Modeling and analysis of the compressor for the closed cycle system on anti-surge process

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Abstract. In order to study the interaction mechanism of the pipe network, the compressor and the control system in the process of the anti-surge regulation, the simulation model of the overall Closed Cycle System (CCS) is established in this paper. By comparing the simulation results with the target values at the Design Operation and the Maximum Mach Operation, the calculation deviation is less than 1%, which verifies the accuracy of the model. At the Maximum Mach Operation, the analysis of the CCS during the quasi steady process and the dynamic process is carried out respectively. According to the result of quasi steady state analysis, the effectiveness of the designed anti-surge circuit during the normal operating process of the CCS is verified. By opening the Anti-Surge Valve, additional 38.5% surge margin is provided. And the surge margin at the simulation process would be slightly higher than the design value for the variation of the inlet condition from the different operations. Through the dynamic analysis, the changes of the different performance parameters are studied in the process of sudden blockage in the pipe network, and during this process the compressor surge could be induced easily due to the sharp decline of the inlet pressure. To ensure the safety of the compressor during the acceleration and deceleration process, the moving trajectory of the operation point on the Compressor Characteristic Map should be studied by considering the effect of the resistance characteristics of the CCS pipe network. In addition, the anti-surge system should have a high response frequency to deal with the sudden blockage.

1. Introduction
The test bed of Closed Cycle System (CCS) is very important for the compressor manufacturer such as Shenyang Blower Works Group Corporation. This test bed could be used for the special gas experiments (like Co2, N2 and He) and the experiments of the sensor calibration. It could save a lot of time and fund. The compressor is usually used to drive the air in the wind tunnel circuit, and to provide the required pressure ratio for the test section. Since the wide operating range and abundant regulation means of continuous wind tunnel, the higher safety requirements of the CCS tunnel compressor is put forward. However the relevant researches are very rare. Due to similarity of the wind tunnel and the closed cycle compressor system, the researches on the anti-surge of the continuous wind tunnel can provide the effective references.
The Continuous wind tunnel is a closed cycle system, and has the advantages of the excellent flow field quality, wide operation range and continuous operation, so requirements of the anti-surge is very strict [1]. The flow uniformity and the mass flow at compressor inlet would affect the blade inlet flow angle, and once the air flow angle increases to a certain value, the non-working face of the blade will stall [2]. Coupling with the wind tunnel pipe network system, the strong abrupt stall could cause the compressor surge. Parameters in wind tunnel such as pressure and flow would present low-frequency
and large amplitude longitudinal pulsation oscillation, which could result in the interference between rotor and stator, leading to major accidents [3-4]. The mechanism of compressor surge has been studied deeply. By analyzing a transonic compressor, James gives the evaluation criteria of the compressor performance and stall line [5]. Xu Xiaoju puts forward the surge mechanism and anti-surge control method for an industrial compressor [6]. In references [7] and [8], the feasibility of two anti-surge measures, namely direct venting regulation and bypass regulation, of wind tunnel compressor is analyzed. The compressor surge boundary of two wind tunnels in china (namely NF-6 and av90-3) has been tested by Gao Chao and Zhou Enmin [9-10]. Zhang Wen achieves the real-time judgment and automatic control of surge by the use of PLC process control and WinCC platform [11]. In the existing literatures about the anti-surge control of wind tunnel compressor, the researchers are still mainly focused on experimental research [6-11]. Although the experimental study is more reliable, it needs to establish a complete wind tunnel test system before the research, which has significant lag. And considering the safety and cost, it is impossible to carry out destructive test to obtain the wind tunnel system operating parameters under the limit conditions. Through establishing the simulation model, the surge process is analyzed in the design stage, which can be used to guide the design of anti-surge system and formulate anti surge control strategy, and can simulate the operation process of extreme conditions. A series of the related researches have been carried out for the industrial compressor[12-14], but there is no relevant research report about wind tunnel compressor.

Ref. [11] points out the factors such as the Mach number, the opening aero of Two-Throat, the attack angle and the pipe network characteristics are available to cause compressor surge. However, the above situation are caused by personnel adjustment at normal operation point, and the occurrence of surge is gradual and predictable. However, due to the sudden falling off of the components or test pieces, the throat of the pipe network is blocked and could cause surge. This process is unpredictable and difficult to carry on an experimental study for its destructiveness. The dynamic simulation is an effective research method to solve this kind of problems. In this paper, the quasi steady model and the dynamic model of the Closed Cycle System (CCS) are established to study the surge process, especially in the extreme conditions, to obtain the influencing mechanism. By this way, it’s helpful to further understand the surge process and formulate reasonable anti surge strategy.

2. Analysis of the quasi steady state process

2.1 Analysis area of the CCS system

The analysis area includes the overall CCS, as shown in Figure 1, including the motor, the compressor, the heat exchanger, the silencing section, the main valve, the anti-surge circuit, the anti-surge valve and the pipeline system. The input parameters are listed as follows: (1) the compressor characteristic data, (2) the size, friction coefficient and heat transfer coefficient of pipeline system, (3) the wall temperature and the heat transfer coefficient of heat exchanger, (4) the corresponding relationship between the flow coefficient and the valve opening angle. Valve A is the main valve, and the impact of pipeline local blockage on the CCS is simulated by adjusting the angle of this valve. Valve B is anti-surge valve, which controls the open/close status of the anti-surge circuit.
2.2 Mathematical model

2.2.1 Governing equations
The flow process in pipeline is described by the gas state equation, the mass conservation equation, the energy conservation equation and the momentum equation, the equations are shown as follows:

\[ pV = R_sT \]  \hspace{1cm} (1)

\[ \frac{dm}{dt} = \sum_{\text{boundaries}} \dot{m} \]  \hspace{1cm} (2)

\[ \frac{d(me)}{dt} = -p \frac{dV}{dt} + \sum_{\text{boundaries}} \left( \dot{m}h - h_{in} \right) - h_{loss} \]  \hspace{1cm} (3)

\[ \frac{dm}{dt} = \left[ dp + \sum_{\text{boundaries}} \left( \dot{m}u \right) - 4C_f \frac{p u}{D} \frac{dx A}{dx} - C_p \frac{p u}{2} A \right] \]  \hspace{1cm} (4)

Where: \( \dot{A} \) is the heat transfer area, \( T_{wall} \) is the wall temperature, \( C_f \) is the friction coefficient of the pipeline, and \( CP \) is the local pressure loss coefficient.

2.2.2 Compressor Model
The compressor model is established by the compressor characteristic data. The compressor performance at different inlet conditions is accurately calculated by using reduced parameters, the equations of the reduce parameters are shown as follows:

\[ RPM_{re} = \frac{RPM_{act}}{\sqrt{T_{in}}} \]  \hspace{1cm} (5)

\[ \dot{m}_{re} = \frac{\dot{m}_{act} \sqrt{T_{re, in}}}{p_{re, in}} \]  \hspace{1cm} (6)

Where: the subscript \( re \) represents the reduced parameter according to the entrance conditions, and the subscript \( act \) represents the actual parameter.

The enthalpy, power and enthalpy are shown as the following equations.

\[ h_{out} = h_{in} + \Delta h / \eta \]  \hspace{1cm} (7)

\[ P = \dot{m} \left( h_{out} - h_{in} \right) \]  \hspace{1cm} (8)

\[ \Delta h = c_p T_{in} \left( PR - 1 \right) \]  \hspace{1cm} (9)

Where: \( \dot{m} \) is the mass flow, \( \eta \) is the isentropic efficiency, \( PR \) is the total pressure ratio, the above parameters are determined by interpolation according to the compressor characteristic data.
2.3 Validation of the steady state model

The CCS Design Operation (Oper_D) and the Maximum Mach Operation (Oper_M) are selected as the verification operations, the calculation accuracy of the model is determined by comparing the calculated and the target values of the heat exchanger outlet temperature, the Mach number at the test section, the compressor inlet parameters (total temperature, total pressure and mass flow), and the compressor performance parameters (pressure ratio, efficiency and power). The calculation accuracy is shown in Table 1. In Table 1, T_Cooler is the outlet temperature of heat exchanger, Tt is the total temperature, Pt is the total pressure, PR is the pressure ratio, Eff is the isentropic efficiency, and Power is the compressor power. The calculation deviation of each parameter in Table 1 is less than 1%, the calculation accuracy of the model is accurate.

| Parameter | T_Cooler | Compressor inlet | Compressor performance |
|-----------|----------|------------------|------------------------|
| Oper_D    | -0.03    | -0.03 0.11 -0.02 | 0.00 -0.24 0.39        |
| Oper_M    | 0.00     | 0.00 0.16 0.03   | -0.13 0.00 -0.10       |

Note: Calculation Deviation = (Calculated Values – Target Values)/Target Values x 100%

2.4 Anti-surge control system

In order to ensure the safety of the compressor, three protection lines are set, namely Alarm Line, Valve Opening Line and Deceleration Line, as shown in Figure 2. When the combination operation point of the compressor and the pipe network system moves to the Alarm Line, the sound-light alarm would be sent out; when the combination operation point moves to the Valve Opening Line, the anti-surge valve would be turned on, and the response time of the anti-surge valve is 3s; when the combination operation point moves to the Deceleration Line, the compressor speed would reduce by 20%, and the response time of speed reduction is 3s. The anti-surge control system is established according to the above three control lines. When the combination operation point moves to different areas, the corresponding protection measures would be triggered such as alarming, valve opening and decelerating in the dynamic model.

![Figure 2 Protection lines of the anti-surge control system](image)

2.5 Establishment of Dynamic model

Macro dynamic processes discussed in this paper include the quasi steady state process and the dynamic process. During the quasi steady state process, the parameters of compressor change slowly
and continuously, which usually occurs in the normal operation process of the CCS compressor. The dynamic process simulation is used to study the emergency situations, such as the sudden falling off of the components or test pieces, which could cause local sudden blockage, make the parameters change sharply and induce surge. The speed change in the above process is necessary to simulate by considering the power difference between the motor and the compressor, as well as the influence of inertia. In this model, PID algorithm is used to simulate the motor power control system in real time to ensure that the compressor speed can converge to the target speed. The control process is shown in Figure 3. When the actual speed of the compressor deviates from the target speed, the power correction is calculated by Proportion (P), Integral (I) and Derivative (D), and the motor output power is adjusted. The compressor speed could converge to the target speed. PID control parameters are determined by debugging.

![Figure 3 Algorithm diagram of PID](image)

3 Analysis of the quasi steady state process

As shown in Figure 2, the surge margin of Oper_M operation is minimum, more attention should be paid to this operation to avoid the compressor surge. So Oper_M is selected to study the influence mechanism. The position of the combination operation point on the Compressor Characteristic Map is controlled by adjusting opening of Valve A on the main pipe. By reducing the opening of Valve A gradually, the combination operation point moves from Oper_M to the small flow area along the constant speed line. By this way, the slow and conventional adjustment process of the CCS is simulated, so namely quasi steady state process.

Seven operating points are selected for further analysis on the constant speed operation line. The first five operating points are Oper_M, Alarm Point (Point A in Figure 2), Valve Opening Point (Point B), Deceleration Point (Point C) and Surge Point (Point D). The last two operating points are Valve-Opening-Deceleration Point (point E, coinciding with point C) and Valve-Opening-Surge Point (Point F, coinciding with Point D), the last two points separately operate at the Deceleration line and Surge line with the Anti-Surge Valve opening. The last two points are used to analyze the ultimate anti-surge capacity of the designed anti-surge circuit. During all the seven quasi steady state processes (from Oper_M to A, B...F), the anti-surge control system is effective, which ensures compressor operating safely. The results of the seven operation points are shown in Table 2. The design value of surge margin is obtained in the design process when the inlet conditions are constant. The negative value for the calculated surge margin means the additional surge margin provided by anti-surge circuit.

According to Table 2, from Oper_M to Point D, the opening of the Valve A gradually decrease. With the operation moving to the small flow area, the outlet temperature of the compressor increases, while the capacity of the heat exchanger remains constant, so the total temperature at the outlet of the heat exchanger increases. By reducing the opening of Valve A, and the total pressure loss in the main pipe increases and the compressor inlet pressure decreases. According to the compressor similarity criterion, the reduced flow rate of compressor surge point remains constant under different compressor inlet conditions. When the operating point moves to the small flow area, the total temperature increases and the total pressure decreases, according to Eq.(6), which leads to the relative increase of surge margin, from 10% to 13.1%. At the Point F, the flow rate of the main pipeline in the main pipe is ultimate minimum value of the CCS, and the anti-surge circuit can provide an additional 38.5% surge margin.

Table 2 Compressor inlet parameters and surge margin for each operating point
| Operation | Inlet Temperature /K | Inlet pressure /Pa | Calculated surge margin % | Design surge margin % |
|-----------|---------------------|-------------------|---------------------------|----------------------|
| Oper_M    | 300                 | 70857             | 13.1                      | 10                   |
| A         | 300.31              | 69757             | 8.5                       | 7                    |
| B         | 300.62              | 69413             | 5.9                       | 5                    |
| C         | 301.0               | 69000             | 2.2                       | 2                    |
| D         | 301.17              | 68810             | 0.0                       | 0                    |
| E         | 301.02              | 68964             | -36.3                     | -                    |
| F         | 301.18              | 68791             | -38.5                     | -                    |

4 Analysis of dynamic process

In the dynamic process, the influence of the local blockage on the CCS compressor is simulated by suddenly closing the flow area of the Valve A. Three cases are listed as follow. (1) The angle of the Valve A reduces from the open angle of Oper_M to the open angle of Point A within 0.1 s, namely Oper_M to Point A, and the Valve B keeps close during this process. (2) The angle of the Valve A reduces from the open angle of Oper_M to the open angle of Point D within 0.1 s, namely Oper_M to Point D, according to the anti-surge control strategy, Valve B is open and the compressor speed is reduced by 20%. (3) The angle of the Valve A reduces from the open angle of Oper_M to the open angle of Point E within 0.1 s, namely Oper_M to Point E, Valve B is open and the compressor speed is reduced by 20%.

4.1 Dynamic process from Oper_M to Point A

The changes of different parameters in the dynamic process are shown in Figure 4. According to the changes of the parameters in the Figure 4, the open angle of the Valve A suddenly is reduced to the open angle of Point A at t=150s, which simulates the effect of the sudden local blockage in the CCS on the compressor. The mass flow through the Valve A suddenly decreases (reduced by 17.2%), meanwhile the compressor inlet mass flow does not change, so that the air in the pipeline between Valve A and compressor is pumped out, the air temperature and pressure drop. While the gas pressure at compressor outlet does not change significantly, the compressor pressure ratio suddenly increase (increased by 4.2%). According to the compressor characteristics, the operating point quickly moves to the small flow area. The compressor surge occurs almost at the same time as the local blockage (t=150s). Due to the reduction of mass flow, the power consumption used for compressing the air decreases, and the output power of the motor keeps constant, so the compressor speed increases.

When the open of the Valve A suddenly decrease, a part of air is blocked in front of the Valve A, the subsequent air would compress this part air and make its pressure and temperature increase. When this part air with the higher temperature and pressure flows into the compressor, the pressure ratio decreases rapidly, and the flow rate begins to increase, the compressor gradually exits the surge state, finally the operating point coincides with Point A. The moving trajectory of the compressor operating point is shown in Figure 5 and the trajectory is consistent with the previous analysis. When the Valve A is turned down, the compressor enters the surge state, and then exits the surge after 2s. Generally, the anti-surge system needs to monitor the temperature and pressure to determine the position of the compressor operating point and the corresponding protection plan, which has a certain hysteresis (delay time set as 3s). The designed protection system exists certain shortcomings in dealing with this kind of dynamic processes. The response frequency should be increased to deal with the sudden blockage.

Comparing the results in Table 2, the actual surge margin of the Point A is 8.5%, but the dynamic simulation results show that the compressor enters surge state during the process. According to the above analysis, local blockage leads to the pressure at the compressor inlet reduce sharply, and so the pressure ratio increase significantly, and could induce surge easily. The existing experimental and simulation researches on processes of the steady-state or quasi steady state can't present actual operation of compressor for these sudden events.
4.2 Dynamic process from Oper_M to Point D

The changes of different parameters in this process are similar to that shown in Figure 4. The differences are that the anti-surge valve is open and the compressor speed is reduced by 20% at t=153s. The moving trajectory of operation point is shown in Figure 6. The blockage first causes a significant increase of the pressure ratio, and compressor enters the surge state. With the Valve A opening, the pressure ratio decreasing and mass flow increasing, the compressor is gradually exit surge state. The compressor speed is reduced safely under PID control.

Figure 4 Changes of the different parameters in the dynamic process from Oper_M to Point A

Figure 5 Moving trajectory of the compressor operating from Oper_M to Point A
4.3 Dynamic process from Oper_M to Point E

The changes of different parameters in the dynamic process are similar to that in Section 3.2. With the Valve A opening, the compressor will exit the surge state, but during the process of deceleration, the compressor will enter the surge state again. According to Table 2, the surge margin of Point E is about 2%, but as shown in Figure7 the speed can’t decrease safely. The reason is that the CCS has its special pipe network resistance characteristics, and result in a specific moving trajectory of the combination operation point on the compressor Characteristic Map. Due to the impossibility to decelerate safely for Point E without any adjustment means, the mass flow of this operation in main pipe may be unreachable, the additional surge margin of the anti-surge circuit calculated by during the quasi steady state process is not surely to be reasonable. So the simulation analysis of the dynamic process is an effective way to test the safety of the compressor during the dynamic process, especially for the extreme operations.

5 Conclusion

In this paper, the overall model of the CCS is established, including the pipeline model, the compressor model, the valve model, the anti-surge control model and PID control model. The accuracy of the model is verified by comparing the steady-state calculation results with the target data. Then, the analysis of the quasi steady state process and dynamic process are carried out respectively, and the following conclusions are obtained.

1) According to the results of the quasi steady state analysis, the design anti-surge circuit is effective during the normal operating process of the CCS, the design anti-surge circuit could provide additional 38.5% surge margin. And the surge margin at the actual operation process would be slightly higher.
than the design value for the variation of the inlet condition from the different operations, the surge margin of Maximum Mach Operation increases from design value of 10% to 13.1%.

(2) Through the dynamic analysis, the changes of the different performance parameters are studied in the process of the sudden blockage in the pipe network, the sharp decline of the inlet pressure is the main reason to induce the compressor surge. As the blockage could cause surge in a short time, the anti-surge system should have a high response frequency to deal with the sudden blockage.

(3) In the deceleration process of the compressor, the operation point would enter the surge state again from the safe state due to the effect of the special resistance characteristics for the pipe network. So it’s an effective method to accurately study the interaction mechanism of the pipe network, the compressor and the control system in the process of the anti-surge regulation, and analyze the safety of the compressor during the dynamic process, especially for the extreme operations.

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