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Exergy-based control strategy selection for flue gas recycle in oxy-fuel combustion plant

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HIGHLIGHTS

- The characteristics of the flue gas recycle system based on a 3 MW_{th} dynamic model were investigated.
- Two potential control schemes for the flue gas recycle process were proposed.
- Three typical types of disturbance tests were performed.
- Dynamic exergy evaluation was applied to evaluate the efficiency of the proposed control schemes.

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ABSTRACT

Control system design is one of the key elements which need to be studied before commercial implementation of oxy-fuel power plants. Among others, the control strategy for flue gas recycle process should be firstly considered as it is one of the major differences between oxy-fuel combustion and traditional power plants. In this paper, a dynamic model combined with exergy analysis was firstly proposed to design the control system and evaluate the performance of potential control schemes for flue gas recycle process. The dynamic model had been extensively validated using static and dynamic data from a 3 MW_{th} oxy-fuel combustion facility. Based on the dynamic model, the characteristics of the flue gas recycle system was investigated and two possible control configurations, **RR** (recycle valve coupled with recycle fan) and **SR** (stack valve combined with recycle fan), were proposed. The control performances of the two candidates were tested in three typical types of disturbances usually occurred in the operation and further evaluated from the perspective of exergy efficiency. It was shown that both control loops could maintain the target variables (flue gas recycle ratio and recycled flue gas pressure) stable in the disturbances, while the total exergy destruction of flue gas recycle system in **RR** is 2.4%, 1.7% and 0.6% higher than that in **SR** during the disturbance tests, respectively. The exergy-based control strategy selection method proposed in this paper provides good insight to obtain the optimum control method for other subsystems in the power plant.

1. Introduction

The concentration of CO_2 in the atmosphere has reached 394 ppm in 2012, which was about 40% higher than the level of the pre-industrial era, and the resulting greenhouse gas effect has become more and more serious [1]. It is suggested that carbon capture and storage (CCS) technology must be implemented to avoid this situation goes even worse under the premise of sustainable development of the social economy at current level [2]. Previous studies on oxy-fuel combustion, focusing on combustion characteristics [3–6] and pollutant formation mechanisms [7–9] as well as the evaluation of the economic feasibility of oxy-fuel combustion plants [10,11], had proved that it can be one of the feasible choices which can capture CO_2 economically in the near future.

In 2008, the first 30 MW_{th} oxy-fuel pilot plant was constructed at Schwarze Pump in Germany. So far, several test campaigns have been carried out on the facilities. The test results demonstrated that operation of oxy-fuel combustion technology is practicable and the goal of CO_2 capture had been accomplished [12–14]. The 30 MWe Callide oxy-fuel unit in Australia, which was the first retrofit application of oxy-fuel technology, is also capturing CO_2. To promote the development of oxy-fuel technology in China, a 3 MW_{th} full chain system (FCS) had been constructed in 2011 [15] and a 35 MW_{th} unit is ready for commissioning. In addition,

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the Spain CIUDEN oxy-fuel unit is the first circulating fluidized bed (CFB) application [16]. For commercial scale oxy-fuel power plants, Shenhua Group has just finished the feasibility study of a 200 MW oxy-fuel power plant in China and prepared to move into the next stage. Besides, the final investment decision of a 426 MW White rose oxy-fuel power plant will be made by the end of 2015 in UK and it is probably to start construction in 2016 [17]. All these projects have strongly demonstrated that the commercial implementation of oxy-fuel power plant is just around the corner. On the other hand, several problems still exist which inhibit the application of oxy-fuel technology, such as high investment cost and energy penalty [16]. Currently, the most feasible way might be designing flexible units that can be operated under both air-firing and oxy-fuel conditions. For the compatible oxy-fuel power plants, mode transition process from air-firing to oxy-fuel combustion is one of the most severe challenges which need to be overcome. Studies about the dynamics of transition process between air-firing and oxy-fuel combustion have been already discussed [18–21]. The results have indicated that a unit which can be operated under both air-firing and oxy-fuel conditions is feasible.

In oxy-fuel power plant, pure oxygen is used as oxidizer instead of using air, and flue gas must be recycled to the boiler in order to obtain similar combustion conditions as in air-firing case. The addition of flue gas recycle process, along with the oxygen injection, air separation unit (ASU), CO_2 compression and purification unit (CPU), are the major differences between oxy-fuel power plant and traditional power plant. Flue gas recycle ratio, i.e., the portion of flue gas recycled, is one of the key parameters that should be controlled in the flue gas system, which has a significant effect on combustion characteristics, such as adiabatic flame temperature, thermal radiation and thermal capacity [22]. Recycled flue gas pressure, at the outlet of recycle fan, is another important factor which needs to be controlled, as its fluctuations could lead to an adverse effect on the mixing process of recycled flue gas and oxygen supplied from ASU as well as coal transportation process. Therefore, to establish a control loop aimed at maintaining the flue gas recycle ratio and recycled flue gas pressure stable is of great significance under oxy-fuel operation condition.

Control loop design mainly focuses on selecting the best control scheme for paring manipulated and controlled variables. Several common methods, such as Relative gain array (RGA) and Niederlinski index (NI), have been developed for control loop design [23,24]. RGA analyzes the effect of a manipulated variable on one controlled variable and indicates which controlled and manipulated variables should be paired. NI will then be used to investigate whether or not the resulting control loops are stable based on the RGA analysis [24]. However, these methods only consider the controllability of a process and cannot evaluate the energy efficiency of the potential candidates.

Exergy is a significant concept in the thermodynamics. Exergy is defined as "the maximum theoretical useful work (shaft work or electrical work) obtainable as the systems interact to equilibrium, heat transfer occurring with the environment only" [25,26]. Exergy analysis could be used to determine the thermodynamic efficiency of a process; therefore, exergy analysis has been widely used in the analysis of process optimization [27–32]. However, the study combining exergy analysis with control strategy selection was seldom seen in the publications. Munir et al. [33,34] established an exergy eco-efficiency factor to further evaluate the control candidates based on exergy analysis and thus select the best control loop configurations with higher exergy efficiency. However, in his work, the exergy results in the dynamic simulation were simply calculated using steady state results with large errors. Moreover, the exergy evaluation factor could not be interpreted with a definite physical meaning. Therefore, an accurate calculation tool for exergy in dynamic simulation aiming at control system design and an evaluation factor with a clear physical meaning should be developed to select the best control loop. Ray et al. [35] developed a Matlab-simulink model to investigate different controllers by comparing the exergy destruction. The result showed that exergy destruction rates varied significantly even the energy consumption is similar, which indicated that exergy analysis is very useful and essential in control strategy selection.

In this paper, a dynamic model was developed based on a 3 MW_{th} oxy-fuel test facility using Aspen Plus Dynamics and validated with test data. The controlled and manipulated variables of the control system for oxy-fuel gas recycle system were then analyzed and the potential control configurations were proposed. The common technical methods for control loop assessment, i.e., RGA, NI, were preliminarily used to explore the feasibility of the possible control candidates. The potential control loops were tested in three typical types of disturbances usually occurred in the operation and further evaluated from the perspective of exergy. The exergy destruction of different control loops was compared and the most efficient control loop was selected.

2. Control system design

2.1. Process model development

An oxy-fuel power plant mainly consists of the air separation unit (ASU), boiler island and the flue gas compression and purification unit (CPU). ASU is used to produce high purity oxygen to support coal combustion instead of air, and CPU is used to compress the flue gas to obtain high purity CO_2 after removing moisture and other non-condensable components, e.g. N_2, Ar. As the main purpose of this study is to investigate the control system for flue gas recycle process of boiler island, the ASU and the CPU are not included for simplicity.

As shown in Fig. 1, the boiler island of 3 MW_{th} oxy-fuel combustion system mainly consists of boiler, air quality control system (AQCS) and flue gas recycle system. Unlike commercial power plant, this 3 MW_{th} oxy-fuel test facility does not include any steam, thus no turbine exists in this facility. The boiler is a refractory-lined furnace with two tube banks inside the furnace. The heat of flue gas is transferred to water through the tube bank 1 (TB1) located near the burner via radiative heat transfer, and further through the tube bank 2 (TB2) in the upper furnace via convective/radiative heat transfer. The flue gas then passes through tube bank 3 (TB3) in the rear of furnace, which functions as economizer, and finally the flue gas pre-heater before it leaves the boiler. The water from the cooling tower splits into three streams and goes to TB1, TB2 and TB3. After being heated by high temperature flue gas, the water goes out of the tube banks, merges and then goes back to the cooling tower. The AQCS includes a bag filter unit, a wet desulfurization unit and a flue gas condenser. The flue gas could flow to the atmosphere through the stack valve and stack, or recycle to the boiler through recycle valve and recycle fan, or go to the CPU when the CPU is in operation, which is in parallel with stack flue gas flow and recycled flue gas flow. For simplicity, the CPU is not studied in this paper. As shown in Fig. 1, the flue gas recycle system mainly consists of induced draft (ID) fan, recycle valve, stack valve and recycle fan.

In oxy-fuel combustion, most parts of the flue gas would be pre-heated in the pre-heater and then splits into two parts, i.e., primary air (PA) and secondary air (SA). The rest of flue gas remains cold to regulate the PA temperature. PA is used to dry and transport the coal; and SA is used to support coal combustion. The O_2 is injected into RFG ahead of burner, such that PA and SA are premixed oxidant.