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Enlarging the operation range of a centrifugal compressor by cutting vanes based on CFD

J T Mo¹, C H Gu², X H Pan¹ and S Y Zheng²

¹ Department of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China

² Institute of Chemical Machinery, Zhejiang University, Hangzhou 310027, China

E-mail: zhengshuiying@zju.edu.cn

Abstract. Many centrifugal compressors are liable to insufficient operation range. The purpose of this paper is to enlarge the operation range of a centrifugal compressor used in turbocharger by cutting vanes. Some numerical works have been done based on CFD. The comparison of the calculated and measured results shows good agreement. The overall performance characteristics of the centrifugal compressor with different cutted vanes are observed and analyzed. The performance characteristic curves show that cutting vanes can increase the operation range by more than 50% with the loss of the highest efficiency limited in 1%. The flow fields are also shown in this paper and related explanations about the change of the performance characteristics curves are given. Shock wave is also detected in the simulation, and some related characteristics are summed up.

1. Introduction

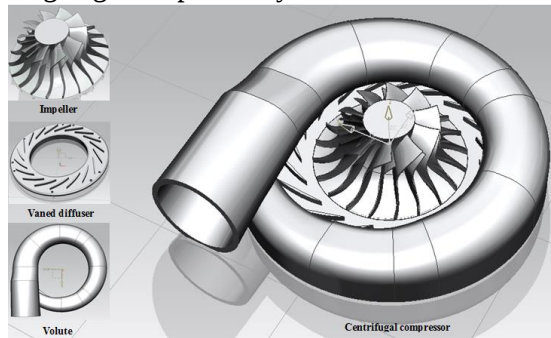
Centrifugal compressors are commonly found in small gas turbine engines, turbochargers as well as refrigerators for its reliable performance and compact structure. References [1-5] manifest that many of them are faced with insufficient operation range. The operation range can be defined as the range between the choke point and the surge point. A lot of papers focus on increasing working range without too much loss in efficiency. Some numerical and experimental works by Abraham Engeda^[6-7] illustrate that cutting vanes can increase the operation range despite lower pressure recovery. Abraham Engeda also shows some numerical comparison between the pressure fields with different cutted vanes at design flow, near surge flow and near choke flow respectively. But the pressure field in Abraham Engeda's research is gained with flat plate vanes at a relatively low speed and the selected near choke flow may not reflect the real pressure field at choke point. The distribution of pressure may be quite different with streamlined airfoil at choke point with a higher speed. So a numerical study about the effect of cutting vanes on centrifugal compressor's performance will be necessary to keep balance between the operation range and the efficiency and it will be meaningful to perform a research into the inner flow field characteristics. The numerical result shows that the overall performance of the compressor in this paper has been improved successfully.

2. Numerical approaches

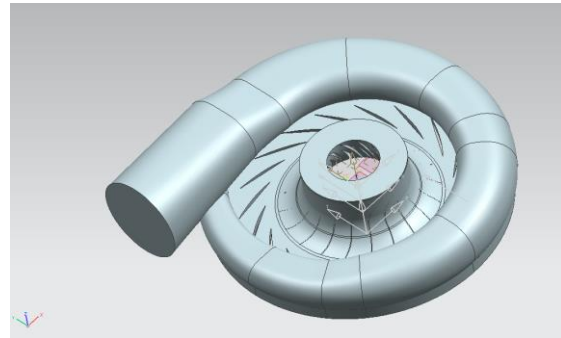
2.1. Numerical model



The UG model in Fig1(a) illustrates the structure of the centrifugal compressor used in turbocharger. This centrifugal compressor is made up of three parts, impeller, vaned diffuser and volute. The impeller with an outer diameter of 258 mm, has 10 long blades and 10 short blades. The vaned diffuser has 19 vanes with an inlet angle of 75° , with the leading edge set at a diameter of 1.15 relative to that of the impeller. The Fig1(b) shows the computational domain. Vanes are cut off from the trailing edge for the purpose of simulating the effect of cutting vanes as shown in Fig2. The shape of the trailing edge is replaced by smooth curve.

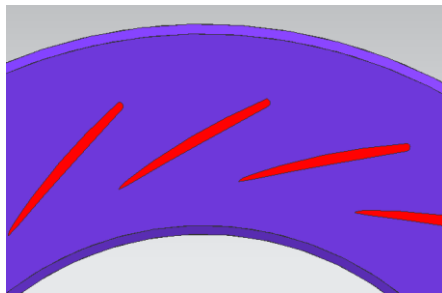


(a) The structure of the centrifugal compressor



(b) The model for simulation

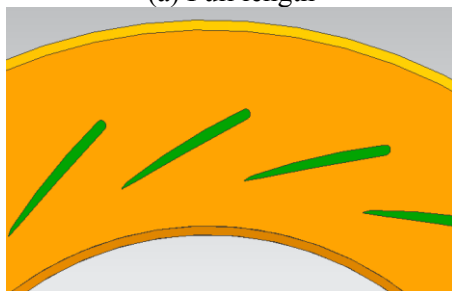
Figure 1. The UG model of the centrifugal compressor.



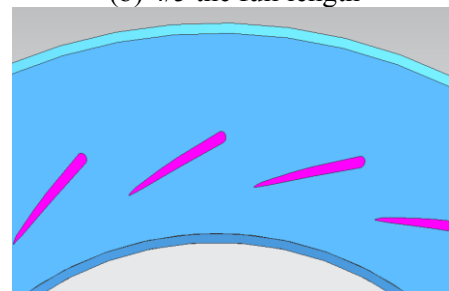
(a) Full length



(b) 4/5 the full length



(c) 2/3 the full length



(d) 1/2 the full length

Figure 2. The vanes of different length in the vaned diffuser.

The mesh model is established in Gambit. Unstructured tetrahedral meshes are adopted due to the complexity of the geometry. The simulation work is done by the Fluent. The pressure inlet and the pressure outlet are applied to the inlet and outlet respectively^[8]. The intersection between the impeller and the vaned diffuser is analyzed by the interface, on which the variables such as velocity and pressure are equal. The viscous effects are simulated by the standard $k-\varepsilon$ turbulence model and Multiple Reference Frame Model is selected. The shear stress on solid surfaces is prescribed by the wall function. Convergence criterion for the continuity equation maintains 10^{-4} and the others are reduced to 10^{-5} .

The compressor surge point is the capacity below which the compressor operation becomes unstable. And the flow at which surge occurs can be determined by slowly reducing the flow rate at the test speed until indications of unstable or pulsating flows appear^[9].

The boundary condition of pressure inlet and the pressure outlet has been applied to the inlet and outlet of the compressor separately. The performance characteristics curves can be started with a relative low pressure in outlet, and slowly reduce the mass flow rate by increasing the outlet pressure. When the outlet pressure reaches a point where the backflow occurs and can even flush the whole flow field, the surge point is supposed to be found.

2.2. Validation

A comparison between the numerical and experimental performance characteristics curves at the speed of 30000r/min and 32400r/min has been done as the Fig3 shows. It is easy to find that the numerical and experimental results agree well, which proves that the model in this paper is reasonable.

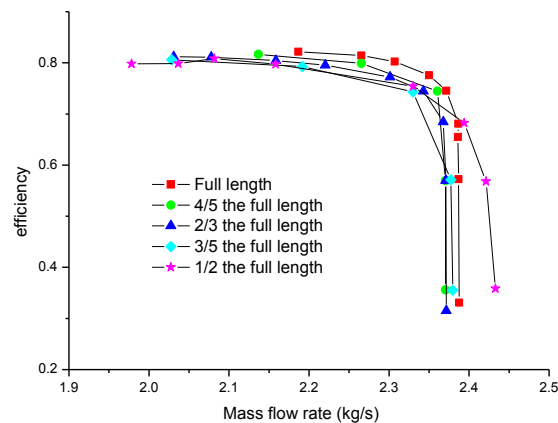
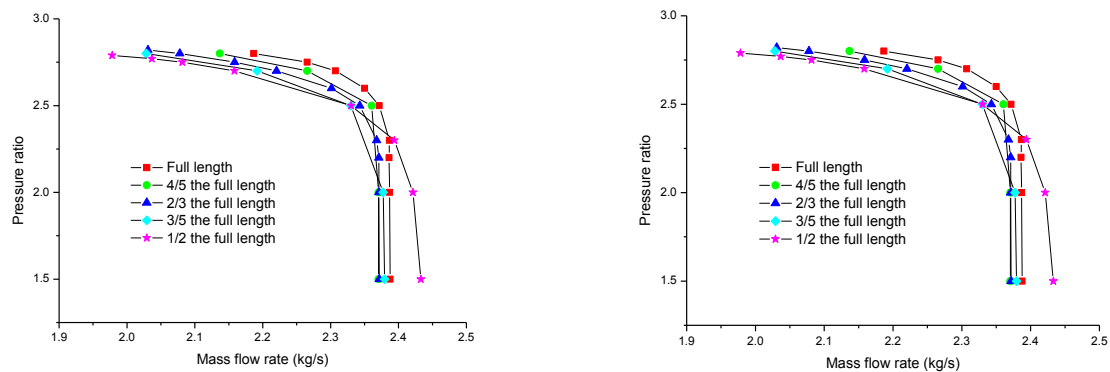


Figure 3. The numerical and experimental pressure ratio with respect to the mass flow.

3. Results and discussion

3.1. Calculation results

The Fig4 shows the overall performance of centrifugal compressor with different cutted vanes. The shorter the vanes, the wider the operation range it will be. And the increase of the operation range can be divided into two parts, i.e. the decrease of the mass flow rate near the surge point and the increase of the mass flow rate near the choke point. The efficiency curves in Fig4(b) show that the efficiency doesn't have much change. The relationship between the operation range and the efficiency is listed in the Table1. The lose of efficiency in the table represents the loss of the highest efficiency.



(a) Pressure ratio with respect to the mass flow

(b) The efficiency curves

Figure 4. The overall performance of vaned diffuser with different cutted vanes.

The Table1 shows that the operation range can be increased a lot with relatively less loss in the highest efficiency. But shorter vanes may demonstrate lower pressure recovery according to Fig4. This may be solved by changing the speed of the compressor.

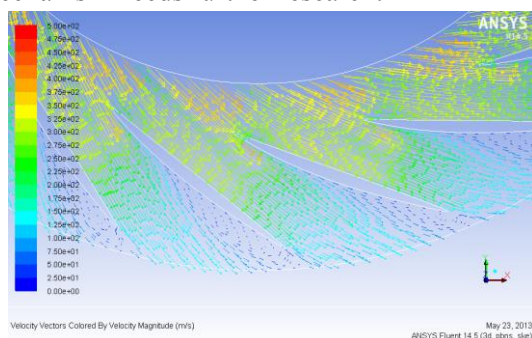
Table 1. The relationship between the operation range and the efficiency.

The length of vanes	The percentage of the increase of the operation range(%)	The percentage of the lose of the highest efficiency (%)
4/5 of the full length	16.376	0.513
2/3 of the full length	69.547	0.969
3/5 of the full length	74.823	1.55

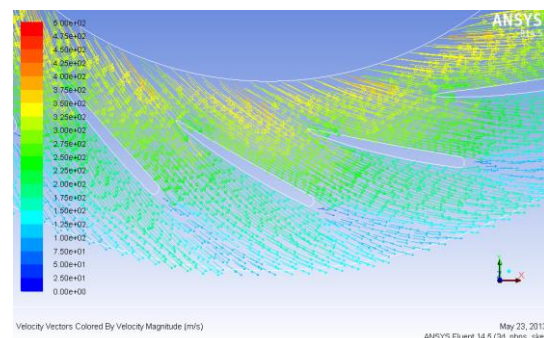
Some explanations about the change of the performance curves may be found through the flow field in the vaned diffuser.

3.2. Influence on the surge point

The flow range is limited at low mass flow rate due to vane stall. Shorter vanes can suppress the development of the vane stall by preventing the boundary layer separation from the suction surface. The suction surface is the vane surface facing the impeller, while the pressure surface is the vane surface facing away from the impeller. Some explanation for the decrease of the mass flow rate near the surge point can be found by looking into the secondary flow. Another explanation for this mechanism can be found in terms of friction. The velocity field at the pressure ratio 2.7 with vanes of full length and 2/3 the full length is shown in the Fig5. The boundary layer separation can be seen on the pressure surface in the Fig5(a) and it will become weak with shorter vanes shown in Fig5(b). As the boundary layer separation can separate the mainstream of the air from the wall of vanes, the friction between the air and the wall will be relatively small. But when the vanes are cutted short, as the Fig5(b) shows, the boundary layer separation will be destroyed and become weak. So the mainstream gets closer to the wall of the vanes, and the friction will be raised. The mass flow rate will decrease because of the resistance of the friction. Higher positive induce angle will further destroy the boundary layer separation. The change of the skin friction coefficient along the vanes of different length is shown in the Fig6. The skin friction coefficient is a parameter used to define the friction on the wall, the higher the coefficient the larger the friction. Region A marked in the Fig6 represents the influence of the front tips of the vanes, and the region B illustrates that the skin friction coefficient will increase when vanes become short. This explanation will appear lack of convincing because for the short vanes the air would have a longer routine in the diffuser, which would increase the friction between the air and the wall. However it can be regarded as a supplement for the mechanism. The mechanism needs further research.



(a) Full length



(b) 2/3 the full length

Figure 5. The velocity field at the pressure ratio 2.7 with different vanes.

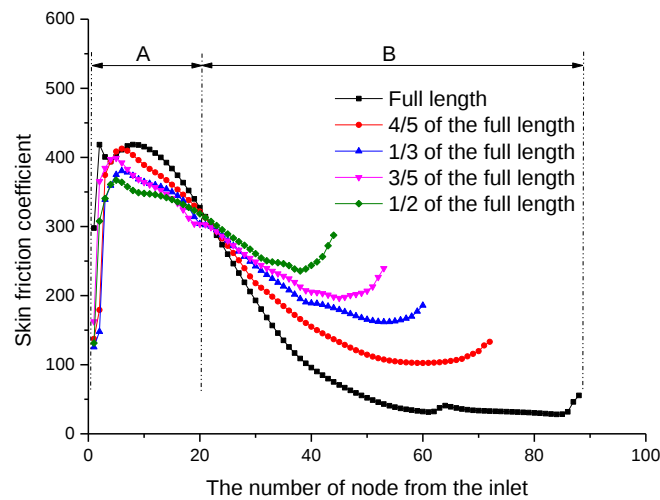


Figure 6. The skin friction coefficient with different vanes.

3.3. Influence on the choke point

As the Fig4(a) shows, when the vanes are cutted from the full length to 4/5 the full length, mass flow rate near the surge point decreases, and when the vanes are cutted more from 4/5 the full length, mass flow rate near the surge point increases. Some explanations can be found through the flow field.

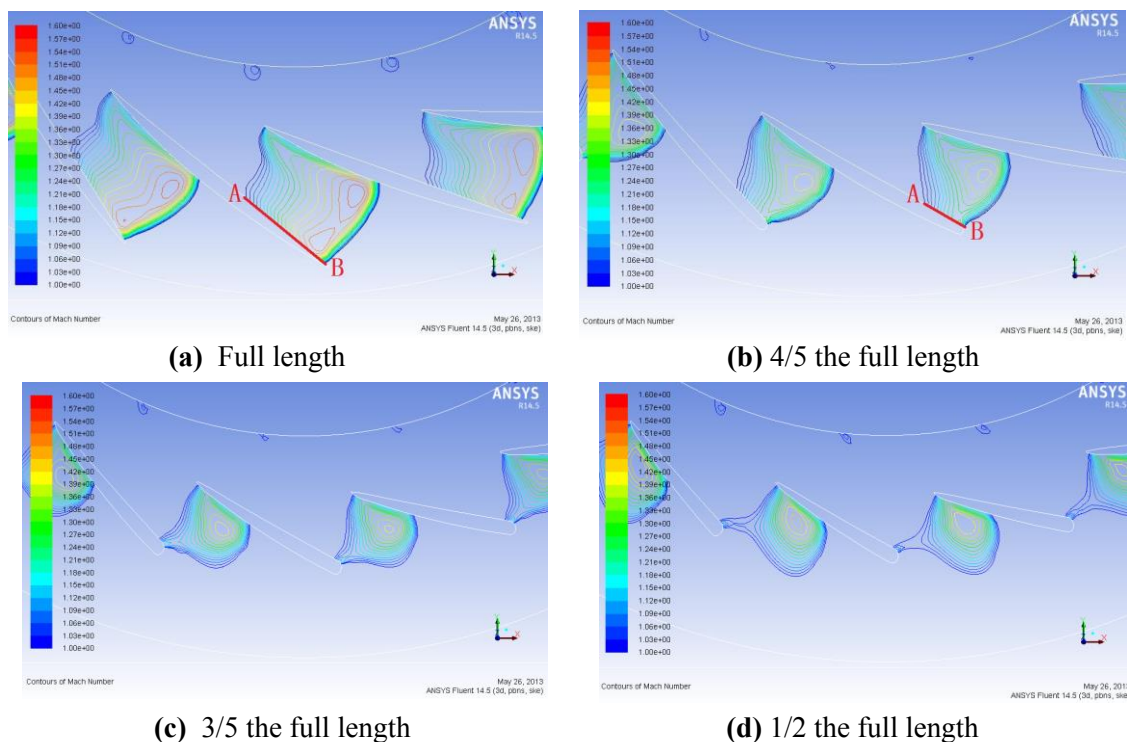
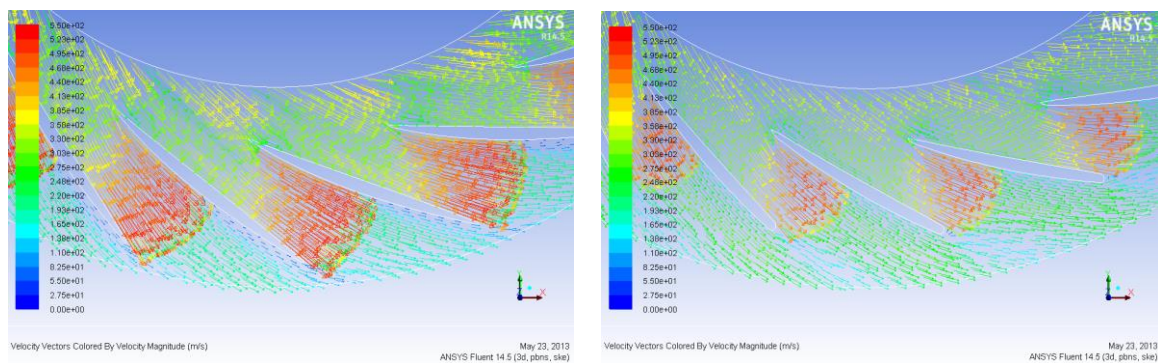


Figure 7. The mach number distribution with different vanes at pressure ratio 2.0.

The Fig7 shows the mach number distribution with vanes of different length at pressure ratio 2.0. For the purpose of easier description, only the part where the mach number is greater than 1 is shown. As the Fig7(a) shows, the vaned diffuser in this paper works as a nozzle. The subsonic air get accelerated under the influence of the diffuser and became supersonic when it reaches the outlet of the diffuser, the length of the part for acceleration, which is marked by red line in Fig7, is subjected by the trailing edge of the vanes, then the speed of the air decrease suddenly which results in a sudden change

in pressure and the shock wave can be detected. So when the length of the vanes reduces from the full length to 4/5 the full length, as the acceleration part of the nozzle becomes short, the speed of the air becomes slower, the mass flow rate will drop because of the reduction in the effect of acceleration. But when the vanes are cutted more from 4/5 the full length, as the Fig7(c) and Fig7(d) show, the mass flow rate will increase with larger cross-sectional area. The Fig8 shows the velocity field with vanes of different length at pressure ratio 2.0, obvious boundary layer separation is detected in Fig8(a). Some references illustrate that when the air passes the shock wave, the sudden increase in pressure will result in strong adverse pressure gradient and the boundary layer separation will occur. The interaction between the shock wave and the boundary layer will cause a huge loss in energy. So when the vanes are cutted as the Fig8(b) shows, the decline of the boundary layer separation and the shock wave will save a lot of energy and the mass flow rate will be prone to increasing.



(a) Full length

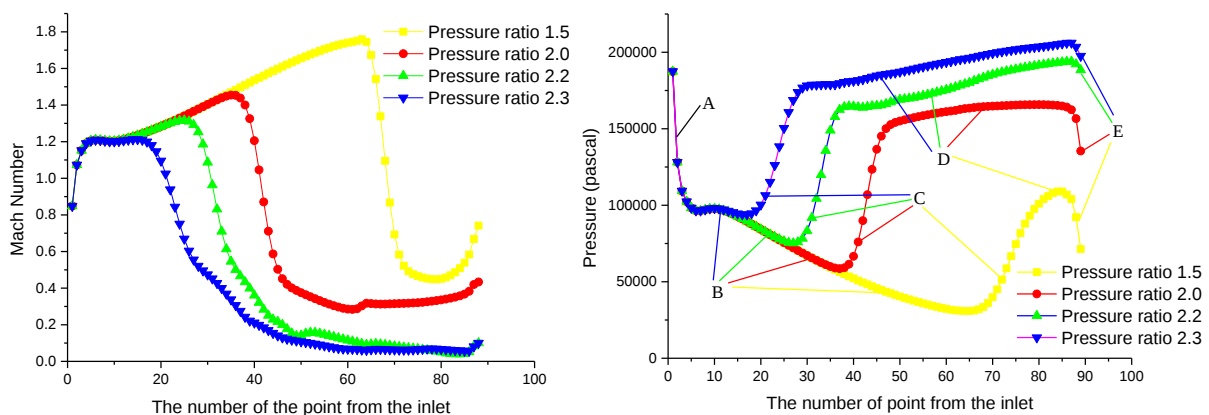
(b) 4/5 the full length

Figure 8. The velocity field with different vanes at pressure ratio 2.0.

These conclusions can explain why the change of the working range is flat at first but becomes steep with the increase in the length of the cutted part.

3.4. Shock wave

The Fig9 shows the distribution of the mach number and the pressure along the vanes at different pressure ratio. The steep falling edge indicates the position of the shock wave. With the increase of the pressure ratio, the falling edge of the curve gets close to the leading edge of the vanes and the upstream of the supersonic air is hardly influenced by the pressure change in the downstream.



(a) Mach number

(b) pressure

Figure 9. The mach number and pressure distribution along the vanes

4. Conclusion

Cutting vanes is an effective and convenient way to improve the operation range. The numerical result shows that the operation range may be increased for more than 50% with the loss in the highest efficiency limited in 1%. The problem is the lower pressure recovery. This may be solved by a higher speed of the centrifugal compressor. Some conclusions can be summed up through the flow field:

1. The decrease of the mass flow rate near the surge point has close relationship with the friction between the air and the wall of the vanes. The friction will be relatively small when the boundary layer separation separates the mainstream from the wall of vanes.

2. At choke point, the diffuser works like a nozzle, when the vanes are cutted short, the mass flow rate will decrease first with the decline of the effect of acceleration and will begin to increase with the vanes cutted more. The increase of the mass flow rate may be influenced by the change of the cross-sectional area and the reduction in the energy loss of the interaction between shock wave and boundary layer separation.

3. The shock wave can be detected in the simulation. The position of the shock wave has relationship with the pressure ratio, i.e. the higher the pressure, the closer it will get to the front edge of the vanes.

References

- [1] Dixon S L 2010 *Fluid mechanics and thermodynamics of turbomachinery* (Boston: Butterworth-Heinemann/Elsevier)
- [2] McMillan and Gregory K 2010 *Centrifugal and axial compressor control* (New York: Momentum Press)
- [3] Lapina and Ronald P 1982 *Estimating centrifugal compressor performance* (London: Butterworths)
- [4] Ferguson and Thomas B 1963 *The centrifugal compressor stage* (Boston: Butterworth-Heinemann/Elsevier)
- [5] Kovats and Andres. 1964 *Design and performance of centrifugal and axial flow pumps and compressors* (New York : Pergamon Press)
- [6] Engeda A 2003 *Experimental thermal and fluid science* **28**(1) 55-72
- [7] Engeda A 1996 *A generalized design approach for low solidity vaned diffusers for centrifugal compressors* (USA: Turbomachinery Lab, Michigan State University)
- [8] He Xiaoliang 2009 *Transonic centrifugal compressor Three-Dimensional Flow field numerical analysis* (Harbin: Harbin Engineering University)
- [9] ASME 1997 *Performance Test Code on Compressors and Exhausters* (New York: ASME)