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Dynamic modeling and control for pulverized-coal-fired oxy-combustion boiler island

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ABSTRACT

Oxy-fuel combustion is one of competitive and promising carbon capture technologies for restraining CO_2 emissions from power plants. Dynamic simulation of oxy-combustion system, which is essential for gaining its dynamic characteristics, can help to evaluate and improve process design, and to develop control system and operational strategies. This paper focuses on dynamic simulation and control design for a conceptual 600 MWe oxy-combustion pulverized-coal-fired boiler. The steady-state model using a pseudo coal to substitute real coal is established, validated, and then transformed into the dynamic model which uses pressure-driven solution. The control system, which aims to automatically regulating flue gas O_2 concentration within reasonable range (2–7 mol.% in this study), is designed and applied to the dynamic boiler model. Three planned disturbances of load change, oxygen purity (from cryogenic air separation unit) ramp change and air in-leakage (from boiler) step change are conducted. Detailed dynamic behavior from water side and flue gas side is obtained and analyzed to help engineering operation in real plant. Mode switching process and alternative control strategy are simulated and discussed. Comprehensive dynamic model with specified control system provides possibility to study the dynamic characteristics of full-train oxy-combustion power plants.

1. Introduction

To mitigate the greenhouse effect on climate change, carbon capture and storage (CCS) technology is proposed as an attractive method for restraining anthropogenic CO_2 emissions from power plants. Oxy-combustion technology, one of promising pathways to capture enormous CO_2 from coal-fired power plants, is economic competitive and ready for commercial demonstration. It can be simply interpreted as a process that mixture of oxygen (typically 95 vol.% or higher) from cryogenic air separation unit (ASU) and recycled flue gas (RFG) mainly containing CO_2 and H_2O rather than air is used to combust with fuel. About 70% (the volume-based ratio of the RFG to the sum of the RFG and the final flue gas exiting the boiler (Davidson and Santos, 2010)) of flue gas is recycled to the boiler 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 gases consist primarily of CO_2 and water vapor, which then can be easily separated from CO_2 through condensation. 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.

Dynamic simulation allows us to investigate the transient responses of a particular unit or a whole system to disturbances

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Abbreviations: ACQS, air quality control system; AD, Aspen Plus Dynamics; AH, air heater; AP, Aspen Plus; ASU, air separation unit; AT1, 2, 3, spray water attemperators; BI_O$_2$, boiler inlet O_2; CC_O$_2$, flue gas O_2 control; CC_OXY, oxidant O_2 control; CCS, carbon capture and storage; CPU, compression and purification unit; DFG_O$_2$, dry flue gas O_2; ECO, economizer; ESP, electrostatic precipitator; FD, forced draft fan; FGC, flue gas cooler; FGD, flue gas desulphurization; FRH, final reheater; FSH, final superheater; ID, induced draft fan; IGCC, integrated gasification combined cycle; MBZ, main burner zone; MFT, master-fuel-trip; NC, non-conventional; NMPC, nonlinear model predictive control; NRTL, non-random-two-liquid; OFZ, over fired zone; PA, primary air fan; PC, pulverized-coal-fired; P_Furnace, furnace exit pressure; PO, primary oxidant; PO_O$_2$, primary oxidant O_2; PV, process variable; RFG, recycled flue gas; RH, reheater; SCR, selective catalytic reduction; SHPA, superheater panel; SHPL, superheater platen; SO, secondary oxidant; SO_O$_2$, secondary oxidant O_2; SP, setpoint; V-AIR, air inlet valve; V-CPU, flue gas to compression and purification unit valve; V-FW, feed water inlet valve; V-OF, over fired oxidant valve; V-OS, oxygen to secondary oxidant valve; V-OXY, oxygen inlet valve; V-PO, primary oxidant valve; V-PO$_2$, primary oxidant bypass valve; V-RFG, recycled flue gas valve; V-RS, reheat extraction flow inlet valve; V-SP1, primary spray water control valve; V-SP2, second spray water control valve; WFG_O$_2$, wet flue gas O_2; WW1, 2, water wall.

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1750-5836/

or operational variables, and thus provides general guidelines for the design, control, and operation of a process (Pottmann et al., 2011). When involved in the design phase, it 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 (Luyben, 1989). Because of these outstanding advantages, dynamic modeling and simulation for air-combustion and oxyfuel combustion power plants would be a powerful way to gain their dynamic characteristics and provide valuable information for operations. For air-combustion power plants, enormous papers (Liu et al., 2001; Flynn, 2003; Lu, 1999; Maffezzoni, 1997) can be found to identify their dynamic behavior. However, limited studies have been conducted on dynamic simulation and analysis of oxy-combustion power plants. These investigations reported in the literature can be divided into dynamic simulation and control. On the dynamic simulation front, several studies were conducted to gain the dynamic behavior of oxyfuel combustion power plants. Using an oxyfuel combustion power plant as an example, Engl et al. (2010) illustrated some challenges of integrating the model into the plant engineering workflow, and presented approaches for reduction and integration of models implemented in different simulation tools when applying dynamic simulation for plant engineering. Based on the same consideration and approach, dynamic simulation and analysis of oxyfuel CO_2 CPU (Pottmann et al., 2011) was conducted to study transient processes, to evaluate and improve process design concepts, and to develop control and operational strategies. Postler et al. (2011) established dynamic process model of an oxyfuel 250 MW power plant. They studied two unsteady simulation cases, namely load change operation from 60% to 100% with ramp rate of 2%/min and the mal-operation of RFG fan followed by a Master-Fuel-Trip (MFT). And their next step is to integrate boiler model and CPU model developed in different simulation software. Dynamic model of an 800 MWe coal-fired oxyfuel power plant (Kuczynski et al., 2011) 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. Chansomwong et al. (2014) investigated dynamic behavior of CO_2 CPU for an oxy-coal-fired power plant through their mathematical models in gPROMS. Although these studies provided fairly good references for comprehending how to build the dynamic model and which variables or scenarios should be investigated, they are not enough for fully understanding dynamic performance of oxy-combustion power plant. Therefore, more efforts are still needed on attaining its dynamic behavior and then providing practical information for real operation.

Dynamic simulation can also be widely used to develop control system to handle normal operation around the desired steady state. The designed control system can be used to resist unexpected disturbances for avoiding unnecessary emergencies, adjusting related actuators automatically to complete the required demand, and improving the operability and reliability of plants. Control system would be an indispensable component for a high reliable and robust oxy-combustion power plant because it is unrealistic for operators themselves to manipulate the actuators in a commercial scale plant. However, designing a control system for oxy-combustion power plant will be challengeable because combustion atmosphere and plant configuration are altered in boiler island. As gas specific heat capacity and density are increased in oxy-combustion, control strategies for stable combustion adapted in air-combustion might be required to make modification. In order to solve unstable combustion issue, a method (Yamada et al., 2013) that setting an amount of oxygen to be supplied to a boiler body on the basis of boiler load demand and controlling a recirculation flow rate of combustion exhaust gas on the basis of a heat absorption amount of the boiler body to control an oxygen concentration in all the gas guided into the boiler body was proposed. Then, owing to part of flue gas recycled to boiler for moderating the flame temperature, flexibility of control options and dependence on oxygen measurement and control (McDonald and Zadiraka, 2007) are increased than those of air-combustion. Different from air combustion, flue gas O_2 control and/or oxidant O_2 control (Hultgren et al., 2014) can be used to gain a reasonable combustion process. Like air combustion, flue gas O_2 control can be realized via the secondary pure O_2 or oxidant flow. For oxidant O_2 control, the first method (Hultgren et al., 2014) is the primary and secondary pure O_2 flows are used to control the respective O_2 content. Another one (Terushita et al., 2008) is the signal of boiler-brought-in oxygen concentration, which is an oxygen concentration for a total amount gases entered into boiler and calculated from measurements of composition and flow rates, can be sent to a flow control on RFG to keep this concentration within a prespecified range (25–30 wt.%). From these potential control strategies, choosing which one for the final control might need more investigations. In addition, coordinated control between different subsystems will be more complicated as the additions of ASU and CPU. Apart from these control concepts, which lay a favorable foundation for installing a feasible control system for oxy-combustion power plants, a nonlinear model predictive control (NMPC) system for a water-tube boiler system with oxy-fuel combustion process (Haryanto et al., 2008) to maintain the water and pressure levels in the drums, the steam temperature in the secondary superheater, and the oxygen percentage in the flue gas was proposed. To overcome the adverse effects and design a suitable control system for oxy-combustion power plants, model-based control system design for oxy-combustion power plant is required.

Aspen Plus (AP) and Aspen Plus Dynamics (AD) are widely considered to be proper steady-state and dynamic simulation tools for complex systems, respectively. They are 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. For dynamic simulation and control, several researches based on AD have been conducted on power plant likes integrated gasification combined cycle (IGCC). (Robinson and Luyben, 2008, 2010, 2011) The purpose of this paper is to explore dynamic behavior and control performance of a conceptual 600 MWe oxy-combustion pulverized-coal-fired (PC) boiler through detailed dynamic simulation and control system design using simulation tool AD.

The structure of this paper is organized as follows. In Section 2, the steady-state and dynamic models for control system design are established in AP and AD (version 7.1). Then, detailed control design procedures, based a systematic top-down analysis and bottom-up design method, for oxy-combustion PC boiler is presented in Section 3. Section 4 discusses the transient performance of oxy-combustion PC boiler based on designed control system through dynamic tests under load change process and planned disturbances of air in-leakage from boiler and oxygen purity (oxygen flows from ASU). In Section 5, mode switching strategy, alternative control strategy, and the limitations and possible developments for dynamic operation are discussed.