental impact is much greater. If we gasify the coal and remove all these pollutants or undesirable materials from the coal, then the environmental impact is much less. Also, from this removal of pollutants, we can recover different types of valuable materials like H2S gas, ammonia, or any other material. So, after the gasification unit, whatever syngas we get, that syngas can be used to initially operate one gas turbine-based power cycle, followed by generating much more electricity based on the steam turbine-based power generation.

So, overall, if we see the units, initially coal will be gasified, and after this gasification, we will run the gas turbine and steam turbine. So, initially coal, then it is gasified. It is cleaned to remove all the pollutants. We run the gas turbine cycle. We run the steam turbine cycle. That is why it is called the integrated gasification. We are doing this gasification. and it an integrated way, so that the gaseous product or syn gas is used to run the combined cycle which is based on the gas turbine followed by the steam turbine. So here coal will be used it will be gasified so coal gasification will be there and the syn gas will be used to run gas turbine and followed by the steam turbine that's why it is called the integrated gasification as well as the combined cycle power generation known as the IGCC and if required we can also generate some quantity of heat if there is some other plant is there which needs some steam or heating is required for their other production of chemicals and other so in the same plan we can also co-generate some quantity of heat directly burning the coal or using the steam or exhaust energy from the gasification unit so from the same plan we can also give heat to other plants. So as a result, it will be an integrated plant where all the units can be placed or located at the same location. So, in case of IGCC a single plant coal is used to fulfill the multiple purpose, so in case of this plan Only coal will be burned or it will be gasified in only one unit and that unit will be supplying electricity, heat, steam, everything to multiple purpose. So here coal will be used to fulfill the multiple purpose. Here, initially coal is gasified to produce CO, H2, methane and other gas mixture that is known as the syn gas. And during this gasification, we remove or recover different type of sulfur and other type of impurities also like H2S, ammonia, etc. that we remove and this syn gas is used. as a fuel gas in the gas turbine. So, overall if we see the combined cycle power generation, initially this oxygen and steam will be used to gasify the coal here. So, this is the representation of the gasifier. So, here coal and limestone will be added as per the principle required for gasification, and we will get ash or slag from this coal.

After this gasification unit, the product gas goes for gas cleaning or gas cooling. Initially, cooling removes the excess heat, and it goes to the gas cleaning chamber where H2S and other gas impurities are removed, which is known as the desulfurization unit for fuel gas. This unit depends on the types of pollutants present. If only sulfur is present, desulfurization will be required. If other gases like ammonia are present, we can also remove them and place such units here. And after this, this syngas will go to the gas turbine cycle, where it will produce electricity. After the gas turbine, the exhaust heat will go to the next cycle, which will proceed to the steam turbine cycle. So, if we see the overall circuit, this is the steam turbine cycle (ST). This is the gas turbine cycle (GT). This is the gas cleaning chamber, and this is the gasification chamber. So here, we can see gasification is present. Gas cleaning is present; we are operating the gas turbine, we are operating the steam turbine, and even if required, in this gas cooling chamber, we can also extract excess heat or enable co-generation of heat here. So overall if we see point wise in case of GT electricity is generated and exhaust heat is used to generate steam for the steam turbine-based power generation and produce heat during gasification is used as byproduct which is called as the cogeneration, that is byproduct heat that can be used to produce steam or any other purpose as per the plant requirement. In parallel, syn gas also can be used for production of chemicals. If we want to go for the coal to chemicals plant from the steam plant, we can also send some portion of this produced steam gas to produce coal to chemicals or to produce hydrogen gas or to produce methane gas from the syn gas. So, from the same unit, that is the coal-based unit, we can operate one gas turbine-based cycle, one steam turbine-based cycle. We can operate or we can supply necessary heat or cogeneration of heat or steam to other plant.

Also, we can supply individual gases like hydrogen or methane or we can send this gas to the Fischer-tropsch reactor for producing chemicals from the coal. So, multiple plants can be installed in the same location where one feedstock will be there which will be cooled and all the units will be operating in much environmentally cleaner way as there will be no pollution as we will be removing all the pollutants after the cleaning of gases. And any change in the coal properties that will be absorbed by the coal gasification units. So that the further unit will get same amount of syn gas without having any major change in the environmental pollution or pollutants. Major advantage is that we can get much higher efficiency, we can have minimum amount of pollution along with production of chemicals. These are the major advantage for the IGCC based plant. Higher efficiency is possible compared to one single steam turbine-based cycle. If we compare the IGCC based power production as well as the steam turbine-based power cycle, we have seen in the Rankine based power cycle operational efficiency is about 42% and exact efficiency is much below that 42% considering all other type of losses. And if we see the combined cycle efficiency, here if we operate the same gas turbine followed by the steam turbine, we can easily get efficiency of 46 to 47% and even in some cases 50% or higher also. Their major efficiency is that we can achieve much higher efficiency, output efficiency, or electrical efficiency if we operate an IGCC-based plant compared to a steam turbine or Rankine cycle-based plant. Their disadvantage is that if we opt for an IGCC-based plant, there are too many units to control simultaneously. For example, we have to control the gasification plant, the gas turbine plant, and the steam turbine-based plant. So, there are too many plants to operate, and they must be synchronized simultaneously to ensure all units operate at their best efficiency without energy loss or environmental impact. This is the major complexity in the process control of the plant—the control is very difficult and complex. Additionally, if any unit is not operating properly, the entire plant output may be impacted. Moreover, the investment or installation cost for such a plant is on the higher side. If we consider the investment cost, it is higher because we have to install multiple plants here, such as steam turbine plants, gasification plants, and gas turbine blade plants. Too many units must be handled at the same location, which is also a significant logistical challenge. We need a large amount of space to install all these plants simultaneously. However, if we compare it with a steam turbine-based cycle, it is relatively simpler than an IGCC plant, where coal is directly burned to produce electricity. Although the efficiency here is lower, plant operation is not as complex as in the case of an IGCC plant.

So, overall, if we conclude this module, we can see that coal is the major fuel used in power generation, and Rankine cycle-based power plants are mostly used. Other types of fuel can also be used in Rankine cycle plants. We can also use different types of liquids in Rankine cycles as heat transport mediums, such as steam, mercury, or any other organic liquid. Mostly, coal is used in all types of power generation. If we consider the present Indian scenario, even in 2025, about 53% of electrical energy consumption is based on coal, and around 20% is based on other fossil fuels. So, even today, coal remains the major fuel used in power generation, and most plants operate on Rankine cycle-based methods. Gas turbines and combined cycles are not very popular because, in the case of gas turbines, efficiency is lower compared to Rankine cycle-based plants and if we opt for a combined cycle plant, it is too complex, and too many units must be synchronized simultaneously. So, they are not very popular. They have many operational as well as economic disadvantages. The theoretical energy efficiency of the Rankine cycle is about 42%, but considering all types of losses, it is less than 40% in actual scenarios. Steam quality is the major concern for power generation.

If we for constant output or very efficient operation of the plant always steam quality has to be maintained. And indirectly, it represents the quality of coal. If quality of coal, its combustion characteristics, its heat release characteristics is uniform, then steam quality will be maintained properly and output electricity will have desired frequency which is required for the production. grid to absorb or to accept the electricity. So, to maintain the output electricity quality steam quality has to be maintained and to maintain the desired steam quality in coal quality or coal combustion characteristics has to be maintained. So indirectly we can see that for electricity generation, coal quality and coal combustion characteristics have to be maintained it has to be consistent as per requirement, IGCC unit can be used for the electricity generation as well as for downstream to many other plants like coal to chemicals, production of hydrogen, methane, other gases as well as cogeneration plants.

Now due to operational complexity, IGCC plants are not so much popular. At present condition there are some IGCC plant is there but it is not so much popular because it is a too much complex units are there and so many units has to be installed there and there has to be individual consumer for each of every unit. So, for power generation IGCC units are not so much popular at present is worldwide Very few plants are there which operates on the IGCC plants and most of the plants are directly produced electricity using the Rankine cycle-based plants. Gas turbine-based plants are also very less. They operate mostly using the liquid fuel as well as the gaseous fuel where cost of the fuel is on the higher side.

So overall potential of IGCC is that it is a much cleaner technology compared to direct Rankine cycle-based power plant. And there is different type of challenges that to get so many types of consumers for these IGCC based plants so that all the plants will have individual consumer and all the product can be sold in the market. The also challenges are that the quality of coal has to be get consistent to operate the gasification plants as well as the electricity plants, further ranking cycle. So, overall, the major challenge is to get the suitable type of coal or the desired type of coal with desired combustion characteristics as well as desired coal properties, which is the main challenge in operating all such power-based units. This is a major textbook you can follow. I have discussed many times that the power plant engineering by Professor P.K. Nag is a very good book, particularly for this chapter on power production from coal-based thermal power plants.

Thank you.