

Study on the Design Method of a New Type of Compressor Slotted Blade

Jianfei Yang^{1, a}, Zhenggui Zhou^{1, b}

¹College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, China.

^a 2476163272@qq.com, ^b zzgon@nuaa.edu.cn

Abstract. the compressor has been developing towards the direction of high pressure ratio, high efficiency and wide stability margin. The flow in the air compressor blade channel presents a strong inverse pressure gradient. In order to reduce losses and improve the stability of the pressure aircraft, this paper adopts a slot structure from the leading edge of the blade to the suction surface. Air is injected from the front edge of the blade and discharged from the suction surface. The automatic optimization method is used to design the slot. The results show that the blade profile with inlet Mach number 0.4 and the diffusion factor 0.6, the total pressure loss of slotted blade profile is lower than that of unslotted blade profile, and the airflow Angle is greater than that of unslotted blade profile in the whole range of low loss incident Angle. In the incidence of 0 degree, due to the control effect of slotted jet on the boundary layer of the blade suction surface, the boundary layer separation zones on the blade suction surface becomes smaller and the wake also decreases, so the total pressure loss of the slotted blade profile decreases by 37%. When the incidence angle is 4°, the separation area of the suction surface boundary layer is larger, and the slotted jet has a better control effect on the boundary layer of the blade suction surface. However, When the incidence angle is -6°, boundary layer separation zones on the suction surface becomes smaller, and the boundary layer separation zones appears on the pressure surface, so the slotting effect is poor.

Keywords: compressor, automatic optimization, slotted blade profile, boundary layer.

1. Introduction

Compressor not only plays a decisive role in the performance parameters such as thrust-to-weight ratio of aero engine, but also has a significant impact on the stability and reliability of the whole engine. Therefore, its performance is of great significance to the overall performance of aeroengine. The development experience at home and abroad shows that the success or failure of compressor development directly affects the overall development of engine. The length of the compression system accounts for 55% to 60% of the aero engine, and nearly 40% of the manufacturing cost and 30% of the maintenance cost come from the compression system [1]. The blade is an important part of the compressor, and its aerodynamic shape and structure have an important impact on the flow characteristics inside the compressor. The rotor blade inputs mechanical work or flange work Lu to the air flow, which increases the pressure and the velocity of the incoming air flow. The stator blade then converts the kinetic energy of the incoming gas into an increase in static pressure and control the direction of the flow to suit the needs of the next stage or downstream components.

In today's computer technology and CFD technology is widely used, based on CFD technology blade automatic optimization technology is possible. Automatic optimization design method is to combine numerical optimization technology with forward problem flow field calculation method. The general process is to first set the initial blade design parameters, generate new design parameters through numerical optimization method, generate corresponding blades. Then the grid is automatically generated in the computer, and the blades are numerically simulated, and the objective function is calculated on the calculated results. If yes, the design parameters are optimized again and repeated calculation is performed. If the calculated results meet the requirements, the design geometric parameters of the target blade can be output. Using the automatic optimization

design method of compressor blade, which makes the experience of the designer replaced by the numerical calculation process, and greatly reduces the dependence on the experience of the designer in the blade design process. However, the blade optimization design with multi-objective, multi-row blade and unsteady flow requires higher computer resources.

As early as 1983, Sanger[2] first proposed to combine the numerical optimization method with the forward problem flow field calculation to realize the aerodynamic optimization design of the controlled diffusion stator blade profile. However, it was not until the end of 1990s that the automatic optimization technology of compressor blade developed rapidly. Zhou Zhenggui[3-6] has done a lot of research on the aerodynamic optimization design of turbines. He combined the simplex method with the forward flow field problem calculation method to optimize the two-dimensional compressor blade profile, and the aerodynamic performance of the compressor blade profile was enhanced after optimization. Moreover, genetic algorithm was applied to optimize the two-dimensional ultrasonic compressor blade profile, and the multi-shock wave in the cascade channel was successfully organized, and the efficiency of the ultrasonic profile was improved. On this basis, an optimization platform based on parallel genetic algorithm was developed to realize the combinatorial optimization design of fan/compressor geometric parameters such as stack line, meridian plane, 2-D blade profile and stagger, and good results were obtained. Moreover, in recent years, this optimized design platform has been continuously improved, and a complete design system from the flow design of S2 flow surface, S1 flow surface design to three-dimensional blade design has been realized, and good results have been achieved in the optimization design of turbomachinery.

In recent years, the compressor has been developing towards the direction of high pressure ratio, high efficiency and wide stability margin. When the aircraft is in the take-off, maneuver overload and landing state, the compressor often works in the small flow state. At this time, the flow in the compressor presents a strong inverse pressure gradient, a large boundary layer separation zones will appear on the suction surface of the blade, and the compressor is easy to enter the stall surge state, and the working stability of the compressor decreases[7-8]. Therefore, in order to increase the single-stage aerodynamic load of the compressor blades, reduce the compressor stages, and expand the working range, it is necessary to use reasonable active or passive flow control technologies to inhibit boundary layer separation[9-11]. The active flow control technologies often require the input of external energy, and need to add complex additional devices, which increase the difficulty of engineering application, such as boundary layer suction technology, synthetic jet technology, plasma pneumatic excitation technology, etc. Passive flow control technologies rely on the optimal design of compressor geometry to achieve the optimization of internal flow, such as casing treatment, non-axisymmetric ring wall, tandem/slotted blades, etc.

In the late 1960s, Rockenbach et al. [12] conducted a slotting experiment on the rotor and stator of a single-stage axial flow compressor. The blade was slotted from the pressure to the suction surface, and slotted jet was formed by using the pressure difference to inhibit the boundary layer separation of the blade. The test shows that the slot can inhibit the flow separation in the middle section of the blade, but the flow field in the endwall zone does not change significantly. Mdouki Ramzi et al. [13] studied the passive control of cascade opening of low Mach number and high load compressor. The NACA 65(18)10 profile was used to analyze the effects of the width, position and slope of the slot on the flow. Finally, it was concluded that the flow turning angle of the slotted blade relative to unslotted blade was increased by about 5° and the total pressure loss was reduced by 28.3%. Zhou Min et al. [14] designed a two-stage transition slot structure scheme, and conducted slotting treatment on the stator blades of a axial flow compressor. The research results showed that the efficiency and pressure ratio of the compressor could be improved by slotting the stator blades in a large working range of the compressor. The margin of the slotted stator blade was increased, and the flow rate of the compressor was increased, and the separation vortex at the tail of the blade was obviously weakened by the slotted jet.

The slot is designed from the blade suction facing the pressure surface, and the pressure difference between the pressure and suction surface is used to form a slotted jet to inhibit the boundary layer separation of the blade. As a passive flow control method, it is simple in structure and does not require the input of external energy, but its jet velocity is generally low. In this paper, a slot structure is created from the front edge to the suction surface of the blade profile. Under the pressure difference between the leading edge and the suction surface of the blade profile, part of the leading edge air will flow out from the suction surface through the slot. This high-speed air flow can effectively improve the kinetic energy of fluid in the boundary layer of the trailing edge of the blade suction surface, thereby controlling and delaying the boundary layer separation. Therefore, the aerodynamic performance of the blade profile can be effectively improved, and the stable working range can be expanded by slotting.

In this paper, the automatic optimization method is used to design the slotted blade profile with inlet Mach number 0.4 and diffusion factor 0.6, so that the slotted blade profile can be designed with good aerodynamic performance without excessive dependence on the designer's experience.

2. Initial Blade Profile and Flow Field Calculation Settings

2.1 Introduction of initial blade profile

The main geometric parameters of the initial blade profile used in this paper are shown in Table 1. Inlet Mach number is 0.4, flow turning angle is 38.70° , cascade solidity is 1.19, diffusion factor is 0.60.

Table 1. Main geometric parameters of the initial blade profile

Inlet Mach number	Flow turning angle	Cascade solidity	Diffusion factor
0.4	38.70°	1.19	0.60

2.2 Introduction of NUMECA Software

In 1992, NUMECA was founded in Belgium to create the world's leading industrial CFD simulation software. Its product FINE/Turbo adopts a full-second-order precision structured grid solver to ensure the calculation accuracy, a density-based solution that speeds up the convergence of the flow field and uses multi-grid technology to further improve the computational speed. The flow of compressible/incompressible fluids at different speeds can be simulated by solving the time-dependent N-S equations. By writing the software core program (formerly known as the European pneumatic numerical solver EURANUS), the database structure can be optimized to minimize the memory occupation; Through the task manager, processor cores can be allocated for single-node/cross-node parallel computing, and a large number of computing tasks can be highly automated. NUMECA software has the advantages of high precision, fast convergence speed, good stability and easy operation, and is widely used in the field of turbomachinery.

FINE/Turbo software mainly includes four modules: IGG/AutoGrid, FINE, CFView and monitor. The IGG/AutoGrid module is used to generate a flow field grid and set boundary properties. The main function of the numerical calculation module FINE is to calculate the flow field and set the boundary conditions. There are a variety of turbulence models, spatial discrete formats and other solution methods to choose from. The post-processing module The post-processing module CFView can process the flow field information in batches and export the required flow field parameters. The main function of Monitor is to monitor and view the calculation process and convergence history of multiple examples.

2.3 Grid Division and Calculation Settings

The mesh quality of the initial blade profile is shown in Fig. 1. The Igg/Autogrid5 module of NUMECA software was used to generate the grid for the initial blade profile. In NUMECA calculations, the minimum orthogonality is generally required to be greater than 5° , the maximum

aspect ratio is less than 5000, and the maximum extension ratio is less than 10. The mesh of the initial blade profile is uniformly distributed in radial direction, and the number of nodes is 9. At the same time, mirror boundary is adopted for radial boundary, periodic boundary is adopted for circumferential boundary, and solid boundary is adopted for blade surface. The total number of grids is about 200,000, the minimum orthogonality is 18.4° , the maximum aspect ratio is 484.8, and the maximum expansion ratio is 2.9. The initial flow surface of blade S1 adopts O4H grid structure. Fig. 2 is the grid diagram of S1 calculation domain.

In the flow field calculation, this paper pays more attention to the influence of the overall flow field than the internal details of the flow field. Therefore, N-S governing equation is adopted, the turbulence model is Spalart-Allmaras model, the discrete scheme adopts the second-order upwind difference scheme, and the multi-grid technique is adopted to accelerate the convergence of the calculation. The inlet working medium is perfect gas. The inlet total pressure is set to 101325 Pa and the total temperature is set to 288.15K. In order to achieve the inlet Mach number of 0.4, the outlet static pressure is set to 95600Pa.

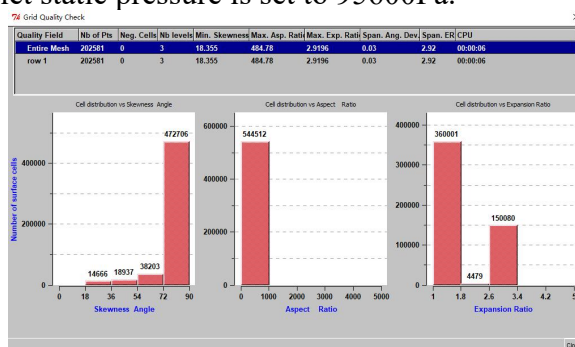


Fig.1 Grid quality report of initial profile

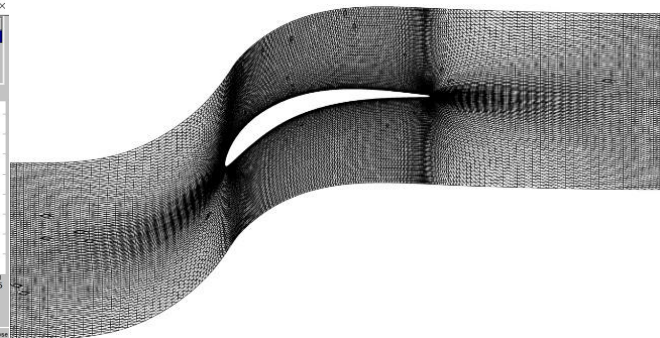


Fig.2 Grid diagram of S1 calculation domain

3. Optimization Process and Parameterization Settings

3.1 Introduction to the Shape of the Slot

Typical parameters of the slot include inlet width δ_1 , outlet chord position C_1 , outlet length δ_2 and outlet width δ_m , where C_1 and δ_2 are dimensionless based on chord length, and their definitions are shown in Fig. 3. The black color thick line is the two-dimensional blade profile, and the red thick line is the two sides of the channel.

Because the inlet of the slot is located at the front edge, the airflow velocity at the front edge of the blade profile is higher, so the jet velocity at the outlet of the slot can be increased; At the same time, ensure that the turning curve of the profile line on both sides of the slot are smooth, and reduce the friction loss of the jet in the slot; The direction of the slot outlet is tangent to the suction surface profile line, so the direction of the jet can be controlled to be the same as the main stream of the suction surface, and the mixing loss can be reduced when the slotted jet and the main stream converge. Therefore, the slot structure can better improve the aerodynamic performance of the blade.

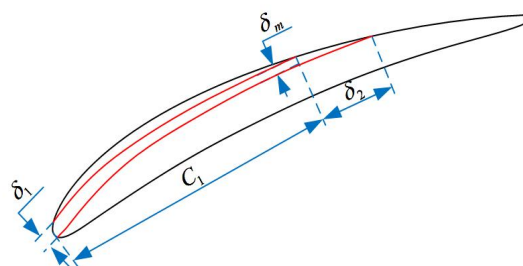


Fig.3 Typical parameters of the slot

3.2 Automatic Optimization Parameter Settings

The automatic optimization method is used to design the slot for the initial blade profile. The design variables are the position and width of the slot outlet, and the variation range of the design variables is set as shown in Table 2. The distance between the inlet point of the suction surface and front edge point is set at 0.50mm, and the distance between the inlet point of the pressure surface and front edge point is set at 0.50mm.

The optimization is carried out for a total of 10 generations, the number of individuals in each generation is 32, the crossover operator is 0.8, and the mutation operator is 0.05. The convergence curve reaches a plateau at about 1000 steps, so the number of individual iteration steps is set to 1200 steps. Because the slot has little effect on the diffusion factor, the optimization goal is to minimize the total pressure loss. The self-variable of the optimization objective function selects the total pressure loss, and the objective function is:

$$F = c_1(1 - \omega) \quad (1)$$

In the function, c_1 is the coefficient of weight, ω is the total pressure loss, and the weight of total pressure loss is 100. In the process of optimization, a new profile is generated by genetic algorithm, and each generated profile is numerically simulated to seek the maximum of the objective function and finally a blade profile with lower loss is obtained..

Table 2. Optimization parameter setting

Parameter	Lower limit	Upper limit
Slot outlet position	0.30	0.85
Slot outlet width/mm	0.10	0.80

3.3 Optimization Results

After optimization, the blade profile and slot are shown in Fig. 4. The slot outlet position is 74.5% chord length, and the slot outlet width is 0.419mm. The slotted blade grid structure is shown in Fig. 5. The inlet and outlet borders of the slot are fitted with the front edge of the blade and the suction surface respectively. The outlet end of the slot is merged into the main channel grid of the blade profile through an extended grid block. After slotting, The total number of grids is about 200,000, the maximum orthogonality is 18.4° , the maximum aspect ratio is 1325.5, and the maximum expansion ratio is 2.9, which meets the mesh quality requirements.

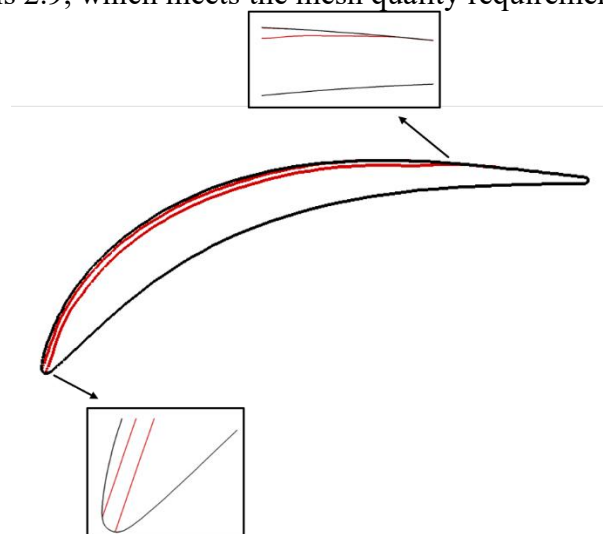


Fig.4 The blade profile and slot after optimization

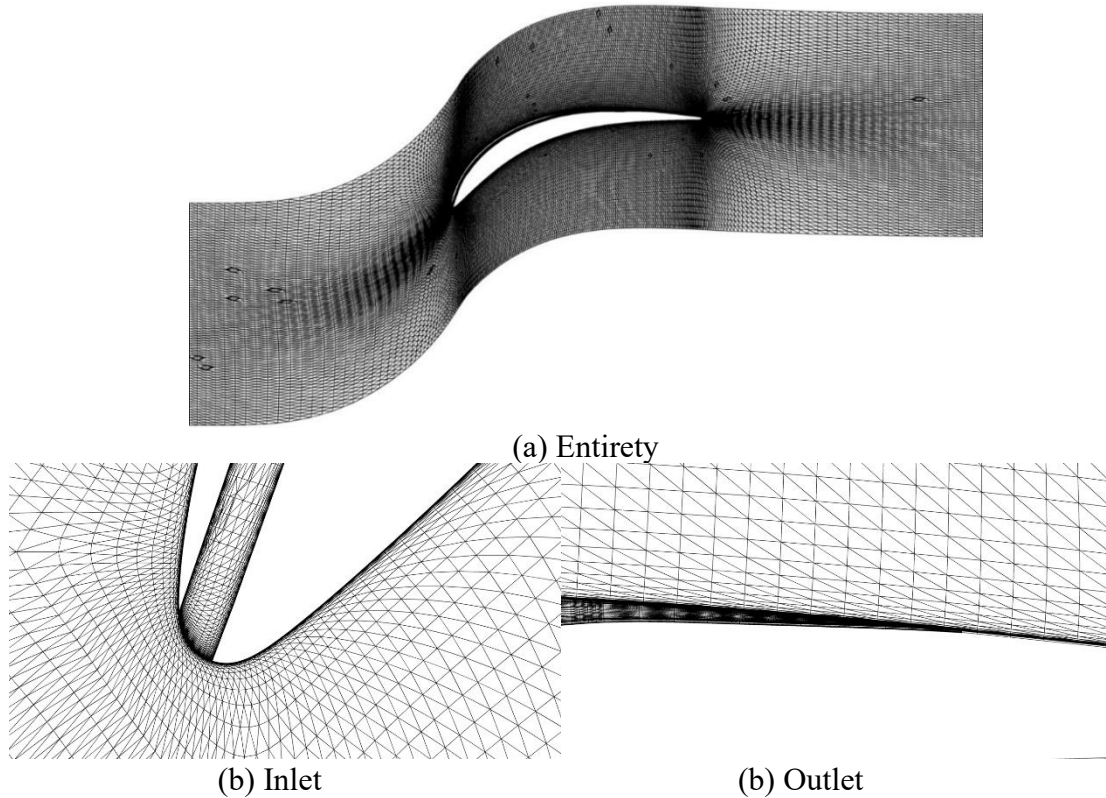


Fig. 5 Slotted blade grid structure

4. Comparison of slotted and unslotted blade profiles

Fig. 6 shows how the total pressure loss coefficient and flow turning angle of the blade profile change with the angle of incidence before and after slotting. The low loss negative angle of incidence and positive angle of incidence boundary are determined by twice the minimum loss, and the incidence of 0 degree is determined by the minimum loss incidence angle.

The figure shows that in the whole range of low loss incidence angle, the air flow turning angle of the slotted blade profile is larger than that of the unslotted blade profile, and the total pressure loss of the slotted blade profile is lower than that of the unslotted blade profile. Moreover, the optimization effect of the slotted blade profile is more obvious under the positive incidence angle.

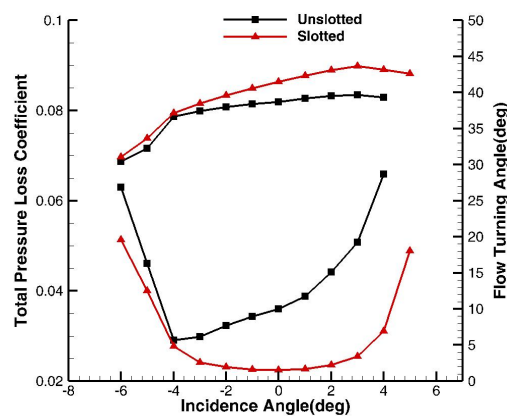


Fig. 6 Characteristic lines of slotted and unslotted blade profiles

For the flow in subsonic blade profiles without shock waves, in order to further study the rule and mechanism of the influence of slotting in suction surface on blade profile performance, the loss of each part of the blade profile is divided into boundary layer loss and wake loss, which is helpful to better grasp the details of the flow field of the blade profile and analyze the effect of slotting. Fig.

7 shows the partition method of blade channel losses. The boundary layer loss is defined as the partial loss from the aerodynamic inlet of the flow field to the predestination boundary of the blade tail, and the wake loss is defined as the partial loss from the predestination boundary of the blade tail to the aerodynamic outlet of the flow field.

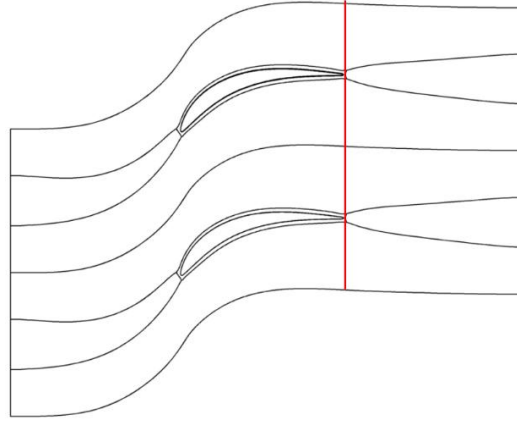


Fig. 7 Blade channel loss division

The boundary layer loss refers to the friction loss caused by the viscous flow of air flow and the separation loss caused by the reverse pressure gradient. Wake loss refers to eddy current loss in the wake zone and mixing loss between wake and main stream.

The boundary layer loss is calculated using the tangential mass flow average total pressure, and the calculation formula is

$$P_{layer}^* = \frac{\int P_t^* \rho C_a dY}{\int \rho C_a dY} \quad (2)$$

$$\omega_{layer} = \frac{P_1^* - P_{layer}^*}{P_1^* - P_1} \quad (3)$$

In the formula, P_{layer}^* is the average total flow pressure of the end edge section of the blade profile, P_t^* , ρ , C_a are the total pressure, density and axial velocity of the trailing edge section at any position along the tangential direction.

The wake loss expressed as the difference between the total pressure loss and the boundary layer loss,

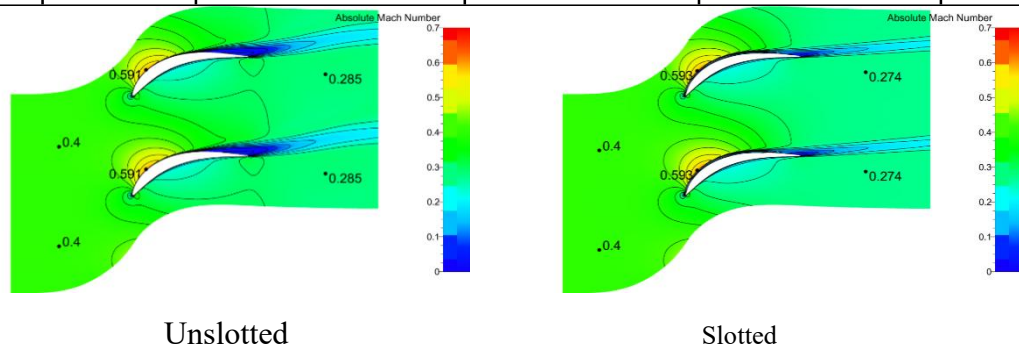
$$\omega_{wake} = \omega - \omega_{layer} \quad (4)$$

The comparison of aerodynamic performance parameters of slotted and unslotted blade profiles are shown in Table 4, and the Mach number cloud map of different angles of incidence is shown in Fig. 8. In the design inlet angle, i.e., 0° incidence angle, due to the control effect of slotted jet on the suction surface boundary layer, the separation area of the suction surface boundary layer of the slotted blade profile becomes smaller and the wake also decreases. Therefore, the boundary layer loss and wake loss of the slotted profile are smaller than that of the unslotted profile, the total pressure loss decreases by 37%. At the same time, the diffusion factor of the slotted blade profile is greater than that of the unslotted blade profile, and the slotted blade profile enhances the deceleration and diffusing capacity of the blade. In the -6° incidence angle, the boundary layer separation area of the suction surface is small, but the boundary layer separation area of the pressure surface is large, so the slotting air cannot play a full role. Moreover, slotting brings about certain slot loss and the mixing loss between the slotted jet and the main stream, so the boundary layer loss of the blade profile hardly changes after the slotting. When the incidence angle is 4° , the suction surface boundary layer separation area of the blade profile is larger, and the slotted jet has a better control effect on the suction surface boundary layer. Therefore, compared with the design inlet

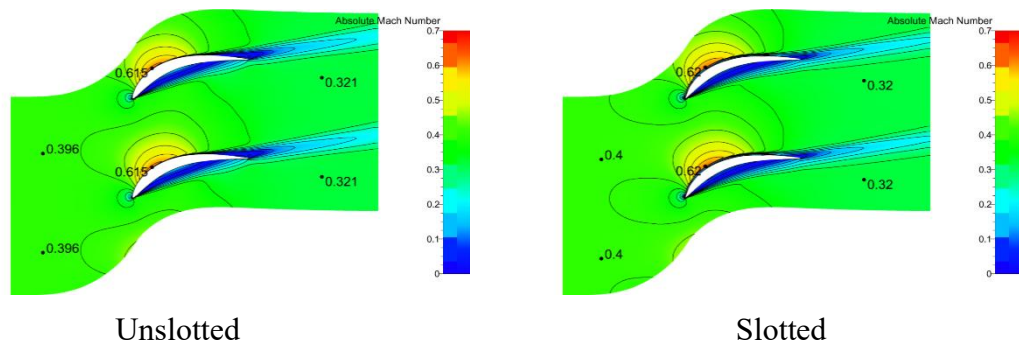
angle, the total pressure loss of the blade profile is reduced more significantly after the slotting, and the total pressure loss is reduced by 53%.

Table 4. Aerodynamic performance parameters of slotted and unslotted blade profiles

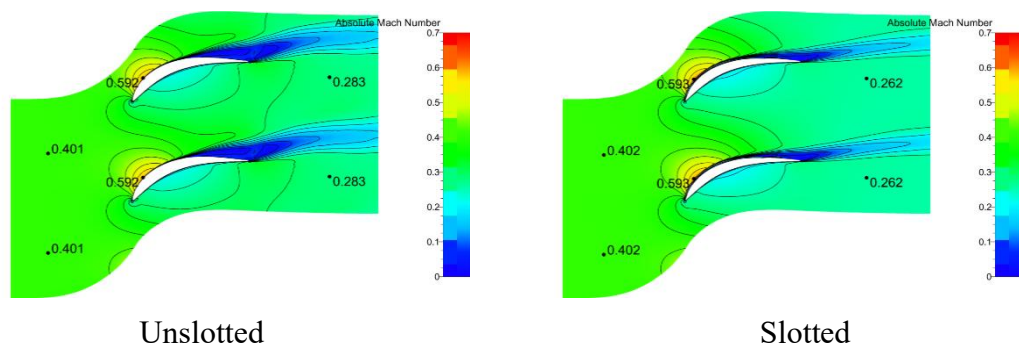
Incidence angle/ $^{\circ}$	case	Total pressure loss	Diffusion factor	Boundary layer loss	Wake loss
0	Unslotted	0.0358	0.5928	0.0231	0.0128
	Slotted	0.0225	0.6064	0.0173	0.0051
-6	Unslotted	0.0630	0.4466	0.0449	0.0181
	Slotted	0.0513	0.4563	0.0443	0.0070
4	Unslotted	0.0659	0.6242	0.0363	0.0296
	Slotted	0.0311	0.6643	0.0227	0.0084



(a) Incidence of 0 degree



(b) Incidence of -6 degree



(c) Incidence of 4 degree

Fig.8 Mach number cloud map at different incidence angles

The isentropic Mach number distribution of slotted and unslotted blade surfaces is shown in Fig. 9. Because the slotted jet inhibits the boundary layer separation of the suction surface and the diffuser ability is enhanced, the Mach number at the trailing edge of the blade profile is reduced. At 74.5% chord point, the abrupt change of isentropic Mach number curve is caused by micro-jet at the slot outlet.

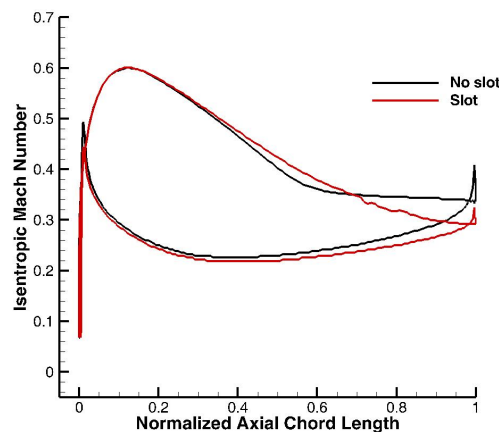


Fig. 9 Isentropic Mach number distribution on the blade surface

5. Summary

In this paper, the automatic optimization method is used to design the slot for inlet Mach number 0.4 and diffusion factor 0.6 compressor blade profile. The following conclusions are obtained:

In the whole range of low loss angle of incidence, the flow turning angle of slotted blade is greater than that of unslotted blade; The total pressure loss of slotted blade is lower than that of unslotted blade, and the optimization effect of slotted blade is more obvious under the positive incidence angle.

In the design inlet angle, because of the control effect of slotted jet on the suction surface boundary layer, the diffusion factor of the blade profile increases after slotted, and the cascade deceleration and diffusing capacity is enhanced. After slotting, boundary layer separation area of the suction surface is obviously smaller, and the wake is also reduced, so the total pressure loss of the slotted blade profile is reduced by 37%. In the incidence of -6 degree, the boundary layer separation area of the suction surface is small, but the boundary layer separation area of the pressure surface is large, so the slotting air blowing cannot play a full role. Moreover, slotting brings about certain slot loss and the mixing loss between the slotted jet and the main stream, so the boundary layer loss of the blade profile hardly changes after the slotting. When the incidence angle is 4°, the suction surface boundary layer thickens, and the slotted jet has a better control effect on the boundary layer of suction surface. Therefore, the total pressure loss of the blade profile decreases more obviously after the slotting.

Because the slotted jet inhibits the boundary layer separation of the suction surface, the diffuser ability is enhanced, and the Mach number at the trailing edge of the blade profile is reduced.

References

- [1] Steffens K. Advanced Compressor Technology—Key Success Factor for Competitiveness in Modern Aero Engines[R]. ISABE Paper, ISABE-2001-1009.
- [2] Sanger N L. The use of optimization techniques to design controlled diffusion compressor blading[J]. ASME J Eng Power, 1983, 105: 256-265.
- [3] Zhou Zhenggui. Automatic Optimization Design of compressor blade [J]. Journal of Aerospace Power, 2002,17 (3): 197-200.
- [4] Zhou Zhenggui, Wang Guangwen. Research on Supersonic fan Blade Profile Design [J]. Journal of Aerospace Power, 2009. Issue 1:127-131.
- [5] Wang Guangwen, Zhou Zhenggui. Aerodynamic Optimization Design of fan/compressor blade based on Parallel Genetic Algorithm [D]. Nanjing University of Aeronautics and Astronautics,2009.

- [6] Zhou Zhenggui. Automatic Optimization Design of Compressor/fan blade [M]. Beijing: National Defense Industry Press, 2013:5-7.
- [7] Bright M M, Culley D E, Braunscheidel E P. Closed Loop Active Flow Separation Detection and Control in a Multistage Compressor[R]. AIAA 2005-0849.
- [8] Sanjay G. NASA Glenn Research in Controls and Diagnostics for Intelligent Aerospace Propulsion Systems[R]. NASA TM-2005-214036.
- [9] Lei V M, Spakovszky Z S, Greitzer E M. A Criterion for Axial Compressor Hub-Corner Stall[J]. Journal of Turbomachinery, 2008, 130(3).
- [10] Zhang Y, Mahallati A, Benner M. Experimental and Numerical Investigation of Corner Stall in a Highly-Loaded Compressor Cascade[R]. ASME 2014-GT-27204.
- [11] Beselt C, Eck M, Peitsch D. Three-Dimensional Flow Field in a Highly Loaded Compressor Cascade[R]. ASME 2014-GT-25947.
- [12] Rockenbach R W. Single stage experimental evaluation of slotted rotor and stator blading, part 9 Final report. 1968.
- [13] Ramzi M, Bois G, Abderrahmane G. Numerical Study of Passive Control with Slotted Blading in Highly Loaded Compressor Cascade at Low Mach Number[J]. International Journal of Fluid Machinery and Systems, 2011, 4.
- [14] ZHOU Min, WANG Rugen, Bai Yun, ZENG Lingjun. Numerical study of Effect of stator blade slotting on Characteristics of Single stage Compressor [J]. Acta Aerodynamica Sinica, 2009, 27(01): 114-118