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**Influence of Surface Roughness on a Highly Loaded Axial Compressor Stage Performance at Low Reynolds Number**

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**ABSTRACT**

In the present study, a numerical simulation was conducted to investigate the influence of surface roughness on the aerodynamic performance of a 1.5-stage highly loaded axial compressor at low Reynolds number. It was especially considered how the roughness Reynolds number ($k^*$) affected the change of the inlet and outlet conditions, the growth of the separation bubble (LSB), the status of the limiting streamline, the patterns of the wake. Regarding the roughness settings, five roughness magnitudes were mainly studied. The results showed that at low $Re$, surface roughness mainly improved the stage performance by reducing the length and width of the LSB, delaying the occurrence of three-dimensional flow separation, and increasing the turbulence level near the wall. However, it also aggravated the incoordination between the subsequent stages to a certain extent, which limited further improvement of the overall aerodynamic performance. Generally, with $k^*$ increasing, the compressor aerodynamic performance improved, and achieved the best at $k^*$= 137.8. The maximum increases in the total pressure ratio, peak efficiency, and choked mass flow rate were approximately 4.01%, 5.34%, and 2.24% respectively.

**INTRODUCTION**

When an unmanned aerial vehicle (UAV) cruises at high altitudes, the Reynolds number based on the blade chord decreased sharply, which adversely affects the separation, transition and other flow conditions of the compressor blade surface (Bons, 2010). At a low Reynolds number ($Re<10^5$), the flow separation including two-dimensional boundary layer separation bubble and three-dimensional separation on the blade surface is greatly advanced, the transition process is delayed, and there is an obvious transition process from laminar flow to turbulent flow (Li, et al., 2019). As the $Re$ further decreases, there is usually only laminar separation but no turbulent reattachment on the blade surface, which leads to a seriously reduce in the aerodynamic performance and steady work range of a compressor (Bammert, et al., 1972).

In order to effectively regulate the process of boundary layer separation and transition near the compressor blades, and to improve the aerodynamic characteristics under low Reynolds number conditions, scholars have adopted several active and passive techniques including blade surface layer suction, casing treatments, and pulsed vortex generator jets, (Pacciani, et al., 2006; Volino, 2003; Bons, et al., 2012). Compared with the methods above, the surface roughness control method has shown comparative advantage in effectively affecting the development of the boundary layer without imposing additional complicated geometric shapes on the blade. In the past few decades, investigating the influence of
blade surface roughness on the compressor performance has become a hot research topic, and the flow control method based on roughness has great application potential (Roberts, et al., 2006).

Research on the effects of surface roughness of compressor cascades started early, and extensive experiments and numerical calculations have been carried out to investigate the effects of surface roughness in detail. Back et al. (2009) measured the profile loss and deviation angle of a certain low-speed compressor cascade under different degrees of roughness, and found that both properties increased with increasing roughness. In addition, the results showed that the roughness of the suction surface leading edge was the dominant factor in leading to variations in cascade performance, while the pressure surface roughness had little effect. Kong et al. (2017) reported that roughness promoted strong turbulent separation near the trailing edge compared to smooth blades, which resulted in increased flow losses and asymmetrical waves along the circumferential direction. Gbadebo et al. (2004) covered the stator suction surface with sandpaper. The experiment revealed that the compressor performance significantly decreased when the rough surface was set between the leading edge and the peak velocity of the suction surface, while the influence could be ignored when the roughness was set downstream of the peak velocity. Ju et al. (2013) measured the velocity distribution and profile loss of the boundary layer by using the LDV technique. The results indicated that the size of the separation bubble was inhibited at the leading edge and the turbulence level at the turbulent boundary layer decreased at $Re = (2.1\sim3.8\times10^5)$, leading to a reduction in the cascade profile loss.

For multistage axial compressors, much work has also been made in studying the surface roughness influences on the compressor stage performance. Syverud et al. (2006; 2007) performed a sequence of accelerated deterioration experiments on the General Electric J85-13 compressor to explore the influence of surface roughness on compressor stage performance. And they found that increased magnitudes of the roughness and certain Reynolds numbers would cause an increase to the profile losses, and the isentropic efficiency was also obviously reduced. Morini et al. (2010; 2011) carried out numerical simulations to analyze the influence of dirt deposition and roughness level on the NASA stage 37 performance. The results showed that the decreased efficiency in the choked flow region mainly comes from the increase in flow blockage while the roughness itself had little influence. Moreover, they proposed that the stage performance was mainly affected by the rotor roughness compared with the stator roughness, and the affection of suction surface roughness was larger than that of the pressure surface. Bammert and Woelk (1980) took a three-stage axial flow compressor as the research object, compared the aerodynamic performance of blades with smooth and rough surfaces, and observed that the total pressure ratio was reduced by a maximum of 30%, and that the volume flow rate was reduced by 15%-20% as the roughness of the blade increased. Chen et al. (2012; 2013) pointed out that increasing surface roughness had little effect on the stable working range of the compressor, while increasing blade thickness reduced the stable working range. Furthermore, their numerical calculation of the stage 35 showed that the compressor performance dropped sharply when the roughness was located near the root of the rotor, and that the roughness near the leading edge had a greater influence on the performance than the roughness near the trailing edge. In addition, the roughness of certain positions improved the compressor performance to a certain extent.

In spite of many efforts above, previous researches have mainly focused on high Re conditions, under which surface roughness was likely to reduce peak efficiency and deteriorate compressor performance. Thus far, a few studies focusing on low Re conditions have been carried out on large-scale cascades. However, few studies have been conducted on small-scale compressors, thus further exploring the effects and mechanism of the surface roughness on small compressors at low Re was quite essential. Therefore, this paper presents a numerical simulation of a small-scale 1.5-stage highly loaded axial compressor under 20-km altitude conditions ($Re=4.5\times10^5$) to investigate in detail the effects of the blade surface roughness magnitudes on the overall aerodynamic performance, as well as the flow field characteristics.

**INVESTIGATED MODEL**

The compressor used in this study is a small-scale 1.5-stagel highly-loaded axial compressor designed and tested by laboratory of Institute of Engineering Thermophysics, Chinese Academy of Sciences (Yang, et al., 2015). It is a typical axial compressor for small aero-engine. At design point, the rotor operates at a speed of 25000 rpm. Detailed geometric and aerodynamic parameters are listed in Table 1.

| Parameter                  | Design value |
|----------------------------|--------------|
| Design rotating speed/ (r/min) | 25000        |
| Total pressure ratio       | 1.72         |
| Number of blades           | 31/36/59     |
| Tip clearance/ (mm)        | 0.2          |
| Hub clearance/ (mm)        | 0.15         |
| Inlet chord length / (mm)  | 23           |
| Design tip speed/ (m/s)    | 361          |
| Work coefficient           | 0.46         |
| Inlet hub/tip radius ratio | 0.72         |
NUMERICAL METHODOLOGY

In this paper, the Numeca AutoGrid5 module was used to generate the O4H topology structure at the blade root and tip clearance, while the HOH topology structure was adopted at the blade surface. The grid height in the viscous sublayer region near the wall was fine enough (max value 0.003 mm) to ensure dimensionless wall distance y⁺< 1, to meet the requirements of the turbulence model selected in this simulation for a highly accurate prediction. At the rotor tip clearance, 17 mesh nodes were set along the radial direction, and "butterfly mesh" was adopted to guarantee the mesh resolution and improve the calculation accuracy, as shown in Figure 1. A grid independence study was also done, and results showed that the grid number of 2.2million approximately had reached the requirement of grid independence. Therefore, the subsequent results and discussions were based on the computational grid.

Figure 1 Computational grid of the compressor  Figure 2 Comparison of the computational and experimental results

Numerical simulations were conducted by the commercial CFD software ANSYS CFX. The code solves the 3D Reynolds-averaged form of the Navier-Stokes equations based on the finite-element method. The shear stress transport (SST k-ω) turbulence model coupled with the γ-θ transition model was employed after comparison and selection between different turbulence models in this steady computation. The model considers the influence of shear stress transmission on the turbulent viscosity coefficient, effectively avoiding overestimation of the eddy viscosity coefficient and allowing for high-precision predictions of the separated flow under the inverse pressure gradient so that the flow details and field structure under low Reynolds number can be accurately predicted.

The steady boundary conditions were given at both the inlet and outlet. Total pressure P₀₁ and total temperature T₀₁ were uniformly specified at the inlet, while average static pressure Pₛ was given by means of simple radial equilibrium law. And the inlet turbulence intensity was set to 5%(medium intensity) based on the experimental condition(Yang, et al., 2015). The mixing plane method was applied to deal with the rotor/stator interface and the pitchwise boundaries were connected by periodic conditions. Nonslip and adiabatic conditions were imposed on the blade surfaces and the endwalls. The design rotation speed was 25000 rpm and 100% corrected operating speed was applied throughout this research. The different working points on the compressor characteristic curves were acquired by gradually increasing the average outlet static pressure. When approaching the near-stall point, the average outlet static pressure was increased with a small value (20Pa) until the calculation results cannot achieve convergence to accurately capture the compressor near-stall point.

Automatic rough wall processing for the turbulence model method was used in this study, which could automatically convert from a wall function to the low-Re near-wall formula, allowing for greatly precise calculations at the viscous sublayer portions of the boundary layer (ANSYS CFX documentation). Moreover, this method in the γ-θ model was applied to simulate the effects of surface roughness and the separation and transition phenomenon at low Reynolds number by combining automatic near-wall processing with the transition model.

Figure 2 presented the numerical validation between the computational results and experimental data at the design rotation speed. The abscissa represents the normalized mass flow rate. According to the error, the error bars represent 3% of the data for the performance parameters. In general, the result showed that the simulation results was in good agreement with the experimental test, and the error of the numerical simulation was within the allowable range. Therefore, the turbulence model and numerical method were used in subsequent calculations and investigations.

Roughness parameter

Roughness usually refers to the geometric roughness of a processed or contaminated surface and is expressed by geometric mean roughness Rₐ, while fluid mechanics is generally described by equivalent sand roughness kₑ. Koch et al.(1976) pointed out that the wall friction coefficient C_f can be calculated from kₑ (see Eq.(1)), that the roughness Reynolds number k* can be expressed by Re, C_f, and kₑ (see Eq.(2)), and kₑ, Re satisfy the relationship. (see Eq.(3))
\[ C_f = (2.87 + 1.58\lg\frac{C}{k_s})^{2.5} \]  
\[ k^+ = Re \frac{k_s}{C} \left(\frac{C_f}{2}\right) \]  

where,
\[ k_s = 6.2R_a \]  

The dimensionless roughness parameter \( k^+ \) is a useful criterion for dividing the roughness range. At low Reynolds number, the blade surface transition was delayed and the laminar separation zone was large, which led to the increase of the thickness of the boundary layer. To effectively stimulate the transition and cover as many roughness magnitudes as possible, a total of 12 roughness levels ranging from \( k^+ = 1.5 \) to \( k^+ = 171.4 \) were set. The geometric roughness \( R_a \) and the dimensionless roughness parameter \( k^+ \) corresponding to these 12 roughness magnitudes are shown in Table 2. In addition, the comprehensive surge margin definition is adopted in this paper. (see Eq.(4))

\[ SM = \left[ \left( \frac{\pi}{G} \right)_S - \left( \frac{\pi}{G} \right)_t \right] \frac{C_f}{\mu_m} \times 100\% \]  

### Table 2 Roughness magnitudes on the rotor blade surfaces

| Case number | \( k^+ \) | \( R_a / \mu_m \) |
|-------------|-------------|------------------|
| 1           | 0           | 0                |
| 2           | 1.0         | 5.6              |
| 3           | 3.3         | 16.1             |
| 4           | 7.3         | 32.4             |
| 5           | 20.8        | 80.6             |
| 6           | 35.9        | 129.0            |
| 7           | 46.6        | 161.3            |
| 8           | 57.7        | 193.5            |
| 9           | 75.1        | 241.9            |
| 10          | 105.6       | 322.6            |
| 11          | 137.8       | 403.2            |
| 12          | 171.4       | 483.9            |

### RESULTS AND DISCUSSION

**Effects of surface roughness on the aerodynamic performance**

**Overall trend of aerodynamic performance parameter**

The rotor blade surface roughness would greatly affect the aerodynamic performance of the compressor under low-Reynolds number conditions. Figure 3 showed the variation of compressor peak efficiency and corresponding total pressure ratio with the increase of dimensionless roughness parameter \( k^+ \). The result showed that the peak efficiency and the total pressure ratio of the compressor first raised rapidly with the increase of \( k^+ \), then the increase in performance parameters gradually slowed down after \( k^+ = 80 \). Finally, both of them reached the maximum and tended to be stable at \( k^+ = 137.8 \).

![Figure 3 Changing trend of peak efficiency and total pressure ratio at various \( k^+ \)](image)

![Figure 4 Comparison of wake velocity of the rotor at various \( k^+ \) at 50% blade height](image)
From the above 12 roughness schemes, six typical roughness schemes including $k^+=0, k^+=3.3, k^+=20.8, k^+=46.6, k^+=105.6$, and $k^+=137.8$ were selected for further analyze. In Figure 4, the relative velocity $W$ downstream the rotor at 50% span was plotted against the blade-to-blade angle position $\theta_{BB}$ for the six cases analyzed. With increasing roughness, no obvious shift of the center of wake toward either the pressure or the suction side can be noticed, but the mass flow area of the channel decreased due to fluid dynamic blockage. Furthermore, the velocity magnitude at the potential wake core increased. This led to a decrease in the width and depth of the wake, which reached the minimum at $k^+=137.8$. Meanwhile, the compressor aerodynamic performance achieved the best.

Figure 5 showed the characteristic curves of the compressor at different $k^+$. The variation trends for the total pressure ratio and isentropic efficiency were similar for the six roughness magnitudes. However, roughness caused the curve to shift to the upper right, and the degree of deviation increased with the increase of $k^+$. It can be noticed that the impact of roughness on the aerodynamic performance of the compressor was reflected in the increase of total pressure ratio and isentropic efficiency on the one hand, and in the change of overall flow rate on the other hand. The maximum increase in total pressure ratio, peak efficiency, and choked mass flow rate were approximately 4.01%, 5.34%, and 2.24% respectively at $k^+=137.8$. The effects of surface roughness on the compressor efficiency and pressure ratio were greater compared with that on the choked mass flow rate. In addition, roughness increased the compressor surge margin to some extent, and the choked mass flow rate increased more than the near stall flow rate. In fact, the surface roughness at low $Re$ can effectively restrain the boundary layer from growing rapidly after the transition, thus reducing the blocking and mixing loss of blade trailing edge. Furthermore, the compressor overall mass flow rate increased, and the steady work range was broadened (Li, et al., 2017).

![Figure 5 Effects of surface roughness on the aerodynamic performance of the compressor](image)

Figure 5 Effects of surface roughness on the aerodynamic performance of the compressor

Figure 6 reported the radial profiles of the mass-averaged stage total pressure ratio and isentropic efficiency at the rotor outlet section for the six cases. With increasing $k^+$, the total pressure ratio slightly decreased at 5%~30% span, and significantly increased at 30%~90% span. Moreover, the increasing degree of parameters was significantly greater than the decreasing degree. At $k^+=137.8$, the total pressure ratio at the blade root reduced approximately 3.67%, while it increased about 9.49% at the blade tip. The variation trend in the spanwise isentropic efficiency was similar to that of the total pressure ratio. Roughness somewhat reduced the efficiency of the blade root while dramatically improving the blade tip efficiency until both values almost remained constant. In addition, the efficiency of the main flow field of the cascade channel was significantly higher than that near the endwall due to the loss of the endwall.

![Figure 6 Spanwise variation of performance parameters at compressor rotor outlet section](image)

Figure 6 Spanwise variation of performance parameters at compressor rotor outlet section
Blade loading and wall shear stress

Figure 7 demonstrated the blade loading distribution of different cases at different spanwise heights (10% span and 90% span). The static pressure along the y-axis was nondimensionalized by the reference pressure (inlet total pressure, i.e., 5529.3 Pa). In Figure 7(a), the overall static pressure distribution of the pressure surface (PS) changed little. As $k^+$ increased, the acceleration zone of the suction surface (SS) leading edge (10%-30% $C_x$) and the middle section (45%-55% $C_x$) gradually disappeared, resulting in a decrease in momentum of main flow and an increase in flow loss. In addition, the transition occurred earlier with increasing roughness. The overall blade loading of the SS decreased from the middle section to the trailing edge, and the zone of the pressure envelope also decreased. The performance ability of the blade root decreased. Figure 7(b) showed that both the PS and SS loading significantly changed at 90% span. The static pressure of the PS increased, and the deceleration section downstream of the SS leading edge shock wave (10%-40% $C_x$) gradually transformed into an acceleration section. The momentum of the main flow increased after acceleration, and the ability to resist the reverse pressure gradient was also enhanced, so the laminar flow separation loss was effectively suppressed. Furthermore, the zone of the pressure envelope increased, which meant the performance ability of the blade tip was enhanced. In addition, due to the increase of radial pressure gradient, the radial migration of the fluid toward the blade tip was more difficult. As seen at $k^+ = 46.6$, laminar separation and turbulent reattachment occurred on the SS at 45% $C_x$ from the leading edge, that was, there was a laminar separation bubble (LSB) that accounted for approximately 15% of the SS from the leading edge, and the area where the LSB was located presented a "platform" distribution. The blade loading changed little as $k^+$ increased from 105.6 to 137.8.

The skin friction coefficient for the rotor SS was given in Figure 8. For the smooth blade, the laminar flow separation zone and the flow loss were large. As the blade surface was roughened with $k^+ =46.6$, the laminar separation of the blade tip was effectively inhibited, and the length of LSB was approximately 10% of axial chord length, while the LSB was approximately 25% of the axial chord length at the blade root. As $k^+$ increased to 137.8, there was no laminar separation on the rotor SS. Figure 8 showed that with $k^+$ increasing, the LSB at the root and tip of the blade were gradually suppressed or even eliminated, and the wall shear stress would rise to a high level.

Figure 9 illustrated the relative Mach number contours of the flow field. At the blade root(10% span), because the flow velocity of the main stream was small, the stronger viscous dissipation in the turbulent region caused by roughness was dominant. Therefore, the boundary layer continued to accumulate and develop under the action of friction. This led to significant thickening of the boundary layer at the trailing edge (as seen in Figure 9(c)), which meant the mixing loss and flow blockage were intensified. In contrast, at the blade tip(90% span), because of the high speed of main stream, so the effect of roughness to restrain laminar flow separation was dominant. The development of the boundary layer was effectively restricted and the width and depth of the wake continued to decrease.
Figure 8 Skin normalized wall shear of suction side at \( k^+ = 46.6 \) and 137.8

**Figure 9** Relative Mach number contour versus \( k^+ \) at different span locations

**Streamlines of rotor suction surface**

Figure 10 showed the rotor SS streamlines for the four typical cases (Smooth, \( k^+ = 20.8 \), \( k^+ = 46.6 \) and \( k^+ = 137.8 \)). Compared with the smooth case, the laminar flow separation from the tip to the middle of the blade was delayed as the blade was roughened, and the transition began sooner. As seen in Figure 10(c), turbulent reattachment and turbulent separation occurred after the transition, and the overall separation zone greatly reduced. At \( k^+ = 20.8 \), the laminar separation point moved downstream approximately 4.1\% \( C_x \) and reattached on the wall at about 36.5\% \( C_x \) downstream of the separation line. With \( k^+ \) increasing to 46.6, the laminar separation point continue to move downstream, and the LSB shortened by approximately 10.2\% \( C_x \). Turbulent separation appeared at the trailing edge. As \( k^+ \) increased to 137.8, roughness greatly suppressed the development of the LSB, of which the length and maximum thickness decreased significantly, and the turbulent separation zone at the trailing edge nearly disappeared. In general, roughness delayed laminar flow separation, promoted the transition to occur in advance, and accelerated turbulent reattachment, which reduced the separation loss, and improved the aerodynamic performance of the compressor to a large extent.
Inlet flow conditions of the rotor

The roughness of rotor blade surface resulted in the change of the rotor SS shear stress, static pressure distribution, and the mass flow rate inside the compressor, which generally change the rotor inlet flow conditions. Figure 11 showed the variations in the inlet condition of the rotor (under the same outlet back pressure). With the increase of roughness, the inlet angle decreased, the angle of attack also decreased, and the rotor spanwise inlet axial velocity increased. Therefore, the ability of the fluid in the blade boundary layer to overcome the viscous momentum and resist the reverse pressure gradient was enhanced, resulting in the decrease of low-energy fluid. In other words, the flow field around the rotor area was optimized, and the compressor efficiency was improved.

Inlet flow conditions of the aft stator

Figure 12 reported the change trend of the spanwise inlet flow angle and axial velocity of the aft stator at different $k^+$. As shown in Figure 12(a), the inlet flow angle at 5%-80% span increased a little, that is to say, the attack angle and flow turning angle increased. Therefore, the flow adverse pressure gradient was enhanced and the centrifugal force generated by the flow deflection advanced the flow separation, leading to the increase of flow loss. However, at 80%-95% span, the inlet flow angle decreased, which optimized the flow field and improve the efficiency. In Figure 12(b), At the blade tip, the axial velocity increased, thus the momentum of main flow increased and the flow loss decreased. At the blade root, the axial velocity decreased, which made the corner separation more likely to occur. Generally, it was difficult to distinguish which part of blade root and blade tip was dominant, so further analysis was required.

![Comparison of inlet flow angle and axial velocity spanwise distribution for rotor](image1)

(a) Inlet flow angle of rotor  
(b) Inlet axial velocity of rotor

![Comparison of inlet flow angle and axial velocity spanwise distribution for the aft stator](image2)

(a) Inlet flow angle of the aft stator  
(b) Inlet axial velocity of the aft stator

Figure 13 presented the stator suction surface streamlines for the typical four cases. With the increase of $k^+$, the position of the overall separation of the stator suction surface gradually advanced, and the corner separation further intensified. In other words, the roughness of rotor blade surface increased the flow loss of the aft stator and aggravated the incoordination between stages, which limited further improvement of the overall aerodynamic performance of the compressor.
CONCLUSIONS

The surface roughness control method was effective in controlling the separation and transition process of the boundary layer (two-dimensional LSB structure), changing the three-dimensional flow characteristics, and affecting the loss of the aft stator and the matching relationship between the rotor and stator at low Re without imposing additional complex geometric shapes on the blade. This paper concentrated on the effects of rotor blade surface roughness ($k^*$) on the aerodynamic performance of a small-scale 1.5-stage highly-loaded transonic axial compressor under 20km altitudes condition ($Re=4.5\times10^4$) by using a commercial CFD code. The main results and conclusions were summarized as follows:

1. The peak efficiency and the total pressure ratio of the compressor first increased rapidly with the increase of $k^*$, then the speed of the increase gradually slowed down after $k^*$ = 80. Finally, both of them reached the maximum and tended to be stable at $k^*$=137.8. To be specific, the maximum increases in the total pressure ratio, peak efficiency, and choked mass flow rate were approximately 4.01%, 5.34%, and 2.24% respectively at $k^*$=137.8. Moreover, the steady work range of the compressor was broadened to some extent.

2. The results showed that at low Re, the surface roughness mainly improved the stage performance by reducing the length and width of the LSB, delaying the occurrence of three-dimensional flow separation, and increasing the turbulence level near the wall. Moreover, the main effects brought by surface roughness were different at the root and tip of the blade respectively, which led to different results. Generally speaking, the positive effect of roughness at the blade tip was obviously greater than the negative effect of roughness at the blade root, leading to an improvement in the overall compressor performance.

3. The roughness of rotor blade surface can dramatically improve the rotor aerodynamic performance. However, the incoordination between the subsequent stages was aggravated to a certain extent, which limited the further improvement of the overall aerodynamic performance of the compressor. In addition, the roughness almost did not shift the center of the wake toward either the pressure or the suction side, but only affected the width and depth of the wake.

NOMENCLATURE

| Symbol | Meaning                                      |
|--------|----------------------------------------------|
| $C$    | Chord length                                 |
| $k_s$  | Equivalent sandgrain roughness               |
| $k^*$  | Nondimensional roughness height              |
| $R_s$  | Geometric roughness                          |
| $y^*$  | First grid distance from the wall            |
| $y$    | Normal distance, Cartesian coordinate        |
| $P_0$  | Inlet total pressure                         |
| $T_0$  | Inlet total temperature                       |
| $P_e$  | Outlet average static pressure               |
| $\theta_{\text{hub}}$ | Circumferential angle                       |
| SM     | Surge margin                                 |
| $C_f$  | Skin friction coefficient                    |
| $C_x$  | Axial chord length                           |
| $W$    | Axial velocity                               |
| SS     | Suction surface                              |
| PS     | Pressure surface                             |
| RANS   | Reynolds-averaged Navier-Stokes              |
| CFD    | Computational fluid dynamics                 |
| Ma     | Mach number                                  |
| $Re$   | Reynolds number                              |
| LSB    | Laminar separation bubble                    |
| UAV    | Unmanned aerial vehicle                      |

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REFERENCES

Bons, J.P. 2010. A review of surface roughness effects in gas turbines. *Journal of Turbomachinery-Transactions of the Asme*, 132(2), 021004.
Li, H.J. & Yang, Z.Y. 2019. Separated boundary layer transition under pressure gradient in the presence of free-stream turbulence. *Physics of Fluids*, 31(10),104106.

Bammert, K. & Milsch, R. 1972. Boundary layers on rough compressor blades. *Mechanical Engineering*, 94(6),54-68.

PACCIANI, R., SPANO, E. & ASME 2006. Numerical investigation of the effect of roughness and passing wakes on LP turbine blades performance. *Transactions of the Asme*, 125(4),754-764.

Volino, R.J. 2003. Passive flow control on low-pressure turbine airfoils. *Journal of Turbomachinery-Transactions of the Asme*, 125(4),1713-1722.

Bons, J.P., Pluim, J., Gompertz, K. & Bloxham, M. 2012. The application of flow control to an aft-loaded low pressure turbine cascade with unsteady wakes. *Journal of Turbomachinery-Transactions of the Asme*, 134(3),031009.

Roberts, S.K. & Yaras, M.I. 2006. Effects of surface-roughness geometry on separation-bubble transition. *Journal of Turbomachinery-Transactions of the Asme*, 128(2),349-356.

Back, S.C., Jeong, I.C., et al. & ASME 2009. Influence of Surface Roughness on the Performance of a Compressor Blade in a Linear Cascade Experiment and Modeling, gt2009-59703.

Kong, D., Jeong, H. & Song, S.J. 2017. Effects of surface roughness on evolutions of loss and deviation in a linear compressor cascade. *Journal of Mechanical Science and Technology*, 31(11),5329-5335.

Gbadebo, S.A., Hynes, T.P. & Cumpsty, N.A. 2004. Influence of surface roughness on three-dimensional separation in axial compressors. *Journal of Turbomachinery-Transactions of the Asme*, 126(4),455-463.

Im, J.H., Shin, J.H., Hobson, G.V., et al. & ASME. 2013. Effect of leading edge roughness and Reynolds number on compressor profile loss, gt2013-95487.

Syverud, E., Bakken, L.E. & ASME. 2006. The impact of surface roughness on axial compressor performance deterioration, gt2006-90004.

Syverud, E., Brekke, O. & Bakken, L.E. 2007. Axial compressor deterioration caused by saltwater ingestion. *Journal of Turbomachinery-Transactions of the Asme*, 129(1),119-126.

Morini, M., Pinelli, M., Spina, P.R. & Venturini, M. 2010. Computational fluid dynamics simulation of fouling on axial compressor stages. *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme*, 132(7),072401.

Morini, M., Pinelli, M., Spina, P.R. & Venturini, M. 2011. Numerical analysis of the effects of nonuniform surface roughness on compressor stage performance. *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme*, 133(7),072402.

Bammert, K. & Woelk, G.U. 1980. The influence of the blading surface roughness on the aerodynamic behavior and characteristic of an axial compressor. *Journal of Engineering for Power-Transactions of the Asme*, 102(2),283-287.

Chen, S. W., Wang, S. T., Wang Z. Q. & ASME 2012. Study on the impact of fouling on axial compressor stage, gt2012-68041.

Chen, S. W., Sun, S. J., Xu, H., et al. & ASME 2013. Influence of local surface roughness of a rotor blade on performance of an axial compressor stage, gt2013-94816.

Yang, C.W., Lu, X.G., Zhang, Y.F.,et al. & ASME 2015. Numerical investigation of a cantilevered compressor stator at varying clearance sizes, gt2015-42124.

ANSYS CFX 17.1 Documentation. (2016) ANSYS Inc.

Koch, C.C. & Smith, L.H. 1976. Loss sources and magnitudes in axial flow compressors. *Journal of Engineering for Power-Transactions of the Asme*, 98(3),411-424.

Li, Z.H. & Liu, Y.M. 2017. Effect of end-wall roughness on performance of transonic axial compressor. *Proceedings of the Institution of Mechanical Engineers Part G-Journal of Aerospace Engineering*, 231(7),1213-1224.