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Experiment study of vaned diffuser effects on overall performance and flow field of a centrifugal compressor

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Abstract. The vaned diffuser has important effects on the overall performance and flow field of a centrifugal compressor, but the related experiment investigation is deficient. This paper compares the overall performance and flow field of a centrifugal compressor with three different diffusers: a vaneless diffuser and two vaned diffusers by experiment tests. The results show that, the vaned diffuser decreases the stable operating range and the flowrates at the choke and stall points. But it achieves higher total pressure ratio and efficiency at the low flowrate points. The vaned diffuser decides the flowrate at the choke point, and the impeller always operates with low flowrate. Therefore, the pressure always goes up from the impeller inlet to the leading edge of main blade within the whole operating range, and the original position of tip clearance leakage vortex is always near the leading edge of main blade.

1. Introduction

The diffuser will slow the fluid coming from the impeller with very high flow speed, transferring the kinetic energy into pressure effectively, and so the diffuser has important effect on the performance of centrifugal compressor. The diffuser has two types: vaneless diffuser and vaned diffuser. Generally, the centrifugal compressor with vaneless diffuser has wide stable operating range, and it is more convenient to process, but the centrifugal compressor with vaneless diffuser gets lower efficiency. The vaned diffuser can get higher pressure recovering efficient and efficiency, but it will induce a smaller stable operating range. Therefore, with the increasing requirement of high compressor performance, studying different types of diffusers and optimizing them have become an important topic.

The study results show that, the distance from inlet of vane diffuser to outlet of impeller, setting angle at vaned diffuser inlet and solidity have important effects on overall performance and flow field of the centrifugal compressor. For example, Wu[1] and Oh[2] studied the effects of setting angle at vaned diffuser inlet on overall performance and flow field of a centrifugal compressor, Abdelwahab[3] studied the effects of setting angle at vaned diffuser inlet and solidity. The distance from inlet of vane diffuser to outlet of impeller influences the centrifugal compressor performance by the interaction of impeller and vaned diffuser: (1) the effects of impeller on vaned diffuser, including the “jet-wake” flow, the variation of flow speed and flow angle along the blade span; (2) the effects of vaned diffuser on impeller, including the pressure wave propagation in the impeller induced by the vaned diffuser, the potential effect of vaned diffuser on impeller[4-6]. Oh, et al.[7-8] studied the low solidity vaned diffuser, and analyzed the effects of solidity and vane position on centrifugal compressor performance. The results indicated that, there existed a best solidity or vane position, where the centrifugal compressor performance is the best. Iancu, et al.[9] studied the effects of geometry and flow parameters of vaned diffuser on centrifugal compressor. The results showed that the solidity, flowrate,



the distance from inlet of vane diffuser to outlet of impeller, the interaction of impeller and vane diffuser had important effects on the centrifugal compressor. Oh, et al.[10] compared two types of tandem vane diffusers. For the better tandem vane diffuser, they analyzed the effects of the relative position of two rows of vanes.

The above studies are mostly numerical investigations, and focused on the overall performance of centrifugal compressor. This paper compares the overall performance and flow field of a centrifugal compressor with three different diffusers: a vaneless diffuser and two vane diffusers by experiment tests. As the tip clearance leakage flow is an important factor that influences the stall of centrifugal compressor, this paper further studies the effect of vane diffuser on tip clearance leakage flow.

2. Study method

2.1. Study object

In this paper, the centrifugal compressor applied to a 100kW micro-turbine is chosen as the study object. The experiments are carried out at three rotation speeds: 20000rpm、25000rpm and 30000rpm, respectively. The experiment rig is shown in figure 1. To study the effects of vane diffuser on the centrifugal compressor, the impeller is equipped with three different diffusers: a vaneless diffuser and two vane diffusers(vane diffuser 1 and vane diffuser 2), respectively. The models of two vane diffusers are presented in figure 2(vane diffuser 1 is on the left and vane diffuser 2 is on the right). The basic parameters of centrifugal compressor are presented in table 1.

The experiments test the aerodynamic performance of centrifugal compressor and transient pressure on the shroud of impeller. To get the aerodynamic performance, the static pressure, static temperature and volume flowrate at the inlet and outlet of centrifugal compressor are measured. At the inlet, the pressure sensors and temperature sensors are installed on the pot. At the outlet, they are placed on the pipe before the nozzle flowmeter. The nozzle flowmeter is used to measure the volume flowrate. The transient pressure on the shroud are measured by high-frequency transient pressure sensors, which are mounted on the shroud. As the collected original pressure signal is a group of time-sequence signal, it is necessary to transfer the time-sequence signal to space signal in axial and circumferential directions by phase-locking.



Figure 1. Experiment rig.

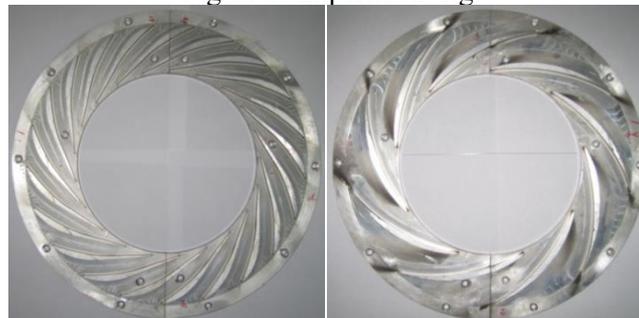


Figure 2. The models of vane diffusers

Table 1. Basic parameters of centrifugal compressor.

| Parameter | Impeller | Vaneless diffuser | Vaned diffuser | |
|-------------------------------|----------|-------------------|----------------|-----|
| | | | 1 | 2 |
| Blade number | 11/11 | / | 21 | 9 |
| Diameter at inlet (mm) | 120 | 220 | 220 | 220 |
| Width at inlet (mm) | 28 | 7.6 | 7.6 | 7.6 |
| Diameter at outlet (mm) | 192 | 370 | 370 | 370 |
| Width at outlet (mm) | 7.6 | 7.6 | 7.6 | 7.6 |
| Setting angle at inlet (deg) | / | / | 15.8 | 13 |
| Setting angle at outlet (deg) | 75 | / | / | / |
| Solidity | / | / | 3.4 | 1.9 |
| Tip clearance (mm) | 0.75 | / | / | / |

3. Results

3.1. Vaned diffuser effects on overall performance

At three rotation speeds: 20000rpm、25000rpm and 30000rpm, the experiments are carried out on the centrifugal compressor equipped with three different diffusers, respectively, and the experiment results are compared. As shown in figure 3, taking the vaned diffuser 1 as the example, the performance of centrifugal compressor equipped with vaned diffuser 1 is compared with that equipped with vaneless diffuser. This figure shows that, the vaned diffuser 1 has great effects on the total pressure ratio, efficiency, stable operating range of the centrifugal compressor. Compared with vaneless diffuser, the vaned diffuser 1 decreases the stable operating range, the flowrate at the choke point and the stall point. It indicates the flowrate at the choke point is decided by the vaned diffuser 1, when the centrifugal compressor is equipped with vaned diffuser 1. The flowrate at the choke point is decided by the impeller, when the centrifugal compressor is equipped with vaneless diffuser. However, when the centrifugal compressor is equipped with vaned diffuser 1, it can operate stably at smaller flowrate, and it achieves higher total pressure ratio and efficiency. What's more, as the rotation speed increases, the effects are more obvious.

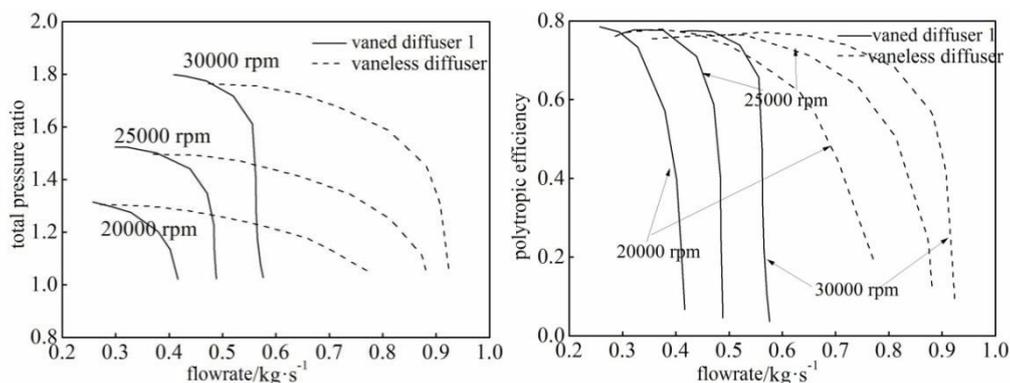


Figure 3. Performances of centrifugal compressor with different diffusers.

As shown in figure 4, the performances of centrifugal compressor with two vaned diffusers are compared. Compared with vaned diffuser 1, the centrifugal compressor with vaned diffuser 2 has smaller stable operating range, smaller flowrate at the choke point and the stall point. It is because the blade setting angle at the diffuser inlet is smaller for the vaned diffuser 2. Although the solidity of vaned diffuser 2 is lower, its throat area is smaller because of the smaller blade setting angle at the diffuser inlet and the vane shape. Therefore, the vaned diffuser 2 has smaller flowrate at the choke point. The vaned diffuser 1 is a wedge diffuser, which is optimized, and the vane of vaned diffuser 2 is a simple airfoil(NACA65), so we can also get that, the centrifugal compressor with vaned diffuser 2 achieves lower total pressure ratio and efficiency than that with vaned diffuser 1. From the above analysis, we can get the blade setting angle at the diffuser inlet has important influence on the stable

operating range of the centrifugal compressor, and the shape of vane has important influence on the total pressure ratio and efficiency of the centrifugal compressor.

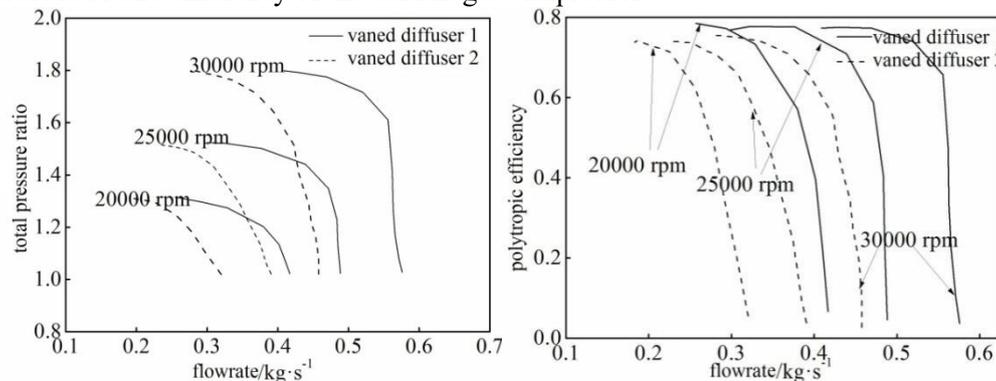
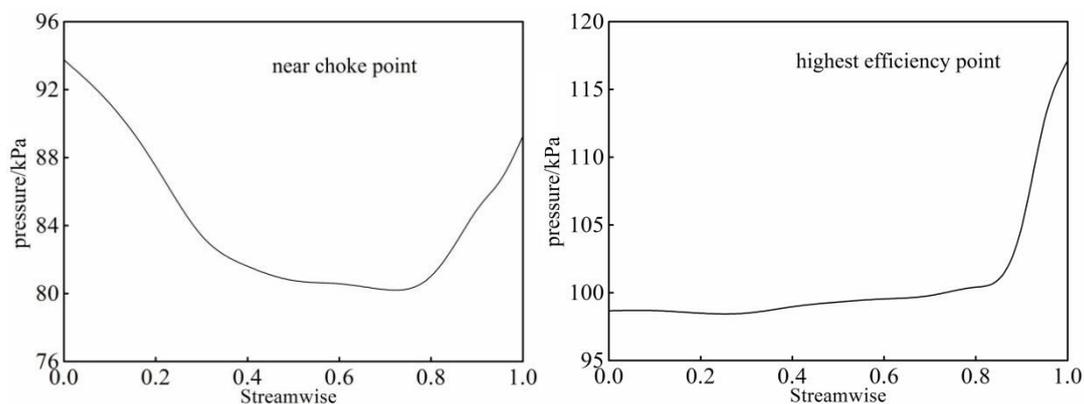


Figure 4. Performances of centrifugal compressor with two different vaned diffusers.

3.2. Vaned diffuser effects on pressure distribution on the shroud

To investigate the vaned diffuser effects on the variation of pressure along the streamwise direction on the shroud, the transient pressure signals on the same axial position are averaged. As shown in figure 5, at the rotation speed of 20000 rpm, when the centrifugal is equipped with vaneless diffuser, the pressure sharply declines from the impeller inlet to the leading edge of splitter at the near choke point. It is because the fluid blocks up at the throat of impeller. The blockage induces the fluid to flow faster, and so the pressure declines. At the near stall point, as the backflow appears near the leading edge of main blade, the pressure goes up from the impeller inlet to the leading edge of main blade. Here, to investigate the vaned diffuser effects on the variation of pressure along the streamwise direction, we take the vaned diffuser 1 as the example. As presented in figure 6, the pressure always goes up from the impeller inlet to the leading edge of main blade within the whole operating range., and the variation of pressure distribution is very small from middle-flowrate to the near stall point. The phenomena are different from the vaneless diffuser. The reason is the vaned diffuser decides the flowrate at the choke point, and so the impeller always operates with low flowrate.



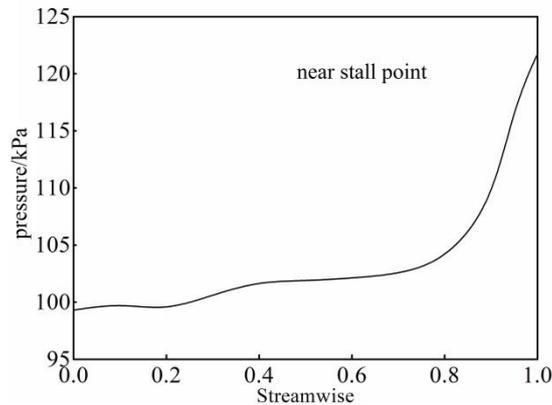


Figure 5. Variation of pressure (vaneless diffuser).

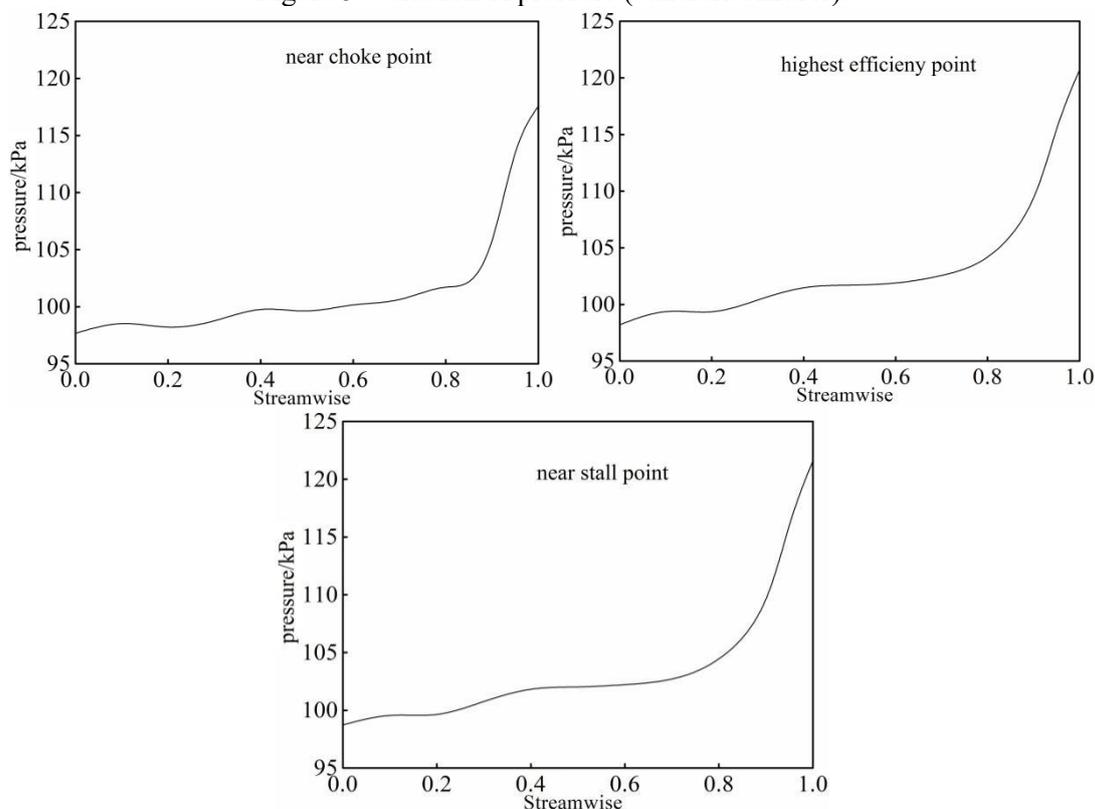


Figure 6. Variation of pressure(vaned diffuser 1).

3.3. Vaned diffuser effects on tip clearance leakage flow of centrifugal compressor

As the tip clearance leakage flow induces a low pressure zone on the shroud, we can get the location of tip clearance leakage vortex by analyzing the pressure distribution on the shroud. To get the pressure distribution on the shroud, the phase-locking average is used to transfer the time-sequence signal to space signal in axial and circumferential directions. As shown in figure 7, the red solid lines are the tip clearance vortex trajectory, the “P” represents pressure. At the rotation speed of 20000 rpm, when the centrifugal compressor is equipped with vaneless diffuser, the tip clearance leakage flow is generated from the pressure side to the suction side of the main blade. Besides, the reversed tip clearance leakage flow is induced as shown by the black box in the figure. As the flowrate decreases, the original position of tip clearance leakage vortex and the zone influenced by the tip clearance leakage flow move towards upstream, and at the near stall point, they reach to the leading edge of main blade. Therefore, the pressure goes up from the impeller inlet to the leading edge of main blade

at the near stall point as shown in figure 5.

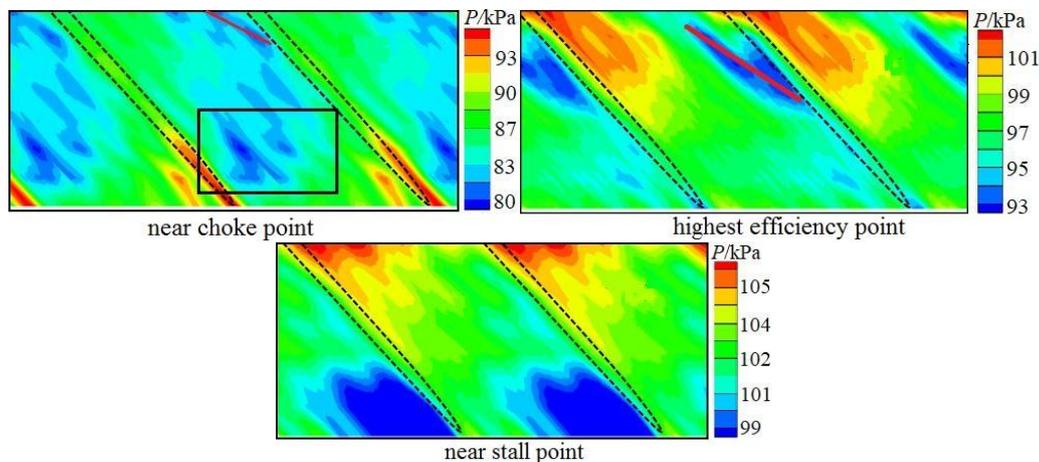


Figure 7. Pressure distribution on the shroud for the vaneless diffuser.

To investigate vaned diffuser effects on tip clearance leakage flow, when the centrifugal compressor is equipped with vaned diffuser 1, the pressure distribution on the shroud is analyzed. As shown in figure 8, it is different from vaneless diffuser, the reversed tip clearance leakage flow does not appear at the near choke point. Because the impeller always operates with low flowrate, the original position of tip clearance leakage vortex is always near the leading edge of main blade. As the flowrate decreases, the angle between the tip clearance leakage vortex trajectory and the suction side of main blade increases. At the near stall point, the angle is nearly 90 degree, and the zone influenced by the tip clearance leakage flow reaches to the leading edge of main blade.

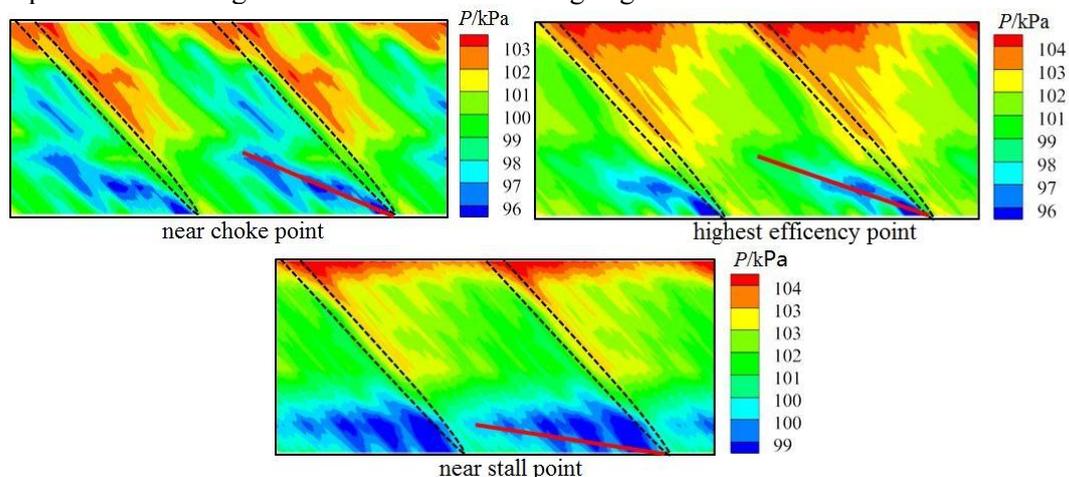


Figure 8. Pressure distribution on the shroud for the vaned diffuser 1.

4. Conclusions

Compared with vaneless diffuser, the vaned diffuser 1 decreases the flowrates at the choke and stall points, and decreases the stable operating range. But it achieves higher total pressure ratio and efficiency at the small flowrate points. What's more, as the rotation speed increases, the effects are more obvious. The blade setting angle at the diffuser inlet, the solidity and the vane shape of vaned diffuser have important effects on the overall performance of centrifugal compressor.

when the centrifugal is equipped with vaneless diffuser, the pressure sharply declines from the impeller inlet to the leading edge of splitter at the near choke point. At the near stall point, the pressure goes up from the impeller inlet to the leading edge of main blade. As the flowrate decreases, the original position of tip clearance leakage vortex and the zone influenced by the tip clearance leakage flow move towards upstream, and at the near stall point, they reach to the leading edge of main blade.

The vaned diffuser decides the flowrate at the choke point, and the impeller always operates with low flowrate. Therefore, the pressure always goes up from the impeller inlet to the leading edge of main blade within the whole operating range. The original position of tip clearance leakage vortex is always near the leading edge of main blade. As the flowrate decreases, the angle between the tip clearance leakage vortex trajectory and the suction side of main blade increases. At the near stall point, the angle is nearly 90 degree, and the zone influenced by the tip clearance leakage flow reaches to the leading edge of main blade.

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