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Sensitivity analysis of oxy-fuel power plant system

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ABSTRACT

A comprehensive sensitivity analyses has been conducted to assess the performance of a purpose-designed 600 MW supercritical steam oxy-fuel bituminous coal-fired power plant system, which includes three modes for the recirculation of flue gas (RFG), *i.e.* dry, half-dry and wet. The assessment was conducted by considering the changes to eight major operating parameters, the flue gas acid dew point, and the fuel consumption rate. Optimization of the system was also considered to minimize the energy loss of the oxy-fuel process. The results suggest that air leakage exerts the largest impact on the output of the system. The half-dry RFG oxy-fuel system is the most practical due to its high efficiency and easiness in operation, compared with the other two flue gas recirculation modes. The acid dew point of the half-dry RFG system is about 10 °C higher than that of the dry RFG system and approximately 5 °C lowers than the wet RFG system. For the optimization purpose, the improvement in the turbine system through utilizing the thermal energy of the hot flue gas is of prime importance. By heating the feed water at the outlet of the secondary feed water heater upstream of the deaerator and cooling down the hot flue gas to a temperature which is 10 °C above its acid dew point, the net efficiency of an oxy-fuel process can raise by around 1.0%, which narrows the energy penalty to less than 10% compared to the reference air-firing system. This is smaller than an energy penalty of around 12% for the oxy-fuel process without the recovery of heat in the hot flue gas. It is also found that the efficiency elevation through the thermal integration with turbine system is greater for the wet model than the other two models. The oxy-fuel mode has a slightly larger net efficiency gain upon decreasing the fuel consumption rate from 600 MW to 300 MW.

1. Introduction

Global warming has been deemed a major threat to the existing way of life of mankind. According to International Energy Agency (IEA), 80% of the total world energy is derived from the combustion of fossil fuels. In 2013, the global CO_2 emissions due to fossil fuel use were 36 Giga Tons. This is 61% higher than 1990 (the Kyoto Protocol reference year) and 2.3% higher than 2012. The global CO_2 emissions in 2014 are projected to increase by an additional 2.5% over the 2013 level [1]. A variety of solutions has been proposed and is under development to mitigate CO_2 emission. Of those, a short-term option is the capture and sequestration of CO_2 (CCS) from power plant flue gas. Oxy-combustion (or oxy-fuel) technology is just one option for centralized power generation.

Oxy-fuel technology [2] is considered a feasible choice to reduce CO_2 emission from the coal-firing power plant through combining a conventional pulverized-coal-firing power plant (PC) with an air separation unit (ASU) and a flue gas treatment unit. The process of oxy-fuel combustion can be simply described as a process that eliminates nitrogen from the oxidant for the combustion of a fuel in either nearly pure oxygen or a mixture of high-purity oxygen and a CO_2-rich recirculated flue gas (RFG), resulting in a tail gas containing mainly carbon dioxide and water vapor. After the removal of water vapor via condensation, the remaining gases, including pollutants such as NO_x and SO_x (which can be removed before compression) are compressed to approximately 150 bars and transported for storage.

Due to the inclusion of ASU and CO_2 compression unit (CPU) processes, a cycle efficiency penalty occurs in oxy-fuel plant system. The cycle efficiency of oxy-fuel power plants is reduced by 9–13% points compared to conventional air-firing power plants [3,4]. For an oxy-fuel plant system, a net power output decreases by 25–30% and an electricity generation cost increases by 30–50% [5–7]. However, the economic feasibility of the oxy-combustion technology still holds with reasonable CO_2 tax, CO_2 sale price and policy rewards. Recently, some scholars found that

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Nomenclature

A	the energy loss per unit fuel consumption in the auxiliaries except the turbine	PF	primary fan
ASU	air separation unit	RFG	recirculated flue gas
B	fuel consumption rate	*Rc*-cold	flue gas recirculation rate for primary gas
CCS	capture and sequestration of CO_2	*Rc*-hot	flue gas recirculation rate for secondary gas
ESP	electrostatic precipitator	SF	secondary fan
FGD	flue gas desulfurization	TEG	triethylene glycol
FGU	flue gas treatment unit	*W*	the net output power of the system plus the energy loss of auxiliaries
HX	heat exchanger	*Q*	low heating value of the fuel
IF	induced fan	η	net electric efficiency of a power plant

membrane-based air separation unit can be used to reduce efficiency penalty significantly, by about 3–4% points [8].

Many studies have been conducted to assess the performance of oxy-fuel power plant. In a simulation of the whole oxy-fuel cycle with realistic boundary conditions using Aspen Plus™, the results from a thermodynamic and economic feasibility study on this process have been discussed, and research areas relevant for future process development were also identified [9]. In another similar study for a 300 MW oxy-fuel power plant using Aspen Plus™ where the emission of NO_x is considered [10], the process simulation results showed that replacing atmospheric air by a $21\%O_2/79\%CO_2$ mixture leads to the decrease on flame temperature from 1789 °C to 1395 °C and the equilibrium amount of NO_x declines obviously. Instead, the emissions of SO_x remain the same level. In another study employing both Aspen Plus™ and Thermoflex™ to model the pressurized oxy-fuel combustion power cycle [11], a sensitivity analysis was conducted to evaluate the influence of a variety of key operating parameters, including combustion temperature, outlet temperature of the heat recovery steam generator, oxygen purity from the ASU and the concentration of remaining oxygen in flue gas. Based on a 10 bar operating pressure and the high available latent enthalpy in flue gases, the proposed approach was found to achieve a net efficiency of 33.5% (HHV) or 34.9% (LHV) that is higher than the atmospheric counterpart. A cost analysis of the proposed system was also conducted. Using commercial programs GateCycle and Aspen Plus™, a supercritical power output of 460 MW has been built [12] and thermodynamic analysis and economic analysis were conducted to assess their oxy-fuel system. The optimized results suggest an efficiency reduction by only ~3.5% points. The oxy-combustion power plant could be economically comparable with a reference plant without carbon dioxide capture when the price of allowances falls between 34 and 41 €/tonne. For another process simulation of an 800 MW_{th} supercritical oxy-combustion pulverised-coal plant [7], the results showed that, the purity of CO_2 can reach $\geqslant$ 80% in the crude flue gas and 99% after flue gas treatment unit (FGU). The authors in [7] also discussed a number of critical parameters including RFG recycle ratio and the oxygen concentration from the ASU. It was found that a recycle ratio of 0.705–0.726 is optimum for cold flue gas recycle, whereas 0.617 is recommended for the hot recycle case; The CO_2 concentrations in flue gas reaches 84–92 mol% for cold recycle cases and 57–58 mol% for hot recycle cases, respectively; oxy-fuel cases have higher SO_x amount emitted but a much lower NO_x concentration in flue gas. To better understand the thermodynamic characteristics, an exergy analysis on the oxy-firing process has also been conducted [13]. Another study was conducted by examining five different scenarios for the recirculation of flue gas and the injection of oxygen at different locations in a boiler, leading to plenty of understanding and knowledge to proceed to the next step of large (100–350 MW_e) oxy-fired demonstration plants [14]. Special considerations were also given to lignite [15] and high-ash coal [16] for the application of oxy-fuel combustion to them. The results indicated that, the heat integration from every unit in the process is essential to lower as much as possible the efficiency penalty, and the use of CO_2 – rich flue gas to moderate flame temperature is beneficial in increasing the CO_2 concentration in boiler exit.

The concentration of SO_3 in flue gas is crucial for the cost and efficiency penalty related to flue gas treatment. Through experimental investigation, a rise of 20–30 °C for the acid dew point of oxy-fuel flue gas has been proposed [17]. Through measuring the concentration of SO_3 for the oxy-fuel combustion of three Australian bituminous coals in a 150 kg/h IHI combustion test facility [18], it is shown that the SO_3 concentration was approximately 2.5–3.0 times higher in oxy-fuel conditions than in the air-firing condition. To date, the concentration of SO_3 in flue gas and its influence on the performance of an oxy-fuel plant has not yet been considered.

Most of the published techno-economic literature mainly focused on the evaluation of different conceptions for oxy-fuel power plant system. However, attention has not been paid to assess the parameters that affect the operation of a practical power plant system. In the literature mentioned above, only the literature [14] conducted a brief analysis on the implementations of primary recirculated flue gas, secondary recirculated flue gas and the locations where oxygen could be introduced into the boiler. The analysis on all these implementations aimed for oxy-fuel burner design, whereas the influences of these implementations and coal mill system on the overall performance of the whole plant was not considered.

In this paper, a comprehensive sensitivity analysis has been conducted to evaluate the performance of three RFG types (dry, half-dry and wet) for a 600 MW_{th} oxy-fuel power plant system. A large size of 600 MW_{th} boiler was simulated here, considering that it can offer the supercritical steam condition to minimize the energy penalty related to air separation and CO_2 compression for an oxy-firing power generation. The effects of each system on the flue gas fan and the coal mill system were included. The other important influences such as the acid dew point, power consumption of various auxiliaries, and fuel consumption were also examined. For the variation on the power consumption of auxiliaries, the method of renormalization has been employed. Based on the results achieved for the influences of individual operating parameters, this study concludes with the overall optimization of the oxy-fuel power plant system.

2. Simulation methodology

The reference (air-firing) and oxy-fuel power plant systems were simulated using the professional thermal system design