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Research Paper

Thermodynamic and economic investigation of coal-fired power plant combined with various supercritical CO_2 Brayton power cycle

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HIGHLIGHTS

- Modeling and simulation of various sCO2 power cycle was conducted.
- Thermodynamic result of individual power cycle was compared via enthalpy distribution diagram.
- LCOE on individual power cycle was calculated by total revenue requirement.

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ABSTRACT

The supercritical CO_2 Brayton power cycle is well known as a promising power generation technology, and researches for applying it to various applications are being actively carried out. In this study, performance analysis of coal-fired power plant combined with supercritical CO_2 Brayton power cycle was performed. If various existing supercritical CO_2 Brayton power generation cycles are applied to coal-fired power generation systems, the expected power generation efficiency and levelized cost of electricity (LCOE) are thoroughly estimated. In conclusion, it is expected that the power generation efficiency is improved by 6.2–7.4% compared to the steam Rankine cycle applied to the existing coal-fired power plant, and the LCOE of the coal-fired power plant combined with the supercritical CO_2 Brayton cycle is reduced by about 7.8–13.6% compared to that of coal-fired power plant combined with steam Rankine cycle. In addition, design criteria for retaining the economic dominance were presented through sensitivity analysis of factors affecting O&M cost and capital cost.

1. Introduction

The generating capacity of coal-fired thermal power plant is expected to increase up to 2127 GW by 2030. [1] This is a large market as it consists of 32% of the total electricity production, and as a result, many different development plans and researches are being conducted in collaboration with both the industry and the academia [2,3]. These researches are especially focusing on the development of technologies for clean coal-fired power plant to minimize the polluting emissions by enhancing the low efficiency of the traditional coal-fired power plant [4]. Such coal-fired power plant technology includes Ultra Supercritical Cycle (USC) technology, Integrated Gasification Combined Cycle (IGCC) technology, Oxy-Pulverized Coal (Oxy-PC) technology, and Supercritical CO_2 Cycle (S-CO_2 Cycle) technology [5]. Thermodynamic analysis, and provided an economic estimation between the Ultra Supercritical steam Rankine power cycle (that requires an operating condition above 300 bar/600 °C), and the superheated/supercritical steam Rankine power cycle was conducted [6–10]. In recently times, concepts of Advanced USC (A-USC) are being developed that achieve a power generation efficiency over 45% (HHV-based) by means of increasing the steam condition to over 700 °C. In addition, research and development on turbine and materials are actively being conducted that can withhold high temperatures and pressures [11–17]. Some researcher has verified that the IGCC technology is a highly promising power generation technology that could decrease the pollution from SO_x, NO_x, CO_2, and PM that are released into the atmosphere compared to the traditional technologies that directly combust coal [18–21]. Researches on maximizing the environmental effect and effectiveness of the IGCC technology are also being conducted currently [22–24]. Moreover, research on confirming the high economic efficiency and environmental friendliness of the oxy-fuel combustion technology for

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Nomenclature

ASU	air separation unit
A-USC	advanced ultra supercritical steam cycle
CPU	compression and purification
HTR	high temperature recuperator
IGCC	integrated gasification combined cycle
LCOE	levelized cost of electricity
LTR	low temperature recuperator
Oxy-PC	oxyfuel combustion pulverized coal
O&M	operation and maintenance cost
PCHE	printed circuit heat exchanger
sCO_2	supercritical carbon dioxide
TCO_2	transcritical CO_2 cycle
TIT	turbine inlet temperature
TRR	total revenue requirement
USC	ultra supercritical steam cycle

coal-fired power plant by comparing the pre-combustion and post-combustion oxy-fuel combustion were conducted [25,26]. Through thermal energy optimization and exergy analysis, Fu et al. and Soundararajan et al. conducted a research on identifying the methods to increase the overall performance of the power plant via enhancing the performance of the air separation unit (ASU) and the compression and purification unit (CPU), which are the key technologies of the oxy-fuel combustion technology [27–29]. Supercritical CO_2 Brayton cycle technology is a power generation technology that uses the supercritical phase CO_2 as the working fluid of the power cycle. CO_2 has a similar density as its liquid phase is at 73.8 bar, 30.98 °C. In addition, it has a similar viscosity as gas, which allows minimization of the power consumption of the turbomachinery that is necessary its miniaturization, compression, and recirculation. As such, it is expected to have a high power generation efficiency when compared to the traditional commercial coal-fired power plant [30]. Electricite De France (EDF) and Pratt & Whitney Rocketdyne devised a cycle that could increase the power generation efficiency and CO_2 capture by applying s-CO2 cycle on the topping cycle [31,32]. The Korea Institute of Energy Research (KIER) has also devised a supercritical CO_2 Dual Brayton cycle that could enhance the power generation efficiency by differentiating the supercritical CO_2 Brayton cycle from the previous researches [33]. The Institute for Advanced Engineering (IAE) has developed a high-performance supercritical CO_2 Brayton cycle that could be applied on the coal-fired power plant, and is currently conducting a research on predicting and analyzing the levelized cost of electricity of the applied power cycle. In addition, IAE has conducted a thermodynamic sensitivity analysis on predicting the overall cycle performance depending on the type of boiler and coal [34]. In this study, a thermodynamic analysis and modeling is performed using a commercial software ASPEN Plus, to quantitatively analyze the thermodynamic efficiency when supercritical CO_2 Brayton power cycle (suggested or developed by previous researches) is applied on the commercial class coal-fired power plant. The individual cycle characteristics are visually represented on the enthalpy distribution diagram to analyze the thermodynamic result depending on the application of the supercritical CO_2 Brayton cycle to coal-fired power plant. Furthermore, the thermodynamic analysis of the advanced power cycle combined with transcritical CO_2 Rankine cycle is also conducted to compensate for the weaknesses of the supercritical CO_2 Brayton cycle. In terms of economic feasibility, the levelized cost of electricity (LCOE, \$/kWh) of each of these technologies are quantitatively estimated by using the TRR (Total Revenue Requirement) method, as well as the thermodynamic analysis results. Finally, this research predicts a changing trend of LCOE based on the variation of the main parameters that affect each of the categories of LCOE, which include carrying charge, O&M cost, and fuel cost. Based on the predictions, this study suggests design criteria for the supercritical CO_2 power cycle to gain a competitive edge over the coal-fired power cycle combined with steam Rankine cycle.

2. Thermodynamic modeling and analysis of coal-fired supercritical CO_2 Brayton power cycle

2.1. Coal-fired steam Rankine cycle

A coal-fired power plant is mainly composed of a closed steam Rankine cycle that uses the steam and water as the working fluids. The thermal energy generated from the combustion process of coal and air in the coal boiler is transferred to water and steam (i.e., the working fluid), and the steam that is transformed to subcritical or supercritical phase is fed to the HP/IP/LP turbines. The coal-fired steam Rankine cycle has a high heat capacity, and it has been used globally as it uses chemically stable water as a working fluid.

2.2. Supercritical CO_2 Brayton power cycle

Fig. 1 shows the temperature-entropy diagram for a recompression supercritical CO_2 cycle. Although it is similar to the widely known Ideal Brayton Cycle, few differences exist. While gas turbine engine Brayton cycle consists of vapor phase from the high-pressure region to the low-pressure region, all regions of supercritical CO_2 Brayton cycle consist of the supercritical phase. In addition, the compression ratio is lower than that of the gas turbine Brayton cycle, and its theoretical compression is rather low due to the high density in the supercritical phase. For such reasons, extremely compact turbomachinery can be selected compared to that of the steam Rankine cycle. A recuperator is necessary to enhance the cycle performance due to the low expansion ratio of supercritical CO_2 turbine, but the scale of the overall power system can be decreased by choosing a printed circuit heat exchanger. For this reason, the simple recuperation supercritical CO_2 cycle is getting much support in the context of power generation and heat recovery system.

2.3. Various approaches to adopt supercritical CO_2 Brayton cycle in coal-fired power plant

The expansion ratio of the turbine supercritical CO_2 Brayton cycle is lower than that of steam Rankine cycle. This is due to the increase of exhaust temperature of the turbine followed by the decrease of enthalpy change rate, and as such, the importance of using the recuperator for cycle performance enhancement has been noted. However, the outlet temperature of the heat source increases due to the regenerated heat through recuperator. Therefore, for the supercritical CO_2 Brayton cycle to expand its application on coal-fired power plant, it must overcome such challenges. Many research organizations are conducting investigations on various cycle layouts and thermodynamic cycle performance assessments to overcome such limitations. Moullec suggested a desirable coal-fired power plant combined with supercritical CO_2