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Redesigning and simulation evaluation on large-flow high-temperature high-pressure bypass surge-out system

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Abstract

Aiming to the bypass surge-out system redesign project of a large-scale compressor test rig in this article the CFD (Computational Fluid Dynamics) method is applied to evaluate the exhausting capability for 6 schemes (including the former one), and by the principle of minimum diameter of exhausting pipe as well as standardization, confirm the final scheme. On the base of the former bypass surge-out system, the new one increases 200% of the exhausting capability, satisfies the exhausting requirement and left 27% margin. Meanwhile, according to the simulation result, the total pressure uneven zone has been obtained, improves that the outlet AIP (Aerodynamic Interface Plane) is far away from that zone and will not influence the result of outlet test, which supports the reliability of the test article outlet test scheme. The bypass surge-out system redesign scheme has been taken into application and operates well, the test data satisfied the simulation results in a certain high level. This research offers new thoughts and methodology for further test rig exhausting system deep study and improvement.

Keywords: bypass surge-out system, CFD, compressor test rig, redesign scheme, exhausting capability evaluating

1. General Introduction

An active high-scale single-shaft double-bypass compressor test rig has been taken in use since the 90th of last century. Limited by the technical level and situation at that period, there are severe restrictions on pressure and temperature of the test compressor exhaust from important exhaust components such as inner and outer bypasses as well as exhaust controlling value which is used for forcing the test compressor to get into surge state. Among the restrictions above exhaust temperature is the severe one, since a too high exhaust temperature will introduce a tremendous distortion of the exhaust controlling value, lead losing control and obstructing of the system. The obstructing problem of the exhaust controlling value will lead serious test safety risk. As what has been indicated above, obstructing of the exhaust controlling value commonly occurs when the test compressor is at a high state with high rev and high exhausting temperature, which means without valid method to help exhausting, the only way to bring down the test compressor state to resume the controlling of the exhausting value for a test operator is to slow down the rev of the compressor. If the opening of the exhaust value keeps unchanged, bringing down the rev of the compressor will make the state point in its flow-pressure ratio performance curve moving to its left side[1], as indicated in Figure. 1:

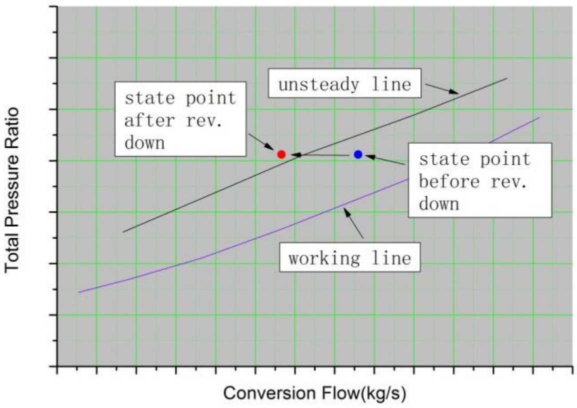

Figure.1 State point changes when the rev. of the test compressor is down

Has the obstructing problem occurred before the test compressor's unsteady state (stall or surge, when at high state the unsteady state is usually surge) , when the state point moves to its left side, the test compressor may get into unsteady state unexpectedly, and because of the obstructing of exhaust controlling value, no valid method can be used to get the test compressor out of the unsteady state, leading to further damages; much worse, has the obstructing occurred right at the moment that the compressor is at unsteady state, the compressor has to keep operating at adverse state for a long period since no valid out-surge method can be used, leading to a high risk of test compressor and test rig, even makes serious safety accidents including but not limited to blade fracture, flying off, cascade breakdown, test rig hurt or even damage, etc[2][3]. For this reason, evaluations on exhaust temperature of the test compressor according to Formula (1) must be executed before the compressor test[4].

$$T_{out} = \left(\frac{\pi^{\frac{\gamma-1}{\gamma}} - 1}{\eta} + 1\right) \times T_{in} \tag{1}$$

T_{out} ——total temperature at outlet of the test compressor;

T_{in} ——total temperature at inlet of the test compressor;

π ——total pressure ratio of the test compressor;

η ——the design efficiency of the test compressor;

γ ——gas specific heat ratio.

At the beginning of the test rig application, since the design rev and pressure ratio level at that time is not that high, the parameter such as exhaust temperature did not exceed the allowed range too much, which means even at standard intake conditions have the exhaust temperature slightly over the allowed range the test operators have choice to process the test at a low temperature intake condition and not influence the test safety. However, along with higher compressor design level, requirements on high exhaust temperature increased rapidly, initial test rig was lake of capability to support that, and offering additional exhaust facility for the test rig was demanded, namely bypass surge-out system.

Early structure of bypass surge-out system is pretty simple, as indicated in Figure 2:

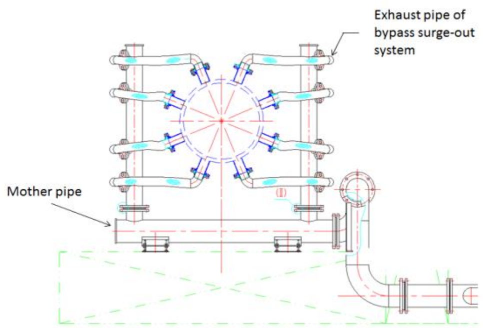

Figure 2 Structure of bypass surge-out system

According to Figure 2, several exhaust pipes of bypass surge-out system are connected with the exhaust holes of the test compressor's outlet cascade, and the pipes are gathered together to a main pipe. By controlling the quick-open value assembled on the pipe. Once the obscuring of the exhaust controlling value occurs or the test compressor is forced to get into unsteady state the quick-open value will active in a very short time, makes the high pressure, high temperature exhaust flow out from the exhaust pipes of bypass surge-out system, brings down the state of the test compressor to guarantee the safety of test compressor and rig[5][6].

Study the structure of bypass surge-out system it can be known that its exhaust capability is decided by the number of exhaust pipes as well as area of each one, or, total area of all exhaust pipes. Since the space that can be used for assembling the bypass surge-out system is restricted, space must be used effectively and the pipe's diameter is required to be as small as possible. For this reason early bypass surge-out system picked 4 small diameter pipes as its exhaust pipe based on engineer experience without valid evaluation method. Although the early system was actually enough for test requirements at that stage, researchers still doubt about the exhaust capacity. Along with further increase of flow and temperature of exhaust, it is obviously that former system cannot support test present, redesigning the system is required imperatively.

Valid evaluation method on exhaust capability is still essential, especially the controlling regular of bypass surge-out system changes distinctly. The risk of lack of exhaust capability is not acceptable. Early experience is not sufficient to obtain a design scheme with enough precision, and blowing test method is lack of economic efficiency and will take a long period of time, both of them are not suited for this work. Thanks to rapid developing CFD technology and powerful CFD software offering a feasible scheme, by applying CFD technology with logical topology and fine mesh, several waiting schemes can be evaluated collaterally.

In this article the advantages of CFD method is exhumed and a full-developed simulation scheme is built up for evaluating the exhausting capabilities of series of schemes candidate, and finally picks up the most satisfied one. The simulation scheme and evaluation results are given below.

2. Simulation Scheme

Although the structure of bypass surge-out system is simple, its inner flow is extraordinarily complicated; furthermore since the system is part of a large-scale test rig, the mesh constructing for a total model is extra-highly difficult, and meshing for each part of the model and merge them into one with interfaces has disadvantages on bad data transformation, low precision and unsatisfactory constringency even dispersing during the solving stage. Consider that this system is so important to the safety of test rig, it is essential to apply all means to guarantee the simulation's precision, for this reason in this article all the models are applied for total-model meshing. Definitely， to modeling for an actual system, a huge number of elbows and junctions cannot be ignored, which will bring high difficulty on mesh construction. Consider that these structures can only bring some total pressure loss along the flow but not alter the flow characteristic inside the system, for this reason these structures above can be simplified and decrease the value of total pressure set at outlet of the model with former experience and relative standard. The model built after simplifying is shown in Figure 3, and the mesh constructed for the simplified model is shown in Figure 4.

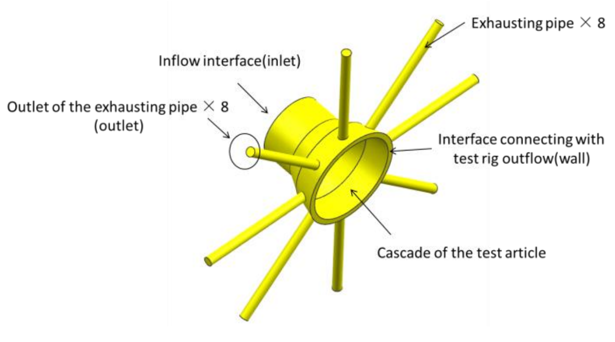

Figure 3 Detailed model

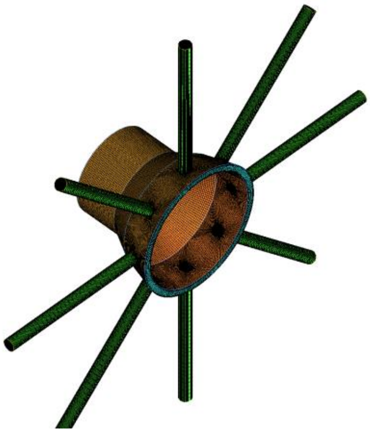

Figure 4 Meshing of detailed model

Although former bypass surge-out system operated without any problems, there is no proper method and opportunity to evaluate or test the exhausting capability of this system, that's why in this article the first stage is to solve the problem for an improvement, and then on the base of this bring out schemes candidate, in this way direction of simulation as well as diameters selected for the exhausting pipes of the by-pass surge-out system can be defined and improve the design efficiency. For lack of sufficient test data, initial boundary conditions are not able to be given directly. However, with studying the structure of the bypass surge-out system combined with aerodynamics principles, flow characteristics in the system can be predicted.

Combined with the longitude of the bypass surge-out system to study the inner flow characteristics to search for the method of giving out initial boundary conditions, the longitude of the system is shown in Figure 5:

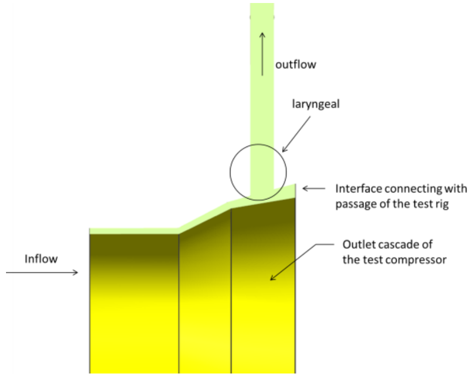

Figure 5 Longitude section sketch of a bypass surge-out system

According to Figure 5, in the bypass surge-out system the connection between the system and outlet cascade is called "laryngeal", before and after the "laryngeal", the outlet cascade and exhaust pipe actually form a contraction structure. According to the "one dimensional isentropic flow" principle, for a contraction structure, when the Mach number of "laryngeal" reach to 1, namely the flow reaches to local sound velocity, at the "laryngeal" there is "choking phenomenon"[7], the flow at "laryngeal" will attain its theoretic ultimate value, and that is nearly the exhaust capability of the bypass surge-out system.

The flow right through the "laryngeal" is complicated, loss of total pressure will occur in a very short distance in the pipes. Definitely the larger the Mach at laryngeal, the fiercer the mixture of flow occurs after the laryngeal, with more total pressure losing. One can be certain is that for the loss of total pressure after laryngeal, Mach at outlet of the exhausting pipe is smaller than that at laryngeal, namely the flow at outlet of the exhausting pipe is subsonic. By the analysis above a small value of Mach at outlet of the exhausting pipe, and by simulation the relationship between Mach at laryngeal and outlet of the pipe is given by the form of the formula (2):

$$Ma_{out} = kMa_{laryngeal} \tag{2}$$

In the formula the Ma_{out} and $Ma_{laryngeal}$ are Mach at outlet of the exhausting pipe and laryngeal respectively, k is a factor smaller than 1. The value of k lies on the Mach at laryngeal but may only have a small fluctuate by experience, in the initial stage of design k can be solved as a constant. With the predetermination above the simulation scheme is built up as the flow chart blow:

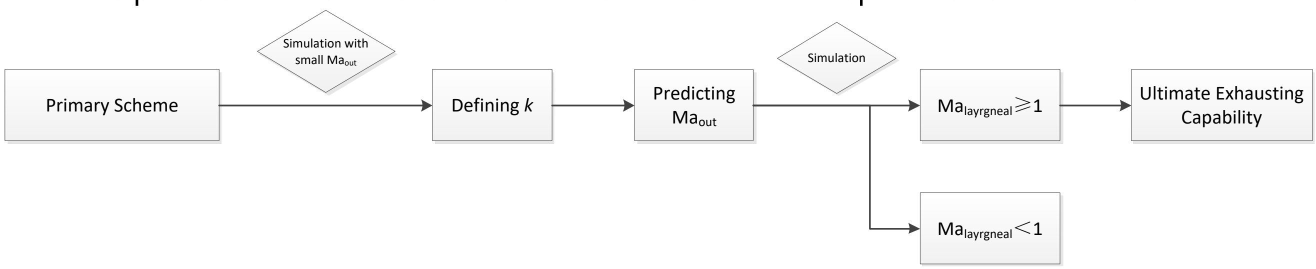

Figure 6 Scheme flow chart of simulation

Since the Mach number at outlet of pipe cannot be given directly, while among a series of combinations of initial boundary conditions, total pressure at inlet combined with static pressure at outlet is the most robust and has the best constringency[8], for this reason in this article the

combination above is adopted, in these total pressure at inlet can be given directly by compressor designer, and static pressure at outlet can be calculated with the help of relative aerodynamics function table and assume that the total pressure recovery coefficient at outlet is 1.
Detail results are given out in the next section.

3. Simulation Results

6 schemes of bypass surge-out system with different pipe diameters (including former one) are primary selected as simulation targets, marked from Scheme1 to Scheme6, among these Scheme1 is the former system, and the diameter of the exhausting pipe is DN_0. Table 1 gives out maximum exhausting capability of each scheme as well as the outlet Mach under maximum exhausting capability condition.

Table 1 Maximal exhausting capability and relative Ma at outlet for each scheme

Scheme No.	Diameter of the exhausting pipes	Maximal exhausting capability	Relative Mach at outlet
Scheme1	DN_0	0.43M	0.798
Scheme2	$1.625DN_0$	1.05M	0.745
Scheme3	$1.75DN_0$	1.18M	0.725
Scheme4 (Standard part)	$1.8DN_0$	1.17M	0.578
Scheme5 (Standard part)	$2DN_0$	1.27M	0.475
Scheme6	$2.25DN_0$	1.62M	0.520

In Table 1 M stands for the required maximum exhausting quantity. For safety purpose 15% to 20% margin is usually left in an engineer application, since that Scheme3 to Scheme6 satisfy the design requirement.
As described above, for arrangement space restriction, too big pipe diameter is not allowed, and to decrease cost and stocking period, standard diameter is optimized. For the reasons above, the final scheme should be selected from Scheme4 and Scheme5
One required to be noticed is that in this simulation the inflow environment of the test high-pressure compressor is standard environment, with inflow total temperature 288.15K, and inflow total pressure 1atm. According to the transfer form of conversion flow calculation formula:

$$W = W_c \frac{P_{in}^*}{101325}\sqrt{\frac{288.15}{T_{in}^*}} \tag{3}$$

In the Formula (3) W and W_c stand for physical flow (namely bypass surge-out system exhausting quantity) and conversion flow of the compressor, P_{in}^* and T_{in}^* are inflow total pressure and total temperature at inlet of the test compressor. When at a given conversion speed, W_c is define as constant, meanwhile P_{in}^* changes slightly, W has an inverse linearity relationship with evolution of T_{in}^*. Since the exhaust system of the test rig has exhausting temperature limit, to bring down the exhausting temperature of the test compressor, this kind of tests are commonly executed in winter with extremely low environment temperature, in this case W will increase. As the average environment temperature in winter night at the location of the test rig is about -18℃(255.15K)， W will increase about 6.2%, in this case Scheme4 cannot satisfy the requirement, for this reason Scheme5 is selected for bypass surge-out system redesign scheme.
Simulation result for Scheme5 is given below to deep discuss the inner flow of bypass surge-out system.
The first given are 3D streamlines in bypass surge-out system as well as plan streamlines at longitude of the system, as shown in Figure7 and Figure8:

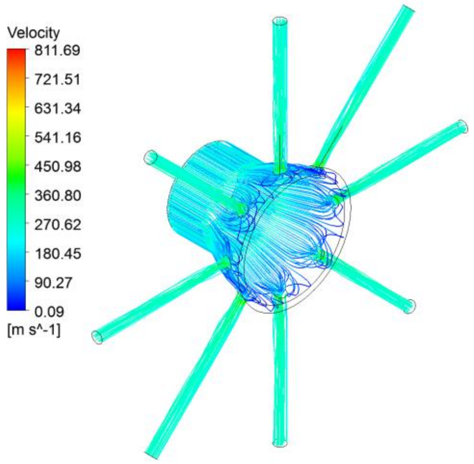

Figure 7 3D streamlines in the system

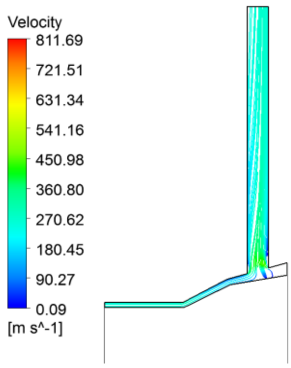

Figure 8 surface streamlines at the longitude of the system

According to Figure 7 and Figure 8 it can be known that except for the zone near laryngeal, flow of others is even. Since there are excessively turn-over and shrink structures, in this zone a distinctively accelerating flow forms. To evaluate the total pressure loss condition, in Figure 9 total pressure contour at longitude of the system is given:

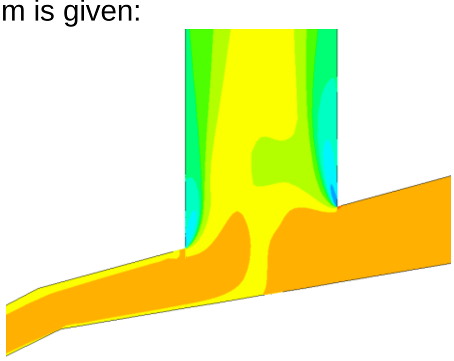

Figure 9 Total pressure contour at longitude of the system
(Only the zone nearby the laryngeal showed)

According to Figure 9, before laryngeal, the distribution of total pressure in the outlet of cascade of the test article is even. When flow through laryngeal, because of engulfing into exhaust pipe, at the forward section of laryngeal there is a sunken trend of total pressure into the exhausting pipe, and form a flow-hold zone (namely “dead zone”). The total pressure distribution in outlet cascade near laryngeal totally forms a “T” structure and extinctive flow separation characteristics in exhausting pipe as well. Along with flow away from laryngeal, after mixture the total pressure distribution comes back even. Since total pressure fiercely changes only occur at zone near laryngeal, while AIP of test article outlet is at a location far away from that zone, the application of the bypass surge-out system will not influence the test of the compressor outlet.

After calculation, the total pressure recovery efficiency of bypass surge-out system redesign scheme is 0.82.

4. Application Conditions

The simulations in this article have been done primarily in 2020, and the redesigned bypass surge-out system first operated in 2021. To validate the simulation results total pressure probes as well as static pressure probes were assembled at the location near laryngeal. Currently the system operates well, and satisfies the required maximum exhausting quantity. The simulation results match the test results, indicates that the simulations have a high reliability.

5. Conclusions

In this article former bypass surge-out systems as well as 5 redesigned schemes for a compressor test rig are simulated to evaluated exhausting capability. Combined with application conditions, the conclusions are below:

1 There is no sufficient exhausting capability for former bypass surge-out system, the capability of

the former one is only able to support 40% of maximum exhausting quantity requirement.

2 According to exhausting pipe diameter minimization and standardization principles, combined with actual operating environment of the bypass surge-out system, one redesigned scheme with 2 times of former exhausting pipe diameter is selected, the maximum exhausting capability has been improved 200%, not only satisfies the exhausting quantity requirement but also left 27% of margin.

3 Simulation results indicate that during operation, only total pressure distribution at the zone near laryngeal in the outlet cascade is influenced, the outlet testing AIP of test article far away from laryngeal is not influenced, former testing scheme does not have to take adjustability modification;

4 The redesigned scheme has been actualized and the bypass surge-out system operates well, test results and simulation results match well, indicates that the simulations have a high reliability.

This research has accomplished redesigned scheme for the bypass surge-out system of a large-scale compressor test rig, with simulation method to evaluate the maximum exhausting capability and obtain test validation. The well-designed mesh construction method and simulation scheme design flow are not only solve the problem such as lack of test data support, difficulty on given initial boundary conditions and mesh construction, etc. but also provide new thoughts and methodology for deeper study and redesign on the exhausting system of the test rig.

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7. Copyright Statement

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