



Plantwide control and operating strategy for air separation unit in oxy-combustion power plants



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ABSTRACT

To ensure that air separation unit can bear high ramp rate and flexible operations when integrated into oxy-combustion power plant, this paper focuses on the investigations of plantwide control design and operating strategy for double-column air separation unit without or with liquid oxygen storage drum through dynamic simulation. It is found that three air separation unit types (normal, oversize, and downsize) with the proposed control structure configured with logic control loops (strategies 1, 2, and 3) can achieve 5%/min of high ramp rate and flexible operations such as peak and off-peak or/and energy storage. Compared between the latter two logical controls, strategy 2 would be better because its oxygen product qualities can be maintained closer to their targets. Three integrated patterns between air separation unit and oxy-combustion boiler are proposed to improve operating flexibility, among which oversize case would be more suitable for oxy-combustion power plant since its energy saving (20.33 MW) is larger and operating strategy is more flexible than those in downsize (10.76 MW) and normal cases. Process control for flexible operations would be an opportunity for engineering, and comprehensive dynamic model with specified control system provides possibility to integrate air separation unit with full-train oxy-combustion power plants.

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1. Introduction

Carbon capture and storage (CCS) technology is proposed as an attractive and effective method for mitigating greenhouse effect on climate change since it can restrain enormous CO₂ emissions from fossil fuel fired power plants. Generally, CCS can be divided into three main categories: post-combustion, pre-combustion (e.g., integrated gasification combined cycle, IGCC), and oxy-combustion. For oxy-combustion, it is considered as a technically feasible and economically competitive pathway even though more energy consumption [1] and economic cost [2] result from the additions of CO₂ compression and purification unit (CPU) and air separation unit (ASU). Among the current air separation technologies [3] such as adsorption, chemical processes, polymeric membranes, ion transport membrane (ITM), and cryogenic ASU, the latter is considered as the only available commercial technology to produce large scale oxygen products for oxy-combustion application [4]. To satisfy the demand of oxy-combustion, oxygen product should be large volumes (7000–9000 tpd oxygen for 500 MW oxy-combustion power plants) [4], low pressure

(1.2–1.7 bar) [4], relatively low purity (95–99 mol.% compared to the conventional oxygen products with purity of 99.6 mol.% or more) [5] and no demand for any significant quantity of other products (N₂, Ar, or liquid products) [6]. Apart from its typical characteristics [7], ASU for oxy-combustion should also be able to bear load following which occurs frequently in power plants [8], fast ramp rate during mode switching process between air-combustion and oxy-combustion [9], operating flexibility at peak time and off-peak time (POP) [10] or energy storage [11] for efficient and economical operation, and robust control for integration into oxy-combustion power plant. More importantly, reducing energy consumptions and minimizing capital and operation costs would be the primary driving force for ASU technology development [4], which will then reduce the efficiency and cost penalties in oxy-combustion power plants.

Cryogenic ASU, as a mature technology for separating oxygen, nitrogen, argon or other rare gases from air, has been extensively investigated. For conventional cryogenic ASU, researches on process modeling, exergy assessment, control and optimization have been conducted for studying its self-characteristics and applications. Roffel et al. [12] developed first principle dynamic model of cryogenic distillation process to identify its dynamic behavior and controllability. Cornelissen and Hirs [13] conducted exergy analysis for cryogenic ASU to find energy saving potentials.

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Trierweiler and Engell [14] discussed the control structure selection for ASU through the robust performance number (RPN). Vinson [15] reviewed the control challenges, recent developments and future directions for high performance process control in ASU. Xu et al. [16] proposed an automatic load change system for ASU to automatically and rapidly respond to the changing product demand from customers. When it is used for IGCC and oxy-combustion to capture CO₂ emissions from power plants, studies have been carried out to make it more suitable and safe for these applications. In terms of IGCC application, it mainly aims to optimize plant configuration, reduce energy consumption, and design new ASU and its corresponding control system for satisfying load following capacity and economical operation. For optimal design and integration of an ASU with pumped liquid oxygen into IGCC power plant with CO₂ capture, Jones et al. [17] compared power savings for five different ASU configurations and studied effects of air integration on optimal ASU operating pressure. Van der Ham and Kjelstrup [18] compared a double-column and three-column cryogenic ASUs through exergy analysis for identifying their exergy destruction distributions. Then, Van der Ham [19] further investigated effects of adding heat-integrated stages and hot heat exchanger on exergy performance for a double-column ASU. Mahapatra and Bequette [20] mainly focused on process design and control for an elevated-pressure ASU to investigate feasibility and applicability of high ramp rate demands whilst maintaining oxygen product purity. In order to dynamic maximize oxygen yield during load change or/and disturbances, they further proposed a multiple model predictive control (MMPC) algorithm [21]. Roh and Lee [22] designed a self-optimizing control structure for an elevated-pressure ASU in IGCC power plant to operate economically.

When applying to oxy-combustion, investigations focused on novel plant configurations, energy savings and flexible operations. For a new ASU, several process configurations were proposed and compared when considering different factors such as safety, reliability, operating flexibility, efficiency, and low capital cost [23]. Different from the above-ambient distillation, heat pump distillation (a sub-ambient case) would be another new method for producing large scale oxygen with less energy penalty [24]. To reduce energy penalty, urgent requirements for searching potential energy savings in ASU and proposing concepts for heat integration between ASU and oxy-combustion power plant were raised. Based on exergy evaluation, plant performance for ASU can be improved through changing flowsheet structure and decreasing large exergy destruction occurring in compression and distillation [25]. Heat integration method is mainly to transfer heat duty from ASU compressor to other subsystems, either directly (feed water preheating) or indirectly (oxygen preheating, coal drying, or heating any fluid of oxy-combustion system) [4]. When considering compression duty in ASU for preheating boiler feed water, thermal efficiency for oxy-combustion would increase about 0.38% for conventional three-stage compressor and 0.47% for adiabatic stage compressor [26]. On ASU operation with power plant front, it becomes flexible and some corresponding strategies were proposed. The first method is phase CO₂ capture, in which the boiler is periodically operated in air-fired mode and oxy-fired mode whilst keeping ASU at constant load [11]. The second approach is energy storage [11] or peak and off-peak (POP) operations [10], in which the core strategy is to produce and store oxygen during off-peak period whilst to stop or turn down ASU during peak period. From these strategies, it is found that ASU size can be moderated, capital and operating costs would be reduced, and operation flexibility is improved, even though the net efficiency of power plant might be debased. These studies promote the understanding and development of ASU for matching with oxy-combustion application.

However, there are still some challenges for control and operation in ASU. In the first place, boiler usually operates at a ramp rate of up to 6%/min whilst ASU bears a ramp rate of 3%/min at maximum and an operation range of 60–105% [27]. Meanwhile, an oxy-combustion power plant usually starts up from air-fired mode, then switches to oxy-fired mode after operating steadily in air-fired mode, and shuts down with air-fired mode [28]. Due to these inherent properties of oxy-combustion power plant, how to maintain oxygen product purity whilst meet strict demand of high ramp rate during load change [8] and mode switching [9] processes becomes a key issue for ASU. Then, increased renewable penetration in electrical grid and the addition of ASU lead to more flexible operating strategies for oxy-combustion power plants [29]. Thus, measures to grasp the opportunity for improving operation flexibility of oxy-combustion power plants should be taken. On the other hand, to realize flexible operations would lead to challenges for process control in ASU and power plant [10]. Hence, it is essential to design suitable control structure and identify operating strategy in ASU. From now upon, researches for conquering these aforementioned challenges are still very limited.

Based on these considerations above, this study aims to identify process design, control strategy, and flexible operations for ASU in oxy-combustion power plants using steady-state and dynamic simulations. At the beginning, process configurations for three ASUs including normal, oversize, and downsize cases are firstly designed and modeled through Aspen Plus and Aspen Plus Dynamics (version 7.1) in Section 2, since different operating requirements for ASU are presented in oxy-combustion power plants. Control structures for these ASUs are then designed according to a systematic top-down analysis and bottom-up design method, and are validated through high ramp rate process commonly occurring in power plants. Based on the designed control system, different integrated patterns between ASU and oxy-combustion power plants are proposed and operating strategies for flexible operations (POP and energy storage operations) are investigated. Then, limitations, improvements and comparison with other studies are discussed in Section 5. Finally, a conclusion is given in Section 6.

2. Process design and model development

2.1. Process design

Double-column ASU with pumped liquid oxygen (shown in Fig. 1) is adopted here for oxygen production since it still provides an optimal balance between efficiency and cost [23], whilst liquid oxygen storage tank (LOX) [30] is chosen for the storage of liquid oxygen product. The following calculation procedures show detailed information to complete process designs for three ASUs.

- (1) The demand of oxygen product quality including pressure (P_{O_2}), purity (A_{O_2}) and flow rate (M_{O_2}) can be obtained from oxy-combustion boiler operation.
- (2) From oxygen product purity and flow rate, the required amount of feed air (M_{air}) to be provided can be calculated according to oxygen recovery rate equation: $\gamma = \frac{M_{O_2} \times A_{O_2}}{M_{air} \times A_{air}}$, where γ and A_{air} mean oxygen recovery rate and oxygen concentration in air, respectively.
- (3) Based on oxygen product pressure, the operating pressure for low pressure column (LP) bottom stage ($P_{LP,b}$) can be gained, which is then used to calculate the temperature at this stage ($T_{LP,b}$) through combining with the bubble point of oxygen product using Peng–Robinson equation of state for thermodynamic property calculation.

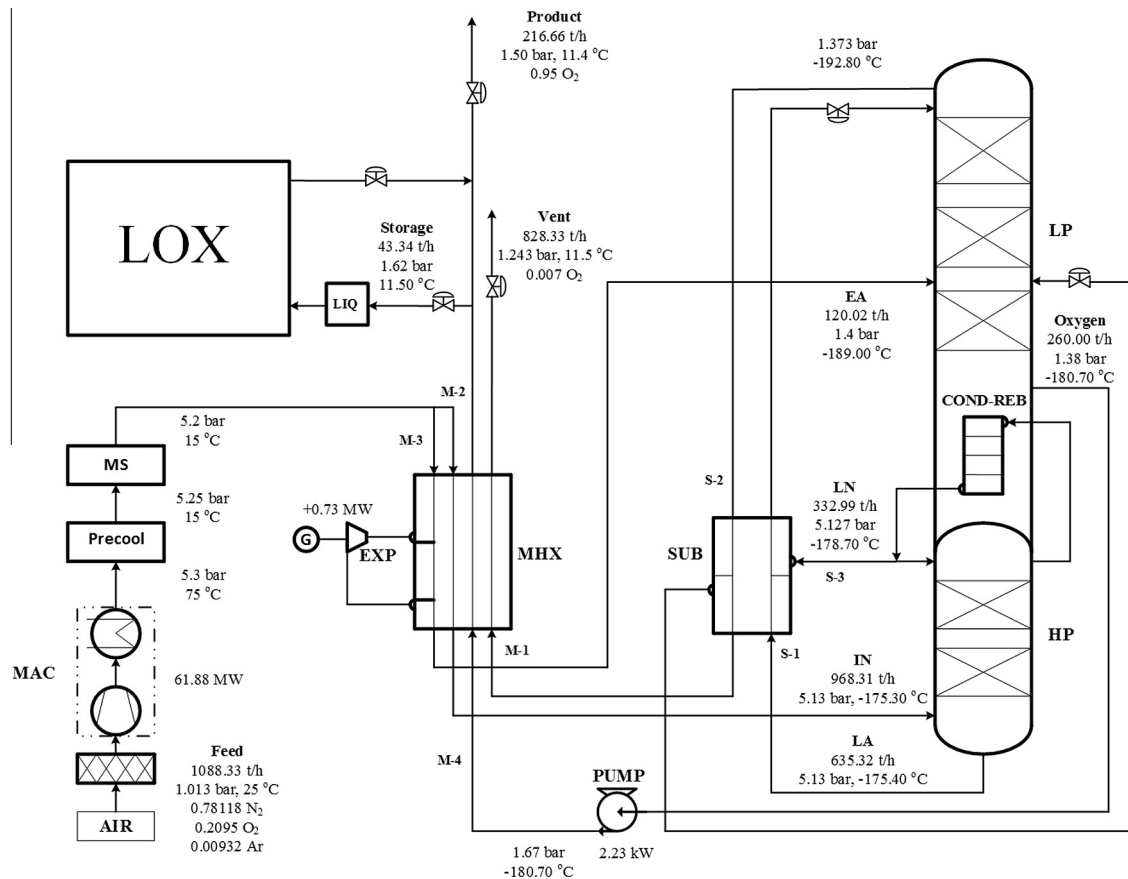


Fig. 1. Process flow diagram of double-column cryogenic ASU with LOX (oversize case).

- (4) Considering temperature approach (2 °C [31]) for condenser–reboiler and combining with the dew point of nitrogen flow from high pressure column (HP) top stage, operating pressure at HP top stage ($P_{HP,t}$) can be determined.
- (5) The pressure at HP bottom stage ($P_{HP,b}$) is established since pressure drops in structured packing are assumed, which can be assumed as the approximate inlet pressure for the air stream entering into the HP.
- (6) Discharge pressure of multistage air compressor (MAC), P_{MAC} , can be gained when considering pressure drops in pre-cool unit, molecular sieves, and pipelines.
- (7) Neat operation (completely heat integration between LP and HP) that HP condenser duty must match LP reboiler duty can be implemented via adjusting the distribution ratio of air sending to LP.
- (8) The size of liquid oxygen storage tank (LOX) [30] installed is flexible depending on the customer availability target and ASU design capacity [23].

After these steps, key theoretical data for ASU is summarized in Table 1. The target for oxygen product aims to satisfy the requirements of oxygen supply in oxy-combustion boiler

operation, whilst other parameters derive from the above calculation equations.

2.2. Steady-state simulation

Fig. 1 presents plant configuration for ASU with LOX from steady-state model. Besides LOX is not configured in normal case, the following assumptions for unit operation equipment are considered for these three cases. (1) Represented by multi-stage compressor model, MAC compresses air to the designed pressure. (2) Pretreatment (Precool Unit (PU) and Molecular Sieves (MS)) cool down compressed air and remove CO₂, water and some hydrocarbons, which are not presented in simulation since pure air components (78.118% N₂, 20.95% O₂, and 0.932% Ar in molar basis) are considered. (3) Main heat exchanger (MHX) ensures that oxygen product leaves the coldbox at a temperature close to that of feed air entering the coldbox. (4) Expander (EXP) produces efficient refrigeration generation for distillation process. (5) Two distillation columns and condenser–reboiler (COND–REB) are simulated through two RadFrac columns that HP with condenser and LP with reboiler for producing oxygen products with 95 mol.% purity. (6) Subcooler (SUB) minimizes the flash losses as refluxes enter the LP column and transfer heat to the waste stream. (7) Liquid oxygen pump (PUMP) is used for boosting liquid oxygen product pressure to the required value by considering the necessary pressure drops occurring in MHX, valves, and pipelines. (8) LOX for storing liquid oxygen liquefied by oxygen liquefier (LIQ) [32] and releasing gaseous oxygen to achieve flexible operations. (9) For improving the fidelity of ASU steady-state model, design specification and calculator modules can be used to ensure full heat integration and

Table 1
The theoretical data from process design in ASU (oversize case).

Design objective	$P_{O_2} = 1.5$ bar, $A_{O_2} = 95$ mol.%, $M_{O_2} = 2.24$ kmol/s		
M_{air} (kmol/s)	10.44	$P_{LP,b}$ (bar)	1.38
$T_{LP,b}$ (°C)	−180.69	$P_{HP,t}$ (bar)	5.13
γ (%)	97.43	P_{MAC} (bar)	5.3

oxygen product quality requirements. (10) The convergence method chosen for simulation are Wengtein for tear convergence and Broyden for design-spec convergence.

From process design and steady-state simulation, main stream and energy flows for three ASUs are listed in Table 2. Compared with these three ASUs, their stream and energy flows are different since the demand of oxygen flow rate for oxy-combustion boilers in three cases are distinctive, but other operating parameters just need slightly adjustments.

2.3. Dynamic model

To develop dynamic model, the details on 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 [9,33]. Then, as presented in Table 3, the geometric sizes of equipment are estimated using some approximate methods to represent dynamic characteristics and controllability of equipment. For heat exchangers, an approximate volume for their inlet and outlet on a given side can be calculated from Eq. (1) [34] whilst diameters for flash separators can be estimated from “F-Factor” method [35].

Table 2
Main stream and energy flows for three ASUs from steady-state simulation results.

Item	Normal (100%)	Oversize (120%)	Downsize (75%)
Feed (t/h)	907.26	1088.33	682.64
IN (t/h)	806.16	968.31	607.07
EA (t/h)	101.11	120.02	75.57
LA (t/h)	528.93	635.32	401.23
LN (t/h)	277.23	332.99	205.84
Oxygen (t/h)	216.66	260.00	162.50
Vent (t/h)	690.60	828.33	520.14
Storage (t/h)	0	43.34	54.17
Product (t/h)	216.66	216.66	108.33
MAC	51.58 MW, 5.3 bar	61.88 MW, 5.3 bar	38.81 MW, 5.3 bar
EXP	+0.62 MW, 1.4 bar	+0.73 MW, 1.4 bar	+0.53 MW, 1.4 bar
PUMP	1.82 kW, 1.67 bar	2.23 kW, 1.67 bar	1.36 kW, 1.67 bar

Table 3
Main equipment sizing in three ASUs.

Equipment	Normal (100%)	Oversize (120%)	Downsize (75%)
MHX (M-1/M-2/M-3/M-4)	40/36/5/16 m ³	47/43/6/20 m ³	30/27/4/12 m ³
SC (S-1/S-2/S-3)	54/95/33 m ³	65/114/39 m ³	41/72/24 m ³
HP			
Section diameter	7 m	8 m	6 m
Maximum fractional capacity	0.354	0.325	0.360
Section pressure drop	0.004 bar	0.003 bar	0.004 bar
Maximum stage liquid holdup	0.361 m ³	0.456 m ³	0.269 m ³
LP			
Section diameter	7 m	8 m	6 m
Maximum fractional capacity	0.575	0.529	0.590
Section pressure drop	0.008 bar	0.007 bar	0.008 bar
Maximum stage liquid holdup	0.468 m ³	0.589 m ³	0.348 m ³
Valves	Equal percentage	Equal percentage	Equal percentage
Pumps	Instantaneous	Instantaneous	Instantaneous
Compressors	Instantaneous	Instantaneous	Instantaneous

$$V = t_R \times v_{ss} \quad (1)$$

where V means volume, t_R represents residence time, and v_{ss} illustrates steady state volumetric flow rate, respectively. With respect to two distillation columns with structured packing (Mellapak Plus, Standard, 252Y), rigorous hydraulic calculations are enabled and rating specifications are configured basing on parameters provided from Sulzer Chemtech in the software database. Meanwhile, valves, pumps and compressors with their corresponding specifications are added for necessary connection between two devices.

After determining the required dynamic inputs, necessary constraint equations are established in initial dynamic model to correspond with the steady-state specifications. Neat operation is completed through two equations (Eqs. (2) and (3)), in which reboiler heat duty equals to condenser heat duty whilst the medium temperature in condenser equals to the reboiler temperature. Then, initial ASU dynamic models without any control loops are established for control system design and dynamic tests.

$$Q_{Reb} = -Q_{Cond} \quad (2)$$

$$T_{Cond-med,HP} = T_{Reb,LP} \quad (3)$$

3. Control system design

3.1. Control structure

Based on dynamic model, a systematical top-down analysis and bottom-up design method [36] is used to design control structure for three ASUs. Here, top-down analysis includes setting control objectives, defining manipulated and measured variables, and determining production rate, whilst bottom-up design consists of designing basic control loops like flow, pressure and level in regular control layer and considering cascade and ratio control loops in supervisory control layer. At first, five fundamental control objectives should be achieved.

- (1) The oxygen purity in oxygen product must be 95 mol.% since it is considered as an optimal value for oxy-combustion power plants [30].
- (2) The oxygen product flow rate must be at the designed capacity.
- (3) The liquid oxygen level in LP reboiler must be maintained between high and low limits.
- (4) As the oxygen product is supplied to oxy-combustion power plant, ASU must be able to handle different ramp rates during load change and mode switching processes.
- (5) For efficient and economical operation, control system must be competent for completing flexible operations such as energy storage and POP.

Table 4
List of input/output variables (oversize case for example).

Inputs			Outputs		
Variable	Nominal	Units	Variable	Nominal	Units
Feed air	1088.33	t/h	Oxygen product purity	95	mol. %
Expanded air	120.02	t/h	LP column pressure	1.37	bar
Oxygen product for supply	216.66	t/h	Liquid oxygen level	3.75	m
Liquid N ₂ from HP	968.31	t/h	HP reflux drum level	6.25	m
Liquid air from HP	635.32	t/h	HP sump level	6.25	m
Vent gas	828.33	t/h			
Liquid oxygen	260.00	t/h			

Inputs and outputs are presented in Table 4 to identify manipulated and measured variables. For simplicity, only parameters in oversize case are listed since these parameters are consistent with their nominal steady-state value as presented before in Table 2. Production rate should be determined because it has significant effects on control structure [37]. Typically, there exist two criteria for setting production rate. First, production rate is set by the flow rate of a fresh feed stream entering the process. Second, production rate is set by the flow rate of product stream leaving the process, which the oxygen product flow is selected in this study because it connects with the downstream unit operation.

Regulatory control layer is designed to prevent the plant drifting away from its set point (SP) and resist local disturbance which can help the supervisory control layer handle the effects of disturbances on the primary outputs. As illustrated in Fig. 2, PID control loops are configured in this layer. Feed air flow control (FC_AIR) is implemented by manipulating the brake power of MAC whilst expanded air flow control (FC_EA) is established through adjusting the speed of expander. When ASU operates between peak time and off-peak time, SPs for oxygen stored to LOX flow control (FC_LOX) and oxygen released from LOX flow control (FC_BACK) are regulated to form control signals for acting on their corresponding valves (V-STO and V-REL), respectively. Oxygen product for supply is maintained via flow control loop (FC_GOX) where control action is put into the supply valve (V-SUP) position whilst liquid oxygen product flow control (FC_LGOX) is realized by altering the speed of the variable-speed pump. LP pressure is maintained by regulating vent gas valve (V-OUT) position whilst liquid levels in HP bottom and top (condenser) are controlled by manipulating the valves (V-6 and V-7) in the liquid lines, respectively.

In the supervisory control layer, composition control loop for oxygen product purity, level control loop for liquid oxygen level in LP bottom (reboiler), and logic control loops for accomplishing flexible operations are configured. In composition control loop, oxygen product purity is maintained around SP through a cascade and feedforward control loop (CC_OXY) in which dead time (DT_OXY) is considered in the primary control loop and secondary control action is sent to the ratio of feed air flow rate to liquid oxygen product flow rate (AIR/LGOX). To keep liquid oxygen level between high and low limits, a cascade control loop (LC_REB) where the primary control signal sends to the ratio of expanded air flow rate to liquid oxygen product flow rate (EA/LGOX) is applied, which liquid level is maintained by manipulating the speed of expander for regulating the produced refrigeration. As marked with “M_NOR, M_ASU, M_LOX” in Fig. 2, it represents logic control loops with strategies 1, 2 and 3 for implementing flexible operations respectively. When switching to “M_NOR”, it is configured for realizing strategy 1 that normal operation such as load change and mode switching can be completed through setting the required ramp rate command in SP of FC_GOX. The “M_ASU” means strategy 2 or “ASU-following” control strategy, which sets up oxygen supply at a given ramp rate from LOX whilst oxygen flow rate supplying to boiler is maintained at the demand via manipulating SP of FC_LGOX remotely. In “M_LOX” control loop, it intends to achieve strategy 3 (namely “LOX-following” control strategy), which is in an opposite way of ASU-following since it sets the oxygen supplying rate from ASU in advance whilst adjusting SP of FC_BACK to satisfy oxygen supply requirement from boiler. Therefore, the detailed control structure is established as shown in Fig. 2, where the logic control loop is not installed for normal case but for oversize and downsize cases.

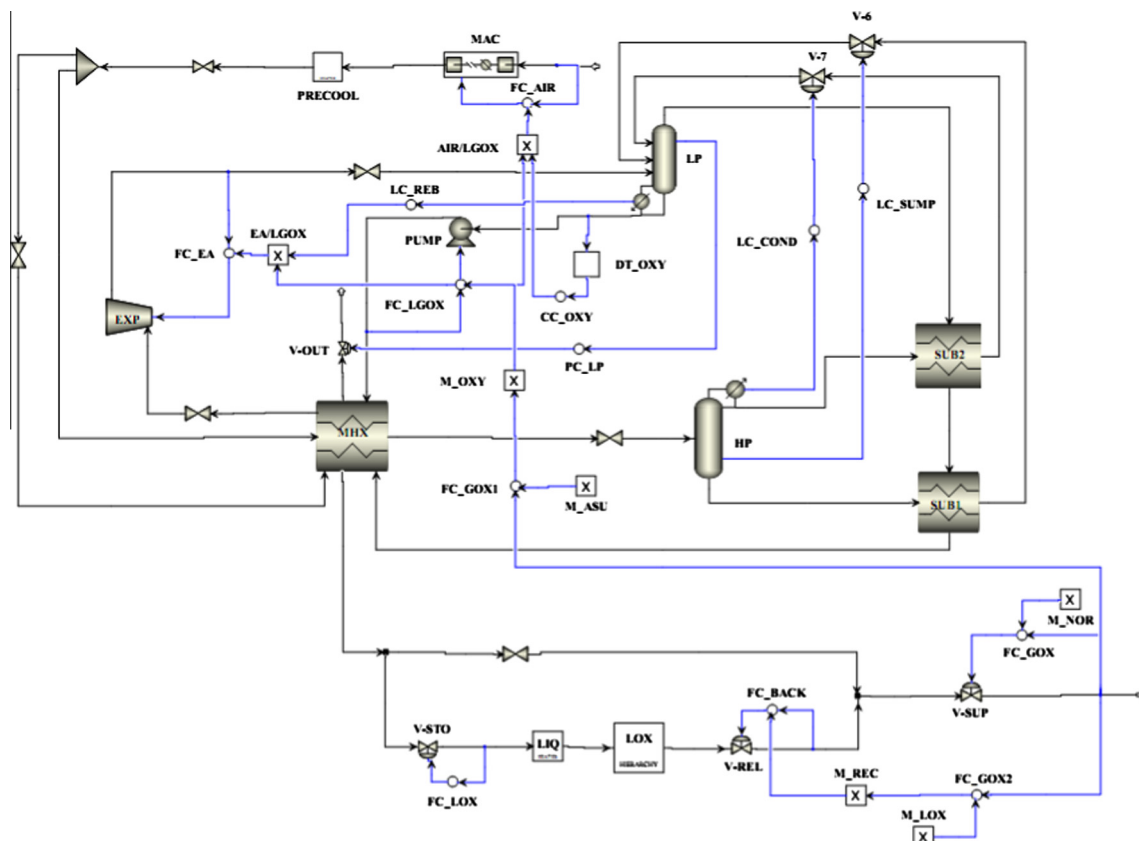


Fig. 2. Dynamic model configured with control structure for ASU: black lines for streams and blue lines for control signals (oversize case). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Validation

For simplicity, dynamic simulation under high ramp rate is chosen to validate the feasibility and reliability of the designed process configuration and control system since it occurs frequently during load change and mode switching processes. Ramping process from 100% to 80% with a rate of 5%/min is applied to dynamic models, and key parameters such as oxygen product supplied to boiler,

LP pressure, liquid oxygen level, and oxygen product purity are monitored to identify their dynamic behavior. Fig. 3 shows the dynamic results under scenario that 20% loads ramping begins at 20th minute and ends at 24th minute, in which three ASUs can run 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. Owing to the inherent characteristics of ASU, similar process dynamic behavior is

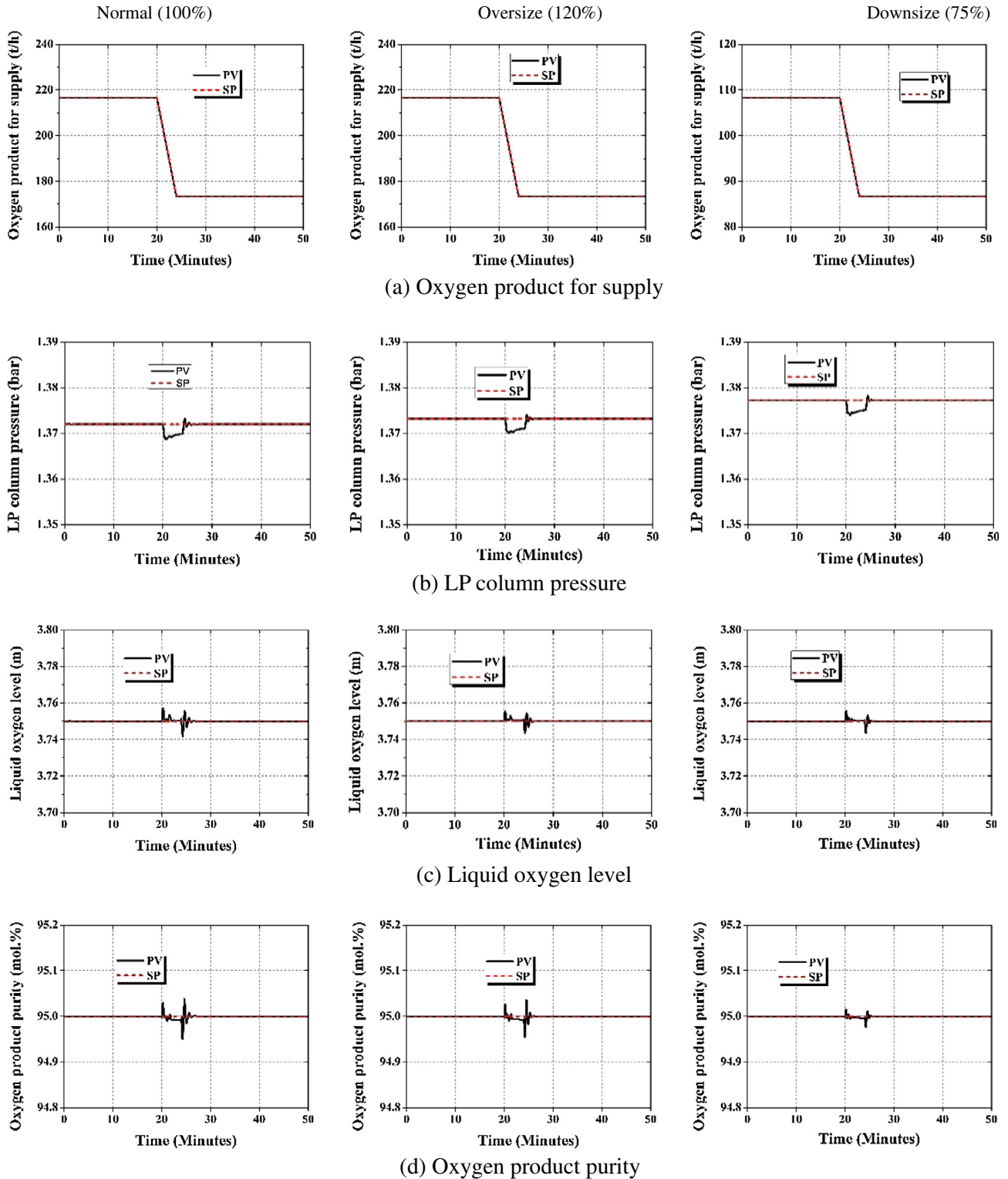


Fig. 3. Process dynamic behavior of ASUs with 5%/min ramp rate.

gained for the three ASUs. The flow rates of oxygen product supplied to boiler changes from 100% to 80% by setting same actions of SPs for flow controllers simultaneously whilst LP pressure gains a stepwise decrease and then increases gradually to their SPs through adjusting vent gas valve (V-OUT) position. Although some vibrations appear in oxygen product purity and liquid oxygen level, they obtain favorable performances and reach to their SPs quickly.

4. Operating strategy

4.1. Integrated patterns

Integrated operation between ASU and oxy-combustion boiler becomes flexible because of different operating requirements in oxy-combustion power plant and varied ASU plant configurations. As shown in Fig. 4, three integrated patterns are proposed for implementing high ramp rate, POP and energy storage operations. The first integrated pattern, coupling normal ASU (100%) without LOX with oxy-combustion boiler, aims to achieve normal daily operations (load change, mode switching, and disturbance) in oxy-combustion power plants. When applied to POP operation, the second pattern means oversizing ASU (120%) with LOX for storing or releasing oxygen product. Under this strategy, oxy-combustion boiler always operates with full load (100%) whilst ASU turns down its operation load (60%) and LOX releases oxygen (40%) during peak time for supplying more power output to electrical grid and maximizes its oxygen products during off-peak time for storing oxygen into LOX (20%). In the third integrated pattern, downsized ASU (75%) with LOX lies in accomplishing energy storage operation. At the beginning, ASU supplies the required oxygen (for example, 50%) to boiler at a specific load (50%) and stores the rest of oxygen (25%) into LOX during off-peak time (16 h). Then, ASU turns down to supply 50% load oxygen and LOX releases oxygen to provide other 50% load oxygen for entering into boiler (100%) during peak time (8 h). The following sections illustrate details on how to implement these operating strategies based on dynamic simulation.

4.2. Operation strategy

As discussed above in Section 3, the first integrated pattern is successfully accomplished through the dynamic test under high ramp rate with 5%/min. For the second integrated pattern, dynamic results for oversize case under POP operation from off-peak time to peak time are presented in left pictures of Fig. 5. From Fig. 5 (a) and (b) for oversized ASU, ASU-following and LOX-following operating strategies are implemented through manipulating the flow controllers (FC_LGOX, FC_BACK, and FC_LOX) whilst keeping FC_GOX unchanged. In LOX-following operating strategy, oversized ASU is reduced to its minimum load (60%) at a given ramp rate (4%/min), oxygen stored to LOX is turned down to 0 through closing V-STO, and the rest of oxygen for supplying to boiler (40%) derives from manipulating LOX in which oxygen can be vaporized. Different from that of LOX-following operating strategy, oxygen supply rate from LOX is predetermined whilst the rest of oxygen for supplying to boiler comes from flow control action on SP of FC_LGOX and oxygen stored to LOX is stopped in ASU-following operating strategy. Compared with the two strategies, similar dynamic responses are gained even though some differences occur. For the variations of oxygen flows as shown in Fig. 5 (a) (left picture), oxygen product from LP and oxygen supply from LOX appear with linear form for LOX-following whilst curve form for ASU-following, owing to that SP of FC_LGOX is automatically manipulated in ASU-following. From left picture in Fig. 5(b), oxygen product for supply almost unchanged in ASU-following whilst it decreases significantly at the first minute (20th–21th minute)

and then spends about 1.5 min on returning back to its SP in LOX-following, which results from oxygen supplying from LOX cannot follow the demand ramp rate at the beginning when oxygen supplying rate from ASU is given. With respect to the variations of LP pressure, liquid oxygen level, and oxygen product purity shown in Fig. 5(c)–(e), their amplitudes in ASU-following is larger than that in LOX-following because of the same reason that cascade control action is applied to ASU. As illustrated in Fig. 5(f), it is encouraged to find that compression power consumption in MAC decreases about 32.85% from 61.88 MW to 41.55 MW during POP operation. Although two operating strategies seem to be both suitable for POP operation, ASU-following would be better from the prospective of maintaining oxygen flow rate and oxygen product purity.

With respect to completing the third integrated pattern, right pictures in Fig. 5 reveal dynamic behavior of downsized ASU with LOX under energy storage operation from off-peak time to peak time. However, only LOX-following operating strategy can be implemented since ASU load is constrained in the range of 60–105% [38] and automatically controlling on FC_LGOX in ASU would be beyond this upper bound at the early stage of oxygen supplying, which results from ramp rate for oxygen flows from ASU and LOX is hard to pair at a desirable relationship to keep up with that rate of oxygen demand. Fortunately, it makes no effect on identifying dynamic characteristics of downsized ASU with LOX under energy storage operation. As illustrated in Fig. 5(a) and (b) (right pictures), oxygen product for supply is ramped up from 50% to 100% whilst other corresponding oxygen flows are adjusted to achieve the oxygen flow target where oxygen produced from ASU is turned down to its 66.67% load, oxygen stored to LOX is stopped, and 50% demand of oxygen requirement from boiler is provided by LOX.

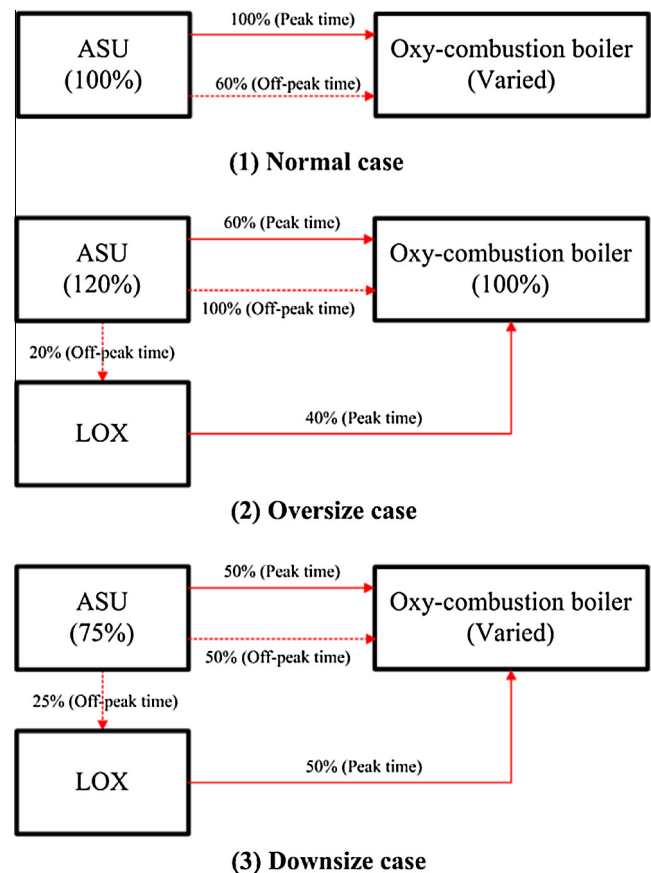


Fig. 4. Integrated patterns between ASU and oxy-combustion boiler.

For LP column pressure, liquid oxygen level, and oxygen product purity in right pictures of Fig. 5(c)–(e), favorable performance is obtained since all the process variables are around their SPs. From

right picture in Fig. 5(f), its compression power consumption in MAC reduces about 27.71% from 38.81 MW to 28.05 MW during energy storage operation.

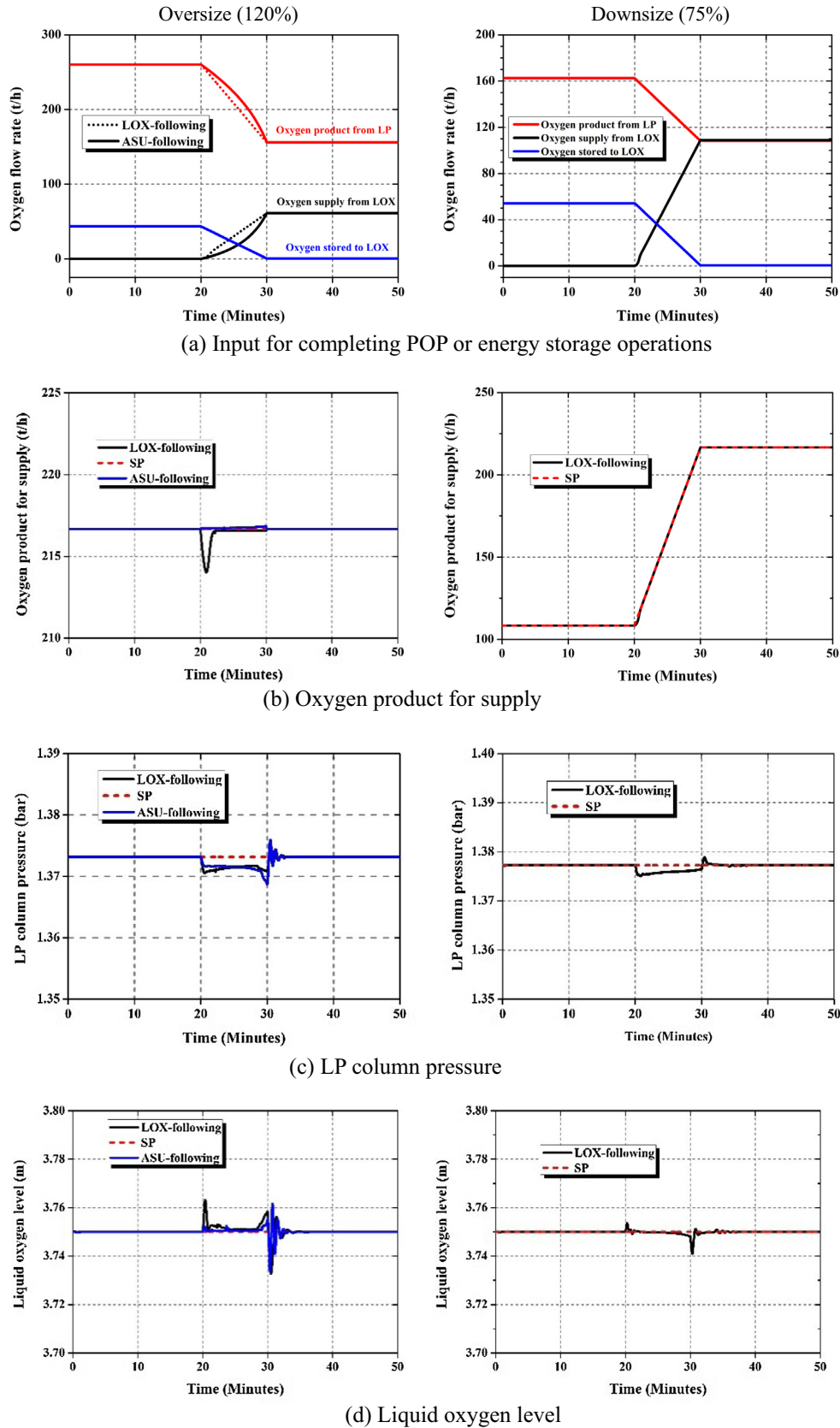


Fig. 5. Dynamic performance under the second and third integrated patterns.

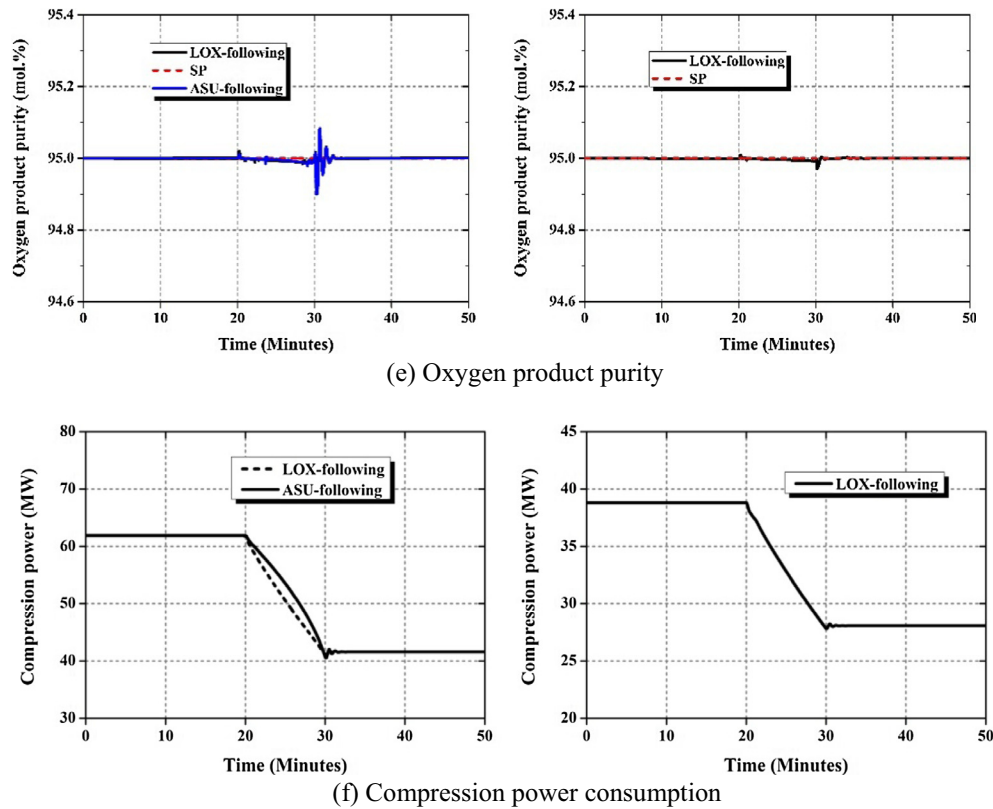


Fig. 5 (continued)

4.3. Case summary

As summarized in Table 5, comparisons of plant configuration, control, operation, and energy saving for three ASUs are presented. Except for normal case that only ASU is installed, oversize and downsize cases include both ASU and LOX. From control design in Section 3, cascade and feedforward control loops are all equipped in three ASUs, whilst logical control loops are set in both downsize and oversize cases. When considering flexible operations for three ASUs, downsize and oversize cases rather than normal case can be achieved, ASU-following and LOX-following operating strategies can be realized for POP operation in oversize case whilst only LOX-following operating strategy can be used in energy storage operation in downsize case due to the convergence problem where process variable would exceed its upper bound. For different ASU cases, oversize case would be more suitable for oxy-combustion from aspects of energy savings and operating flexibility because the decrease of compression power consumption

(20.33 MW) is larger and operating methods are more flexible than those in downsize case (10.76 MW) and normal case.

5. Discussion

In terms of ASU process model, necessary assumptions are used for confirming the proposed control concepts and operating strategies, which still requires more improvements to approach real plant. For equipment sizing, these parameters are not real size but estimated from the steady-state simulation results, and should be adjusted to give a good match to the dynamic simulation results if data on the dynamics of plants are given. The dynamics of heat exchanges and compressors are related to their characteristic curves, which needs obtaining the corresponding data from manufacturers for increasing the accuracy.

From dynamic simulation results, some considerations should be addressed. Operating constraints should be further examined through actual operations in real plant even though they are not found under the proposed operating strategies. For ASU with different capacities, ASU-following and LOX-following operating strategies should be confirmed to determine which method would be suitable and effective. Although the thermodynamic performance and operating flexibility can be considered to provide recommendation that oversize case is suitable for oxy-combustion power plant in current study, further economic property should be identified and compared. For the proposed control concepts and strategies, similar ideas can be applied and tested in other complex ASU flowsheets as aforementioned in the introduction section.

When compared to other studies, the main differences lie in control structure, integrated operation, and operating strategy. Apart from conventional control loops, logical control modules for implementing flexible operations are added, which increase

Table 5
Comparison for three ASU cases.

Case		Normal	Oversize	Downsize
Plant configuration	ASU	Y	Y	Y
	LOX	N	Y	Y
Control structure	Basic loops	Y	Y	Y
	Logical loops	N	Y	Y
Operating strategy	ASU-following	N	Y	N
	LOX-following	N	Y	Y
Operating mode	Daily	Y	Y	Y
	POP	N	Y	N
	Energy storage	N	Y	Y
Energy saving		0	20.33 MW	10.76 MW

the degree of freedom and flexibility for process control. Although several flexible operations between ASU and oxy-combustion power plant were proposed, the presented study confirms the operating concepts, provides detailed information for control and operating strategies, and identifies the dynamic behavior of ASU under flexible operations. Meanwhile, ASU-following and LOX-following control strategies (strategies 2 and 3) are proposed for flexible operations and the corresponding procedures for realizing these operations are presented. Dynamic tests under high ramp rate [6], POP operation [10] and energy storage [11] are executed to demonstrate that ASU can bear the strict demand of oxy-combustion power plant and flexible operations between ASU and boiler is feasible. In addition, successful test under POP operation settles the issue addressed in Ref. [10] that considered that process control for the POP operation of ASU would be a challenge, and indicates that process control would be an opportunity rather than a challenge for flexible operation.

6. Conclusion

The paper investigates process design, control strategy and flexible operations for ASU when integrated into oxy-combustion power plant. The main contributions are to propose novel control system and flexible operating strategies, which are summarized as follows.

Simple control structure with logic control loops (strategies 1, 2 and 3) are firstly configured and tested in three typical ASUs (normal, oversize, and downsize) without or with liquid oxygen storage drum (LOX) through dynamic simulations under high ramp rate (5%/min) and flexible operations. With respect to control structure, ASU-following (strategy 2) and LOX-following (strategy 3) control loops are designed for achieving peak and off-peak (POP) or energy storage operations. The main difference between ASU-following and LOX-following is whether remote control signal sends to ASU or LOX. In ASU-following, it predetermines the oxygen supply at a given ramp rate from LOX whilst oxygen flow rate supplying to boiler is maintained at the demand via manipulating set point of liquid oxygen product flow control (FC_LGOX) remotely. In an opposite way of ASU-following, the oxygen supplying rate from ASU is specified in advance whilst adjusting the set point of oxygen from LOX flow control (FC_BACK) to satisfy oxygen demand from boiler in LOX-following. When comparing ASU-following and LOX-following through dynamic tests under POP and energy storage operations, the former would be better than the latter since the oxygen product purity and oxygen flow rate can be kept closer to their control objectives.

Three integrated patterns for coupling ASU into oxy-combustion power plants are firstly proposed to grasp the opportunity for improving operation flexibility. In these integrating methods, normal ASU without LOX is used for high ramp rate during load change and mode switching processes, oversized ASU with LOX aims to complete high ramp rate and POP operations, and downsized ASU with LOX concerns accomplishing high ramp rate and energy storage operations, respectively. Under oversize case with POP operation, ASU load can be turned down to its minimum value at 60% whilst its compression power consumption decreases about 32.85%, and all the key parameters can be maintained around their setpoints. In downsize case with energy storage operation, ASU load can be reduced to 66.67% whilst other key parameters are maintained around their set points, and its compression power consumption reduces about 27.71%, respectively. ASU-following and LOX-following strategies are suitable for POP operation in oversize case whilst only LOX-following strategy can be applied to energy storage operation in downsize case due to convergence problem that process variable exceeds its upper

bound. Therefore, oversize case would be more suitable for oxy-combustion from the perspective of energy savings and operating flexibility.

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References

- [1] Xiong J, Zhao H, Zheng C. Exergy analysis of a 600 MWe oxy-combustion pulverized-coal-fired power plant. *Energy Fuels* 2011;25:3854–64.
- [2] Jin B, Zhao H, Zou C, Zheng C. Comprehensive investigation of process characteristics for oxy-steam combustion power plants. *Energy Convers Manage* 2015;99:92–101.
- [3] Smith A, Klosek J. A review of air separation technologies and their integration with energy conversion processes. *Fuel Process Technol* 2001;70:115–34.
- [4] Darde A, Prabhakar R, Tranier J-P, Perrin N. Air separation and flue gas compression and purification units for oxy-coal combustion systems. *Energy Proc* 2009;1:527–34.
- [5] Tranier J-P, Dubettier R, Darde A, Perrin N. Air separation, flue gas compression and purification units for oxy-coal combustion systems. *Energy Proc* 2011;4:966–71.
- [6] Dimitri G. Oxygen production for oxyfuel power plant-state of development. Workshop on oxyfuel-FBC technology; 2012.
- [7] Mandler JA. Modelling for control analysis and design in complex industrial separation and liquefaction processes. *J Process Contr* 2000;10:167–75.
- [8] Jin B, Zhao H, Zheng C. Dynamic modeling and control for pulverized-coal-fired oxy-combustion boiler island. *Int J Greenh Gas Control* 2014;30:97–117.
- [9] Jin B, Zhao H, Zheng C. Dynamic simulation for mode switching strategy in a conceptual 600 MWe oxy-combustion pulverized-coal-fired boiler. *Fuel* 2014;137:135–44.
- [10] Hu Y, Li X, Li H, Yan J. Peak and off-peak operations of the air separation unit in oxy-coal combustion power generation systems. *Appl Energy* 2013;112:747–54.
- [11] Perrin N, Dubettier R, Lockwood F, Tranier J, Bourthy-Weber C, Devaux M. Oxycombustion for carbon capture on coal power plants and industrial processes: advantages, innovative solutions and key projects. *Energy Proc* 2013;37:1389–404.
- [12] Roffel B, Betlem B, De Ruijter J. First principles dynamic modeling and multivariable control of a cryogenic distillation process. *Comput Chem Eng* 2000;24:111–23.
- [13] Cornelissen R, Hirs G. Exergy analysis of cryogenic air separation. *Energy Convers Manage* 1998;39:1821–6.
- [14] Trierweiler JO, Engell S. A case study for control structure selection: air separation plant. *J Process Contr* 2000;10:237–43.
- [15] Vinson DR. Air separation control technology. *Comput Chem Eng* 2006;30:1436–46.
- [16] Xu Z, Zhao J, Chen X, Shao Z, Qian J, Zhu L, et al. Automatic load change system of cryogenic air separation process. *Sep Purif Technol* 2011;81:451–65.
- [17] Jones D, Bhattacharyya D, Turtton R, Zitney SE. Optimal design and integration of an air separation unit (ASU) for an integrated gasification combined cycle (IGCC) power plant with CO₂ capture. *Fuel Process Technol* 2011;92:1685–95.
- [18] Van der Ham L, Kjelstrup S. Exergy analysis of two cryogenic air separation processes. *Energy* 2010;35:4731–9.
- [19] Van der Ham L. Improving the exergy efficiency of a cryogenic air separation unit as part of an integrated gasification combined cycle. *Energy Convers Manage* 2012;61:31–42.
- [20] Mahapatra P, Bequette BW. Design and control of an elevated-pressure air separations unit for IGCC power plants in a process simulator environment. *Ind Eng Chem Res* 2012;52:3178–91.
- [21] Mahapatra P, Zitney SE, Bequette BW. Dynamic maximization of oxygen yield in an elevated-pressure air separation unit using multiple model predictive control. In: Proc of 10th IFAC international symposium on dynamics and control of process systems (DYCOPS 2013), Mumbai, India; 2013.
- [22] Roh K, Lee JH. Control structure selection for the elevated-pressure air separation unit in an IGCC power plant: self-optimizing control structure for economical operation. *Ind Eng Chem Res* 2014;53:7479–88.
- [23] Higginbotham P, White V, Fogash K, Guvelioglou G. Oxygen supply for oxyfuel CO₂ capture. *Int J Greenh Gas Control* 2011;5:S194–203.
- [24] Fu C, Gundersen T. Recuperative vapor recompression heat pumps in cryogenic air separation processes. *Energy* 2013;59:708–18.
- [25] Fu C, Gundersen T. Using exergy analysis to reduce power consumption in air separation units for oxy-combustion processes. *Energy* 2012;44:60–8.
- [26] Fu C, Gundersen T. Integrating the compression heat in oxy-combustion power plants with CO₂ capture. *Chem Eng Trans* 2012;29.
- [27] Toftegaard MB, Brix J, Jensen PA, Glarborg P, Jensen AD. Oxy-fuel combustion of solid fuels. *Prog Energy Combust Sci* 2010;36:581–625.
- [28] Stone BB, McDonald DK, Zadiraka AJ. Oxy-combustion coal fired boiler and method of transitioning between air and oxygen firing. Google patents; 2009.

- [29] Pourchot T, Granier F, Goloubevb D, Alekseev A. Oxy-combustion: an ASU integration option and improved operation flexibility. In: 3rd Oxyfuel combustion conference; 2013.
- [30] Dillon DJ, White V, Allam RJ, Wall RA, Gibbins J. Oxy-fuel combustion processes for CO₂ capture from power plant. IEA greenhouse gas R&D programme; 2005.
- [31] Tonziello J, Vellini M. Oxygen production technologies for IGCC power plants with CO₂ capture. *Energy Proc* 2011;4:637–44.
- [32] Dimitri G, Alexander A, Thierry P, François G. Integration of ASU in process of power generation. In: 3rd Oxyfuel Combustion conference; 2013.
- [33] Jin B, Zhao H, Zheng C. Optimization and control for CO₂ compression and purification unit in oxy-combustion power plants. *Energy* 2015;83:416–30.
- [34] Aspen Technology Inc. Aspen dynamics™ 11.1 user guide; 2001.
- [35] Luyben WL. Plantwide dynamic simulators in chemical processing and control. CRC Press; 2002.
- [36] Skogestad S. Control structure design for complete chemical plants. *Comput Chem Eng* 2004;28:219–34.
- [37] Luyben ML, Tyreus BD, Luyben WL. Plantwide control design procedure. *AIChE J* 1997;43:3161–74.
- [38] Beysel G. Enhanced cryogenic air separation: a prove process applied to oxyfuel future prospects. In: 1st Oxyfuel combustion conference; 2009.