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Energy Saving Benefit Analysis of the Compressor Short-Stop Adjustment Method Based on TGNET

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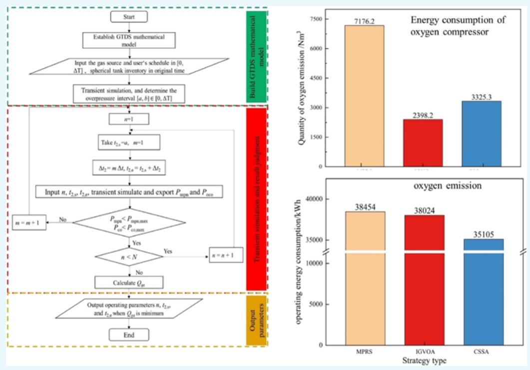
ABSTRACT: Aiming at the problem of gas emissions caused by the high-pressure operation of a large industrial gas (O_2, N_2, and Ar) pipeline network, this study establishes a mathematical model of the oxygen transmission and distribution system (OTDS) based on TGNET software. In addition, the study conducts transient simulation, comprehensively considering theoretical constraints and actual operation requirements, and adopts a large air separation company for the OTDS as a case study. After comparing two traditional adjustment methods, a compressor short stop adjustment strategy is proposed to reduce the peak pressure of the pipe network system. This study determines the energy-saving benefits and the difference in the scope of application of compressor short-stop adjustment. Compared with the medium-pressure release and inlet guide vane opening adjustment (IGVOA) strategies, the compressor short-stop adjustment strategy reduced oxygen emission by 3850.9 Nm^3 and increased by 927.1 Nm^3. Furthermore, the compressor operating energy consumption was reduced by 3349 and 2919 kW h. Compared with the IGVOA strategy, the compressor short-stop adjustment strategy has increased the application range of compressor inlet pressure and medium-pressure pipeline pressure by more than 70%. This strategy is effective for reducing the emission of pipeline gases caused by fluctuations in user demand.



1. INTRODUCTION

In 2020, China produced 996 million tons of crude steel,[1] consumed 106.5−127.8 billion cubic meters of oxygen, and consumed 122.4−168.4 billion kW h of electricity. The power consumption of air separation units (ASUs) accounted for 15−20% of the electricity consumption of iron and steel enterprises.[2] Taking oxygen as an example, processes such as ironmaking, steelmaking, and continuous casting require a considerable amount of oxygen, which is usually produced by a low-temperature air separation device[3] and delivered to users at all levels through an oxygen transmission and distribution system (OTDS). Affected by factors, such as converter intermittent blowing and blast furnace shutdown, the OTDS often leads to loss of oxygen due to unbalanced supply and demand. An annual reduction of 1% of oxygen emission will contribute approximately 0.87% to China's 2030 CO_2 emission reduction target.[4] The nitrogen transmission and distribution system (NTDS) and argon transmission and distribution system (ATDS) are similar to OTDS. Therefore, reducing the gas (O_2, N_2, and Ar) emission caused by the imbalance of supply and demand is very important for industrial consumption reduction, energy saving, and emission reduction.[5]

OTDS, NTDS, and ATDS belong to the gas transmission and distribution system (GTDS), whose functions include compression, transmission, secondary pressure regulation, and distribution and are an important part of steel enterprises. In the GTDS, when the user's gas consumption is reduced, the gas generated by the ASU device exceeds the gas consumption or the gas equipment fails, and the excess quantity exceeds the storage limit. To protect the safety of the GTDS, the safety valve is usually activated, and the gas is released. In recent years, as China's ASU becomes larger and more efficient, the imbalance between gas supply and demand has gradually increased and has become more prominent in the OTDS. Therefore, reducing reactive power consumption, reducing gas emissions, and maintaining the balance of supply and demand have attracted great attention from air separation companies. Taking oxygen as an example, the oxygen supply pressure in the steelmaking process only needs 0.8 MPa to meet the technological requirements. However, to increase the storage capacity of the OTDS, most companies increase the transmission pressure of the pipe network. On the one hand, this method increases the compression energy consumption of gas

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transmission. On the other hand, once the gas consumption is reduced, oxygen can be easily dispersed due to overpressure. In addition, the smelting cycle of a steel furnace in the steelmaking process is approximately 30−45 min, and the oxygen blowing time generally lasts for approximately 18 min. The time taken in oxygen consumption and blowing for different steel types varies. Therefore, oxygen overpressure release is likely to occur when the oxygen demand of the converter users decreases, which also leads to many studies on the user's variable load regulation. To reduce gas emission, the ASU's variable load adjustment is used to achieve the changing rhythm consistent with the converter consumption. For example, the demand response operation of the air separation plant is optimized based on, first, a mixed-integer linear program (MILP).[6] MILP is an optimal scheduling method for multiple sets of air separation equipment with frequent load changes based on the shunt mode strategy.[7] Then, such demand response operation is also optimized based on a two-layer framework automatic variable load system of ASU high- and low-pressure towers proposed in combination with a nonlinear model predictive control.[8,9]

These studies provided adjustment directions and strategies for the ASU's rapid load change. Moreover, other studies focused on user scheduling. Examples include the following: an oxygen decision support system based on linear programming to balance the production, storage, use of oxygen, and to realize the rational use of oxygen;[10,11] the decision support system established based on the MILP model that realizes the multiperiod optimization of the oxygen system and the minimization of oxygen discharge; the production scheduling model established by using mixed-integer linear[12,13] and mixed nonlinear programming methods[14] to minimize oxygen emission; the mathematical model of oxygen optimization scheduling[15] established based on the improved simplex method; the oxygen system transient mathematical model based on the principle of supply and demand balance;[16] and the oxygen scheduling of converter production based on particle swarm optimization.[17] These studies provide solutions for reducing the peak pressure of the oxygen pipe network and reducing oxygen emission. However, research on the OTDS connecting the ASU and the user is insufficient, and reports on reducing the gas emission by adjusting the OTDS are limited.

However, the structure of the OTDS of Chinese iron and steel enterprises is complex, and establishing a transient model is difficult.[18] At present, when solving the unsteady state engineering problems of gas pipelines, relatively mature commercial simulation software (SPS software, TGNET software, etc.) is usually used for comparative analysis.[19−22] Research on reducing oxygen emission focuses on the ASU variable load adjustment and the transient scheduling of the user's production plan. Moreover, research on the adjustment method of the compressor connecting the ASU and the pipe network is limited. When the OTDS is over pressured in the actual operation, the medium-pressure release strategy (MPRS) is usually adopted by enterprises to open the relief valve when the pipeline pressure exceeds the set value to reduce the pressure of the pipeline network. The MPRS and these two research strategies have the following problems: adopting the MPRS has the characteristics of a medium-pressure release, high pressure, large instantaneous flow, and large oxygen loss and the life of the equipment is affected when adopting the ASU automatic load change strategy to adapt to fluctuations in user usage because of the adjustment hysteresis of the ASU. That is, matching the variable load regulation speed of the ASU with the fluctuating speed of gas consumption and frequent switching of valves is difficult, which is not suitable for long-term frequent adjustment. The user's transient scheduling method is adopted to adjust the user's oxygen consumption and production plan, which limits user production and reduces the efficiency of enterprise products to a certain extent. In summary, solving the imbalance between supply and demand without restricting production and user consumption is difficult using the current strategies or methods. Therefore, this study proposes a compressor parallel optimization adjustment [compressor short-term shutdown adjustment (CSSA)] method based on low-pressure release for the fluid mechanical load pipe network (OTDS, NTDS, and ATDS) of iron and steel enterprises when the pressure is too high. In this study, the OTDS mathematical model is established through the Pipeline Studio software TGNET module. Moreover, the historical data of a steel company in China are used as a sample to conduct transient simulations and analyze the changes in the pressure of the medium-pressure pipe network (P_{mpn}) and the pressure of the centrifugal oxygen compressor outlet (OCO) (P_{oco}) during the operation process. These data are also used to compare CSSA with the inlet guide vane opening adjustment strategy (IGVOA) and MPRS in detail, analyze the adjustment effects and energy-saving performance, and provide guidance for GTDS adjustment and design.

2. MODEL AND METHODS

The novelty of this strategy lies in the adjustment of compressors to compressor stations, some of which can be shut down for a short time. The advantage of this method is that when the gas consumption is reduced, other normal gas consumption demands can be met, and the processing gas adjustment range is larger. This strategy will not affect the use of the ASU, will not limit the user's production needs, and there is no need to worry about the possibility of compressor surge or blockage.

2.1. Mathematical Model.

The OTDS is a complex looped pipe network with multiple branches, as are the NTDS and ATDS. Therefore, it is necessary to consider the influence of all pipelines and their accessories when establishing the mathematical model, especially the influence on flow and resistance.

2.1.1. Pipeline Hydraulic Calculation. For the OTDS, NTDS, or ATDS, the purity of the conveyed medium is very high. For example, the concentration of the nitrogen product exceeds 99.99 mol %, and the concentration of the oxygen product exceeds 99.6 mol %. However, they are all binary mixed media, while the Benedict-Webb-Rubin-Starling (BWRS) equation is for binary mixtures, and the precision of the actuarial calculation is high. Therefore, in the simulation, the gas state equation uses the BWRS equation, as shown in eq 1.

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$$\rho_0 + \left(B_0RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4}\right)\rho_0^{\ 2} + \left(bRT - a - \frac{d}{T}\right)\rho_0^{\ 3} + \alpha\left(a + \frac{d}{T}\right)\rho_0^{\ 6} + \frac{c\rho_0^{\ 3}}{T^2}(1 + \gamma\rho_0^{\ 2})\exp(-\gamma\rho_0^{\ 2}) - 0.001P = 0 \quad (1)$$

where R is the cross-sectional area of the gas and A_0, B_0, C_0, D_0, a, b, c, d, α, and γ are the parameters related to the composition of the gas in the pipeline.

The calculation during transient simulation adopts the Colebrook White formula[23] shown in eq 2.

$$\sqrt{\frac{1}{\lambda}} = -2 \times \lg\left(\frac{K_e}{37D} + \frac{2.51}{Re\sqrt{\lambda}}\right) \quad (2)$$

where K_e is the Reynolds number and Re is the rugosity of the pipe.

2.1.2. Pressure Loss Correction. To ensure the accuracy of the model, some types of pressure drop during pipeline transportation are analyzed in the study.

1 The valve in the model is 100% open and closed by default. The flow coefficient C_v value of the valve is calculated using the GPSA (generalized pattern search algorithm) correlation method.[24] Besides, the case studied in this paper does not include temperature changes; therefore, the transportation process is simplified to an isothermal process, and temperature changes are not considered in the simulation.

Valve pressure loss is converted into a straight pipe length equivalent to the pressure drop in the model, that is, the valve equivalent length L_e. The valve equivalent correction is used to calculate the flow coefficient C_v of the valve in the model. Table 3 shows the calculation method of the equivalent length of several main valves in the model.

Table 1. Calculation of Equivalent Length of the Main Valve

valve type	equivalent length L_e
stop valve	L_e = 340 D
check valve	L_e = 600 D
block valve	L_e = 400 D

2 The remaining local pressure loss. In addition to the abovementioned two points, pressure loss caused by variable pipe diameters, elbows, flanges, tees, and others is calculated using the remaining local pressure drop. Moreover, the resistance element is used in the model to replace the remaining local pressure drop, and the damping coefficient K is calculated as shown in eq 3 where K is the damping coefficient.

$$K = \frac{(P_i^2 - P_o^2)}{Q^2} \quad (3)$$

2.2. Model Constraints. Before the transient simulation starts, it is necessary to set constraint conditions for the main equipment. The model constraints of the main equipment in this paper are shown in Table 1.

In addition, for steady-state control and transient-state control, the maximum iterations are 200, and the maximum convergence tolerance and the minimum convergence tolerance are set to 0.01 and 0.0001, respectively.

Table 2. Main Equipment Functions and Constraints in the Model (Gas Include O_2/N_2/Ar)

type	module name	module function	functional constraints
gas supply area	gas source	provide gas	maximum flow
	centrifugal compressor	compress gas	minimum inlet pressure
buffer area	spherical tank	store gas when the pipe network pressure is higher than the set value, and release gas when lower	pressure setting range
regulatory zone	drain valve	rapid release of gas when switched on	open and close state
	pressure regulating station	reduce the post-station pressure regulation to the set value	post-station pressure
user area	blast furnace	smelt molten iron	minimum pressure
	converter	process molten iron for steelmaking	
	hot rolling	process molten steel for continuous casting steel	
	other users	small users in the venue use gas	

Table 3. Size of the Pipes Used in the Network

size	quantity of pipes (piece)	length of pipes (m)	length of pipes/overall length (%)
DN530	44	10,060	46.88
DN350	23	1030	4.80
DN300	13	5420	25.26
DN150	5	3550	16.54
DN80	7	1340	6.24
DN50	6	60	0.28
overall	98	21,460	100

2.3. Simulation Methods. The continuous and stable production of gases (O_2, N_2, and Ar) in the air separation plant and the fluctuating gas consumption of some gas users are the main reasons for the fluctuation of the GTDS operating pressure. When the supply exceeds the demand, the gas can be easily released due to overpressure. In China, when the GTDS operating pressure is too high, that is, when P_{mpn} and P_{co} exceed $P_{mpn,max}$ and $P_{co,max}$, companies usually use the MPRS to quickly release the medium-pressure and high-pressure gas in the pipeline. In addition, the compression equipment in the GTDS is usually centrifugal compressors (CCs),[25] which can reduce the amount of air processed by the compressor by adjusting the inlet guide vanes of the CC.[26] This adjustment scheme is called the compressor IGVOA, which is currently only used in CCs.[27] Therefore, this study proposes a low-pressure oxygen release CSSA scheme.

In the GTDS, a CC with inlet guide vanes is mainly used to prevent surge during CC operation. The CC surges when the suction volume flow is lower than the limit lineref 20. To avoid surge, a certain safety margin is set, and the compressor runs at a higher mass flow. Multiple CCs can be connected in parallel, and the compressor units operating in parallel are called centrifugal compressor stations (CCS).[23]

2.3.1. IGVOA Strategy. The IGVOA needs to obtain a set of optimal operating parameters, which refers to ref 27, and the detailed implementation steps are shown in Figure 1. Under the premise that the user's production scheduling plan is known, the orthogonal experiment of the optimal parameters is designed, and the pipeline studio software TGNET module is

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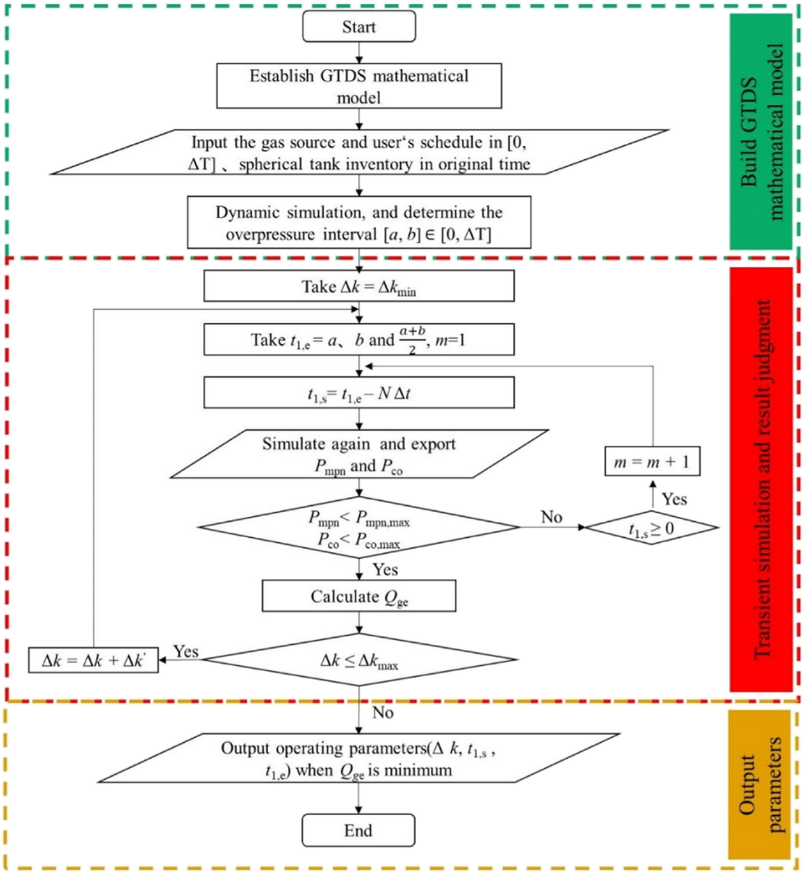

Figure 1. IGVOA optimal parameter acquisition flowchart. *a* is the beginning of the overpressure interval; *b* is the end of the overpressure interval; and *m* is the auxiliary parameter, which is used to adjust the parking time.

used to establish the GTDS transient mathematical model. The user's production demand data are inputted into the model for transient simulation, and P_{mpn}, P_{co}, and other related curves are outputted from the simulation results. According to the compressor inlet flow data and outlet pressure data, the operating data E_{co} is calculated using Matlab software. In addition, according to the judgment requirements of $P_{mpn} < P_{mpn,\,max}$ and $P_{co} < P_{co,\,max}$, the minimum gas emission Q_{ge} corresponding to the minimum is selected from the results. The optimal parameters include the adjustment size of the compressor inlet guide vane opening Δk, the adjustment start time t_1, and the adjustment duration Δt_1.

2.3.2. CSSA Strategy. This paper puts forward CSSA by referring to IGVOA, and the core of the CSSA operation is to change a single CC to CCS. To ensure GTDS supply capacity without reducing, the design capacity of CC in CCS should not be less than its original design capacity, as shown in eq 4. The specific steps of CSSA are as follows. During the operation, when the GTDS pressure is too high, some CCs in the CCS will be shut down for a short time. According to the determined user scheduling data, the compressor outlet pressure and the pressure change of the medium-pressure pipeline located in the converter gas pipeline are simulated during the operation. The medium-pressure pipeline pressure changes in the pipeline through partial CC shut down, and the amount of gas processed by the CC and compressed to GTDS is reduced. The original CC processing gas volume that was stopped is released to the environment, and P_{mpn} and P_{co} during operation are reduced. Moreover, the CC operation energy consumption is reduced because of the CC shutdown. CSSA needs to obtain a set of operating parameters, including three operating parameters, namely, the number of CC parking n, the parking start time and the parking end time $t_{2,e}$, and the parking duration Δt_2. Figure 2 shows the specific acquisition process.

$$\sum_{i=1}^{n} Q_i \geq Q_0 \qquad n = 2,3,4, \ldots.\ N \tag{4}$$

CSSA uses CCs to perform a short-term stop during the OTDS overpressure period, which significantly reduces the amount of gas entering the CC and GTDS, which can quickly alleviate the problem of excessive GTDS pressure. CSSA is based on the following assumptions:

1 The user's scheduling plan has been determined. In the actual production process, the user's gas consumption arrangement is determined in advance, that is, the scheduling plan has been determined.

2 Ignore the runtime required for the decision-making process. The strategy needs to adjust the operating parameters several times to obtain the operating parameters. To ensure the best energy-saving effect, the operating parameters need to be n = 1, and Δt is the minimum adjustment unit.

3 Ignore the impact of the CC start-stop process on CSSA. The study ignores the time required for driving and stopping in the research process strategy.

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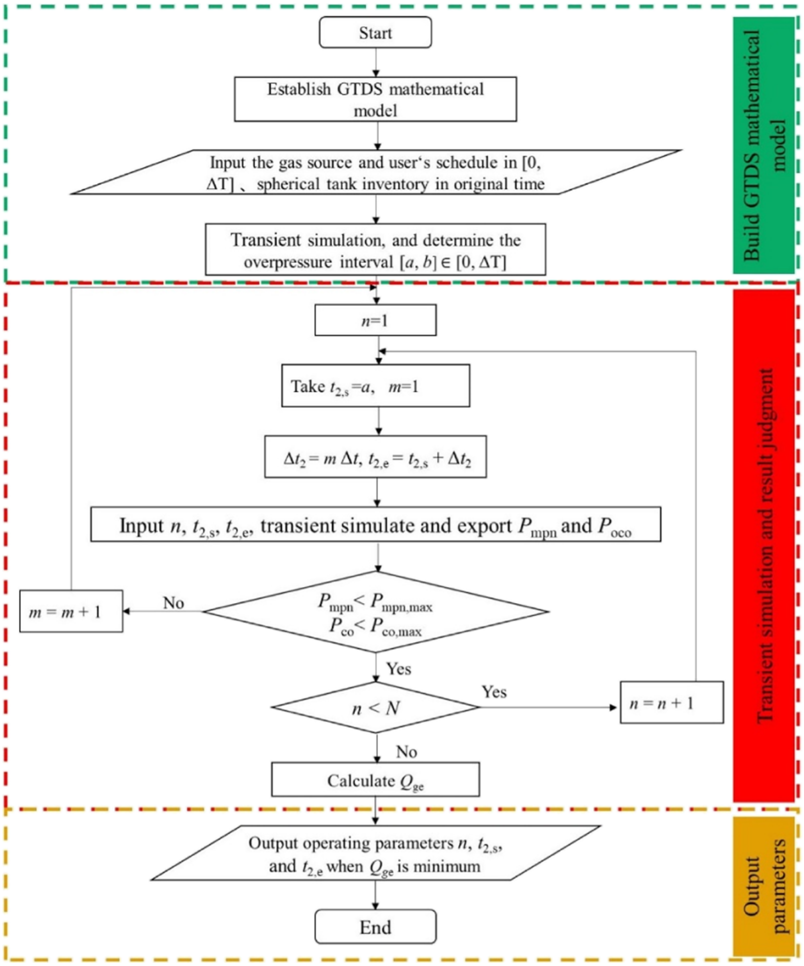

Figure 2. CSSA optimal parameter acquisition flowchart. n is the number of compressors stopped at the compressor station.

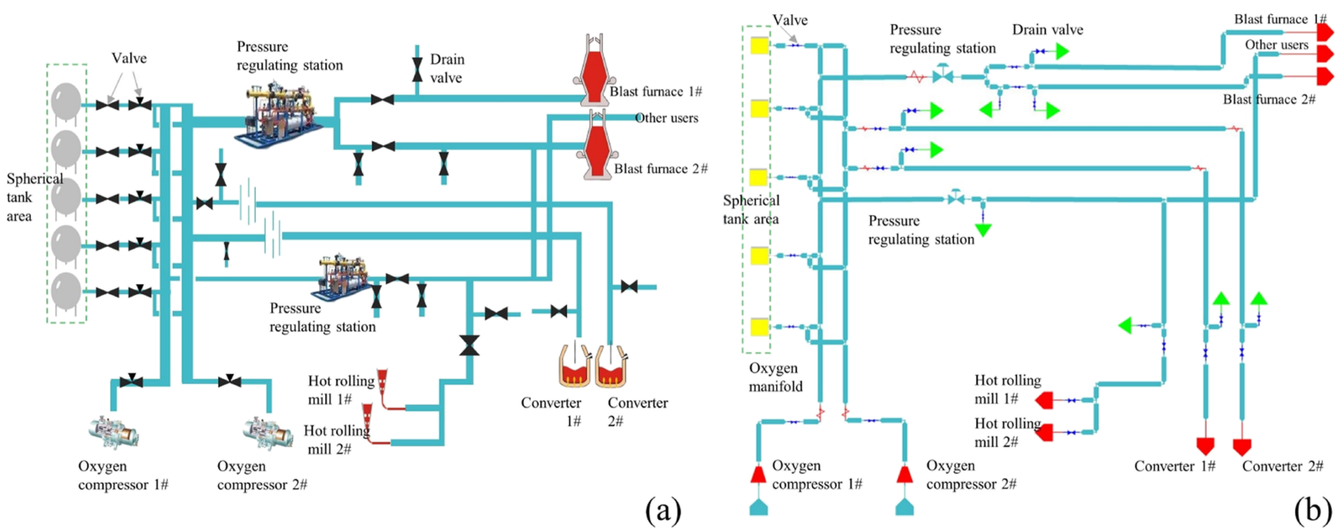

Figure 3. Large-scale OTDS in China. (a) Flow chart of the OTDS and (b) OTDS mathematical model diagram established in the pipeline.

3. SPECIFIC CASE STUDY

3.1. Brief Introduction of the OTDS. To test the effects and differences of the low-pressure release strategy (LPRS) in the GTDS, this article takes the OTDS as a case study. The OTDS is a kind of GTDS, in which the front end is an air separation plant for stable oxygen production, and the back end is a user side composed of different users. The main users in the OTDS are blast furnaces and converters. The total amount of oxygen used accounts for the total amount of oxygen in the steel plant, which is approximately 90%. The OTDS usually contains more than two CCs, pipelines with lengths ranging from several kilometers to hundreds of kilometers, multiple oxygen spherical tanks, various valves, and secondary pressure regulating stations located in the front

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of the user. This study selects the oxygen pipeline network transmission and the distribution system of a large steel enterprise in China and establishes an OTDS transient mathematical model based on the system diagram, as shown in Figure 3. Table 2 shows the size of the pipes.

Figure 3 shows the OTDS diagram and the established mathematical model of a large-scale air separation company in China. The working capacity of two OCOs is 72,000 $Nm^3 \cdot h^{-1}$, and the design capacity is 75,000 $Nm^3 \cdot h^{-1}$. A piece of data recorded with a total duration of 100 min and Δt = 2 min intervals are selected from historical data, and $P_{oco} > P_{oco,max}$ and $P_{mpn} > P_{mpn,max}$ are found in this period. The oxygen production and use of the main equipment during this period are as follows. As shown in Figure 4, the maximum values of P_{oco} and P_{mpn} in this case are $P_{oco,max}$ = 2.53 MPa and $P_{mpn,max}$ = 2.70 MPa, respectively. Besides, in IGVOA, Δk_{min} = 3°, Δk_{min} = 11°, and $\Delta(\Delta k)$ = 2°.

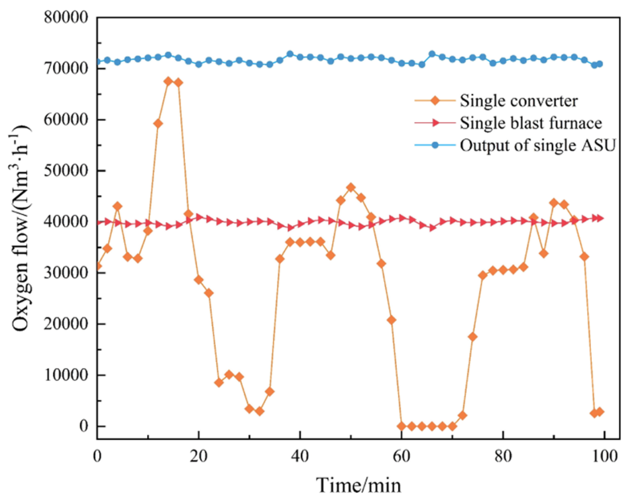

Figure 4. ASU and main equipment oxygen flow.

The results and errors of the model established in this paper when transient simulating pressure are shown in Figure 5. During transient simulation, the maximum pressure error is only 0.115 MPa and the average pressure error is 0.035 MPa, which indicates that the model established in this paper has high accuracy, and the transient simulation results are credible.

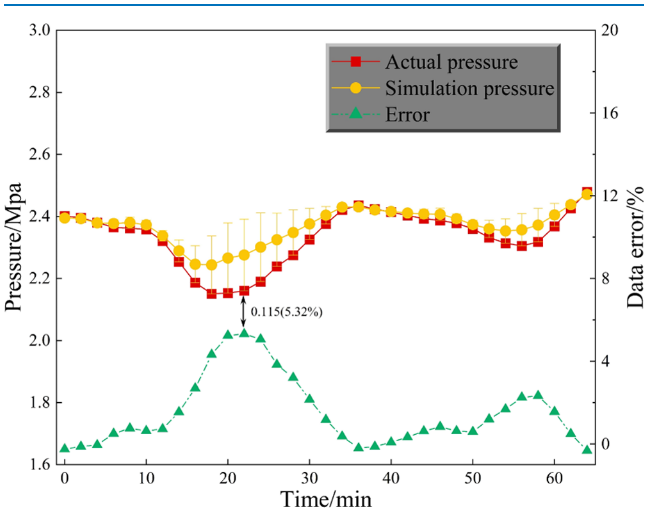

Figure 5. Model accuracy and error.

3.2. Results and Discussion. *3.2.1. Pressure Regulation Result.* Figure 6 shows that the three adjustment strategies of MPRS, IGVOA, and CSSA can all adjust the pressure of the OTDS, but the difference among the three can also be seen. Among them, the MPRS is about to reach $P_{mpn,max}$ and $P_{oco,max}$ before the P_{mpn} and P_{oco} curves. In the beginning, in this case, the operating time period is 68−74 min, and P_{mpn} and P_{oco} fall the fastest in this interval; the method of IGVOA starts some time before the P_{mpn} and P_{oco} curves reach $P_{mpn,max}$ and $P_{oco,max}$ operation, and in this case, the operation time period is 30−40 min. Through the adjustment of 40 min, the P_{mpn} and P_{oco} curves are controlled under the $P_{mpn,max}$ and $P_{oco,max}$ curves. Figure 4 shows that the MPRS adjustment position is same as the IGVOA adjustment position, and Figure 7 shows that the operating time period of MPRS is similar to that of MPRS, ranging from 64 to 70 min, and the adjusted P_{mpn} and P_{oco} curves are similar to those of IGVOA.

3.2.2. Energy Consumption Calculation of the Centrifugal Oxygen Compressor. In this study, the energy consumption of the centrifugal oxygen compressor (COC) is calculated by the performance curve.[28−30] The regress function in Matlab R2014a software is used for fitting to obtain the relationship among the flow-pressure, flow-shaft power, and opening of the oxygen compressor. Table 4 shows the calculation steps of COC E_{co}.

CSSA adjusts the original single large COC to a COCS that does not reduce the total design capacity. Figure 3 shows that the two COCs in the OTDS are completely symmetrical. The following is a single COC to analyze the adjustment results of CSSA. The COC adjustment scheme with a design capacity of 75,000 $Nm^3 \cdot h^{-1}$ in this strategy consists of the following two cases. Figure 7 shows the result. Table 5 shows the design capacity of each parallel COC, the inner diameter, and the wall thickness of the pipe connecting the CC. The design capacity of the COC based on eq 4 is adjusted, and the inner diameter and wall thickness parameters of the connecting pipe are designed according to "Oxygen Station Design Specification GB50030." The improved COCS can realize a short stop that increased the adjustment method and adjustment ability. This study mainly examines the short stop adjustment ability of the COCS.

Figure 8 shows the energy consumption comparison of the three regulation strategies in this case. Within 100 min of operation, in this case, the operating energy consumption of the oxygen compressor of the MPRS was 38,454 kW h, and the operating energy of oxygen compressors of IGVOA and CSSA was 38,024 and 35,105 kW h, respectively. In terms of total oxygen emission loss, IGVOA and CSSA are far less than the MPRS, saving 66.58 and 53.66% respectively; but in terms of oxygen compressor operating energy consumption, CSSA saves the most, which is 3349 kW h less than the MPRS. IGVOA reduced 2919 kW h.

3.2.3. Calculation of Oxygen Emission. During the operation of the OTDS, the relief valve opens to release oxygen when the pressure of the gas pipeline is too high. The pipeline pressure drops below the setting pressure after Δt_2 time. During this period, the theoretical calculation of the total amount of oxygen emission Q_{ge} is as follows

$$Q_{ge} = \int_{t=0}^{t=\Delta t} Q_x \mathrm{d}t \tag{5}$$

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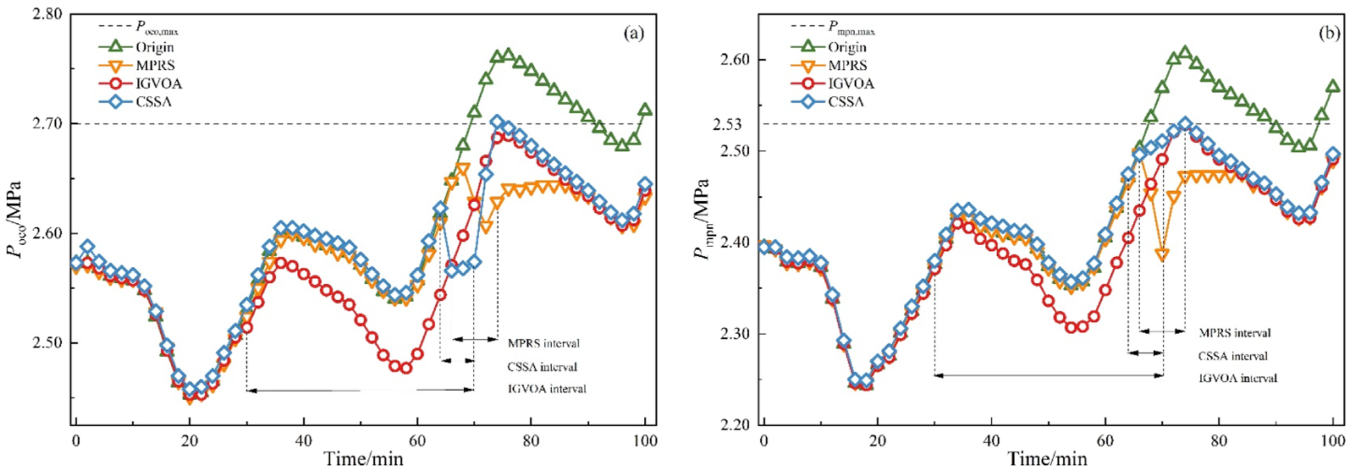

Figure 6. Pressure changes at key locations during OTDS operation. (a) pressure of the centrifugal OCO and (b) pressure of the CC outlet.

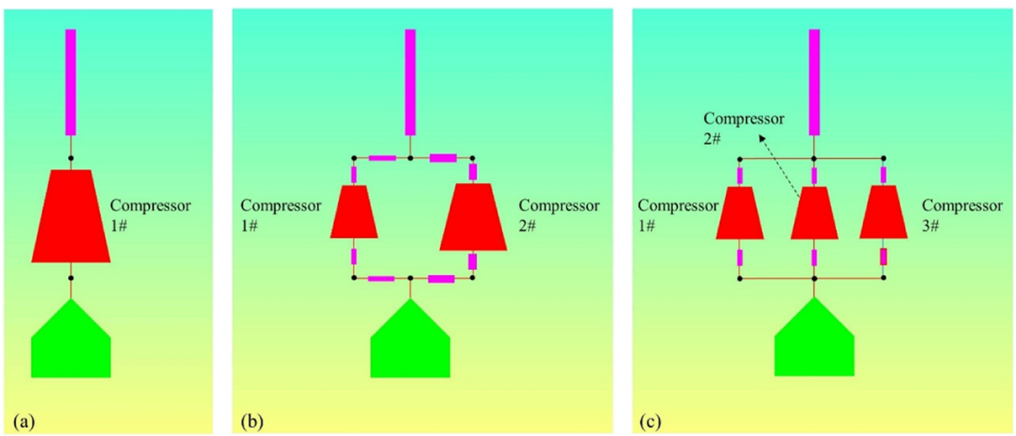

Figure 7. Oxygen compressor adjustment plan results in CSSA. (a) single compressor structure; (b) compressor station composed of two compressors of different sizes; and (c) compressor station composed of three equal volume compressors.

Table 4. Calculation Steps of Oxygen Compressor Energy Consumption

procedure	specific operation
STEP1	use Matlab R2014a software to calculate the inlet guide vane opening k according to the intake flow Q_i and exhaust pressure P_o
STEP2	calculate the shaft power N_z from the inlet guide vane opening k and the intake airflow Q_i
STEP3	calculate the isothermal efficiency η_T combined with the isothermal efficiency calculation formula of the CC
STEP4	use the trapz function in Matlab R2014a software to calculate the integral of the shaft power N_z during the study period to obtain the value of the total energy consumption E_{co}

Table 5. Calculation Steps of Oxygen Compressor Energy Consumption and Efficiency

	parameter		
object	serial number	designed capacity/$Nm^3 \cdot h^{-1}$	connecting pipe's inner diameter/wall thickness/mm
(a)	compressor 1#	75,000	510/10
(b)	compressor 1#	25,000	309/8
	compressor 2#	50,000	460/10
(c)	compressor 1#	25,000	309/8
	compressor 2#	25,000	309/8
	compressor 3#	25,000	309/8

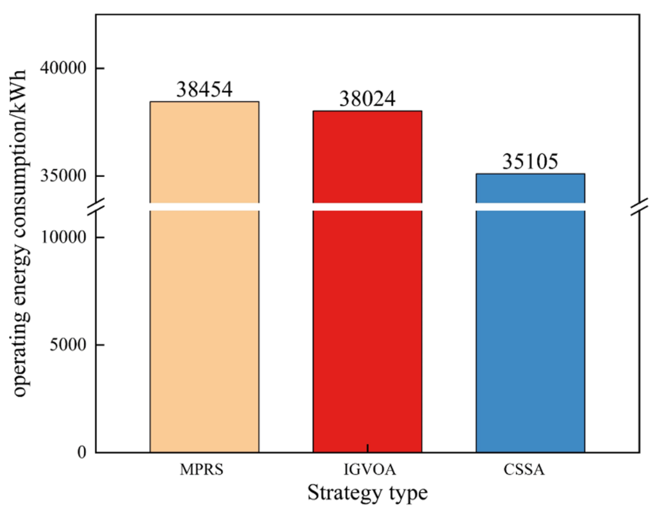

Figure 8. Comparison of operating energy consumption of the oxygen compressor.

CSSA shows excellent performance in the control of oxygen emission loss and the convenience of oxygen compressor operation energy consumption control. Figure 9 shows the total oxygen emission comparison of the three regulation strategies in this case, in which the total oxygen emission loss of the MPRS in the 6 min emission interval is 7176.2 Nm^3, and the total oxygen emission loss of IGVOA and CSSA is 2398.2 and 3325.3 Nm^3, respectively. Compared with the MPRS, the oxygen emission losses of IGVOA and CSSA are reduced by 4778 and 3850.9 Nm^3, respectively.

3.2.4. Comprehensive Energy Consumption Comparison. To better compare the energy-saving performance of IGVOA and CSSA based on the MPRS, the unit consumption of oxygen η_{O_2} is introduced, and the saved amount of oxygen emission is converted into electricity consumption and then combined with the comprehensive analysis of the energy consumption of the compressor. The specific calculation method is as follows

$$E_{total} = \Delta Q_{ge} \times \eta_{O_2} + \Delta E_{co} \quad (6)$$

In this paper, the average annual comprehensive unit consumption of oxygen production by the research company in 2019 is about 0.96 kW h. Figure 8 Figure 10 shows that CSSA saves about 2029 kW h more power than IGVOA, which has higher energy-saving performance.

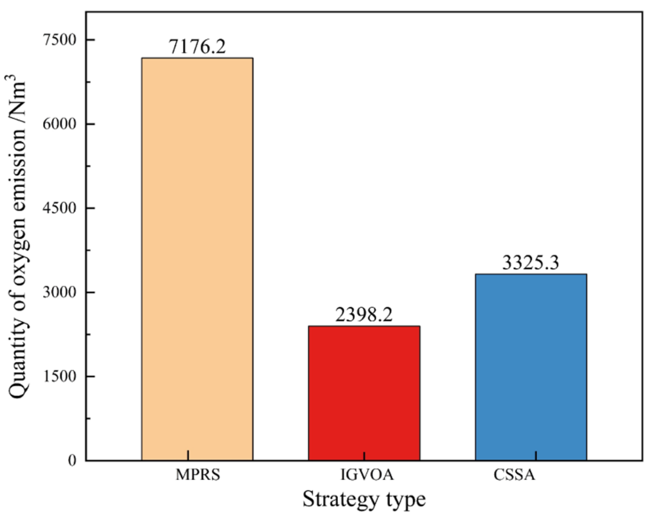

Figure 9. Comparison of total oxygen emission.

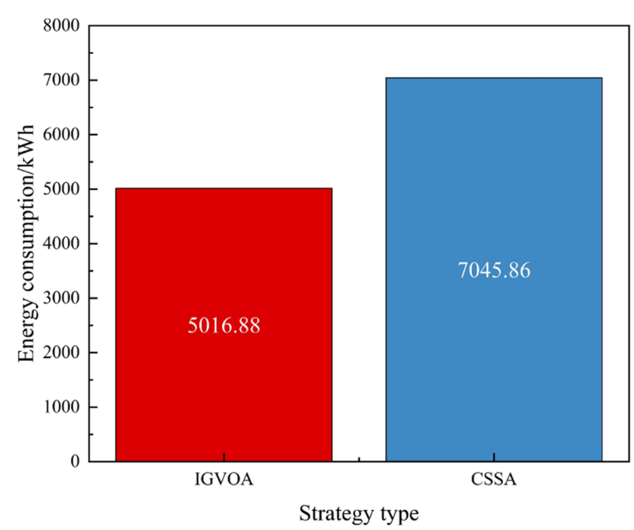

Figure 10. Comprehensive energy consumption comparison.

3.2.5. Comparison of Adjustment Methods. Comparison of CSSA with MPRS and IGVOA shows that the adjustment position is different from the object, and Figure 11 shows the difference between them.

1 The MPRS is currently the most popular adjustment method, and the safety valve will automatically open after setting the pressure;

2 IGVOA is a theoretically feasible adjustment method. IGVOA reduces the CC processing gas volume by reducing the CC inlet guide vane opening in a small range and releases oxygen in a low-pressure manner in advance, but estimating Q_{ge} is not easy; and

3 CSSA adjusts the CC to the CCS to stop for a short time when the pipe network is overpressured, and oxygen is released hypoxically in advance.

Although IGVOA is excellent in reducing the amount of oxygen released, CSSA is more significant in terms of compressor energy-saving and has a wider adjustment capacity and adjustment range. IGVOA and CSSA belong to the LPRS, but their adjustment capabilities are different. IGVOA and CSSA can be used to alleviate the problem of excessive pressure in the pipe network and oxygen emission caused by oversupply. The action positions are in front of the gas supply main pipe, and the targets are compressors, but IGVOA adjusts the compressor inlet guide vanes. IGVOA is only applicable to CCs with inlet guide vanes, whereas CSSA adjusts the start and stop status of the compressor, which is applicable to all compressors.

The instantaneous flow regulation characteristics of IGVOA and CSSA are classified into continuous and intermittent types. Figure 12 shows the different characteristics of IGVOA and CSSA in flow regulation. The three closed ranges formed by curves in the figure represent the safe working ranges of 25,000, 50,000, and 75,000 $Nm^3\ h^{-1}$ CC; IGVOA is continuous. The line L_0 represents the initial state of adjustment in the case, and L_1 is the lower limit of the adjustment of IGVOA. The shaded parts of L_0 and L_1 indicate the adjustment range of IGVOA, which also shows that the adjustment range of IGVOA is continuous, that is, the initial state of compressor work L_0 can reach any working state in the shaded area by adjusting k theoretically. CSSA is intermittent. The initial state L_0 can go through the A_1 line to the L_2 line state (n = 1 corresponding state), and if necessary, L_0 can go through the A_2 line to the L_3 line state (n = 2 corresponding state). The initial state L_0 can also directly reach the L_2 line via the A_3 line (n = 2 corresponding state). In addition, from the L_0 state to the L_1 state and from the L_0 state to the L_2 state or the L_3 state, CSSA greatly exceeds IGVOA in terms of flow regulation capability.

4. CONCLUSIONS

This paper proposes a new adjustment strategy to reduce oxygen emission in the OTDS. This method adjusts the compressor to the compressor station structure, stops some compressors in a short time when the pipe network is overpressured, and quickly reduces the pressure of the pipe network. Aiming at the gas emission problems often caused by the high-pressure operation of large-scale industrial gas pipeline networks, taking OTDS as an example, transient simulation is carried out through the established mathematical model, and the three adjustment methods of MPRS, IGVOA, and CSSA are analyzed by analyzing the pressure and flow of key parts and equipment. The conclusion is as follows:

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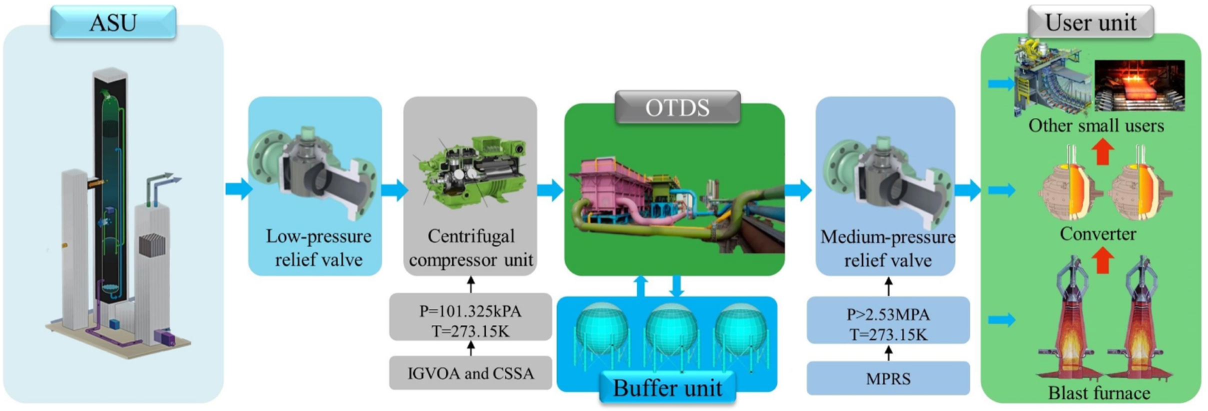

Figure 11. MPRS, IGVOA, and CSSA regulation principle in the OTDS (ASU photograph is from the literature;[31] low-pressure and medium-pressure relief valves are from the literature;[32] the OTDS is from the literature;[33] buffer unit is from the literature;[34] the CC is from the literature;[35] user photographs are from the literature[36,37]).

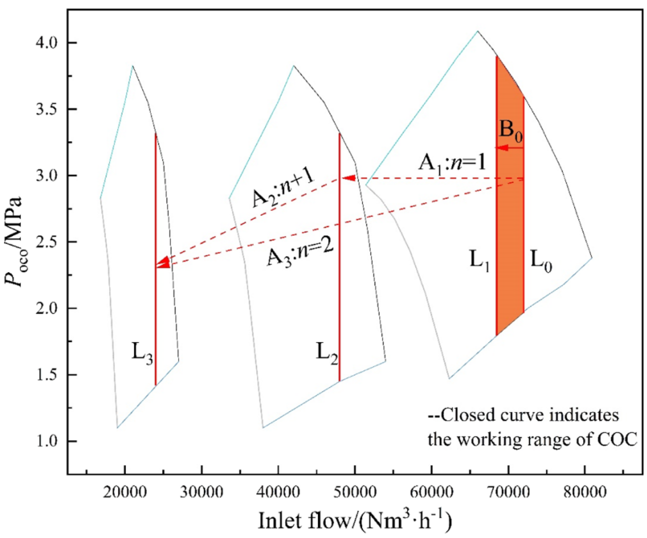

Figure 12. IGVOA–CSSA instantaneous flow adjustment comparison in case.

1 Transient simulation through TGNET modeling can accurately reflect the change of the flow process, and the simulation accuracy is high (maximum pressure error is 0.115 MPa).

2 CSSA is a new type of strategy with a significant energy-saving effect. CSSA fully utilizes the compressor's adjustment function and adds optional new adjustment methods to the GTDS.

3 CSSA reduces the compressor processing gas volume and the gas volume entering the gas pipe network system, reduces the compressor outlet pressure and the medium-pressure pipeline pressure, reduces the compressor operating energy consumption, and significantly reduces the amount of gas emission.

4 Both IGVOA and CSSA can reduce oxygen emission and reduce compressor energy consumption, but CSSA has greater instantaneous adjustment ability and requires a shorter adjustment time compared to IGVOA.

5 Compared with MPRS and IGVOA, CSSA reduced oxygen emission by 3850.9 Nm^3 and increased by 927.1 Nm^3; compressor operating energy has been reduced by 3349 and 2919 kW h. In addition, the operation time periods of CSSA and MPRS are similar, 64–70 and 68–74 min, respectively, whereas the start time of IGVOA operation is earlier, and the operation time is longer, which is 30–70 min.

5. DISCUSSION

A compressor short stop adjustment strategy is proposed to reduce the peak pressure of the pipe network system after comparing two traditional adjustment methods. The strategy is based on three assumptions (see Section 2.2.3). Assumptions 1 and 2 have less impact on the strategy, and assumption 3 has a greater impact because the compressor start and stop time increases with the increase in compressor processing capacity. If the time required for the compressor to start and stop exceeds the time required for the short-term stop of the strategy, oxygen emission will be increased, which will increase the energy consumption of the system and greatly reduce the energy-saving effect. In future research, the time required for the compressor to start and stop can be used as a constraint for further research.

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Notes

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NOMENCLATURE

D, pipe inner diameter [mm]
Re, dimensionless number of Reynolds [-]
Q, the gas flow rate [m^3/h]
k, inlet guide vane opening [°]
t_1, IGVOA adjustment time [min]
t_2, CSSA adjustment time [min]
Q, flow of centrifugal compressor [m^3/h]
P, pressure [MPa]
T, temperature [K]
E, operating energy consumption [kW h]
t, time[min]

SUBSCRIPTS

min	minimum
max	maximum
s	start
e	end
co	centrifugal compressor
oco	oxygen compressor outlet
oe	oxygen emission
ge	gas emission
mpn	medium-pressure pipe network
i	in
o	out

GREEK SYMBOLS

λ	coefficient of friction
ρ_0	the gas molar density [kg/mol]
Δ	difference (−)

ACRONYMS

ASU	air separation unit
OTDS	oxygen transmission and distribution system
GTDS	gas transmission and distribution system
MPRS	medium-pressure release strategy
LPRS	low-pressure release strategy
IGVOA	inlet guide vane opening adjustment strategy
CSSA	compressor short-term shutdown adjustment strategy
CC	centrifugal compressor
CCS	centrifugal compressor stations
COC	centrifugal oxygen compressor

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