Dynamic Simulation and Control Design for Pulverized-Coal-Fired Oxy-Combustion Power Plants

Bo Jin, Haibo Zhao, and Chuguang Zheng

Abstract

Oxy-combustion is a technically feasible and economically competitive pathway for capturing CO_2 emissions from coal-fired power plants. However, it still faces with challenges for control and operation since combustion agents and plant configuration are altered. The paper focuses on investigating dynamic behavior and controllability of a pulverized-coal-fired oxy-combustion power plant through dynamic simulation and control system design which is based on a systematical top-down analysis and bottom-up design method. In the proposed control structure, feed-forward control structure for oxygen product purity in air separation unit, flue gas O_2 control structure for favorable combustion, cascade control loops for maintaining steam temperatures in boiler island, and double temperature control structure for CO_2 compression and purification unit are designed to obtain effective and safe operation. A high ramp rate (5 %/min) process is applied to validate the complex control system, and it is found that dynamic model runs smoothly and all the objective parameters are maintained around their setpoints or reached to a new steady-state value. Comprehensive dynamic model with specified control system provides guidelines for engineers to operate commercial oxy-combustion power plants.

Keywords

Oxy-combustion • Dynamic simulation • Control system design • Load change

1 Introduction

Oxy-combustion, as one of the promising carbon capture and storage (CCS) technologies for restraining CO_2 emissions from coal-fired power plants, is ready for commercial demonstration. It can be simply interpreted as a process that a mixture of oxygen from air separation unit (ASU) and recycled flue gas (RFG) primarily containing CO_2 and H_2O rather than air is used to combust with fuel, and then, high purity CO_2 products can be obtained from CO_2 compression and purification unit (CPU). However, its control and operation would face with challenges since combustion atmosphere alters from O_2/N_2 to O_2/CO_2, plant configuration becomes more complex, part of flue gas recycles, mode switches between air-combustion and oxy-combustion, and operation affects among subsystems. Fortunately, dynamic simulation can be helpful because it allows us to identify the transient responses of a particular unit or a whole system to disturbances and thus provides guidelines for design, control, and operation of a process [1].

From now upon, limited researches have been conducted to identify dynamic behavior and controllability of pulverized-coal-fired (PC) oxy-combustion power plants. Postler et al. [2] established dynamic process model of a 250-MW oxy-combustion boiler and studied two unsteady simulation cases. Kuczynski et al. [3] built dynamic model of an 800-MWe coal-fired oxy-combustion power plant using integration of unique modeling package in Doosan Power System for simulating the boiler and Aspen HYSYS

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for modeling the ASU and CPU. Jin et al. [4] firstly investigated mode switching strategy for a conceptual 600-MWe PC oxy-combustion boiler through dynamic simulation. Then, they improved the dynamic model, designed and validated the proposed control system, and studied its dynamic behavior under load change and air in-leakage from boiler and oxygen purity (oxygen flows from ASU) cases [5]. For further testing the feasibility of integrating CPU into oxy-combustion power plant, they also conducted dynamic simulation and control system design for CPU [6]. Nevertheless, sufficient information for understanding dynamic behavior and control performance of whole PC oxy-combustion power plant is not available.

Therefore, the paper aims to investigate process dynamics and control design for PC oxy-combustion power plants through dynamic simulation in commercial software Aspen Plus Dynamics. At the beginning, dynamic process model based on our previous studies is established through steady-state simulation, dynamic preparations (choosing driven approach, adding connections, and estimating equipment sizes), and exporting for dynamic simulation. Then, complex control system for the integrated PC oxy-combustion power plants is designed based on systematical top-down analysis and bottom-up design method. To validate the proposed control system, dynamic test is conducted under load change process between 100 and 80 % with high ramp rate of 5 %/min, and then, dynamic behavior for the integrated system is gained to help real operation.

2 Model Implementation

2.1 Process Description

Process flow diagram of a PC oxy-combustion power plant configured with two double-column ASUs, boiler island, and an auto-refrigeration CPU with two flash separators is shown in Fig. 1. For ASU, it mainly includes main air compressor (MAC), main heat exchanger (MHX), expander (EXP), high-pressure column (HP), subcooler (SUB), low-pressure column (LP), liquid oxygen pump (PUMP), and liquid oxygen storage drum (LOX) for producing oxygen products with purity of 95 mol%. For boiler island, combustion process with main burner zone (MBZ) and over-fired zone (OFZ), heat transfers in furnace including water walls (WW1 and WW2), superheaters (SHPA (superheater panel), SHPL (superheater platen), and FSH (final superheater)), reheaters (FRH (final reheater) and RH), economizer (ECO), and spray water attemperators (AT1, AT2, and AT3) are considered. Before flue gas entering into CPU, selective catalytic reduction (SCR), electrostatic precipitator (ESP), flue gas desulphurization (FGD), and flue gas cooler (FGC) are used to get pure flue gas enriched in CO_2. At the downstream of ESP, the induced draft fan (ID) is used to draw the combustion products through the boiler to the stack. The primary and secondary oxidant (i.e., PO and SO) streams are formed by RFG taken from the position at the exit of FGC and oxygen from ASU and drawn by primary air fan (PA) and forced draft fan (FD), respectively. The oxidant mixtures will gain heat from hot flue gas crossing the air heater (AH). With respect to CPU, the feed flue gas is compressed through a multistage CO_2 compressor (MCC) with intercoolers to 30 bar and then entered into cold box which consists of two multistream heat exchangers (E1 and E2), two flash separators (F1 and F2), and two throttle valves (LCV-114 and LCV-119) for gaining 96 mol% or more purity CO_2 products.

2.2 Steady-State Model

To establish process model for PC oxy-combustion power plant, necessary assumptions for three subsystems are presented as follows.

In ASU, (1) MAC is represented by multistage compressor model for compressing air to the designed pressure, while expander (EXP) produces efficient refrigeration generation for distillation process. (2) Main heat exchanger (MHX) ensures that oxygen product leaves the cold box at a temperature close to that of feed air entering the cold box. (3) Two distillation columns and condenser–reboiler (COND-REB) are simulated through two RadFrac columns for producing oxygen products with purity of 95 mol%. (4) Subcooler (SUB) minimizes the flash losses as refluxes enter the LP column and transfer heat to the waste stream. (5) Liquid oxygen pump (PUMP) is used for boosting liquid oxygen product pressure to the required value by considering the necessary pressure drops occurred in MHX, valves, and pipelines. (6) LOX for storing liquid oxygen liquefied by oxygen liquefier (LIQ) and releasing gaseous oxygen to achieve energy storage or POP operations. With respect to CPU [6], MCC is represented by multistage compressor model to moderate system pressure and drive flue gas, multistream heat exchangers (E1 and E2) by MheatX models to identify heat transfer in cold box, and two flash separators (F1 and F2) by flash models to reflect CO_2 separation process, respectively.

As discussed in our previous study [5], the following assumptions are considered in boiler island. (1) RGibbs reactor models are selected to represent macrocombustion phenomena in MBZ and OFZ, where only gas phase reactions are considered. (2) Heat transfer among water, flue gas, and oxidant streams is represented by MHeatX model which mainly includes WW1, WW2, SHPA, SHPL, FSH, FRH, RH, ECO, and AH. According to operating principle of spray water attemperators, mixer models are used to describe

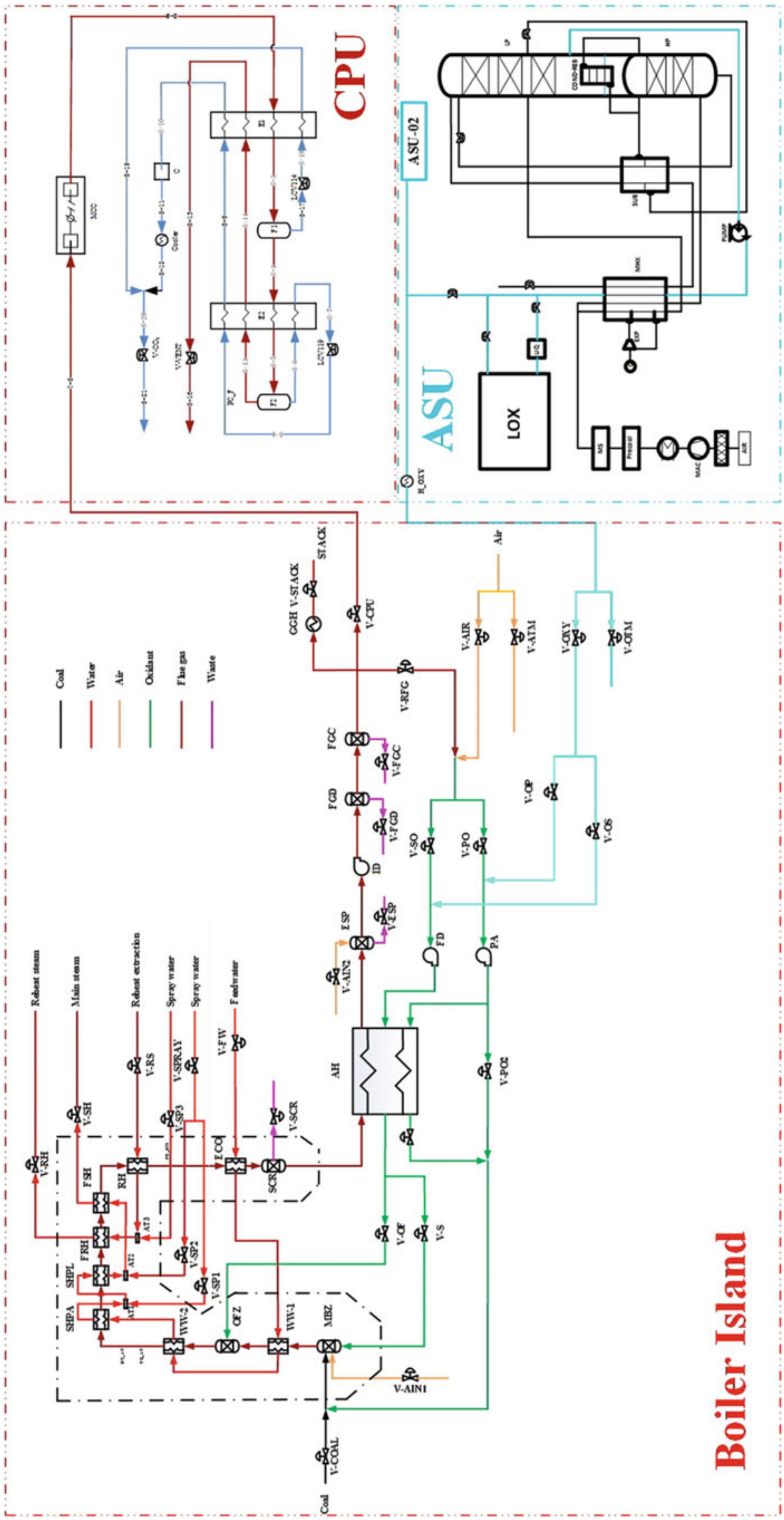

Fig. 1 Schematic diagram of the studied PC oxy-combustion power plant

their physical processes. Gas–gas heater (GGH) is represented by a heater model to increase flue gas temperature to overcome corrosion problems. (3) In air quality control system (AQCS), Sep2 models are considered for representing SCR, ESP, FGD, and FGC processes. For SCR, 90 % of NO_x produced from combustion process are set to be removed. As SiO_2 is the main component, it is considered as ash, which is removed via ESP and does not affect the combustion and heat transfer. 98 % of SO_x from boiler are eliminated in FGD process. Because dry recirculation is considered in this oxy-combustion PC boiler model, FGC process is adapted to remove the condensed water. (4) Three fans (ID, FD, and PA) are considered using integration of compressor and heater models to reflect drawing flue gas processes. (5) The air in-leakage is supposed to be 2 % of flue gas that 1/3 from boiler and 2/3 from ESP.

2.3 Dynamic Model

To develop dynamic model, the details on the preparations for converting steady-state model to dynamic model are explained as follows. Firstly, dynamic simulation type should be determined according to the purpose of research. Flow driven and pressure driven are two main types for dynamic simulation in this software. Pressure-driven modeling approach is selected for this dynamic simulation to identify more rigorous dynamic performance. Then, the geometric sizes of equipment are estimated using some approximate methods [7, 8] to represent dynamic characteristics and controllability of equipment, and some connections (valves, pumps, and compressors) are also added. For heat exchangers, an approximate volume for their inlet and outlet on a given side can be calculated from Eq. (1), while diameter for flash separators can be estimated from "F-Factor" method.

$$V = t_{\mathrm{R}} \times v_{\mathrm{SS}} \tag{1}$$

where V means volume, t_{R} represents residence time, and v_{SS} illustrates steady-state volumetric flow rate. With respect to two distillation columns with structured packing (Mellapak Plus, Standard, 252Y), rigorous hydraulic calculations are enabled and rating specifications are configured based on parameters provided from Sulzer Chemtech in the software database. Moreover, heat operation is completed through two equations (Eqs. (2) and (3)) in which reboiler heat duty equals to condenser heat duty, while the medium temperature in condenser equals to the reboiler temperature.

$$Q_{\mathrm{Reb}} = -Q_{\mathrm{Cond}} \tag{2}$$

$$T_{\mathrm{Cond-med,HP}} = T_{\mathrm{Reb,LP}} \tag{3}$$

Then, initial dynamic models without any control loops are established for control system design and dynamic tests.

3 Control System Design

A systematical top-down analysis and bottom-up design method [9] are used to design control structure for oxy-combustion power plant. Here, top-down analysis includes setting control objectives, defining manipulated and measured variables, and determining production rate, while bottom-up design consists of designing basic control loops such as flow, pressure, and level in regular control layer and considering cascade and ratio control loops in supervisory control layer. At the beginning, required control objectives should be achieved as follows.

(1) For ASU, oxygen product purity in oxygen product must be 95 mol%, while oxygen product flow rate must be at the required quantity. The liquid oxygen level in LP reboiler must be maintained between high and low limits. ASU must be able to handle different ramp rates during load change and mode switching processes since oxygen product is supplied to oxy-combustion power plant. For efficient and economical operation, control system must complete flexible operations.

(2) To gain a stable combustion in boiler, flue gas O_2 concentration is often selected as control objective for representing combustion level. Furnace pressure is kept for slight negative pressure operation on flue gas side, while steam (main and reheat steam) temperatures should be maintained at their setpoints (SPs) since variable pressure operation for once-through boiler is adopted in this study. In addition, engineering tasks including mode switching processes between air-mode and oxy-mode, load change, and operational disturbances should be accomplished under the designed control system.

(3) In CPU, CO_2 product purity must be maintained around its SP or above 96 mol%, while CO_2 recovery rate is expected to be kept at its initial value or above 90 %. Moreover, stream temperatures at liquid line after LCV119 must be maintained around their SPs or greater than CO_2 freezing point.

Then, inputs and outputs are figured out in Table 1 to identify manipulated variables and controlled variables. Production rate should be determined because it has significant effects on control structure [10]. Feed water flow rate is selected as production rate since it reflects the requirement of load demand from steam cycle operation.

After finishing the above procedures, Fig. 1 shows the proposed PID-based control structure for PC oxy-combustion power plants in dynamic process model when regulatory control layer and supervisory control layer are configured as follows.

Table 1 Lists of key inputs and outputs

Input	Output
ASU	
Airflow rate	Oxygen product purity
Expanded airflow rate	Liquid oxygen level
Liquid oxygen	LP column pressure
Oxygen product for supply	HP sump level
Boiler island	
Coal flow rate	Wet flue gas O_2 concentration
Feed water flow rate	Furnace exit pressure
Reheat steam	Main steam temperature
Recycled flue gas flow rate	Reheat steam temperature
CPU	
Flue gas flow rate	CO_2 product purity
MCC discharge pressure	CO_2 recovery rate
F1 temperature	Stream temperature after LCV119
F2 temperature	

(1) To satisfy the requirements of oxygen supplying and flexible operations for energy and economic savings, feed-forward control structure is applied to the designed double-column ASU. Flow rates for feed air, expanded air, oxygen product for supply, and liquid oxygen should be controlled by the corresponding flow control loops, while LP column pressure should be controlled via pressure control loop in regulatory control layer. In supervisory control layer, oxygen product purity is maintained around SP through a cascade control loop in which dead time is considered in the primary composition control loop and secondary control action is sent to the ratio of feed airflow rate to liquid oxygen product flow rate. To keep liquid oxygen level between high and low limits, a cascade control loop where the primary control signal sends to the ratio of expanded airflow rate to liquid oxygen product flow rate is applied, in which liquid level is maintained by manipulating the speed of expander for regulating the produced refrigeration.

(2) In boiler island system, flue gas O_2 control structure [5], which means oxygen concentration in wet flue gas is controlled through manipulating total oxygen flows from ASU, is adopted to ensure favorable combustion process in furnace. For regulatory control layer, steam controls, firing rate controls, and gas distribution controls are included in flow control loops, while furnace pressure control is realized though adjusting the brake power of ID. With respect to supervisory control layer, team temperature control is accomplished through manipulating spray water attemperators in which AT1 and AT2 are used for regulating main steam temperature and AT3 is configured for adjusting main steam temperature.

(3) For maintaining CO_2 purity and avoiding CO_2 freezing point in CPU, double temperature control structure (DTC) designed in our previous study [6] is employed here. In the DTC, flue gas flow rate, liquid levels in flash separators, CO_2 product flow rate, and system pressure are controlled by the corresponding control loops in regulatory control layer. Two composition control loops (CO_2 product purity and CO_2 recovery rate) and two temperature control loops are considered in supervisory control layer. CO_2 product purity is maintained through a cascade controller where dead time is considered in primary control loop, and secondary control action is sent to system pressure controller, while temperature control is achieved via cascade control on the corresponding throttle valve. In addition, a cascade and feed-forward control loop is set for keeping CO_2 recovery rate (Fig. 2).

4 Validation

Dynamic simulation under high ramp rate is chosen to validate the feasibility and reliability of the designed control system since it occurs frequently during load change and mode switching processes. Ramping process from 100 to 80 % with a high rate of 5 %/min is applied to dynamic models, and key parameters such as oxygen product purity, liquid oxygen level, oxygen concentration in wet flue gas, main steam temperature, reheat steam temperature, CO_2 product purity, CO_2 recovery rate, and stream temperature at liquid line after LCV119 are monitored to identify their dynamic behavior. Figures 3, 4, 5, 6, 7, 8, 9, 10 and 11 show dynamic responses of key operating parameters under scenario that 20 % load ramping begins at 20th min and ends at 24th min, in which PC oxy-combustion power plant runs successfully and smoothly under dynamic test with this high ramp rate, and all the interested variables evolve around their corresponding SPs or switch to a new steady state.

As shown in Figs. 3 and 4, ASU manifests favorable dynamic performance for key operating parameters. Although some oscillations occurred, oxygen product purity is maintained around 95 mol%, while liquid oxygen level in LP is kept at 3.75 m during high ramp rate (5 %/min) process.

Figures 5, 6, 7 and 8 show dynamic responses of flue gas O_2 concentration and furnace exit pressure from flue gas side and steam temperatures from water side. In flue gas side,

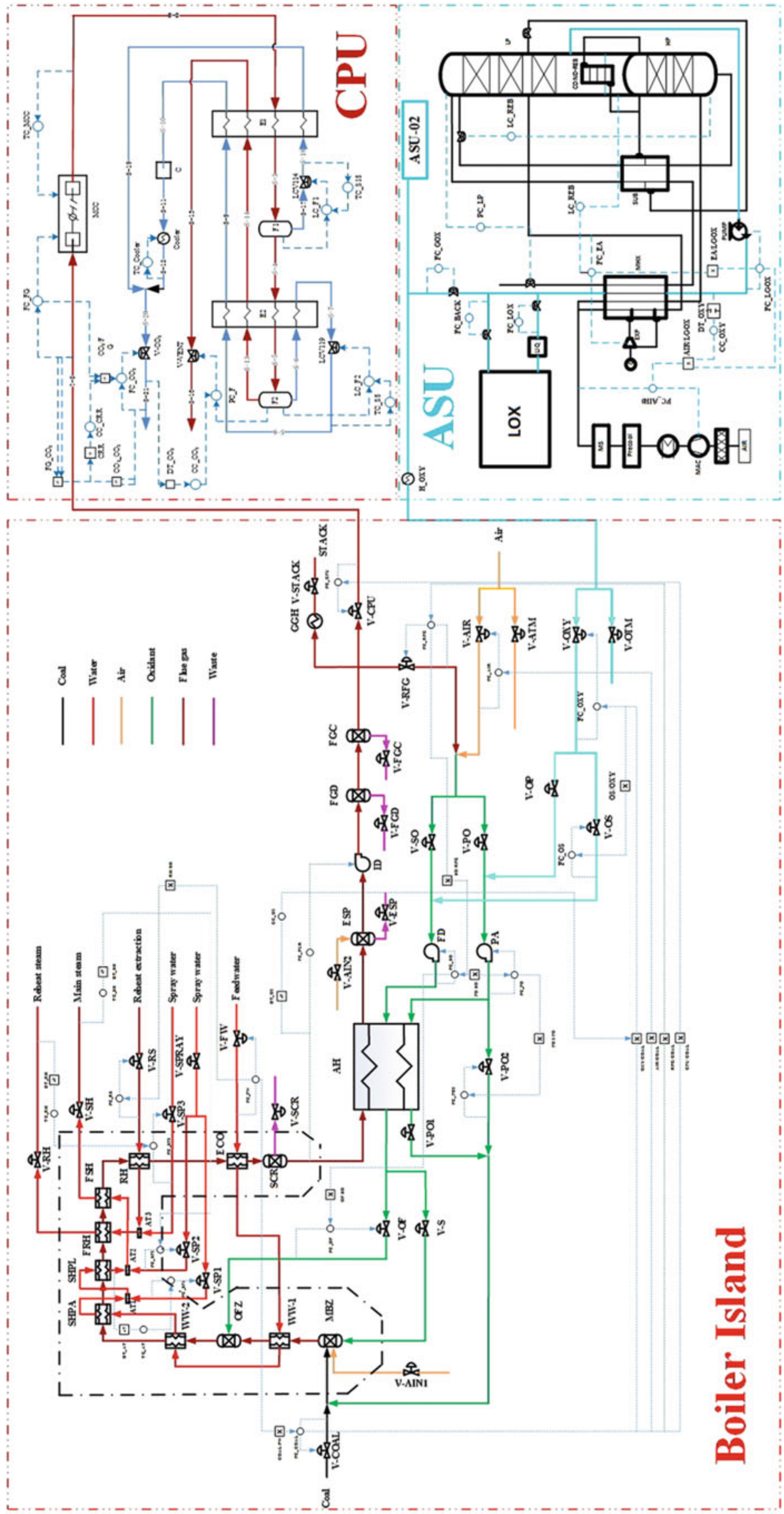

Fig. 2 Dynamic model for PC oxy-combustion power plants with the proposed control system

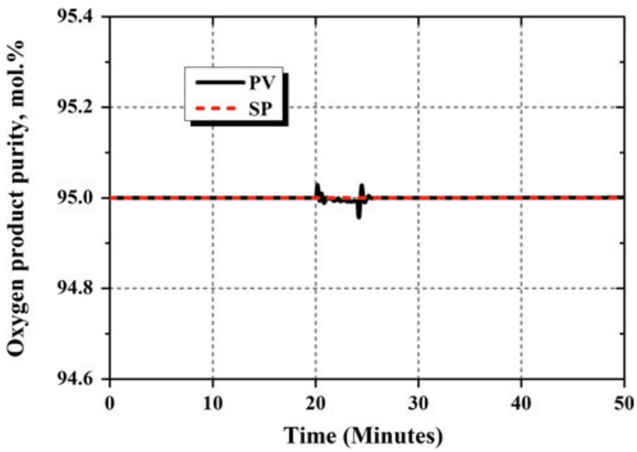

Fig. 3 Oxygen product purity

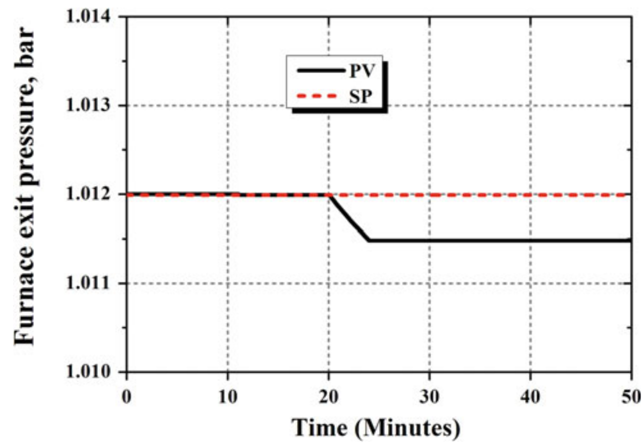

Fig. 6 Furnace exit pressure

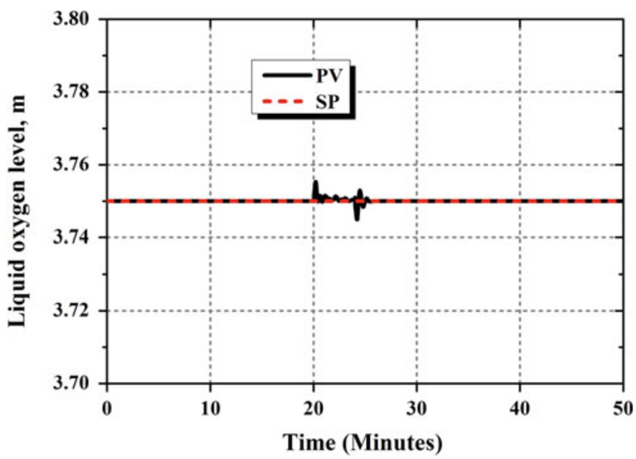

Fig. 4 Liquid oxygen level in LP

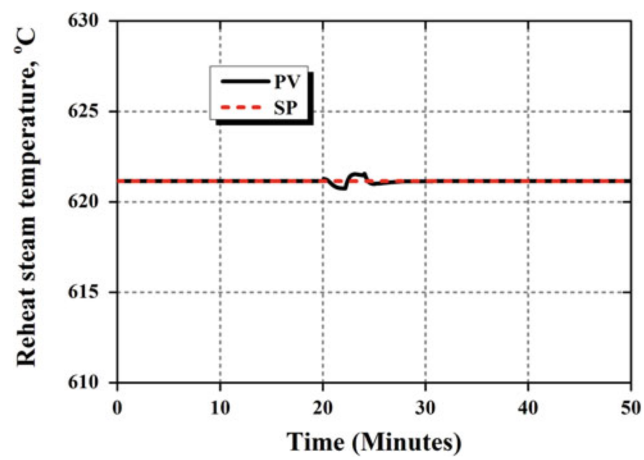

Fig. 7 Reheat steam temperature

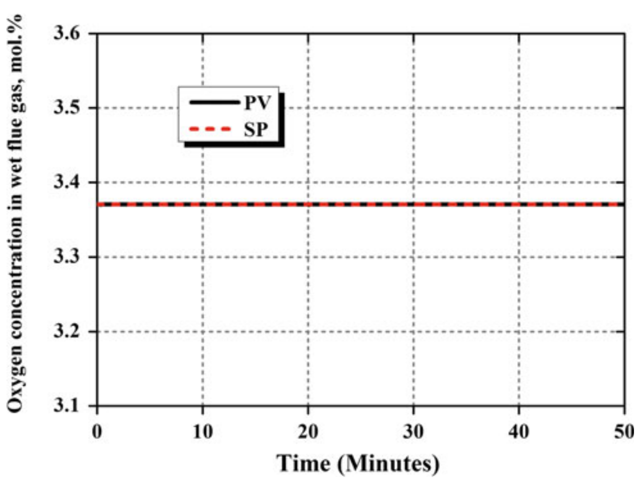

Fig. 5 Oxygen concentration in wet flue gas

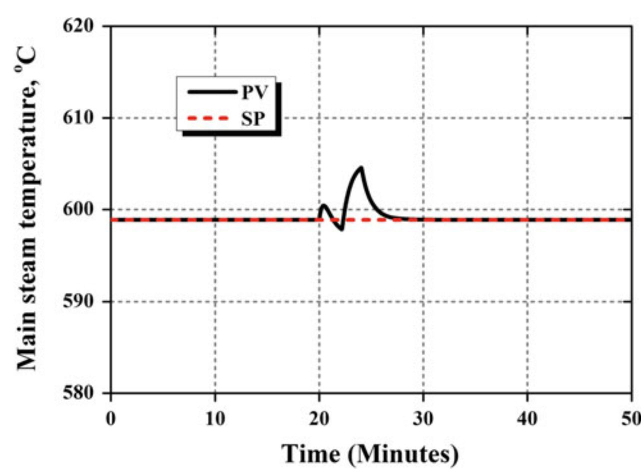

Fig. 8 Main steam temperature

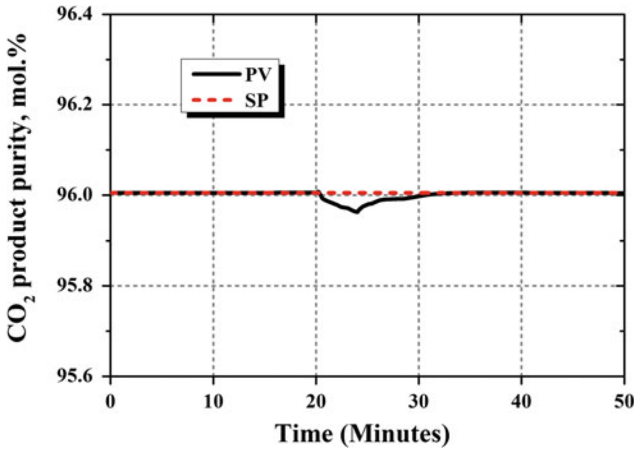

Fig. 9 CO_2 product purity

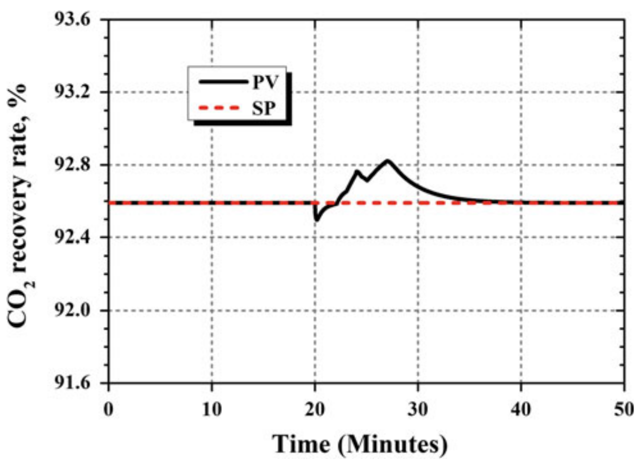

Fig. 10 CO_2 recovery rate

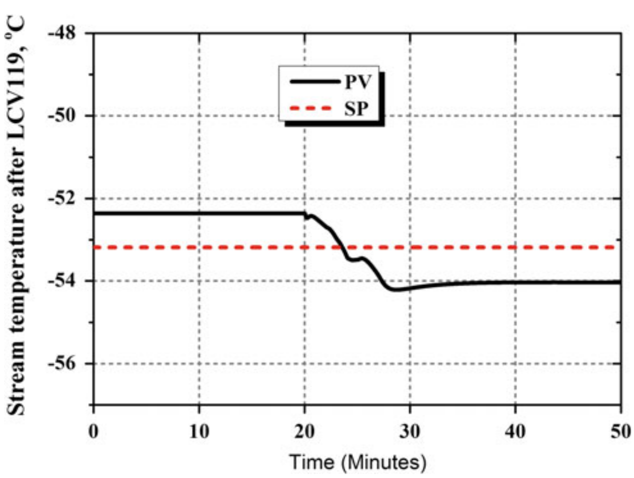

Fig. 11 Stream temperature at liquid line after LCV119

oxygen concentration in wet flue gas is maintained at 3.34 mol% through adjusting total oxygen flow rate from ASU, while furnace exit pressure appears slight decrease in ramp fashion. From water side, steam temperatures are kept around their SPs in which main steam temperature and reheat steam temperature are 598.89 and 621.11 °C, respectively. Additionally, the magnitude variation of reheat steam temperature is smaller than that of main steam temperature because the maximum offset for main steam temperature is about 5 °C while that of reheat steam temperature is 0.5 °C.

For CPU, CO_2 product purity, CO_2 recovery rate, and stream temperature at liquid line after LCV119 are monitored as shown in Figs. 9, 10 and 11. CO_2 product purity decreases during ramping down process and then spends about 6 min returning back to its SP at 96 mol%. Differently, CO_2 recovery rate appears in an opposite direction that it increases from 20th to 24th min and then reaching back to SP at 92.60 % after 11 min. More importantly, temperature attains favorable performance since its value is always above −56.57°C which is the critical point for avoiding CO_2 freezing in the second heat exchanger.

5 Conclusion

Dynamic simulation and control structure for a pulverized-coal-fired oxy-combustion power plant are studied to gain its transient behavior. For obtaining reasonable dynamic model with certain accuracy, necessary assumptions and considerations are applied. In the proposed control system, different control objectives should be implemented for air separation unit, boiler island, and CO_2 compression and purification unit. For air separation unit, oxygen product purity and liquid oxygen level should be maintained. Furnace pressure and flue gas O_2 content should be kept for stable combustion in flue gas side, while main steam and reheat steam temperatures are held around the design value in water side. With respect to CO_2 compression and purification unit, CO_2 product purity, CO_2 recovery rate, and stream temperature are stayed around their setpoints or in a reasonable range. Dynamic model with the designed control structure is validated successfully under high ramp rate (5 %/min) process, in which dynamic run is smooth and all the targets are achieved. Oxygen product purity, flue gas O_2 content, CO_2 product purity, and CO_2 recovery rate vary around 95, 3.34, 96, and 92.60 mol%, respectively. The research promotes the understanding of dynamic operation of pulverized-coal-fired oxy-combustion power plant and provides enormous dynamic information for engineers to help commercial operation.

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