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Enhancing Direct-Fired Power Plants Performance by Use of Gas Turbine Technology

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The maximum temperature of a gas turbine cycle is considerably higher than that of a steam turbine cycle; however, the gas turbine rejects heat at temperatures far above the ambient level. By combining the high-temperature gas turbine cycle with the medium-temperature steam cycle, a high overall efficiency can be reached. Modern combined-cycle plants obtain a lower heating value efficiency of almost 60% with relatively moderate parameters of the steam bottoming cycle, whereas direct-fired steam plants with supercritical pressures and temperatures still operate under the 50% efficiency level. Ways of improving the performance of direct-fired steam plants by integrating a gas turbine within an existing steam plant are addressed. These include utilization of the gas turbine exhaust as a heating medium, as combustion air, and as fuel. Repowering schemes for a waste incineration plant are given, along with schemes, for repowering by the use of a partial oxidation gas turbine and an externally fired gas turbine. The results of a performance analysis are presented.

Introduction

DEVELOPMENTS in power generating efficiency over the years show that direct-fired power plants have reached a plateau on an S-curve (see Fig. 1).[1–3] As an increase of the maximum temperature in the Rankine cycle necessitates an increase in pressure to make full use of expansion to the condensing conditions, a steam temperature of 650°C, for example, calls for a pressure of 300 bar. Such parameters can be achieved only by using special high-temperature steel sorts for superheaters and steam turbines, which require an intensive research and development effort. Because of this, little progress has been attained in steam plant performance since the 1960s. Newly built ultrasupercritical power plants have the same or lower parameters as the Eddystone power plant built more than 30 years ago. An efficiency of around 50% is projected for advanced plants that utilize superalloy and austenitic steels withstanding steam parameters of 650°C/325 bar.[4,5]

On the other hand, developments in the jet engine industry and the availability of cheap natural gas have brought gas turbine technology to its current status, where efficiencies of 42% in simple cycle and 58% in combined cycle operation have been achieved. The gas turbine cycle does not require extremely high pressures, and for modern engines the pressure ratio typically lies under 40:1. The working fluid in a gas turbine cycle produces work in a temperature range between 400 and 1400°C, thus making use of the high-temperature region of the combustion gases and operating closer to the adiabatic flame temperature. In contrast, in a direct-fired boiler the maximum temperature of the working fluid is not that high; thus, the large temperature difference between the combustion gases and the working medium results in a smaller degree of work-potential utilization (Fig. 2). Integrating a gas turbine into the direct-fired plant, therefore, can enhance the performance of the plant.

Different options can be considered because the gas turbine can serve one or more purposes: 1) the use of gas turbine exhaust as a heating medium, 2) the use of gas turbine exhaust as preheated combustion air, 3) the use of gas turbine exhaust as a fuel, and 4) integration of a gas turbine within a direct-fired plant (externally fired combined cycle).

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Option 1

The gas turbine exhaust has a temperature ranging between 420 and 550°C. This temperature level is sufficient to generate steam of moderate parameters. An existing boiler in this case is replaced by a heat recovery steam generator (HRSG). This repowering scheme is also called combined-cycle repowering, or full repowering. In a modified version, known as parallel repowering, both the existing boiler and the HRSG produce steam for the steam turbine. Another option is the utilization of the exhaust heat by preheating the feed water for the existing boiler. These configurations are described well elsewhere.[6–8]

Option 2

Because the gas turbine exhaust contains 14–16 vol % oxygen, it can be passed to the furnace of the boiler as preheated combustion air. To provide the same amount of oxygen to the boiler, a 30% larger flow from the gas turbine is required. At the same time, exhaust heat reduces the heat demand in the boiler, and less oxygen is needed. This concept is known as hot windbox repowering. An improvement in the total plant efficiency can be expected of 3–8% points together with a 20–30% power increase.[9]

Option 3

Partial oxidation of methane proceeds at substoichiometric conditions and usually at high pressure. The reaction produces a mixture of hydrogen and carbon monoxide. Substitution of the conventional combustion chamber in a gas turbine by a partial oxidation reactor allows generation of synthesis gas together with electricity. The resulting synthesis gas can be directed to the furnace of an existing steam boiler, thus providing a preheated fuel for combustion.

Option 4

Because coal as a solid fuel is not quite suitable for a gas turbine, its chemical energy can be delivered to the turbine in an indirect way. In such an externally fired combined cycle (EFCC), compressed air is heated indirectly in a heat exchanger located in the coal furnace. By installing the heat exchanger in the boiler of a steam plant, a temperature mismatch between the working fluid and combustion gases can be diminished, thus improving the overall performance of the plant.

Some examples of these repowering options are considered in the following sections in more detail.

Solid Waste Incineration (Options 1 and 2)

A special case of gas turbine and steam boiler integration is a waste incineration plant, where special care should be taken due to

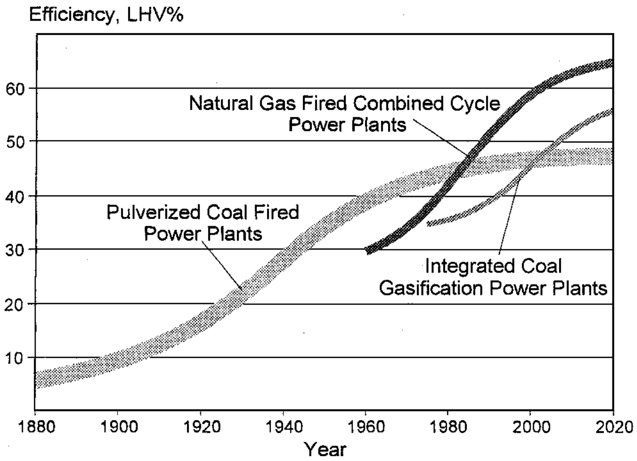


Fig. 1 Developments in power generation efficiency based on data from Refs. 1–3.

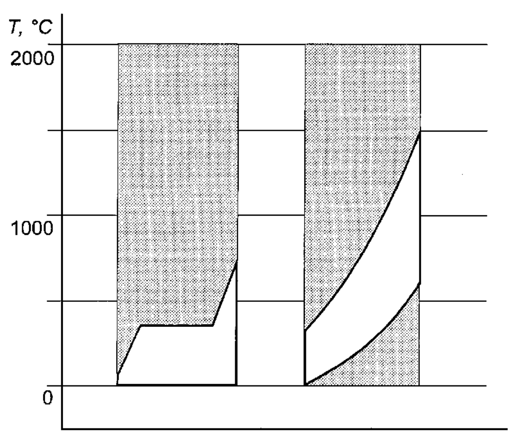


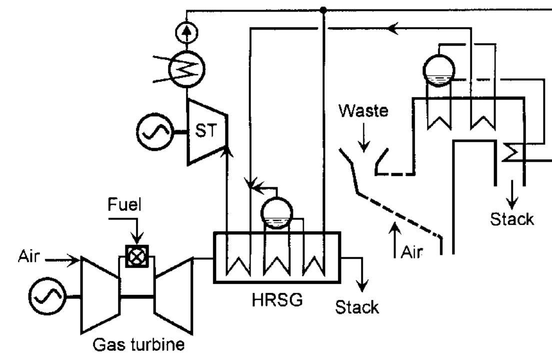
Fig. 2 Rankine cycle vs Joule–Brayton cycle.

the aggressive nature of waste as the fuel. Certain precautions are made to avoid slag deposits, erosion, and corrosion in the boiler and to maintain a sufficient residence time for afterburning. These are achieved by locating the evaporator's tubing in the second pass and the superheater's tube bundles in the second or the third pass, where flue gas temperature drops to an acceptable level.

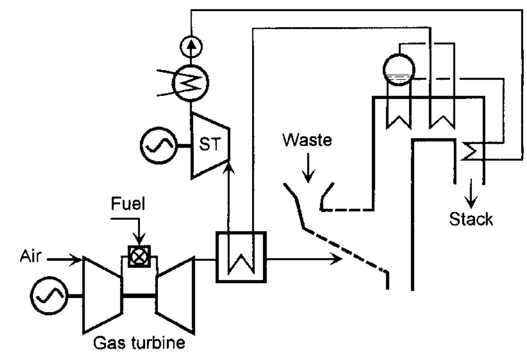
The flue gas, passing through the boiler, is cooled from 1000°C in the radiation section to 600–800°C at the entrance of the convection area. After passing the evaporator's bundles, the gas flows through the superheater and economizer. The aforementioned precautions result in a relatively low temperature of the superheated steam (around 400°C). On the other hand, temperature of the flue gas in the stack should not drop below 200°C due to the risk of condensation of aggressive compounds. These limits constrain efficiency of the steam cycle of the incineration plant.

Some improvement of the cycle can be achieved by raising the temperature of the steam externally, by preheating the combustion air, or by a combination of both. The high temperature of a gas turbine's exhaust makes it well suited for enhancing of a waste incinerator's performance. Exhaust heat can be recovered in an HRSG located behind the gas turbine to supply steam to a steam turbine. This parallel repowering option can be realized in a number of ways, either to pass lower-temperature steam from the incineration boiler to the intermediate pressure section of the steam turbine,[10] or to pass the steam to the superheater/reheater in the HRSG.[11,12] An example of such a parallel repowering scheme with superheat is given in Fig. 3a. However, in both integrated configurations, the gas turbine plays a dominant role, which may consume up to 80% of the fuel input and make the waste incineration boiler an auxiliary unit of the combined-cycle plant.

Utilization of gas turbine exhaust heat as preheated combustion air is another possible integration scheme. In this case, instead of a full-



a) Parallel repowering



b) Hot windbox repowering

Fig. 3 Gas turbine and waste incineration boiler.

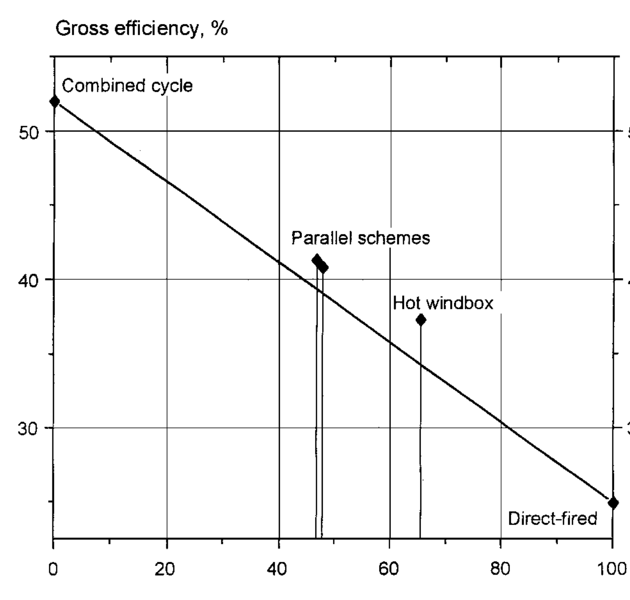


Fig. 4 Waste fraction in the total fuel input vs gross efficiency.

scale HRSG, only a superheater section is employed to increase the steam temperature. After going through the superheater, the exhaust gas is passed into the furnace of the incinerator (Fig. 3b). This hot windbox solution requires a much smaller heat transfer surface than the parallel scheme.

A performance analysis of different schemes, based on a General Electric frame 6 gas turbine, showed that parallel repowering would result in a slightly higher efficiency than the hot windbox scheme.[13] However, it is achieved at the expense of the gas turbine plant: The contribution of natural gas in the fuel input is about 55%. Also, the heat transfer area of the parallel scheme was found to be twice as large as that of the hot windbox option. A comparison between the waste fraction in the fuel input and gross efficiency is given in Fig. 4, with a reference line drawn between a gas-fired combined-cycle plant and a 100%-waste-fired incineration plant. The advantage of the hot windbox integration above this line is 3.6% points against 2.3% points of the parallel alternative.

An exergy analysis revealed the positive effect of combustion with the gas turbine exhaust. The exergy loss in the combustion process dropped from 45 to 36%.

Partial Oxidation Gas Turbine (Option 3)

In the reaction of partial oxidation, fuel does not burn completely due to the lack of oxygen, and a gas mixture of carbon monoxide and hydrogen (also called synthesis gas, or syngas) is produced. Typically, the temperature of the reaction is 1300°C, and the pressure lies between 20 and 60 bar (Ref. 14). Such parameters make it possible to incorporate a partial oxidation (POX) reactor within a gas turbine cycle. The concept of a gas turbine with POX was proposed in the early 1970s by Ribesse for a catalytic reactor[15] and by Christianovich et al.[16] for a gas turbine cycle fired by a heavy oil residue. Oxidation of fuel can be completed either in the second stage of a gas turbine or in the furnace of a direct-fired boiler. The former option was compared with simple and reheat gas turbine cycles in different configurations and at various parameters.[17] It was found that performance of the two-stage POX gas turbine was comparable to a reheat gas turbine cycle. Higher performance values are possible, if an ultrahigh-temperature stage with carbon-reinforced composites is employed, as proposed by Arai and Kobayashi.[18]

Repowering with the POX gas turbine can be accomplished by allowing expansion of syngas to atmospheric pressure and passing the gas to the furnace of a steam plant, as shown in Fig. 5. A similar concept was outlined by Maslennikov and Shterenberg,[19] where the exhaust of a conventional gas generator was directed into the POX reactor, then passed through a power turbine, and finally fed into the furnace. The so-called incremental efficiency of repowering was reported to be as high as 80% (calculated as the ratio of the incremental power to the incremental fuel consumption).

An exergy analysis was done for a repowering POX gas turbine operating with a maximum temperature of 1400°C and a pressure of 40 bar, with a polytropic efficiency of the compressor of 90% and that of the expander of 88%. It was assumed that the methane would be delivered from a pipeline at the required pressure. As seen in a Grassmann diagram (Fig. 6), the overall exergetic efficiency of the POX gas turbine is 85.6%. This is a sum of the power produced by the expander (13.5%) and the exergy of synthesis gas (72.1%). The latter is made up of chemical (68.1%) and thermal (4%) exergies.

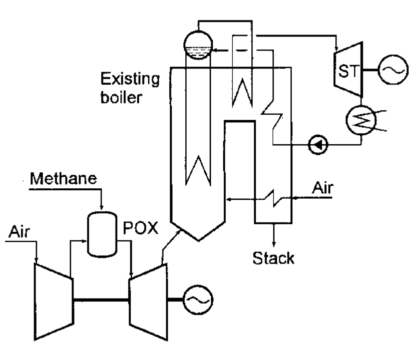


Fig. 5 Repowering with the POX gas turbine.

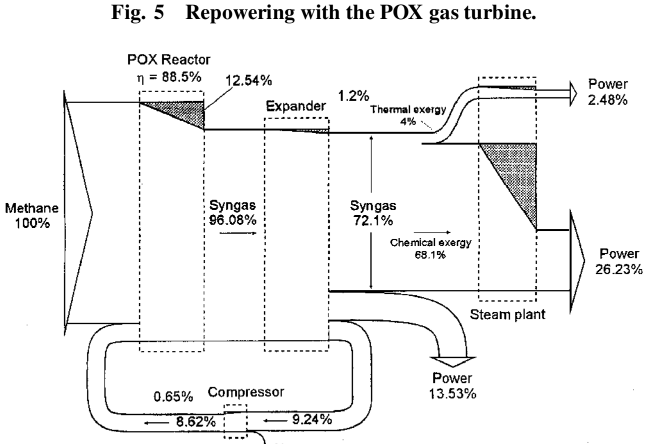


Fig. 6 Grassmann diagram of the POX gas turbine.

In this repowering scheme, the chemical component is utilized in the steam plant as a fuel with the same exergy efficiency as in the nonrepowered case. Given an exergy efficiency of 38.5% (LHV efficiency of 40%), the steam plant output becomes 26.23%. In contrast to the nonrepowered case, syngas thermal component gives an additional input to the steam cycle. According to the calculations by Bolland for heat recovery boilers,[20] exergy efficiency of a steam bottoming cycle varies depending on the complexity of the cycle between 65% (double pressure) and 70% (triple pressure with reheat). If a value of 62% is assumed as a conservative guess, the thermal component results in an additional power output of 2.48%. To sum up, the overall exergy efficiency becomes 42.21%, meaning an increase due to repowering of 3.7% points (42.21% versus 38.5%). The increase in power output is more pronounced: From the original 26.23% in the nonrepowered case, the output grows to 42.21%, which is a 60% rise. Such a value permits considering this scheme as an effective repowering option.

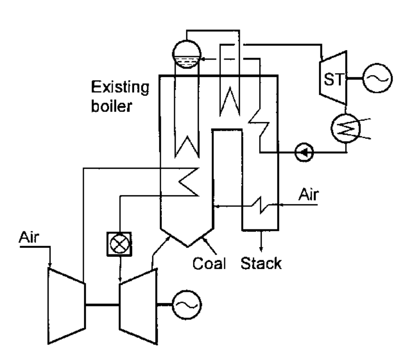
Externally Fired Combined Cycle (Option 4)

The aforementioned options employ a gas turbine that is driven by the combustion of a premium fuel, such as natural gas or distillate oil. By contrast, in an externally fired combined cycle, the gas turbine is integrated in the solid fuel-fired plant so that heat addition occurs indirectly through an air heater located in the furnace. Such an arrangement avoids products of coal combustion entering the turbomachinery while utilizing the high-temperature zone and leaving heat of a lower temperature for the steam cycle. After being heated in the furnace, the compressed air is expanded and sent back to the furnace at an elevated temperature as preheated combustion air (Fig. 7). Part of this air can be diverted to a clean HRSG, working in parallel with the coal-fired boiler. The exclusion of coal combustion products from the gas turbine avoids the expense of hot gas cleanup and corrosion of turbine blades by coal ash.

To raise the air temperature in the air heater to the level of gas turbine inlet temperature (TIT), special materials with a high thermal resistance are required. As superalloys cannot withstand temperatures higher than 950–1000°C (Ref. 21), an additional ceramic heat exchanger would be necessary to reach the TIT of modern turbines. Alternatively, the final rise of temperature can be achieved by natural gas cofiring.[22] The effect of supplementary firing on reducing the air heater surface area and the use of less costly materials was analyzed in a study by Korobitsyn and Hirs.[23] Options with metallic heat exchanger (800°C), oxide dispersion alloys (980°C), and ceramic materials (1165°C) were considered. The latter was the coal-only scheme. All gas turbine plants were based on the Siemens V94.2 engine. Supplementary firing was employed to reach the engine's inlet temperature.

The following LHV efficiencies were calculated: 50.1% for the gas-only combined cycle, 47.7% for the plant with the metallic heater, 45.6% for the ceramic EFCC, and 34.8% for the reference direct-fired plant. Figure 8 gives a comparison between the specific gas consumption for cofiring and an additional air heater surface. Thus, 1 kW of natural gas per 1 kWe produced (case EFCC-800)

Fig. 7 Repowering with an externally fired gas turbine.



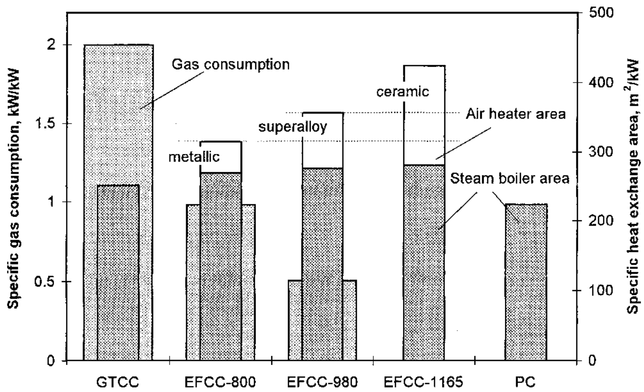


Fig. 8 Specific natural gas consumption and heat transfer area.

can be weighted against 35 m^2 of superalloy and 63 m^2 of ceramic surface per 1 kWe (case EFCC-1165).

Conclusions

Gas turbine technology offers several ways of enhancing direct-fired power plants. For example, in a waste incineration plant the exhaust of gas turbine can be used to increase the temperature of steam generated at the waste heat boiler. The hot windbox scheme with external superheating proved to have the best match between natural gas consumption and the total heat transfer surface.

Expansion of natural gas from pipeline pressure to atmospheric pressure through a partial oxidation gas turbine produces a synthesis gas. By feeding this gas into the steam plant's furnace, a promising repowering option can be realized.

Replacing part of the steam boiler's tubing with an air heater for a gas turbine improves the thermodynamics of the steam plant, thus increasing efficiency and power output. However, enhancement of solid fuel-fired power plants with the use of gas turbine technology should not result in an excessive use of natural gas and a large heat exchange surface.

Also, it should be taken into account that all repowering concepts will require sufficient space for installing a gas turbine and ducting, which could cause problems at sites with limited space.

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