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# EXPERIMENTAL STUDY ON THE EFFECT OF INTERSTAGE BLEEDING ON THE PERFORMANCE OF FULL-SCALE MULTISTAGE AXIAL COMPRESSOR

Zhang Zhibo, Zhang Yihao, Chen Yehui

AECC Shenyang Engine Research Institute, Shenyang 100015, China

## Abstract

The influence of interstage bleed on compressor performance of 9-stage compressor is studied at the speed of 0.965 and 0.8. By comparing the changes of total performance, interstage performance and interstage flow fields, the influence of bleed ratio on compressor matching is analyzed, which provides theoretical and data support for the performance optimization of multistage compressor. The results show that: at the speed of 0.965, the effect of bleed ratio on the performance is mainly the intake flow, which has little effect on the efficiency and pressure; at the speed of 0.8, the bleed ratio has an obvious effect on margin and efficiency in addition to the intake flow; when the bleed ratio increases, the state of the first 4 stage compressor moves to the blocking point, and the state of the rear 5 stage compressor moves to the surge point; interstage bleed changes the radial matching of compressor flow field.

**Keywords:** multistage axial compressor; interstage bleeding; experimental investigation; stage performance matching; interstage flow field

## 1. General Introduction

During the operation of an aero-engine, it is necessary to discharge air from the compressor and use air with the appropriate pressure and temperature to control the cockpit environment of the aircraft, the anti-icing of engine air intakes, the sealing of bearings and the cooling of hot-end components, is a necessary means to ensure the normal operation of the engine and meet the flight requirements of the aircraft. However, extracting air from the compressor will have an impact on the flow field and performance of the compressor. With the complexity and variety of aircraft functions and external environment, and the increasing temperature of the gas at the inlet of the engine turbine, the air flow of the air system is constantly increasing. Whether it is a military or civil aircraft engine, the effect of exhaust gas on the performance of the compressor is more and more significant. Therefore, scholars have conducted a lot of research on the effect of interstage bleed air on the flow field and performance of the compressor [1-2].

A large number of scholars have studied the influence of compressor interstage bleeding, bleed structure and numerical simulation method of interstage bleeding by using CFD or modeling method. Gummer et al. studied the effect of end wall bleeding position on the performance of single-stage axial compressor, and pointed out that the end wall bleeding of stator blade can effectively control the separated flow on the suction surface [3]. Steven and Michal studied the optimal bleeding position for the rotor and stator blades respectively, and they pointed out that the bleed air in the blade channel will cause the fluid to flow back from the bleed air groove to the main flow under a strong pressure gradient, reducing performance [4]. Through the simulation analysis of an 8-stage compressor, Sha et al. Pointed out that interstage bleeding can significantly improve the overall performance of the compressor [5]. Conan et al. combined with the characteristics of bleed flow and the stability of numerical calculation, gave a method for setting boundary conditions in compressor bleed simulation [6]. Zhao et al. proposed a circumferential groove bleed air model, which takes the influence of bleeding into the compressor design [7-8]. Yao et al. conducted a numerical study on the effect of bleed on compressor performance, and pointed out that the effect of bleed on the internal

flow field of single-stage and multi-stage axial flow compressors is basically the same [9].
Due to the complex performance of compressor interstage bleeding flow, high-precision numerical simulation is still difficult, and test is still an important means to study this kind of problems. Leishman et al. carried out the flow mechanism of the influence of different bleeding structures on the compressor performance on the low-speed cascade [10-12]. Gomes and Peltier studied the effect of bleed on the performance of annular cascade [13-15]. Ponick et al. conducted calculation and experimental research on the end wall bleeding of the compressor, and pointed out that it can reduce the flow loss in the main flow area and improve the performance of the compressor [16]. The test conducted by Dobrzynski et al. on the low-speed compressor shows that the suction of the boundary layer at the stator casing can eliminate the blade corner separation and improve the performance [17]. Ponick et al. conducted a simulation and experimental study on the effect of bleed on the compressor end wall, and pointed out that bleed can reduce the flow loss in the mainstream area and improve the performance of the compressor [18].
Through the above analysis, it can be found that the current research on compressor interstage bleed is mainly based on CFD simulation and experimental research in cascade and low-speed compressor, and the experimental research on real multistage compressor is very scarce. As we all know, it is very difficult to carry out high-precision simulation in multistage compressor and the experimental study on low-speed compressor or cascade can not simulate the real flow environment of multistage compressor, which brings great challenges to the quasi deterministic and quantitative evaluation of the impact of bleeding on the performance of multistage compressor.
In this paper, an experimental study on the effect of interstage bleeding on the performance of a full-scale 9-stage axial compressor is carried out. It is hoped that through experimental testing methods, the influence of bleeding on the matching of multi-stage compressors can be obtained, so as to provide data support for the optimization analysis of compressor matching characteristics

## 2. Experimental Compressor and Test Device

### 2.1 Experimental Compressor

This 9-stage axial compressor has 19 rows of blades including the inlet guide vanes. The compressor flow path is shown in Figure 1. Inlet guide vanes and stator blades from stage 1 to stage 4 are adjustable angle blades. The compressor bleed position is located after the 5th and 6th stage stators and the design bleed flow ratio is 4% and 5% of the inlet air flow, respectively. The gas drawn from the 5th and 6th stage stators first enters the gas collection chamber, and then flows out through 8 evenly distributed pipes. The air bleed groove and the air collection chamber after the stator are all designed with streamlines to reduce the total pressure loss.

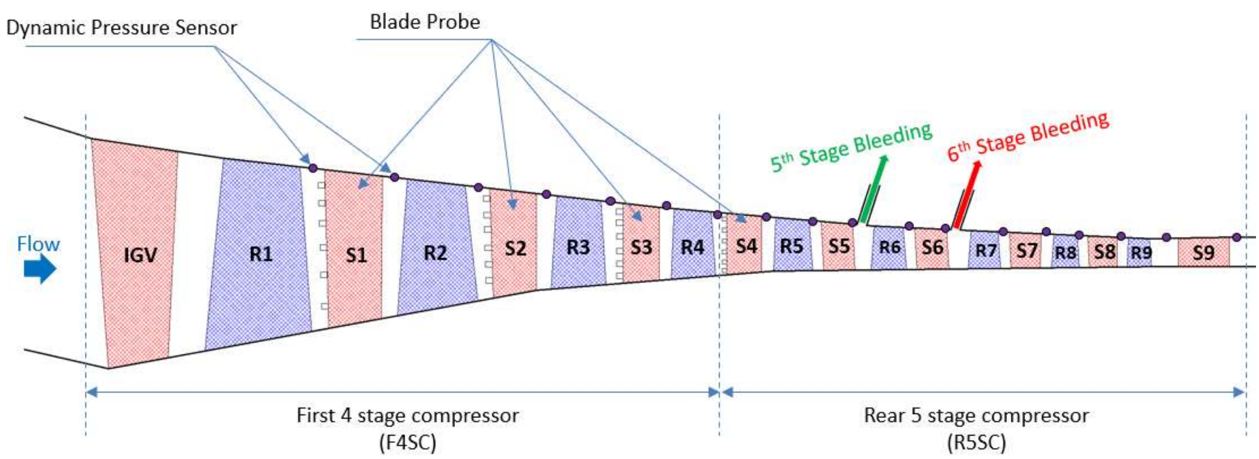


Figure 1 – Schematic of 9-stage axial compressor

### 2.2 Test Device

The test device is shown in Figure 2, which is composed of power system, air intake system, exhaust system, lubricating oil system, electrical system, measuring system, etc. During the test, the gas flows through the inlet flow tube, the front diffuser, the intake throttle, the diffuser and the pressure stabilizing box. After rectifying by the honeycomb and the rectifying net of the pressure stabilizing box, it enters the compressor through the bell mouth, and finally the air flow is discharged through the exhaust system.

The air bleed device is composed of a vacuum pump group, cooler, motor, control system and pipeline. During the test, the speed of the vacuum pump is controlled by a variable frequency motor, so as to change the suction capacity, and then achieve the purpose of changing the bleed ratio.

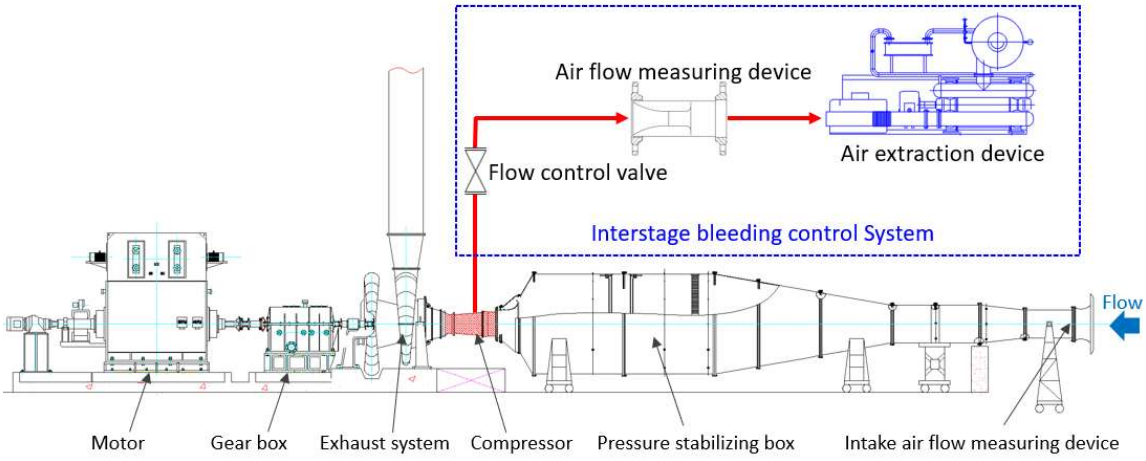



Figure 2 – Schematic diagram of compressor test device

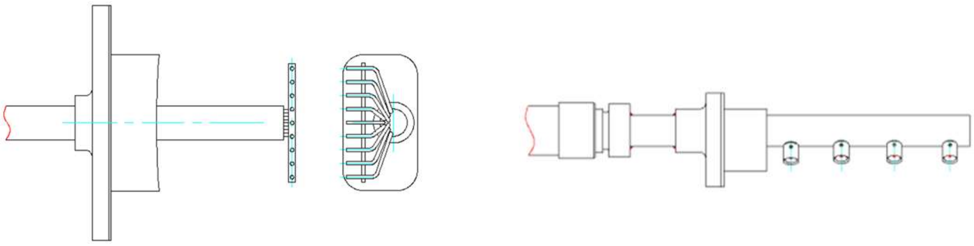
## 3. Test Equipment and Method

### 3.1 Measuring equipment

During the compressor test, the steady-state pressure signal is collected by the pressure scanning valve DSA3217, with an accuracy of ±0.05% F.S. The compressor inlet temperature test equipment is Ex1000A, and the data acquisition accuracy of the equipment is ±0.3K. The outlet temperature measuring equipment is Ex1000A-TC, when the temperature is below 300℃, the data acquisition accuracy of the equipment is ±0.2K. The torque and speed are measured by an ET1200HS torque measuring instrument, and the speed measurement accuracy is ±1rpm.

### 3.2 Overall Performance Test Method

In order to obtain the compressor overall performance, it is necessary to measure the inlet mass flow, inlet and outlet temperature and pressure. The mass flow of the compressor is measured by the flow tube, which is arranged in front of the pressure stabilizing box of the test device (as shown in Figure 2). The physical flow is calculated by measuring the total pressure, total temperature and wall static pressure of the flow tube.



(a) Rake-shaped total pressure probe (b) Comb-shaped total pressure/temperature probe

Figure 3 – Schematic diagram of pressure and temperature test instrument

The total pressure at the compressor inlet is obtained by using two 5-point comb-shaped total pressure probes arranged in front of the guide vane. Six 4-point comb-shaped probes and four 9-point rake-shaped probes were used to measure the temperature and pressure at the compressor outlet (as shown in Figure 3). To judge the surge margin, the pressure pulsation is measured at the compressor outlet and the stall or surge of the compressor is judged according to the pulsation characteristics.

### 3.3 Inter-Stage Flow Test Method

In order to measure the temperature and pressure fields between stages, the total temperature and total pressure blade profile probes are arranged after the first to fourth stage rotor blades. The structure and arrangement of the blade profile probes are shown in Figure 4. After the fourth stage rotors, the blade profile probe has six radial measuring points (located at 9%, 26.7%, 43.7%, 60.2%

and 76.5% blade height respectively).

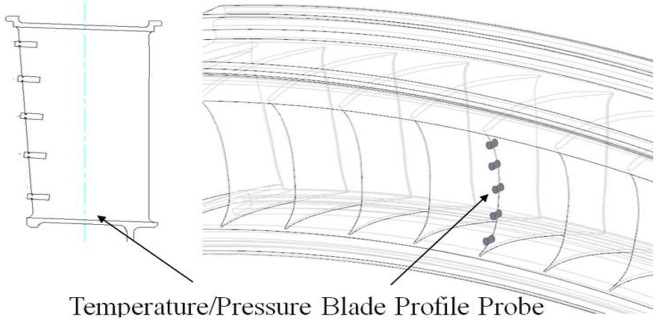



Figure 4 – Schematic diagram of blade profile probe

### 3.4 Interstage bleed air mass flow measurement

Venturi flowmeter is arranged on the exhaust pipe of interstage bleed control system, as shown in Figure 2, which can measure the bleed mass flow after 5th and 6th stage respectively, with a measurement accuracy of about 1%.

## 4. Experimental methods and data processing methods

### 4.1 Experimental methods

In this paper, in order to analyze the influence of air bleed ratio on performance, three sets of air bleed ratio conditions were carried out under the conditions of 0.965 speed from choke point to highest efficiency point, and three sets of air bleed ratio conditions were carried out under the conditions of 0.8 speed from choke point to near surge point. The detailed measurement conditions are shown in Table 1.

Table 1 – Experimental conditions

| Rotating speed | Experimental conditions | The 5th stage bleed ratio | The 6th stage bleed ratio |
|---|---|---|---|
| n=0.965 | From choke point to highest efficiency point | 5% | 4% |
| n=0.965 | From choke point to highest efficiency point | 8% | 4% |
| n=0.965 | From choke point to highest efficiency point | 5% | 7% |
| n=0.80 | From choke point to surge point | 5% | 4% |
| n=0.80 | From choke point to surge point | 0% | 4% |
| n=0.80 | From choke point to surge point | 5% | 8% |

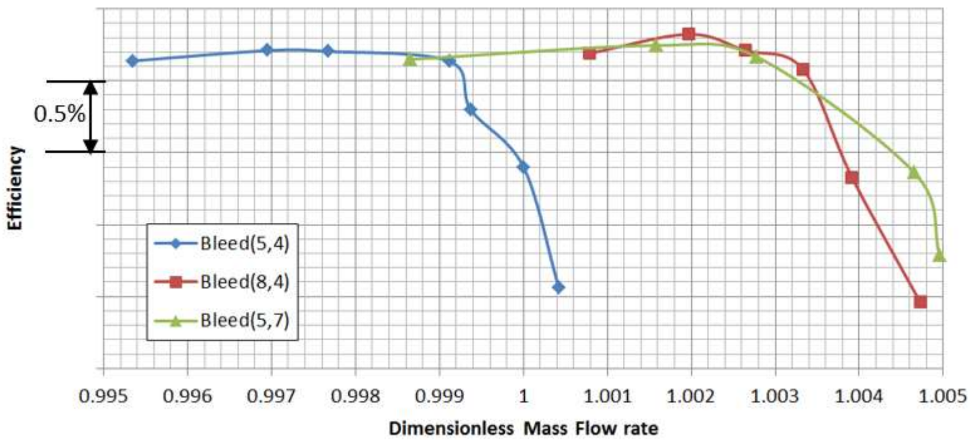
### 4.2 Data processing methods

When calculating the overall performance and stage performance of the compressor, the pressure and temperature measured at different measuring points in the measuring section are averaged by the area weighted average method.

## 5. Test Results and Analysis

### 5.1 Influence of different bleed ratios on overall performance

Figure 5 and Figure 6 show the overall compressor performance under different bleed ratios, in which bleed (a, b) represents the bleed ratios of the 5th and 6th stage are a% and b% of the total compressor inlet flow, respectively. The flow rate and pressure ratio in the figure are normalized based on the design point performance at the condition of design bleed ratio.



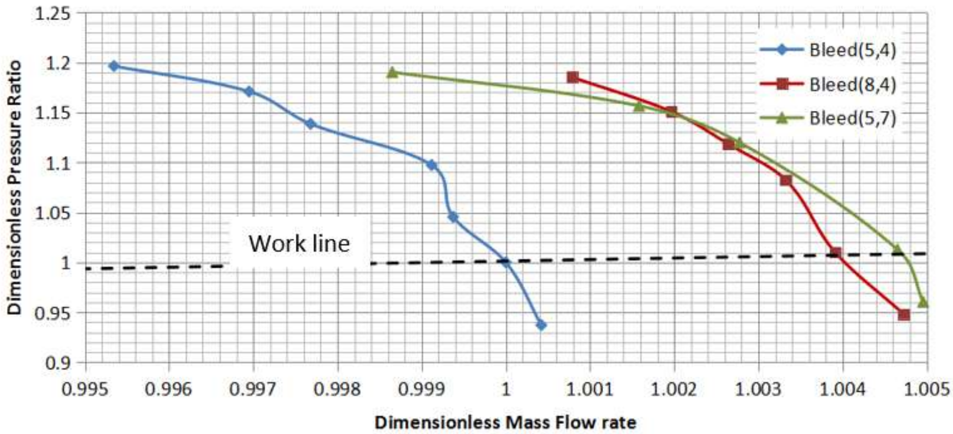
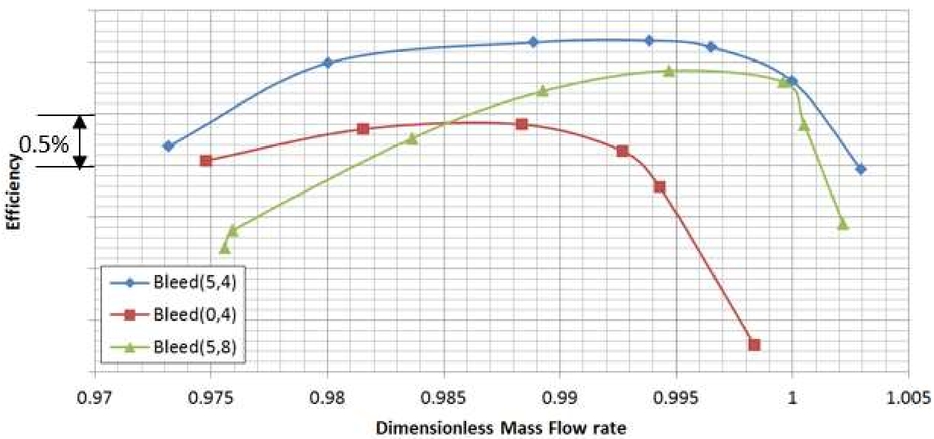




Figure 5 – Overall performance of the compressor at 0.965 speed



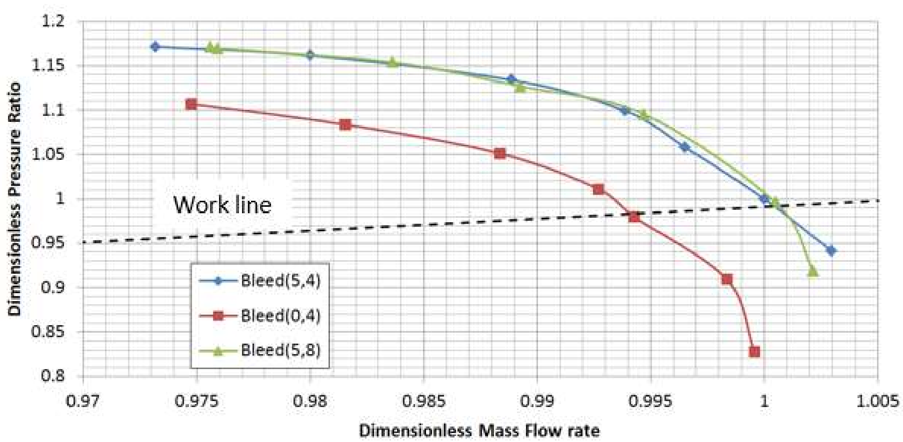




Figure 6 – Overall performance of the compressor at 0.8 speed

Figure 5 shows that at 0.965 speed, the bleeding effect on performance is mainly to change the intake air flow. When the total bleeding ratio increases from 9% to 12%, the mass flow of the design point increases by about 0.5%, and the maximum efficiency and pressure changes little. Compared with working conditions Bleed (8,4) and Bleed (5,7), it can be seen that when the total bleed ratio is constant and the 5th and 6th stage bleed ratio is changing within a certain range, it has little impact on the overall performance.

Figure 6 shows that at 0.8 speed, the change of bleeding ratio has obvious effects on mass flow, pressure ratio and efficiency. When the total bleed ratio is reduced from 9% to 4%, the inlet flow rate is reduced by about 0.5%, the maximum efficiency is reduced by about 0.8%, and the surge margin is reduced by 5.2%. When the total bleed ratio is increased from 9% to 13%, the flow pressure ratio characteristics are similar, but the efficiency between the design point and the surge point is significantly reduced, the maximum efficiency is reduced by 0.3%, the surge point efficiency is reduced by 0.8%, and the surge margin is reduced by about 0.24%.

The test results show that the interstage bleeding has a significant effect on the overall performance, and the degree of influence is differ rent at high and low speeds.

## 5.2 Influence of bleed ratio on matching of front stage and rear stage

According to the total temperature and total pressure measured by the blade profile probe, the pressure ratio and efficiency characteristics between the two rows of stators can be obtained. When analyzing the of the first 4 stage compressor (First4) and the rear 5 stage compressor (Rear5) performance, as shown in Figure 1, the first 4 stage compressor is from IGV to R4 and rear 5 stage compressor is from S4 to S9.

Figure 7-10 show influence of bleed ratio on matching of front stage and rear stage, in which (a, b) represents the bleed ratios of the 5th and 6th stage are a% and b% of the total compressor inlet flow, respectively. The flow rate and pressure ratio in the figure are normalized based on the design point performance of first 4 stage compressor at the condition of design bleed ratio.

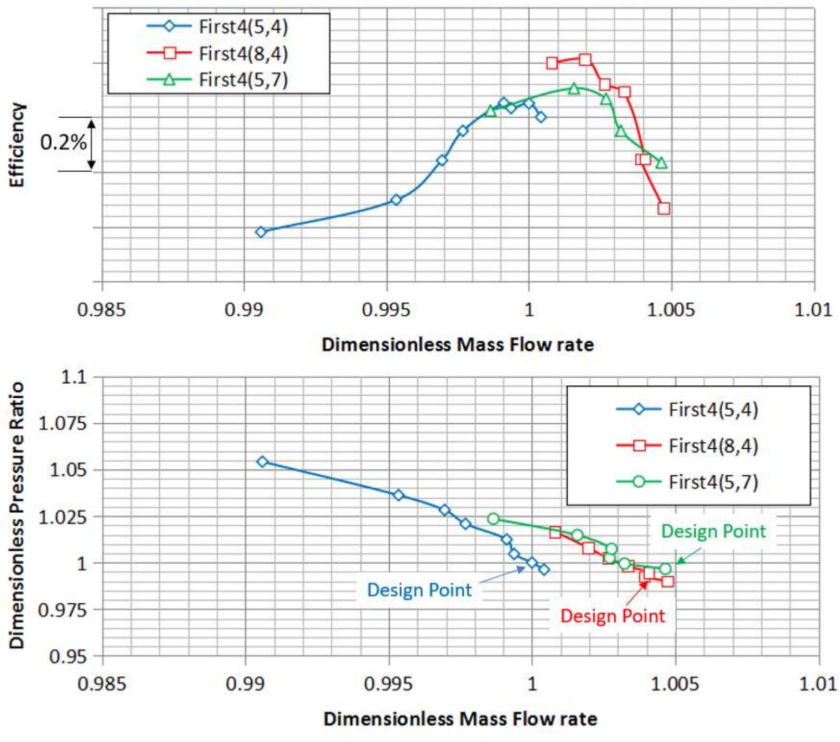



Figure 7 – Performance of the first 4 stage compressor at 0.965 speed

At 0.965 speed, when the bleeding ratio increased from 9% to 12%, the mass flow of the design point of the first 4 stage compressor increased by about 0.5%, and the maximum efficiency increased by not more than 0.2%; the mass flow of the design point of the rear 5 stage compressor increased by 0.2%, and the maximum efficiency decreased by 0.3%. Comparing the performance of the 5th stage and the 6th stage with the bleed ratio of (8,4) and (5,7) respectively, it can be seen that when the total bleed ratio is unchanged, the change of the 5th stage and the 6th stage bleed ratio within a certain range has little impact on the performance of the first 4 stage compressor and the rear 5 stage compressor

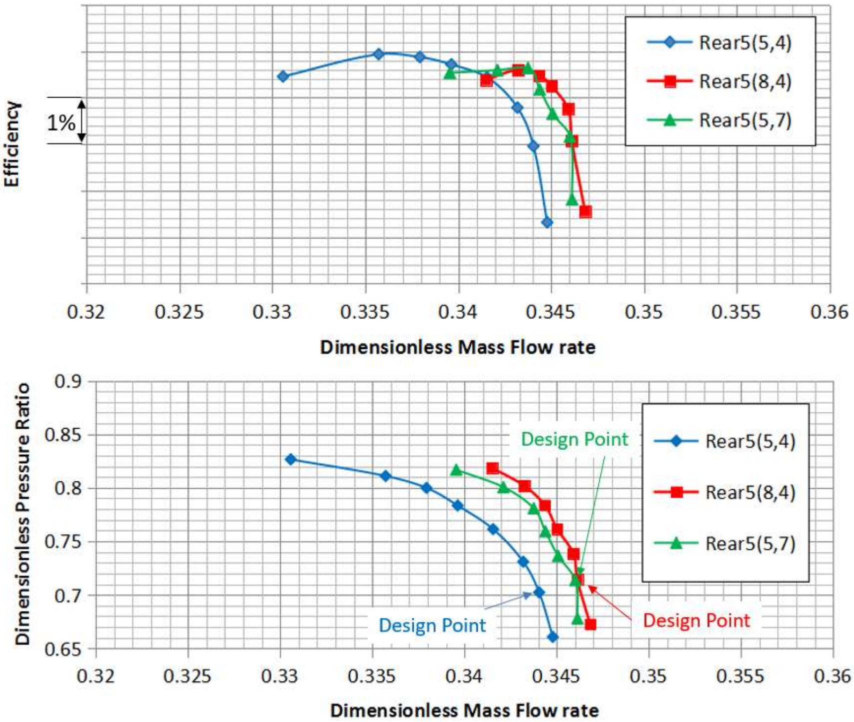



Figure 8 – Performance of the rear 5 stage compressor at 0.965 speed

At 0.8 speed, when the bleed ratio increases from 4% to 13%, the pressure ratio and efficiency of the first 4 stages of the compressor decrease, and the pressure ratio and efficiency at the design point decrease by about 4% and 0.65% respectively, but the maximum efficiency is almost unchanged; With the increase of bleed flow, the pressure ratio of the rear 5 stage compressor increases obviously, and the pressure ratio and efficiency at the design point increase by 15% and 1.9%. It should be pointed out that the efficiency at the design points of Rear5 (5,4) and Rear5 (5,8) is relatively close, but the efficiency of Rear5 (5,8) decreases more obviously when the flow is less than the design point.

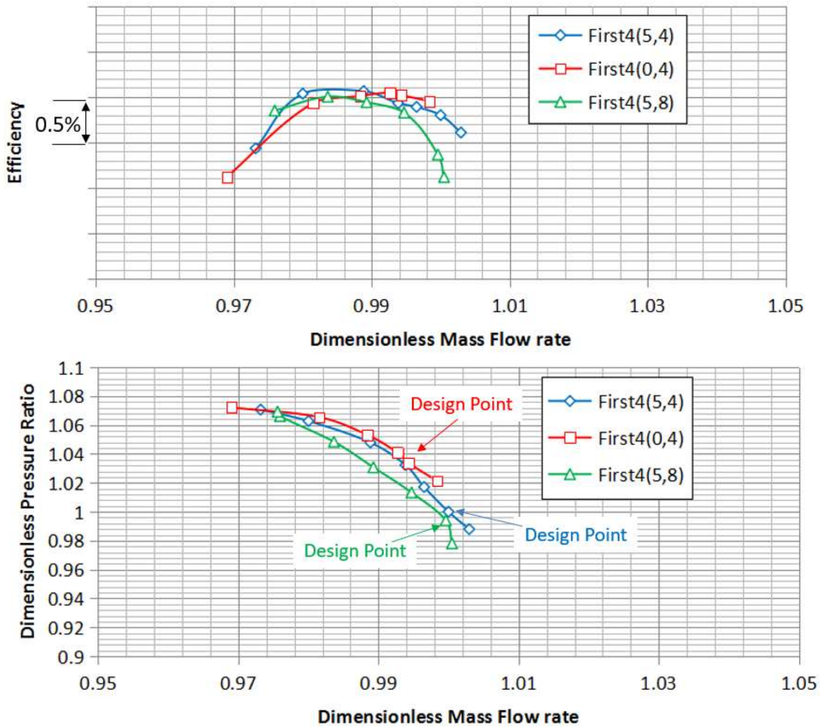



Figure 9 – Performance of the first 4 stage compressor at 0.8 speed

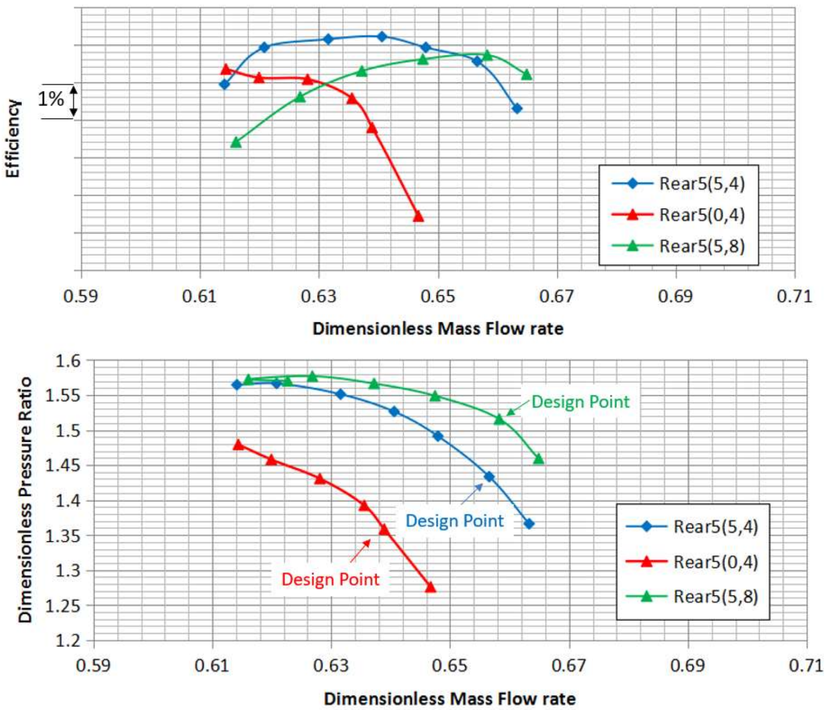



Figure 10 –Performance of the rear 5 stage compressor at 0.8 speed

The comparison of the characteristics of the first 4 stage compressor and the rear 5 stage compressor shows that: when the bleeding ratio increases, the state of the first 4 stage compressor moves to the blocking point, and the state of rear 5 stage compressor moves to the surge point. The performance changes more significantly at low-speed condition.

## 5.3 Influence of bleed ratio on flow field of front and rear stages

Figure 11 and Figure 12 show the radial distribution of pressure ratio and efficiency after the fourth stage rotor and the ninth stage stator under the design condition of 0.985 speed. The pressure ratio in the figure is normalized by using the pressure ratio at the design point of the same measured section.

It can be seen from Figure 11 that at the speed of 0.968, the flow field at the outlet of stage 4 rotor shows that when the bleed ratio increases from 9% to 12%, the pressure ratio decreases as a whole along the radial direction, especially near the blade tip, and the efficiency near the upper blade height decreases. When the total bleed ratio remains unchanged, the pressure ratio of bleed ratio (8,4) is lower than that of the bleed ratio (5,7) after the fourth stage rotor, especially near the blade tip, indicating that the 5th stage bleed ratio has a more significant effect on the performance of the front stage of the compressor than the 6th stage bleed ratio.

According to Figure 12, the flow field at the outlet of stage 9 stator shows that at the speed of 0.968, when the bleed ratio increases from 9% to 12%, the pressure ratio increases as a whole along the radial direction, and the efficiency shows that with the increase of bleed ratio, the near tip efficiency increases and the near root efficiency decreases. When the total bleed ratio remains unchanged, the comparison of the flow fields with bleed ratios of (8,4) and (5,7) shows that the pressure ratio behind the 9th stage stator is lower, indicating that the bleed ratio of the 6th stage has a more obvious impact on the downstream performance of the compressor than that of the 5th stage.

Figure 13 shows that when the bleed ratio increases from 4% to 13%, the pressure ratio at the outlet of the 4th stage stator decreases, especially when the bleed ratio is 4%, its pressure ratio is significantly lower than that when the bleed ratio is 9% and 13%; it also shows that when the bleed ratio is lower, the efficiency near the blade tip is slightly higher.

Figure 14 shows that when the bleed ratio increases from 4% to 13%, the pressure ratio at the outlet of the 9th stage stator gradually increases; it also shows that when the bleed ratio is 4%, the efficiency is the lowest, when the bleed ratio is 9%, the efficiency is close to that when the bleed ratio is 13%, and the efficiency near the middle blade height area is slightly higher, while the efficiency near the blade tip region is slightly lower.

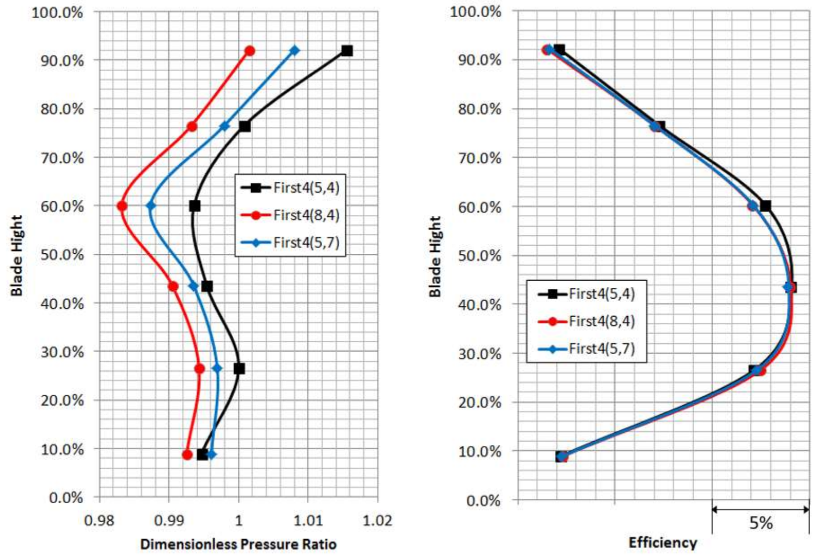



Figure 11 – Radial distribution of pressure ratio and efficiency after the 4th stage rotor under the design condition of 0.985 speed

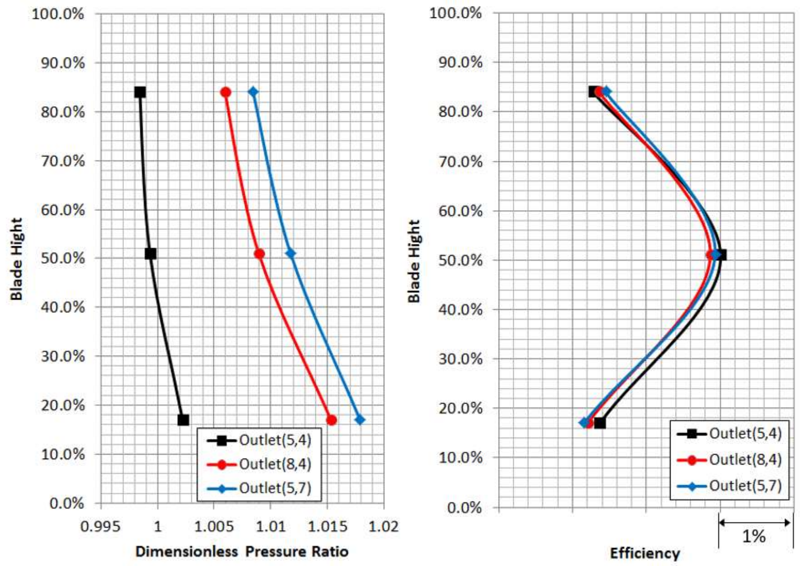



Figure 12 – Radial distribution of pressure ratio and efficiency after the 9th stage stator under the design condition of 0.985 speed

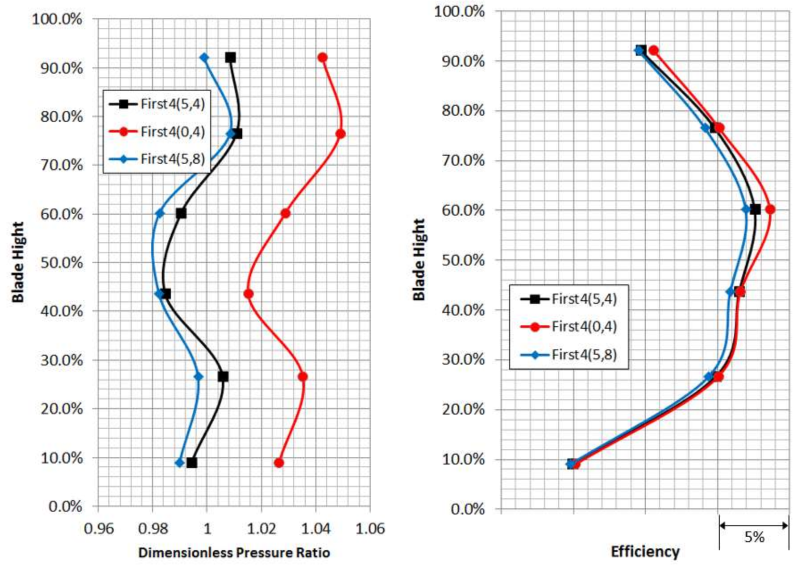



Figure 13 – Radial distribution of pressure ratio and efficiency after the 4th stage rotor under the design condition of 0.8 speed

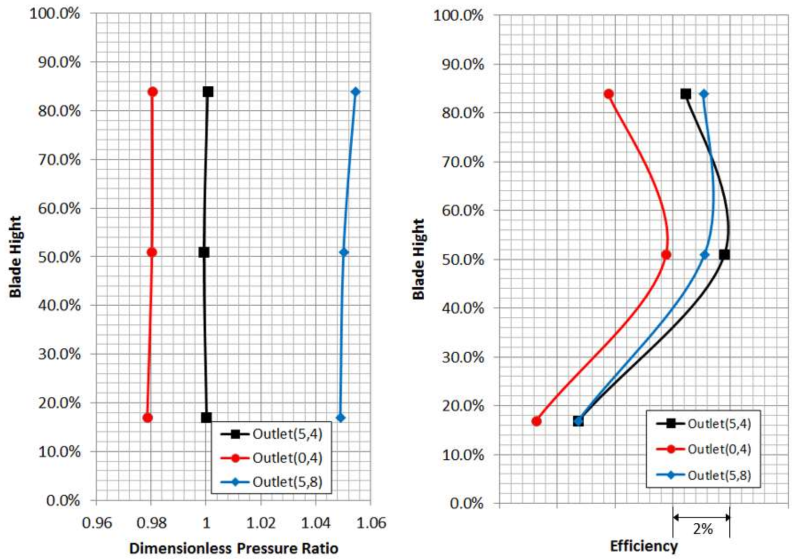



Figure 14 – Radial distribution of pressure ratio and efficiency after the 9th stage stator under the design condition of 0.8 speed

## 6. Conclusion

In this paper, an experimental study on the effect of interstage bleeding on the performance of a full-scale 9-stage axial compressor is carried out. Through the analysis of the overall performance, stage performance and flow fields, the following main conclusions are obtained:

(1) The influence of bleed ratio on the overall performance of the compressor is different at high speed and low speed. At the speed of 0.965, the effect of bleed ratio on the performance is mainly the intake flow, but has little effect on the efficiency and pressure. At the speed of 0.8, the bleed ratio has an obvious effect on margin and efficiency in addition to the intake flow.

(2) The influence of bleed ratio on the performance matching of the front stage and the rear stage shows that when the bleed ratio increases, the state of the first 4 stage compressor moves to the blocking point, and the state of the rear 5 stage compressor moves to the surge point. Especially at low speed, the performance changes more significantly with the bleed ratio.

(3) The radial distribution of compressor interstage and outlet flow field shows that when the bleed ratio changes, the radial distribution of the flow field at the outlet of the fourth stage rotor and the outlet of the last stage stator is changed, and the pressure ratio and efficiency change more obviously near the blade tip, indicating that interstage bleeding changes the radial matching of compressor aerodynamic parameters.

## 7. Contact Author Email Address

Mailto: zhibo346@163.com

## 8. Copyright Statement

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