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Dynamic simulation for mode switching strategy in a conceptual 600 MWe oxy-combustion pulverized-coal-fired boiler

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HIGHLIGHTS

- Dynamic model of a conceptual oxy-combustion PC boiler is established.
- Switching from air-combustion to oxy-combustion and then back is realized.
- Manipulating oxygen, air and RFG flows with different ramp rates is an effective way.
- The switching processes can be accomplished within 17 min.
- Dynamic behavior of material and energy flows during mode switching is gained.

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ABSTRACT

Oxy-fuel combustion as a promising CO_2 capture technology is ready for commercial demonstration. Dynamic simulation of oxy-combustion system, which is essential for gaining its dynamic characteristics, can help to evaluate and improve process design, and develop control system and operational strategies. This paper focuses on dynamic simulation of a 600 MWe oxy-combustion pulverized-coal-fired boiler. The steady-state model using a pseudo coal to substitute real coal is firstly established, validated, and then transformed into the dynamic model which uses pressure driven solution. Mode switching processes between air-combustion and oxy-combustion are particularly investigated for reasonable and effective switching strategy. It is found that manipulating oxygen and recycled flue gas streams with different ramp rates of corresponding valve positions during different switching stages while manipulating air stream with a constant ramp rate of air valve position throughout the switching process could be an effective switching strategy. The switching time of 17 min could realize a stable mode switching either from the air-combustion to the oxy-combustion or from the oxy-combustion to the air-combustion. The dynamic model provides powerful tool to study the dynamic behavior and mode switching characteristics of oxy-combustion boiler.

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1. Introduction

To mitigate the greenhouse effect on climate change, carbon capture and storage (CCS) technology is proposed as an effective way to reduce CO_2 emissions from power plants. Oxy-combustion technology, which now is ready for commercial demonstration, is one of the promising CCS options. In the oxy-combustion, a combination of oxygen with purity of typically 95 vol.% or higher from cryogenic air separation unit (ASU) and recycled flue gas (RFG) which mainly contains CO_2 and H_2O is used to replace air to combust with fuel. RFG with a typical recycle ratio (i.e. 70%) (which is defined as the volume-based ratio of the RFG to the sum of the RFG and the final flue gas exiting the boiler [1]) is used to moderate the adiabatic flame temperature. Because fuel burns in a N_2-lean and CO_2- and H_2O-rich atmosphere, the resulting flue gas consists primarily of CO_2 and water vapor, at the same time the NO_x emission reduces. CO_2 stream having a purity of about 96 vol.% or more can be obtained through compression and purification unit (CPU), which is ready for CO_2 storage and utilization.

The dynamic characteristics of oxy-combustion system, especially mode switching processes between air-combustion and oxy-combustion, are considered as challenges [2,3]. There are very limited researches conducted to seek for appropriate switching strategies and pick up valuable operational highlights on how to control RFG, oxygen and air streams. These researches reported in the literature can be divided into pilot experiment and process simulation. On the experimental front, several oxy-combustion

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pilot plants have been operated to get practical operational experience for commercial demonstration. Kluger et al. [4] provided some operation results of Vattenfall Schwarze Pumpe oxy-combustion pilot plant, where mode switching process from air-combustion to oxy-combustion was realized successfully within about 20 min. The Babcock & Wilcox company also reported the mode switching processes (from air-combustion to oxy-combustion and then back to air-combustion) of a 30 MW_{th} pilot project [5]. Although these operational results provided preferable benchmark for understanding the mode switching process, profound insight into the dynamic characteristics of the novel oxy-combustion power plant is still constrained due to the limits of experimental measurements.

A powerful way to identify comprehensive characteristics of a novel power plant is to apply steady-state and dynamic process simulations to this specific system. Steady-state simulation is an effective tool to help us understand the thermodynamic properties and operating conditions of specific systems. The steady-state simulation results can also be utilized to achieve more sophisticated thermodynamic analysis such as exergy analysis as well as thermo-economic analysis, optimization, and cost accounting [6]. On the other hand, dynamic simulation allows us to investigate the transient responses of a particular unit or a whole system to disturbances or operational variables, and thus provides general guidelines for the design, control, and operation of a process [7]. Dynamic simulation, when involved in the design phase, can also be used to identify the feasibility of process arrangement and the possibility of control structure and operational strategy. Moreover, it allows engineers to test alternative control strategies or operating schemes, operators to test "what if" scenarios, and workers to operate the process virtually. When applied to an existing process, it also can help to gain trade-off between steady-state optimization and dynamic operability [8]. Because of these outstanding advantages, dynamic simulation has played a significant role on the mode switching of oxy-combustion technology. Tourunen et al. [9] developed a time-dependent process model for an oxy-fired circulating fluidized bed (oxy-CFB) power plant, in which the simulation platform APROS™ was used to model the boiler while the commercial process simulation software Aspen Plus Dynamics focused on modeling of the ASU and CPU. Through this model, they studied the dynamic behavior of the oxy-CFB system during load change and mode switching. Using the same simulation software, Postler et al. [10] established dynamic process model of an oxy-fuel 250 MW power plant. They presented results of load change operation and the mal operation of RFG fan. And their next step is to integrate boiler model and CPU model developed in different simulation software. In addition, dynamic model of an 800 MWe coal-fired oxy-fuel power plant [11] was built by using integration of unique modeling package in Doosan Power system for simulating the boiler and Aspen HYSYS for modeling the ASU and CPU. They proposed that the key requirement for integrating these models is to define the boundary assumptions properly which include the specification of variables that will be passed between subsystems and the determination of independent or dependent systems within each calculation step of the overall process. Lappalainen et al. [12] rebuilt their oxy-CFB model [8] in APROS™ alone and the same studies were carried out. They draw the conclusions that control system has a central role to enable the operation of the integrated system in a safe and effective way and very tight coupling of subsystems (e.g. by heat integration) can make the operation more vulnerable to disturbances. On the other hand, method of mode switching process was also investigated. McDonald and Zadiraka [13] illustrated control requirements in an oxy-combustion system and important steps for mode switching. They concluded that increased dependence on oxygen measurement and control was required than in that of air-combustion mode. Stone et al. [14] proposed a boiler structure and method for mode switching from air-combustion to oxy-combustion. This work presented the startup procedure of oxy-combustion boiler starting from air combustion and the switching process from the view of engineering. Generally speaking, dynamic simulation in the literature did not provide sufficient details of control strategy and switching strategy to understand the dynamic characteristics of mode switching.

Aspen Plus Dynamics (AD) is widely considered to be a proper dynamic simulation tool for complex systems. It is at advantage of comprising large thermophysical property database of chemical substances and models that are required for calculating low-temperature gas behavior in expansion turbines, determination of combustion products, electrolytic effects in the condensers, and phase equilibrium in the phase separators and rectification processes. However, dynamic simulation of oxy-combustion systems using AD still faces enormous challenges. To the best of our knowledge, no dynamic simulation of oxy-combustion systems in this common platform was reported in the literature. The purpose of this paper is to explore the detailed and underlying dynamic behavior of mode switching through detailed steady-state and dynamic simulations of a conceptual 600 MWe oxy-combustion pulverized-coal-fired (PC) boiler. Based on these, mode switching strategy on how to manipulate oxygen, air and RFG streams is attained. In addition, dynamic simulation also provides useful information on the dynamic behavior of main material and energy flows for engineers and operators.

The structure of this paper is organized as follows. In Section 2, the steady-state model is firstly developed and validated by using an approximate method to solve the "coal" problem in Aspen Plus Dynamics (version 7.1). Then, the steady-state model is successfully transformed into the dynamic model in Section 3. The consistency between the dynamic model and the original steady-state model is checked. In Section 4, an effective control strategy for mode switching is proposed and dynamic characteristics of mode switching procedures (from air-combustion to oxy-combustion and then back to air-combustion) are analyzed in details. In Section 5, the effectiveness of the control strategy, the reason for choosing this switching strategy, and the limitations and possible developments of the dynamic model and control structure are discussed. Finally, conclusions and an outlook to future research are given in Section 6.

2. Steady-state model

The steady-state process simulation of a complete oxy-combustion power plant using Aspen Plus (AP) is still limited, because it is not specifically designed for process simulation of complex energy systems and its block-wise calculation may lead to a rather poor convergence performance [15]. We have previously carried out a steady-state process simulation for an 800 MWe supercritical oxy-combustion plant [16] and conducted a detailed exergy analysis of a 600 MWe oxy-combustion plant [17]. The configuration of a 600 MWe oxy-combustion system is based on the previous study [17]. In order to gain a relatively high-fidelity dynamic model which can only be developed if detailed design information is available [18], we modify the previous case according to experience from pilot plants [4,5,19–21] and air-combustion power plants. Fig. 1 presents the schematic of a 600 MWe oxy-combustion PC boiler island system, which mainly consists of five components, i.e., boiler (BOILER) for combustion process and heat transfer, flue gas cleaning unit (FGC) for removing water from flue gas and increasing flue gas temperature to overcome corrosion problems, recycled flue gas unit (RFGU) for recycling flue gas and distributing oxidant streams, oxygen unit (OXYGEN) and air unit (AIR) for feeding oxygen and air, respectively. In the

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