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INFLUENCE OF LEADING EDGE EROSION ON THE PERFORMANCE OF TRANSONIC FAN BLADE

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ABSTRACT

Over service time, the leading edge of the aero-engine fan blade will be eroded. This paper takes the fan blade of high bypass ratio engine as the research object to study the influence of the erosion on the aerodynamic performance. The erosion of the leading edge of the blade results in degradation to a blunt blade with roughness. In order to simplify the study, the roughness of leading edge is considered to be uniform. The aerodynamic performance and flow field changes of the original blade and the blunt blade with leading edge erosion of 250μm are compared and analysed. The result shows that the peak efficiency of the eroded blade decreases by 0.86% compared with the original blade. Under the influence of the blunt leading edge, the flow blockage is aggravated and the entropy at the blade tip increases. Besides, the tip shock moves forward, leading to the loss of total pressure and reduction of workability.

INTRODUCTION

With the fantastic advent of aviation industry, the development of civil aviation engine technology has become a top priority. In today's era, except for a few types, turbofan engines have become the mainstream of civil aviation aircraft engine in China, especially those with high bypass ratio. High bypass ratio turbofan engine is widely used in the field of civil aviation and has taken the leading role in civil aviation engine market. During service, the engine components are exposed to a lot of harsh environments. The leading edge of the fan blade is one of the most severely affected parts in turbofan engines because it has a high probability of being impacted by high momentum and foreign particles during take-off and landing. This impact will result in erosion of the pressure side and suction side, reduction of chord length, deformation of the leading edge and enlargement of tip clearance.

In this paper, taking a fan rotor blade of a high bypass ratio engine as the research object, a simplified erosion model is used to simulate the fan rotor blade after erosion. In order to figure out the effect of erosion on aerodynamic performance of fan rotor blades, the isentropic efficiency and the total pressure ratio are compared and the tip shock and the flow field around the fan rotor blades are analysed. RWTH Aachen University studied the eroded compressor blades through numerical simulation and compared the flight status of the blades with conventional maintenance (Herwart et al., 2003). It was found that the eroded leading edge profile increased fuel consumption and shortened the service life of the blades by 25%. The Chinese Academy of Sciences studied the influence of different blade leading edge shapes on performance and flow field in centrifugal compressors (Chu et al., 2008). The study showed that compared with blunt leading edge, circular leading edge and elliptical leading edge improved the flow capacity of the compressor and increase the pressure ratio and efficiency. Some scholars used transonic fan cascades to study the effect of blunt leading edges on engine performance (Alexander et al., 2015). The results of the analysis showed that the aerodynamic performance of the engine gradually lost in the whole working range. At aerodynamic design points, the loss was increased to 25%. German Aerospace Center (DLR) conducted flow experiments on original blade profiles, blunt blade profiles and chord length reduction profiles (Giebmanns et al., 2015). The result showed that under the condition of transonic flow, the leading edge shape had an immense influence on the performance of fan blade profiles. At the same time, the leading edge of the fan blade profile was greatly affected by erosion during operation. This erosion led to deformation and reduction in chord length of the leading edge shape. Using the simplified erosion front morphology with blunt tip and roughness, Civil Aviation University of China found that erosion degraded the aerodynamic performance of fan rotor blades and the deterioration became more serious with the deepening of erosion (Shi et al., 2019).

Given the transonic condition, the shock must be taken into account. To explore the influence of shock and boundary layer on the flow field, this paper studies the flow field structure and shock characteristics of transonic fan rotor blades before and after erosion. Whittle Laboratory of University of Cambridge took a stator blade as the research object in 2009 (Goodhand et al., 2009) and 2011 (Goodhand et al., 2011) respectively, studied the profile loss of elliptical leading edge and circular leading edge under different inlet Reynolds numbers and simulated the flow state of suction side during engine cruising. It was found that the shock / boundary layer interference significantly increased the thickness of the boundary layer and the loss of the boundary layer. In subsequent studies, the influence of elliptic leading edge, circular leading edge and continuous curvature leading edge on static pressure distribution of the suction side was analysed. The suction peak factor was defined and its determination value affecting the flow loss at the leading edge was given. German Aerospace Center (DLR) and Lufthansa Technik AG (LHT) jointly studied the erosion effect of fan blades in transonic engines and found that the long-term erosion has a great influence on the blade performance parameters (Giebmanns et al., 2012). The blunt leading edge caused the shock loss to increase and to move upstream. The change of shock structure in transonic cascade has been studied in detail by PIV measurement and schlieren imaging in a laboratory (Klinner et al., 2014). It was found that erosion causes the leading edge bow shock to expand and move upstream, resulting in additional lip shock and increasing shock loss and cascade loss.

Domestic and foreign scholar have done a lot of analysis on the influence of different leading edge shapes on performance, which verified the influence of blunt leading edge caused by erosion on fan flow loss. However, there are still few researches on the comprehensive effects of the shape and roughness of the leading edge. It is also lack researches on the actual erosion and flow field of transonic fan blades. Through analysing one high bypass ratio engine fan blade aerodynamic performance after the erosion, fan blade aerodynamic performance attenuation after several flying cycle can be observed. Detailed understanding of the influence of erosion on the flow around the blade and performance loss is helpful to optimize aircraft engine fan maintenance cycle and overhaul procedure.

RESEARCH OBJECT

In this paper, the fan rotor blade of a high bypass ratio turbofan engine is taken as the research object (Qian, 2018). The fan rotor components are illustrated in Figure 1.

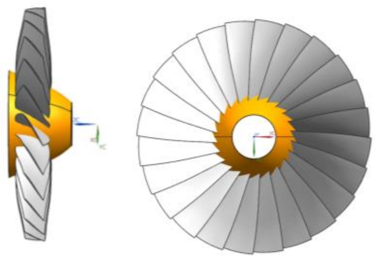

Figure 1 Fan rotor component of a high bypass ratio engine

Table 1. Fan rotor design parameters

Parameter	Numerical
Number of fan rotors	24
Rotor speed	5175 r/min
Inflow velocity	258 m/s
Total import temperature	288.15 K
Total import pressure	101325 Pa
Chord length	0.25m

SIMULATION METHOD

For original fan blades, the calculation is based on FINE / TURBO in NUMECA. Real gas is selected for the fluid model and Spalart-Allmaras model is selected for the turbulence model. The total inlet temperature and the total inlet pressure are given for the boundary condition. The aerodynamic performance of the blade under different working conditions is obtained by imposing different average outlet static pressure.

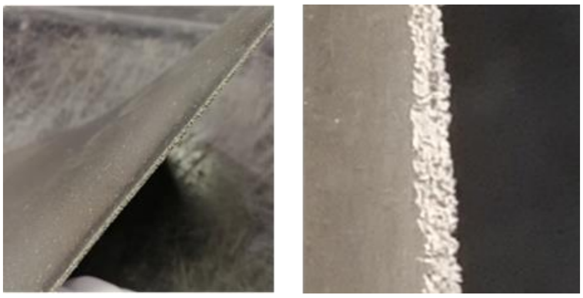

Figure 2 Overall shape and partial enlargement of the eroded blade leading edge

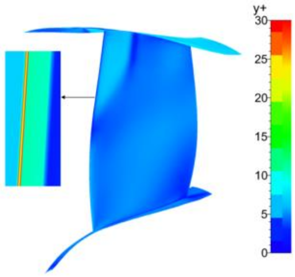

Figure 3 y^+ value of rotor wall

For eroded fan blade shown in Figure 2, the leading edge of the blade has a certain roughness. According to the experimental measurement results, the maximum degree of erosion of the leading edge is 250um. In order to study the influence of the eroded leading edge on the aerodynamic performance of the blade, an erosion model of 250um is adopted for the erosion front from the root to the tip of the blade, and the erosion degree is converted into an equivalent roughness height of 12.9um. For turbulence model, the Spalart-Allmaras Extended Wall model with extended wall function is selected for calculation. The equivalent rough height is input at the boundary conditions of the expert mode, and IROUGH is turned on in the control variables for calculation. The mesh thickness of the first layer is 1um to ensure that y^+ of the rough leading edge wall surface is less than 30 and of the remaining walls is less than 10, which is applicable to the selected turbulence model. y^+ value of fan rotor wall is shown in Figure 3.

GRID INDEPENDENCE VALIDATION

The O4H mesh in accordance with turbomachinery is generated in the AutoGrid5 module. In order to verify the mesh independence, the grid templates of 400000, 600000, 800000, 1000000 and 1200000 are generated respectively for numerical simulation calculation. Flow rate, efficiency and pressure ratio in this paper are dimensionless (Kuang, 2018). The dimensionless treatment of fiow rate, pressure ratio and efficiency：

$$q_{m,norm} = \frac{q_m}{q_{m,d}} \quad (1) \qquad \pi_{norm} = \frac{\pi}{\pi_d} \quad (2) \qquad \eta_{norm} = \frac{\eta}{\eta_d} \quad (3)$$

Where $q_{m,d}$, η_d and π_d are the flow rate, isentropic efficiency and total pressure ratio of 1 million grid at design points respectively.

The dimensionless characteristic curve is shown in Figure 4 and 5. Compared with the calculation results of the five groups of grids, the errors are all within 0.2%, meeting the requirements of grid independence. Finally, 1 million grid with certain accuracy and fast calculation is selected as the template for the subsequent calculation grid.

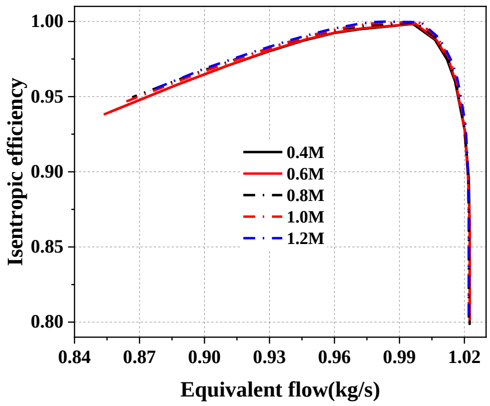

Figure 4 Grid independence check of flow - isentropic efficiency

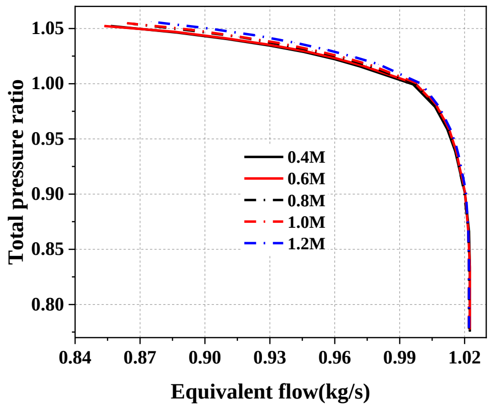

Figure 5 Grid independence check of flow-total pressure ratio

RESULTS AND DISCUSSION

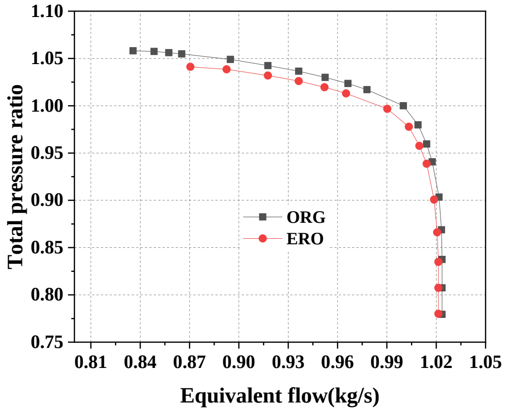

Figure 6 Comparison of flow-total pressure ratio of two blades

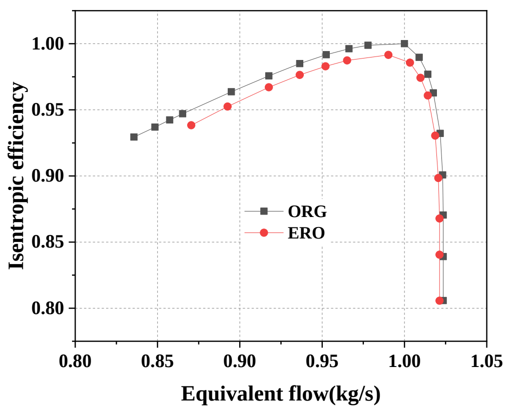

Figure 7 Comparison of flow-isentropic efficiency of two blades

Figure 6 and 7 show the characteristic curves of the original blade and the eroded blade respectively, including the flow-total pressure ratio curve and flow-isentropic efficiency curve. The result shows that the peak efficiency of the original blade after dimensionless is 100% while the peak efficiency after erosion is 99.14% and the aerodynamic performance decreases by 0.86%. The whole characteristic curve tends to move towards lower values. The pressure ratio of eroded blade is also significantly lower than that of the original blade. The blunt leading edge of the eroded blade causes certain airflow disturbance which aggravates the flow obstruction in the passage then is reflected in the decline of the pressure ratio.

Stable working margin SM (shi et al., 2019) is defined as：

$$\mathrm{SM} = \left(\frac{m_d \pi_s^*}{m_s \pi_d^*} - 1\right) \times 100\% \qquad (4)$$

Figure 6 and 7 not only show the aerodynamic performance decline caused by erosion, but also clearly show the decrease of stable operating margin caused by erosion. The original blade can work at a lower flow rate, which means the outlet pressure near stall point is higher. The stable operating margin of the original blade is 26.61% while the stable operating margin of the eroded blade is only 21.66%, which is much lower than that of the original blade.

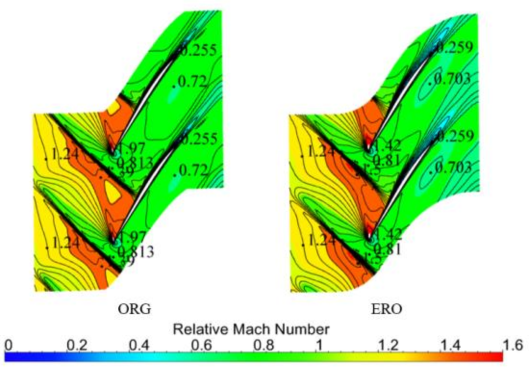

Figure 8 Relative Mach number contour of 95% relative height near stall point

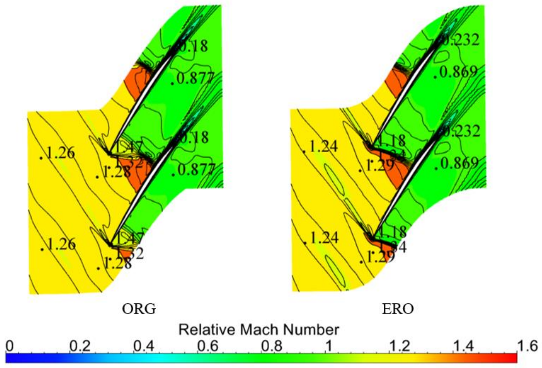

Figure 9 Relative Mach number contour of 95% relative height at design point

The leading edge shock formed at the inlet of the blade, illustrated in Figure 8, is in contact with the suction side of the blade, and the flow through the shock has an obvious decrease in Mach number. Moreover, the width of the boundary layer of suction side gradually thickens and the initial position of the shock moves forward to the leading edge.

A subsonic region in the flow area between the leading edge and the shock is observed in Figure 8, which means that the bow shock in front of the leading edge is a normal shock. Compared the two contours in Figure 8, they reveal the size of normal shock is affected by the shape of leading edge. The subsonic region of the blunt leading edge is evidently larger than that of the original blade, which gives rise to the extension of the normal shock part of the eroded blade and thereby causes the higher shock loss.

Not only the subsonic flow region is discovered behind the normal shock, but also it is observed that only the flow near the outer edge of the suction side boundary layer maintains supersonic speed in the entire interaction region. Interaction between strong shock and supersonic blade suction side boundary layer results in the decreasing mass flow rate and the increasing blade load, which affects the blade surge and makes the blade stable working margin decrease. Under the condition of blunt leading edge, transition will propagate forward to the acceleration region on the suction side.

Relative Mach number contour of 95% relative height at design point is shown in Figure 9. Compared with near stall point, the shock at design points is not fully out of the passage and the bow shock is not formed at the leading edge. The passage shock of original blade still has a certain distance from the leading edge, not completely connected with the block airflow at the leading edge. Nevertheless, the obstruction of the airflow at the blunt leading edge of the eroded blade is intensified, and the expansion near the leading edge intensifies then forms a lip shock on the suction side. In addition, as the intensity of the passage shock increases, the lip shock and the passage shock together form the initial shape of the leading edge bow shock.

Compared with original blade, the shock of the eroding blade is located upstream, resulting in a larger subsonic region. Furthermore, a stronger lip shock emergences in the expansion region of pressure side of the blunt leading edge. The acceleration of the flow near the blunt leading edge is higher, which generates additional lip shock on the suction side. In contrast to the eroded blade, the leading edge of the original blade expands uniformly on the suction side so that the airflow separated to the suction side pass smoothly without causing loss of shock. This is one of the significant reasons for the loss of aerodynamic performance of the eroded blade.

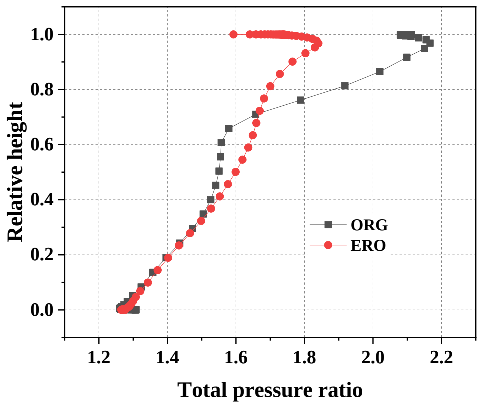

Figure 10 Radial distribution of total pressure ratio near stall point

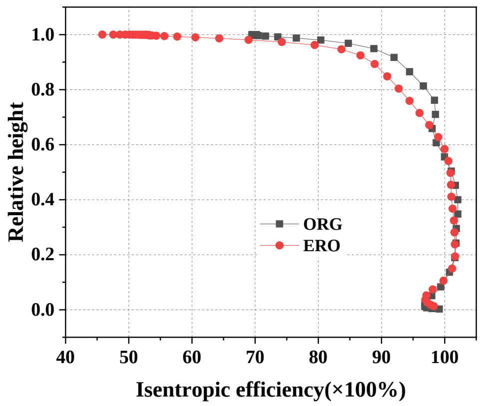

Figure 11 Radial distribution of isentropic efficiency near stall point

The radial distribution curves of the total pressure ratio and isentropic efficiency of blades near stall point are shown in Figure 10 and 11. There is no significant difference between the total pressure ratio curves of two kinds of blades from the blade root to 40% relative height. In the area of 40% to 70% relative height, the total pressure ratio of the eroded blade is even higher than that of the original blade. From 70% relative height to tip, the total pressure ratio of the eroded blade is much lower than that of the original blade. In the low relative height region (blade root - 40% relative height), the blade velocity is low and the flow in the passage area is stable. Therefore, erosion has little effect on the flow then the change of total pressure ratio can be neglected. In the middle relative height region (40% relative height - 70% relative height), the blade velocity begins to increase and the blunt leading edge of the eroded blade causes the disorder of airflow, corresponding to the increase of disturbance in the blade passage and bringing about the increase of the total pressure ratio. In the area near the blade tip (70% relative height - blade tip), the total pressure ratio increases sharply due to the impact of shock and the erosion of blades results in the decline of the total pressure ratio due to the loss of boundary layer caused by the leading edge airflow separation.

Shocks are generated at the leading edge of the transonic blade tip, which induce the separation of the boundary layer on the suction side of the fan rotor blade. As the relative height increases, the tangential velocity of the blade increases, the relative Mach number increases, and the shock intensity increases. Compared with the original blade, the thickness of the boundary layer of the eroded blade is distinctly on the increase, which leads to the increase of flow loss and thus the decrease of fan efficiency.

Inlet airflow reaching the blade leading edge is divided into airflow along the pressure side and the suction side. The change of the one along the suction side is evident. Limit streamline of the suction side near stall point is illustrated in Figure 12. As can be seen from the diagram, after the fluid velocity of suction side decreases overall, limit streamlines along the flow direction turn to distribute along the radial direction due to centrifugal force and shock interference. The flow separation of the original blade occurs at 70% relative height which is also the position where the total pressure ratio begins to change dramatically and the shock emergences. The limit streamline deviation of the eroded blade occurs at the lower height of the blade and the starting position of the shock moves downward. This phenomenon is caused by the lower flow velocity of the airflow separating from the leading edge of the eroded blade along the suction side comparing with that of the original blade. Low velocity flow is more susceptible to the influence of centrifugal force which produces the limit streamline deviation. The curvature of the streamline behind the shock separation point is larger, which leads to the increase of the flow loss.

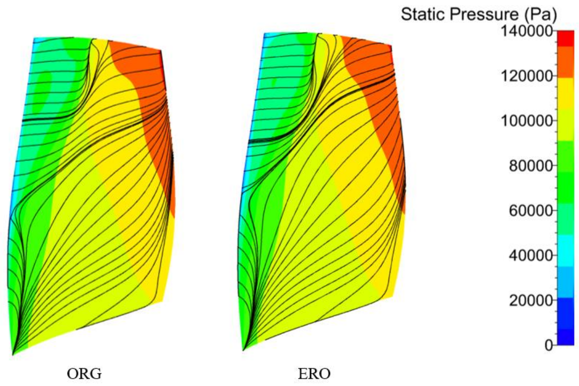

Figure 12 Limit streamline of the suction side near stall point

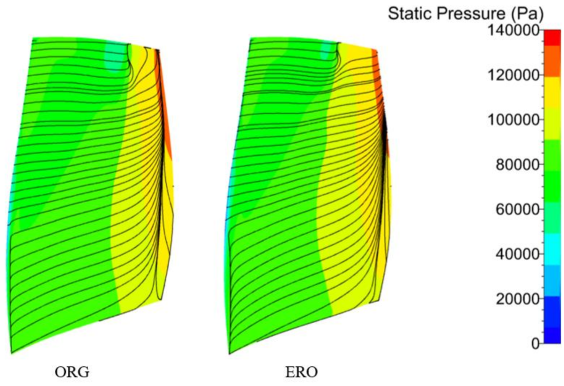

Figure 13 Limit streamline of the suction side at design point

Figure 13 is the limit streamline of the suction side at design point, and the difference of the limiting streamlines in the figure is mainly reflected at the blade tip. The flow separation position of the original blade is closer to the trailing edge than that of the erosion blade, so the shock wave formed is also somewhat behind, which is consistent with the situation in Figure 9.

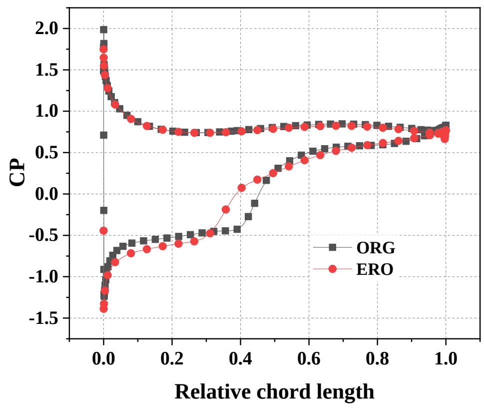

Figure 14 Surface static pressure coefficient distribution of 95% relative height near stall point

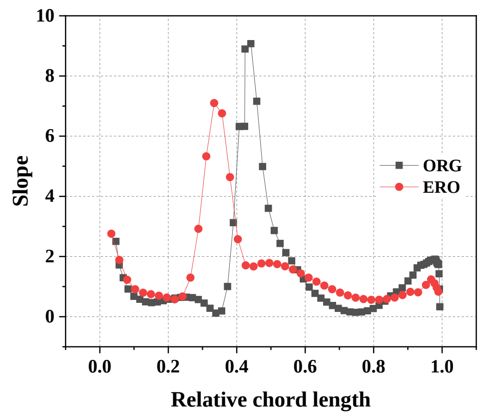

Figure 15 Slope of static pressure coefficient

Figure 14 shows the distribution of static pressure coefficient CP on the blade surface at the height of 95% blade near stall point, and Figure 15 shows the slope of CP. As represented in illustration, the main difference of the surface static pressure coefficient of the two blades is reflected in the suction side. The static pressure coefficient of the eroded blade rises sharply at 34% chord length of the suction side while that of the original blade at 40% chord length. The reason for the discrepancy is that the shock in the passage hits the suction side of the blade causing the loss of the boundary layer and the increase of the static pressure due to the decrease of the flow velocity after flowing through the shock. The aggravation of the airflow disturbance of the eroded blade causes the forward movement of the shock, and thus weakens the work capacity of the blade and degrades the aerodynamic performance of the blade.

Figure 16 shows the wake distribution of 95% relative height at near stall point of two kinds of blades. As the shock moves upstream in the condition of eroded blade, the airflow passes through the shock earlier and the adverse pressure gradient after the shock is stronger, hence the boundary layer on the suction surface thickens. The wake starts at the 50%

chord length of the suction side of the original blade while the wake is generated at the 30% chord length of the eroded blade. Note that the wake generating in the upstream diffuses at the trailing edge and the wake on the suction side of the eroding blade is clearly wider which results in more airflow loss. Wake loss makes the relative velocity at the outlet of rotor blade decrease, bringing about the decrease in total pressure which results in aerodynamic performance decline.

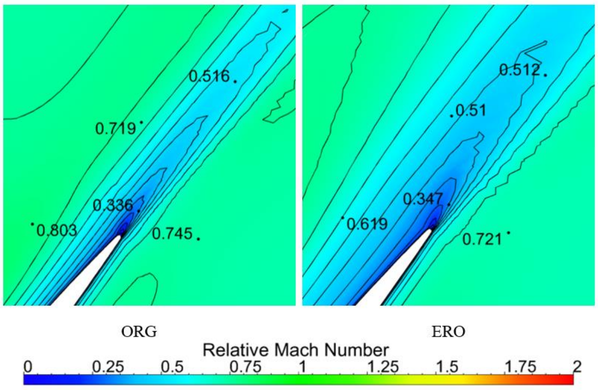

Figure 16 Wake distribution contour of 95% relative height near stall point

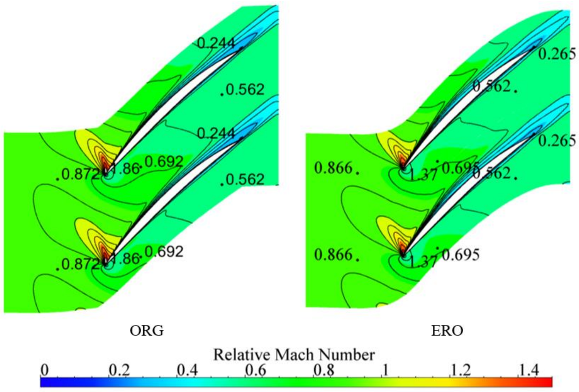

Figure 17 Relative Mach number contour of 50% relative height near stall point

Figure 17 is the Mach number contour of 50% relative height near stall point. Note that there is no shock in the middle area of the blade and thus there is little difference in flow field details. This leads to the conclusion that the aerodynamic performance of the eroded blade is different from that of the original blade and the transonic part varies the most. The erosion results in the reduction of chord length and the formation of a blunt leading edge which causes the change of surrounding flows, leads to the thickening of the boundary layer and the upstream movement of the passage shock and thereby the decrease of mass flow rate. Under the influence of blunt leading edge, the normal shock extends around, making the shock influence area larger than the original leading edge, which means that the blunt leading edge has a greater loss. These above-mentioned effects lead to the decrease of aerodynamic performance of the blade and thus the isentropic efficiency and total pressure ratio decrease which means the characteristic curve moving downward.

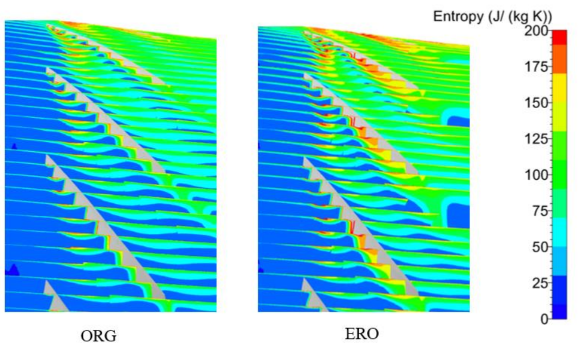

Figure 18 Entropy distribution contour of blade tip near stall point

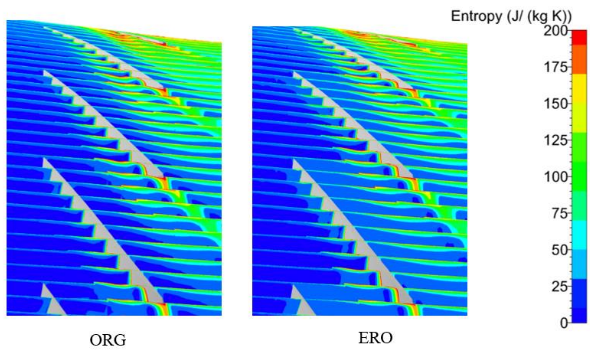

Figure 19 Entropy distribution contour of blade tip at design point

Figure 18 represents the entropy distribution contour of blade tip near stall point, in which the formation of a high entropy area is observed near the wall of the suction side of eroded blade, indicating the chaotic airflow movement. As the air flows from left to right, the high entropy area of the eroded blade is mainly divided into two parts: one part forms at the leading edge mainly due to the influence of leakage flow, the other part forms at the 40% chord strength primarily because of the shock effect. In the process of flowing downstream, the high-energy fluid mixes gradually with the main flow, the whole flow tending to be uniform and the high-entropy region fading out. Figure 19 shows entropy distribution contour of blade tip at design point. It can be seen that the entropy distribution at the blade tip of the design point has little difference.

The flow separation at the leading edge makes extensive effect on the downstream main flow area. The shock occurs near the blade surface and the Mach number in front of the shock ranges from 1.24 to 1.39. The strong boundary layer separation takes place at about 42%-43% of the chord length. The result shows that there is a strong adverse pressure gradient on the separated boundary layer after the passage shock and the boundary layer at the back of the suction side barely reattaches.

CONCLUSIONS

With numerical simulation, the aerodynamic performance of the original and eroded blades of the high bypass ratio engine is obtained. After analysis of the changes of flow field and leading edge shock, the following conclusions are drawn:

1) Erosion turns the leading edge of the fan rotor blade into blunt type with certain roughness, shortens the blade chord length and enlarges the blade tip clearance. The rough blunt leading edge causes the aerodynamic performance of the fan blade to decline, the peak efficiency and total pressure ratio to decrease and thus the stable working margin to decrease.

2) Under transonic conditions, normal shock emergences at the leading edge of fan blade tip. The Normal shock at leading edge of the eroded blade extends, accompanied by obvious upstream movement. Under the influence of flow loss, a local entropy increase region is formed at blade tip, and the loss of shock loss and boundary layer causes the mass flow rate to decrease. Shock hits the suction side, resulting in intense static pressure rise and strong boundary layer separation.

3) The blunt leading edge brings about additional lip shock on suction side, which results in flow loss and wake expansion. The interaction of the flow field shrinkage in the blade passage and the strong shock / boundary layer has a notable effect on the loss of total pressure.

NOMENCLATURE

BLE	blunt leading edge
ERO	erosion blade
ORG	original blade

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