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Status and Perspective of Externally Fired Gas Turbines

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Power generation with an externally fired gas turbine (EFGT) is a promising technology for solid fuels such as coal and biomass because it offers high efficiency, low cost, and low environmental impacts. Different systems of EFGT are presented, including externally fired combined cycles and externally fired humid air turbines. Recent research and engineering development of the technologies are reviewed. Topics including system configurations, thermal efficiencies, and high-temperature heat exchangers issues are discussed. The results of this study can be applied to guide the future development of solid-fuel-based externally fired gas turbine systems.

Introduction

THE characteristics of fuels are of major importance when choosing an option in gas turbine systems. Solid fuels, such as coal and biomass, can be burned in raw form or converted to produce liquids or gases in more or less refined forms. The use of such fuels in gas turbines requires the resolution of technology issues that are of little or no consequence for conventional natural gas and refined oil fuels. Some options for producing power and heat generation using solid fuels under development are direct solid-fuel-fired gas turbine, integrated gasification combined cycle (IGCC), pressurized fluidized-bed combustion (PFBC), and externally fired gas turbines (EFGT).

For direct solid-fuel-fired gas turbines, the main obstacle is particulate control to protect the turbine from erosion, deposition, and corrosion. Another problem is related to the increased combustion time required by solid fuels compared with liquid or gas fuels.[1] In the IGCC, the solid fuel must first be converted to a clean fuel gas before fired in the combustor of a gas turbine. The conversion of solid fuel to clean fuel may require processing, introducing additional pressure and heat losses, and the demand for more auxiliary power. These factors all reduce the overall efficiency. In addition, this technology requires the development of a gasifier and a fuel gas cleanup system. For PFBC systems, questions remain regarding the effectiveness and the longevity of the combustion cleanup system.[2] To increase the inlet temperature to further increase the thermal efficiency of PFBC, a topping combustion technology may need to be developed, which is so-called second generation PFBC.[3] In externally fired gas turbines, the development of a high-temperature heat exchanger is the major challenge. To reach high efficiencies, a topping combustor may also be needed if the heat exchanger cannot withstand the inlet temperature of modern gas turbines.

Each of the advanced technologies is at a different stage of development, but all face some barriers including, for example, limited operating experience and unproven long-term reliability, an unwillingness by the risk-averse utilities to accept products with limited operating experiences, lack of ability to deal with fluctuating loads and alternative modes of operation, and high capital costs. Today, the market of cheap natural gas brings another challenge for using solid fuels such as coal and biomass for power generation. Therefore, the research and development (R&D) strategy should focus on the integration of features of different technologies, for example, PFBC, IGCC, and EFGT, as shown in Fig. 1.

Evaluation and comparison of thermal efficiencies of different technologies have been investigated by previous researchers. Foster-Pegg[4] introduced fuel efficiency by which the fuel characteristics have been considered in this concept. Considering the same inlet turbine temperature, the EFCC and PFBC with topping combustor offer high thermal efficiencies (47–49%) compared with IGCC systems (41–46%) (Ref. 4). McKinsey and Wheeldon also made a performance comparison of advanced coal-based power generation technologies including atmospheric fluidized bed combustion (AFBC), PFBC, PFBC with topping combustor, advanced PFBC [PFBC with a partial gasifier (APFBC)], air-blown gasification cycle, hybrid PFBC, high-performance power system (HIPPS) (an indirectly/externally fired combined cycle with partial gasification), and IGCC. The results show that the efficiencies of HIPPS systems [higher heating value- (HHV-) based efficiencies of 47.9–49.7%] and advanced PFBC systems (HHV-based efficiencies of 46.9–48.3%) are higher than the efficiencies of other systems (HHV-based efficiencies of 33.6–46.2%) (Ref. 5). This paper presents different systems of EFGT, including externally fired combined cycle (EFCC) and externally fired humid air turbine (EFHAT), and reviews the recent research and engineering development. Topics including system configurations, thermal efficiencies, and high-temperature heat exchangers issues have been discussed.

System Configurations and Thermodynamic Performance

Two major advanced system configurations of EFGT have been investigated: EFCC, as shown in Fig. 2, and EFHAT, as shown in Fig. 3. EFCC is an externally fired gas turbine integrated with a bottoming steam turbine. EFHAT is an externally fired gas turbine with a humid air turbine, where the bottoming cycle is not required. In Figs. 2 and 3, the exhaust gas from gas turbine is used as combustion air in the furnace. There are other configurations, in which, for example, the exhaust gas enters a separate heat recovery system while fresh air is used in the furnace.

Figure 4 shows one detailed configuration of the EFHAT systems investigated by Yan et al.[6–8] From the viewpoints of energy conversion and transformation, the system is divided into three main subsystems: the gas turbine subsystem, the solid fuel combustion subsystem, and the heat recovery subsystem. The decomposition of the system into subsystems is arbitrary. It is advantageous to break up an overall system into subsystems to reduce the interactive complexity and find the main thermodynamic parameters that affect the system performance. The thermodynamic analyses show that it is important to optimize the heat recovery subsystem by increasing the effectiveness of recuperation, preheating the combustion air for solid fuel combustor, and increasing the humidity (water-to-air ratio) of compressed air.[6]

A summary of results from previous studies of the thermodynamic performance of EFCC and EFHAT cycles has been reported by Yan.[9] For the EFCC, the system performance has been

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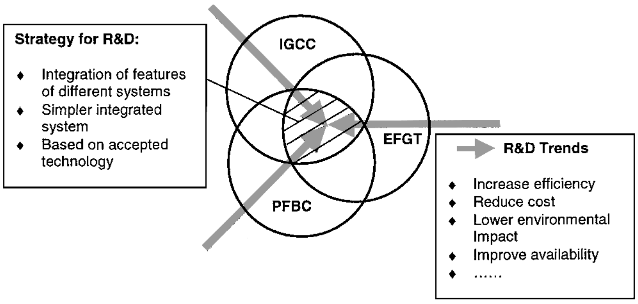

Fig. 1 Strategy for R&D of solid fuel (coal and biomass) power generation technologies.

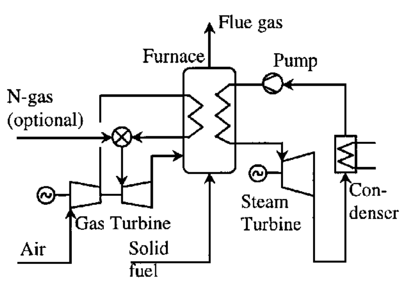

Fig. 2 Simplified configuration of EFCC.

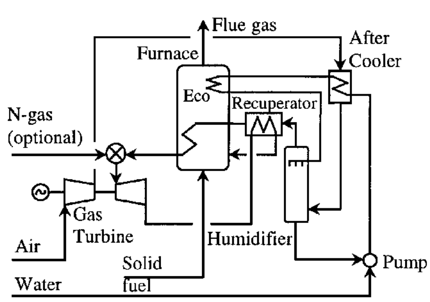

Fig. 3 Simplified configuration of EFHAT.

analyzed by LaHaye and Zabolotny,[10] Foster-Pegg,[4] Huang and Naumowicz,[11] Vandervort et al.,[12] Ruth,[13] Seery et al.,[14] Consonni et al.,[15] Consonni and Macchi,[16] Mathieu and Desoleil,[17] Korobitsyn and Hirs,[18] McKinsey and Wheeldon,[5] Robson et al.,[19] and Klara et al.[20] The results from these researchers on the thermal efficiencies vs turbine inlet temperature are plotted as shown in Fig. 5. Parsons and Bechtel,[21] De Ruyck et al.,[22] Eidensten et al.,[23] Huang and Naumowicz,[24] Yan et al.,[6] Klara et al.,[25] and Robson et al.,[19] have carried out performance investigations of the EFHAT systems. Efficiencies of EFHAT vs turbine inlet temperature are plotted in Fig. 6.

Figures 5 and 6, plots a, b, or c are the different configurations where a metallic high-temperature heat exchanger, ceramic high-temperature heat exchanger, or a topping combustion is used, respectively. Configuration a + c means that the system includes a metallic high-temperature heat exchanger (a) and a topping combustor (c). Configuration b + c means that the system includes a ceramic high-temperature heat exchanger (b) and a topping combustor (c). As shown in Figs. 5 and 6, thermal efficiencies of EFCC and EFHAT are in the range 35–55%. Note that the conditions and assumptions for the system simulations by different researchers might be different, which represents the differences of the calculated results. The inlet temperatures of gas turbines have a great influence on

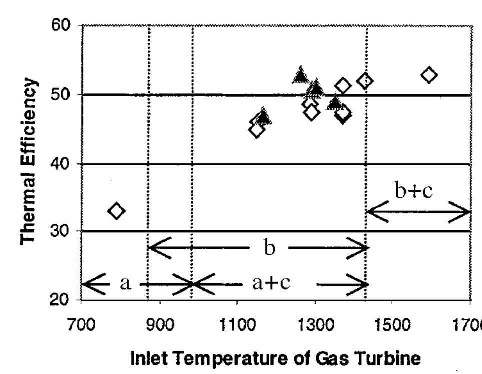

Fig. 5 Thermal efficiency of EFCC; note: a, metallic HTHx; b, ceramic HTHx; and c, topping combustion. ◇, efficiency based on HHV and ▲, efficiency based on LHV.

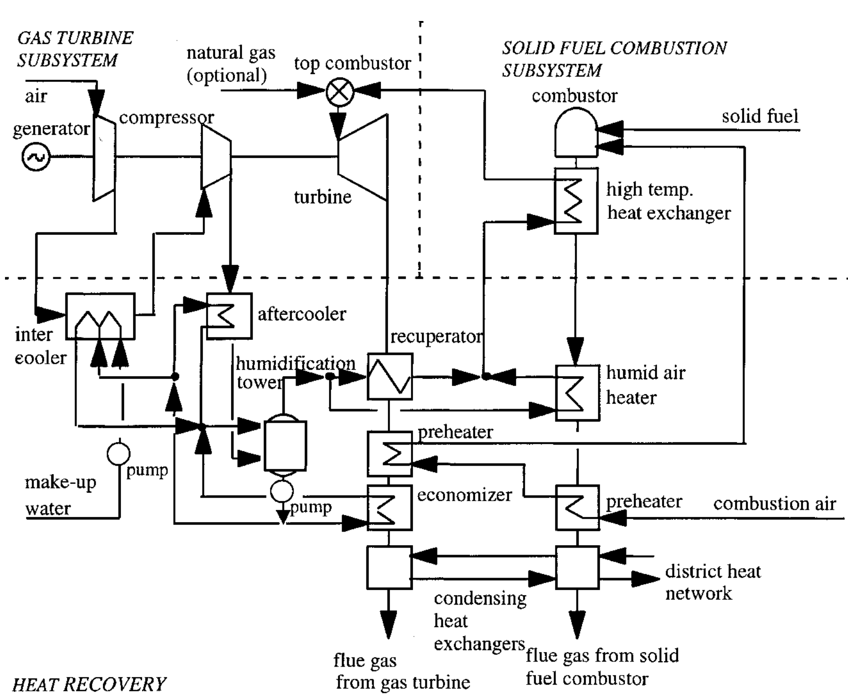

Fig. 4 One of the EFHAT systems fueled by solid biomass with heat recovery district heating.

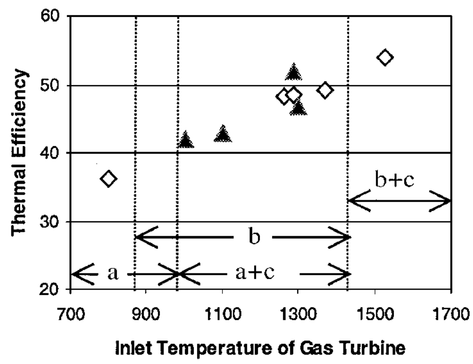

Fig. 6 Thermal efficiency of EFHAT; note: a, metallic HTHx; b, ceramic HTHx; and c, topping combustion. ◇, efficiency based on HHV and ▲, efficiency based on LHV.

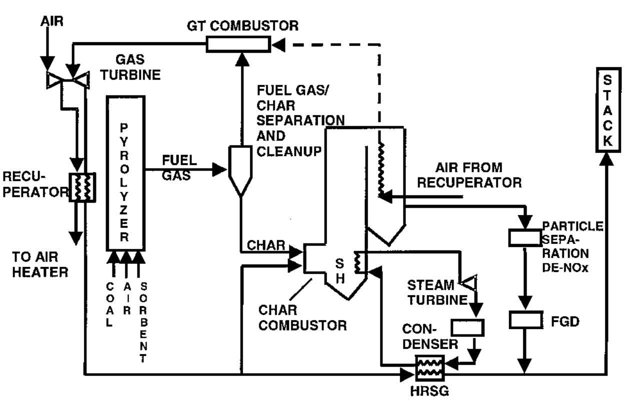

Fig. 7 Foster–Wheeler indirectly coal fired HIPPS (see Ref. 32).

the system performance. This will also reveal the challenge for the technologies of externally fired gas turbines, which depend on the development of the high-temperature material and high-temperature heat exchangers (HTHx). In addition to the development of materials and heat exchangers, a new method for designing the externally fired gas turbine is required, which can make a tradeoff between commercial technologies and underdeveloped technologies to overcome the barriers of this high-temperature limitation.

Engineering Development and Demonstration

Research, development, and demonstration of the EFGT have been widely carried out in the past decade. The U.S. Department of Energy (DOE) has been playing a key role for developing this technology. Several projects have been supported by DOE, including Westinghouse's investigation of the coal-fired indirectly heated gas turbines in the early 1980s by Hamm and Weeks[26] and Berman et al.[27] and in-bed heat exchanger studies by Bannister and Whitlow,[28] Hague International EFCC pilot plant test by Vandervort et al.,[12] and engineering development in HIPPS.[13,29]

In the Hague International EFCC, a ceramic heat exchanger is integrated with a combined cycle. In HIPPS, two different systems have been investigated by industrial teams led by Foster-Wheeler and United Technologies. In both cases, the high-temperature air furnace (HITAF) is the key component. The focus is on high-temperature materials (especially metallic materials) and how to design HITAF by using these commercially available materials. The Foster–Wheeler led team[30–32] uses a conventional boiler but includes a pyrolyzer for prefuel treatment. The Foster–Wheeler indirectly fired combined cycle system is shown in Fig. 7. The United Technologies team[33,34] is modifying the conventional furnace by introducing a radiant air heater. The optimized design employs both radiant and convective air heaters to transfer the energy from coal combustion to the gas turbine working fluid. Because of today's material limit, it is necessary to use a natural gas topping combustor to reach the appropriate turbine inlet temperatures required for high efficiencies.

Similar to the system of Foster–Wheeler, Davison et al.[35] presented an advanced system that includes partial gasification of coal in a circulated fluidized bed (CFB) pyrolyzer and the combustion of the resulting char in a PFBC boiler. The pyrolysis product can be burnt in another combustion chamber that is, a topping combustor, in the presence of the flue gas from the boiler after cleanup. The overall efficiency is high (50% and above) according to their evaluation.

Discussion

Most engineering development is carried out on EFCC due to its similarity to conventional steam turbines and applicability in repowering, which may provide a near-term solution for the market. However, EFHAT is one of the potential system configurations especially suited for small-scale systems.

Note that studies on EFCC systems are furnace oriented, which means that the system configurations are greatly related to the design of furnace. The choice of HTHx, metallic or ceramic, will give a different arrangement of the systems. The former will require topping combustion to reach the required inlet temperature for the modern gas turbines, thus giving a high efficiency. In the topping combustion, additional clean fuel is needed. With the development of high-temperature ceramic materials and the technologies for manufacturing ceramic heat exchangers, a long-term solution would involve a system with a ceramic heat exchanger without topping combustion. Development of a high-temperature and high-pressure ceramic heat exchanger is a challenge. Compromises, such as the use of moderate temperatures but conventional materials for the heat exchanger and topping combustion may give a short-term solution when an extra-high-temperature heat exchanger is not available. The integration of a EFGT with simple gasification, for example the pyrolyzer in Foster–Wheeler's system, is one of the more interesting systems because it is simpler than IGCC, does not need a ceramic heat exchanger, and has the potential of using gasified fuel for the topping combustor.

Figure 8 shows another interesting system configuration for coal and biomass cofiring power generation. In this system, coal is used as the base fuel for the furnace and biomass as the feedstock to an externally heated gasifier to provide the topping fuel of an externally fired gas turbine. This provides the features of increasing the plant size compared to biomass-fired power plants due to the limitation of transportation of biomass fuels and improving the environmental performance compared to a coal-fired power plant. The externally heated gasifier has been developed by Brightstar Synfuels Company (BSC), in Louisiana. The BSC technology gasifies wood (or other biomass) by combining it with steam at a high temperature and passing it very rapidly through a low-to-moderate pressure, externally heated, tubular reformer (gasifier). Passing the hot syngas through a heat recovery boiler or other heat exchangers cools the hot syngas. The inorganics in the feedstock (ash) and the small amount of carbon that is not converted to gas are then removed using a dry filtration system. The clean, cool product gas is then available for fuel or process applications. Because the gasification is an externally heated process without air or oxygen involved in the gasification process, a medium heating value gas can be produced, which is more suitable for topping combustion for the EFCC

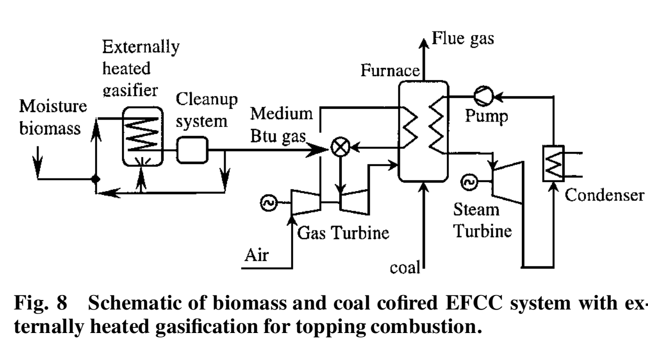

Fig. 8 Schematic of biomass and coal cofired EFCC system with externally heated gasification for topping combustion.

system. Another advantage of the BSC technology is that it can use moist biomass as a feeding stock. This will make the gasification system straightforward without drying the biomass. Further integration of the BSC gasification with externally fired gas turbine is an interesting future work due to the simplicity of the system.

Figures 5 and 6 also show the application range of HTHx with metallic and ceramic materials. Development of HTHx is focused on metallic heat exchangers,[28,36] ceramic heat exchangers,[37,38] and heat exchangers with combination of metallic and ceramic materials.[39] However, more R&D work is required in high-temperature materials and manufacture technologies of heat exchangers for commercialization, which can make it possible to reach the inlet temperature of a modern gas turbine. It is also very important to study the requirements in preventing corrosion, erosion, and deposit of heat transfer surfaces in the furnace. These technical problems have to be solved for the commercial demonstration of externally fired gas turbines.

Conclusions

The new strategy for R&D of solid-fuel power generation technologies requires the integration of advanced technologies with consideration of accepted conventional technology. The externally fired gas turbine, in both combined cycle and humid air turbine modes, provides a high thermal efficiency. The challenge of this technology is the development of high temperature material for its heat exchangers. The new system combining the atmospheric combustion technology with simple gasification for topping combustion may have potential for future development.

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