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Exhaust circulation into dry gas desulfurization process to prevent carbon deposition in an Oxy-fuel IGCC power generation

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A B S T R A C T

Semi-closed cycle operation of gas turbine fueled by oxygen–CO_2 blown coal gasification provides efficient power generation with CO_2 separation feature by excluding pre-combustion type CO_2 capture that usually brings large efficiency loss. The plant efficiency at transmission end is estimated as 44% at lower heating value (LHV) providing compressed CO_2 with concentration of 93 vol%. This power generation system will solve the contradiction between economical resource utilization and reduction of CO_2 emission from coal-fired power plant. The system requires appropriate sulfur reduction process to protect gas turbine from corrosion and environment from sulfur emission. We adopt dry gas sulfur removal process to establish the system where apprehension about the detrimental carbon deposition from coal gas. The effect of circulation of a portion of exhaust gas to the process on the retardation of carbon deposition was examined at various gas compositions. The circulation remarkably prevented carbon deposition in the sulfur removal sorbent. The impact of the circulation on the thermal efficiency is smaller than the other auxiliary power consumption. Thus, the circulation is appropriate operation for the power generation.

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1. Introduction

Abatement of carbon dioxide emission in the heat and power industrial area is imperative because the vast amount of fossil fuel is consumed in the electricity and heat production [1]. Fossil fuel power production, typically coal fueled power generation, is subjected to the spearhead of the reduction of carbon dioxide. Because the CO_2 emission from conventional pulverized coal firing plants are estimated to exceed 870 g-CO_2/kW h, its reduction becomes burning issue in the countries with high dependency on coal firing power plant. In India, coal is used for 55% of its energy generation, and CO_2 emission from coal occupies 70% of the energy generation [2]. In China proportion of thermal power generation exceeds 80% and over than 99% of thermal power generation is fueled by coal [3]. Annual coal consumption is rapidly increasing since 2008, and its 65% was consumed in the country of Asia Pacific region [4]. In contrast to the coal firing power plant, power generation with natural gas fuel is leading technology for the reduction of CO_2 emission. The bland new combined cycle (CC) power generation fueled with liquefied natural gas (LNG) achieved highest thermal efficiency of 59% at lower heating value (LHV) base [5] at Kawasaki thermal power station of Tokyo electric power company, which is attained by introducing 1500 °C grade gas turbine. There is margin for the efficiency improvement up to 61% LHV with 1600 °C grade gas turbine. LNG fueled thermal power plant can drastically reduce its CO_2 emission intensity by improving thermal efficiency with those advanced CC configuration.

On the other hand, coal fueled thermal power plant has essentially high CO_2 emission intensity, while its thermal efficiency is increased by CC technology. Thus, the technological development for CO_2 capture and its sequestration for coal fueled power generation is widely investigated and causes large concern. Although the CO_2 capture may reduce its emission to the atmosphere, considerable decrease in thermal efficiency of the power plant is inevitable. Recent review of process simulation on conventional, air blown coal-fired power plant showed that efficiency penalty of post-combustion CO_2 capture is around 10% absolute value of the net efficiency [6]. Application of oxy-fuel combustion to the coal-fired power plants was extensively considered. Thermodynamic analysis revealed that the auxiliary power for the air separation unit (ASU) is predominant in the penalty of efficiency loss of the power plant [7]. The other work on the thermodynamic comparison of efficiency penalties of post-combustion capture and oxy-fuel combustion at CO_2 capture ratio of 90% showed also that the large ASU power consumption elects the pre-combustion capture as

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favorable process for the coal-fired power plant [8]. In addition to the efficiency penalty, the oxy-fuel combustion has various issue deeply related to the firing itself as reviewed in the literature [9]. There is approach to adopt dry CO_2 capture process to existing coal power plant [10]. The capture process uses CaO as regenerable sorbent for CO_2 capture, however the regeneration of the sorbent still have the oxy-fuel combustion process to obtain the required heat for regeneration of carbonate and concentrated CO_2–H_2O mixture exhaust from the regeneration step. Thus, the oxy-fuel combustion seems to have common ASU issue when it is applied to the coal firing plant. Non-cryogenic oxygen supply is listed at the head of issue for improving efficiency and economy of the next generation oxy-fuel coal firing plant [11].

CO_2 capture from fuel gas in the coal gasification power plant, namely pre-combustion capture is also intensively researched as alternative to the post-combustion capture in the pulverized coal power plant. IGCC with Shell gasifier was analyzed so that the efficiency loss due to CO_2 capture is estimated [12]. The results showed that the efficiency decreased from 46% to 36% in LHV base. IGCC with CO_2 capture was also investigated in viewpoint of optimization of conversion in water gas shift reactor and extent of CO_2 capture in SELEXOL process. The resulting net plant efficiency was estimated as 34.1% in higher heating value (HHV) base, which increased by 1.6% by the optimization [13]. There is another approach in improving efficiency of IGCC with CO_2 capture. The idea is to feed coal as slurry with liquefied CO_2 to eliminate vaporization heat when coal is fed in water slurry. The approach is concluded that plant efficiency is increased by 3–5% points according to the moisture content in the fuel [14]. With coal–CO_2-slurry idea, the plant efficiency does not exceed 33% in HHV base. Although the Integrated Gasification Combined Cycle (IGCC) with pre-combustion CO_2 capture process will exhibit slightly smaller efficiency penalty, the value is estimated as 8.5% absolute value [15]. There is another comparison of thermal efficiency of IGCC with and without CO_2 capture fueled with hard coal or lignite [16]. The evaluation revealed that the efficiency loss due to CO_2 capture reaches 11.0%-points for hard coal IGCC and 10.2%-points for lignite IGCC. According to these investigation, efficiency penalty on IGCC with CO_2 capture falls around 10% points, which is usually smaller than that of conventional coal firing power plant with post-combustion CO_2 capture. Thus, the low emission coal fuel power plants are extensively investigated on the basis of coal gasification technologies [17], and scenario for CO_2 abatement with carbon capture and storage is suggested [18]. The power plant with conventional CO_2 capture, however consequently consumes increased amount of fuel, which will result in diminishing resource. The efficiency loss is mainly aroused by the large energy consumption of the CO_2 capture process for fuel gas or flue gas.

Other approaches are suggested as conceptual coal gasification power plants for reduction of carbon dioxide emission by the procedure that do not rely on conventional pre-combustion type CO_2 capture process. Dry CO_2 capture process using calcium oxide sorbent is introduced to the coal gasification power plant to improve performance in terms of efficiency, emission, and economy. One of the conceptual plant configurations is Zecomix cycle [19], which is suggested by Italian project leaded by ENEA. Zecomix cycle is composed of hydrogasification equipped with the dry CO_2 capture process, combined cycle power generator with semi-closed gas-turbine cycle on syngas oxy-firing, ASU, and CO_2 liquefaction. Its net thermal efficiency is calculated as 44–47% at LHV base with 100% CO_2 recovery. Similar conceptual power plant that is called Zecomag that has open gas turbine for combustion of syngas with air is suggested by the same research project [20]. The expected thermal efficiency is in the range of 45–48% with CO_2 capture ratio of 84–98%. If these conceptual power generation come technically and economically feasible, the confirmed plant will be one of the promising options for CO_2 abatement. We are extensively investigating a new power generation system to avoid absurdity that the conservational utilization of energy in perspective of CO_2 reduction will accelerate the depletion of resource. Central Research Institute of Electric Power Industry (CRIEPI) has proposed a new concept of IGCC power generation system [21], which will reconcile effective CO_2 separation and higher efficiency of the power plant. The concept, which we named as Oxy-fuel IGCC power generation, basically consists of semi-closed cycle operation of gas turbine fueled by oxygen–CO_2 blown coal gasification and efficient CO_2 recovery from circulating exhaust gas by compression and mist separation. Although the researcher of Zecomag also proposed the same concept [20], their conceptual configuration does not clearly mention about the importance of gas cleaning in the plant. The system requires the pre-combustion type sulfur removal process to attain tolerant level of sulfur compounds for the fuel gas when it is consumed in the gas turbine. The removal process should be dry sulfur removal process so that H_2O and CO_2 in the processed gas retained. The remained H_2O and CO_2 will increase the output of gas turbine, and will decrease the potential of carbon deposition in the least.

In this paper, the concept, the system configuration, and advantage of the Oxy-fuel IGCC power generation is briefly introduced. Then, the pre-combustion sulfur removal process is described from the point of view to establish adequate operating condition in the plant. We investigated the countermeasure against carbon deposition that enable the process to remove sulfur compounds within the severe condition of coal gas containing high concentration of CO at high temperature and high pressure. The main purpose of this study is to evaluate the validity of exhaust gas circulation on the proper operation of the sulfur removal process and on elimination of carbon deposition in the process.

2. Efficient power generation with CO_2 capture

2.1. Oxy-fuel IGCC concept

The advantages of Oxy-fuel IGCC are readily understood in comparison with the general process configuration of ICGG equipped with pre-combustion CO_2 capture [12]. The flow diagram of the latter IGCC power generation plant is shown in Fig. 1. The system is equipped with the carbon capture and sequestration (CCS) ready function by introducing the water gas shift reactor and CO_2 capture process in upstream of the gas turbine. The shift reactor injects excess amount of steam to the gas stream to attain higher conversion of the equilibrium reaction. If the process operates at higher CO_2 recovery ratio as 90%, the large energy consumption for CO_2 capture process will significantly diminish the plant efficiency. The efficiency analysis of IGCC with and without CO_2 capture is available from literature [22]. The report summarized that the efficiency of IGCC power plant relatively decreases around 20% by adding CO_2 capture at 90% recovery ratio. Thus, alternative CO_2 separation process is plausible to improve efficiency of the IGCC power plant with CO_2 capture.

CRIEPI has proposed new concept of CCS-ready IGCC power plant [23] as shown in Fig. 2. The distinctive feature of the plant is combination of O_2–CO_2 blown gasifier and semi-closed gas turbine using exhausted H_2O–CO_2 gas mixture with coal gas fuel at combustor. CO_2 for storage is easily obtained by mist separation and compression from the circulating exhaust gas that contains mainly CO_2 and steam. This alternative to conventional CO_2 capture process brought very large efficiency improvement of the plant. Net thermal efficiency of the plant on Fig. 2 revealed to be 44.0% LHV (41.9% HHV) at 99% CO_2 capture ratio [24]. We have named this new IGCC with CO_2 separating concept as "Oxy-fuel IGCC" from its similarity to the oxy-fuel combustion power plant.

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