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Numerical Simulation of Non-Uniform Roughness Distribution on Compressor Performance

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Keywords: compressor, surface roughness, flow field, numerical simulation.

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NUMERICALSIMULATIONOFNONUNIFORMROUGHNESSOISTRIBUTIONONCOMPRESSORPERFORMANCE

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Numerical Simulation of Non-Uniform Roughness Distribution on Compressor Performance

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Abstract- This paper investigated the roughness of NASA Stage 35 test compressor. Surface roughness can change the geometric line in the microcosm, which causes the compressor operation to deviate from the design point under working conditions. Wall function was used in this study to describe roughness. Roughness calculation model in nonuniform distribution was established along the chord and spanwise directions. Basing on certain rules, rotor blades were attached with roughness to determine the influence of blade roughness position distribution on the overall performance of the compressor and internal flow. Results show that when roughness was distributed from the blade leading edge to 40% of the chord, the compressor performance was greatly influenced; in severe performance, compressor efficiency decreased by more than 2%. Roughness position distribution in blade height direction exhibited a minimal effect on the entire compressor performance, which can be ignored.

Keywords: compressor, surface roughness, flow field, numerical simulation.

I. INTRODUCTION

he surface roughness of compressor blade increases gradually during operation because of corrosion, fouling, abrasion, and other factors. An inlet guild van from a compressor which served for 37 months was observed by David Linden; he showed that the aperture could even reach 3.2mm, depth can be 0.8mm caused by pitting. Moreover, Lu Mingliang did some experiments under laboratory condition, after seven days, 14 days and 21 days, the blade surface roughness correspond increased to 6.3µm, 31.7µm, and 86.7 μ m from original 2 μ m. Both these researches have shown that surface roughness is nonnegligible in a compressor. Position distribution of blade surface roughness exhibits significant difference that depends on the operating environment. Increase in blade roughness causes compressor blades to deviate from the design point under working conditions. This phenomenon results in the decrease of performance of the entire compressor. Numerous studies have been conducted to determine the influence of different blade surface roughness on gas turbine properties. Bonus et al. measured a large number of gas turbine blades and obtained practical measurement data of blade

corrosion. Their results were statistically analyzed to study heat transfer characteristics of rough blade surfaces. Pailhas studied how different Reynolds numbers affect the development of turbulent boundary layer of the roughened surface. Foullias et al. performed a test method to study the effect of operating characteristics of gas turbine compressor blades when roughness increases uniformly. Basing on the study of Foulias, Back et al. discussed the effects of different roughness distributions and different Reynolds numbers on compressor blade performance. Chen et al. studied corrosion properties on compressor rotor blades using the computational fluid dynamics (CFD) method. All these studies focus on the overall performance influenced by blade roughness, and no studies were conducted to determine the effect of different roughness distributions on compressor performance. Therefore, this paper established a blade model with non-uniform roughness distribution in tangential and spanwise directions. A wall function method that can describe roughness was also performed to investigate the effect of non-uniform roughness on compressor performance.

II. PRINCIPLE OF NUMERICAL SIMULATION

In this paper, the wall function used in CFX, a commercial software computational tool, to describe surface roughness is the extension method proposed by Launder. In the logarithmic law region, the tangential velocity and wall shear stress near the wall have a logarithmic relationship. We used an empirical formula to connect the near wall boundary conductions of the average flow and the turbulent transport equation. The logarithmic relation of the near wall velocity is

$$u^{+} = \frac{U_{t}}{u_{z}} = \frac{1}{\kappa} \ln(y^{+}) + C \tag{1}$$

In the formula,

$$y^{+} = \frac{\rho \Delta y u_{\tau}}{\mu}$$
(2)
$$u_{\tau} = \sqrt{\frac{\tau_{w}}{\rho}}$$
(3)

Wall surface roughness can significantly increase near-wall turbulence generation items, which leads to increased wall shear stress and heat transfer

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coefficient. To show better agreement between the surface roughness and experimental data, the following relationship was used to consider the effect of roughness.

$$u^{+} = \frac{1}{\kappa} \ln(y^{+}) + B - \Delta B \tag{4}$$

In the formula, *B* equals to 5.2; offset ΔB is the function of dimensionless roughness h^+ ($h^+ = hu_\tau/v$).

For roughness, the offset ΔB can be expressed as follows:

$$\Delta B = \frac{1}{\kappa} \ln(1 + 0.3h_s^+) \tag{5}$$

In the formula, h_s is the average of roughness parameters and h_s^+ is the non-dimensional parameter of h_s . In general, equivalent sand roughness k_s is used to measure the roughness. The relationship between k_s and h_s is molded by Sigal and Danberg and is widely used in roughness research. Also, an empirical equation proposed by Koch and Smith show that k_s are about 6.2 times h_s .

III. Model with Non-Uniform Roughness Distribution along the Tangential and Spanwise Directions

In this investigation, NASA research singlestage compressor Stage 35 is used. The design parameters are provided in table 1. Stage 35 produces 1.8 total pressure ratio at a mass flow rate of 20.2 kg/s at the design speed of 17188 rpm. Details of the Stage 35 geometry are shown in table 1.

Table 1: The design parameters of NASA stage 35

Rotor rpm at 100% speed	17188.7
Tip speed (m/s)	454.456
Hub/tip aspect ratio	0.7
Rotor aspect ratio	1.19
Stator aspect ratio	1.26
Number of rotor blades	36
Number of stator blades	46

NASA Stage 35 rotor blade was divided into 12 regions along the chord direction to establish a model with non-uniform roughness distribution. Except for the leading and trailing edge regions, other regions are aliquot in chord direction (Figure 1).Given the same roughness along the leading edge and chord of the first subregional area, the trailing edge and last area along the chord had also the same subregional roughness. The ten regions divided along the tangential direction are C1, C2,... C10. Depending on the different distributions, roughness was attached to the blade. Ten computing models were set up to simulate the effect of non-uniform roughness on compressor performance. The allocation rules are shown in Table 2, in which all the regions are smooth in CNR0 case to verify and

compare the results. From the blade leading to trailing edge, the roughness of CNR1, CNR3, and CNR5 increased linearly, whereas that of CNR2, CNR4, and CNR6 decreased linearly. From the leading to trailing edge, CNR 7 initially increased then decreased, but CNR8 first decreased then increased linearly. For CNR9, roughness increased by a quadratic law from the leading to trailing edge. For CNR10, the roughness increased logarithmically in the same direction.



Figure 1: Model with non-uniform roughness distribution along the tangential direction

Table 2: Non-uniform regular roughness distribution along the tangential direction (k_{μ} µm)

Number	C1	C2	C3	C4	C5
CNR0	0	0	0	0	0
CNR1	0.1	6.7	13.4	20.1	26.8
CNR2	60.0	53.6	46.9	40.2	33.5
CNR3	0.1	3.3	6.6	9.9	13.2
CNR4	30.0	26.4	23.1	19.8	16.5
CNR5	30.0	33.3	36.6	39.9	43.2
CNR6	60.0	56.4	53.1	49.8	46.5
CNR7	0.1	15.0	30.0	45.0	60.0
CNR8	60.0	45.0	30.0	15.0	0.1
CNR9	0.1	2.4	5.4	9.6	15
CNR10	0.1	18.1	28.6	36.1	41.9
Number	C6	C7	C8	C9	C10
CNR0	0	0	0	0	0
CNR1	33.5	40.2	46.9	53.6	60.0
CNR2	26.8	20.1	13.4	6.7	0.1
CNR3	16.5	19.8	23.1	26.4	30.0
CNR4	13.2	9.9	6.6	3.3	0.1
CNR5	46.5	49.8	53.1	56.4	60.0
CNR6	43.2	39.9	36.6	33.3	30.0
CNR7	48.0	36.0	24.0	12.0	0.1
CNR8	12.0	24.0	36.0	48.0	60.0
CNR9	21.6	29.4	38.4	48.6	60.0
CNR10	46.7	50.7	54.2	57.3	60.0

The rotor blade was also divided into ten domains along the spanwise direction. Every area was quoted along the spanwise direction and attached to corresponding roughness values. The areas are named from the root to tip (S1, S2,... S10) and are shown in Figure 2. Ten group computational models were established in different distribution rules. The distribution rules of roughness in every area are shown in Table 3. Similarly, CNR0 was smooth in all domains and used to verify and compare results. From the root to tip, the roughness of SNR1, SNR3, and SNR5 increased linearly, whereas that of SNR2, SNR4, and SNR6 decreased linearly. SNR7 initially increased and then decreased linearly. By contrast, SNR8 first decreased and then increased linearly. For SNR9, roughness increased by a quadratic law from the root to tip. For SNR10, roughness increased logarithmically in the same direction.



Figure 2: Model with non-uniform roughness distribution along the spanwise direction

Table 3: Non-uniform regular roughness	s distribution
along the spanwise direction (k_s	, μm)

Number	S1	S2	S3	S4	S5
SNR0	0	0	0	0	0
SNR1	0.1	6.7	13.4	20.1	26.8
SNR2	60.0	53.6	46.9	40.2	33.5
SNR3	0.1	3.3	6.6	9.9	13.2
SNR4	30.0	26.4	23.1	19.8	16.5
SNR5	30.0	33.3	36.6	39.9	43.2
SNR6	60.0	56.4	53.1	49.8	46.5
SNR7	0.1	15.0	30.0	45.0	60.0
SNR8	60.0	45.0	30.0	15.0	0.1
SNR9	0.1	2.4	5.4	9.6	15
SNR10	0.1	18.1	28.6	36.1	41.9
Number	S6	S7	S8	S9	S10
SNR0	0	0	0	0	0
SNR1	33.5	40.2	46.9	53.6	60.0
SNR2	26.8	20.1	13.4	6.7	0.1
SNR3	16.5	19.8	23.1	26.4	30.0
SNR4	13.2	9.9	6.6	3.3	0.1
SNR5	46.5	49.8	53.1	56.4	60.0
SNR6	43.2	39.9	36.6	33.3	30.0
SNR7	48.0	36.0	24.0	12.0	0.1
SNR8	12.0	24.0	36.0	48.0	60.0
SNR9	21.6	29.4	38.4	48.6	60.0
SNR10	46.7	50.7	54.2	57.3	60.0

According to literature, average roughness can be used to measure a partial non-uniform distribution of roughness on the entire measurement of roughness height. In this study, average roughness parameter \overline{k}_s was used:

$$\overline{k}_{s} = \frac{1}{A} \int_{A} k_{s} dA \tag{6}$$

In non-uniform distribution models, roughness is attached in 10 partially discrete domains; thus, the

blade average roughness $\overline{k_s}$ can be calculated by the following formula:

$$\overline{k}_{s} = \frac{1}{A} \sum_{i=1}^{10} \left(k_{s,i} A_{i} \right) \tag{7}$$

According to Eq. (7), the average roughness of every model can be calculated and are shown below.

Table 4: Average roughness of each model ($\overline{k_s}$, µm)

Number	CNR1	CNR2	CNR3	CNR4	CNR5
$\overline{k_s}$	28.7	31.6	14.2	15.6	44.2
Number	CNR6	CNR7	CNR8	CNR9	CNR10
$\overline{k_s}$	45.6	26.9	33.1	21.7	38.0
Number	SNR1	SNR2	SNR3	SNR4	SNR5
$\overline{k_s}$	31.3	29.0	15.5	14.3	45.5
Number	SNR6	SNR7	SNR8	SNR9	SNR10
$\overline{k_s}$	44.3	27.1	33.0	24.2	40.6

IV. CFD Results and Analysis on Roughness of Non-Uniform Distribution Models

In this paper, ICEM CFD, a business software, was adopted for mesh generation. CFX physical model was used for the calculation. HOH mesh structure was adopted in computational domains, and O mesh was used near the wall region of the blade. Tip clearance of rotor blade was divided by a "butterfly grid" structure. The grid near the blade was encrypted, and the height of the first layer was set to 5 μ m. Finally, a model with 2.315 million grids divided as above was established and used for grid-independent verification. The value of wall y+ on computational domain was less than ten overall. Figure 3 shows the mesh schematic of the computational domain model.

After a complete mesh generation, blade roughness is given equivalent sand roughness k_s by the approach that deals with wall function of a roughened surface in CFX software. The effect of different roughness distributions on compressor aerodynamic characteristics was calculated. Other boundary conditions are set as follows:

Inlet: Given total airflow pressure 101325 Pa, total temperature 288.15 K, air intake axially.

Outlet: Average static pressure was given by radial equilibrium equation. Pressure value to the analog compressor was adjusted in different operating points.

Wall: Heat insulation, velocity meets the no-slip condition.



Figure 3: Mesh generation of computational domain

Comparison between CFD results and experimental data about Stage 35 smooth blade computing model (CNR0) is shown to verify the accuracy of the calculation method. Experimental data related to this compressor were obtained from NASA report, which was put forward by Moore and Reid. To evaluate the model, performance at 100% and 90% speeds were considered, and results are shown below.

Table 5:	Comparison of	f numerical an	d experimental
	results on the	peak efficiency	y point

	100% of design rotate speed		
	Numerical results	Experimental results	
Mass flow rate (kg/s)	20.05	20.46	
Pressure ratio	1.845	1.842	
Temperature ratio	1.229	1.225	
efficiency	0.834	0.845	
Rotate speed (r/min)	17188	17119.1	
	90% of design rotate speed		
	Numerical results	Experimental results	
Mass flow rate (kg/s)	18.83	19.13	
Pressure ratio	1.63	1.574	
Temperature ratio	1.17	1.16	
efficiency	0.862	0.865	
Rotate speed (r/min)	15469	15451.3	

Table 5 shows the peak efficiency and experimental data in CFD at 100% and 90% speeds. Given that literature has not pointed peak point at 90% speed, the operating points in its vicinity are compared in the table. Except for the pressure ratio at 90% speed, which shows large errors in the table, errors of other parameters are all smaller than 2%. Based on the above analysis, the numerical simulation can be defined as effective.

a) CFD results and analysis on models of non-uniform roughness distribution along the tangential direction

Using the above method, models with different regular distributions along the chord direction under design speeds were calculated. Characteristic line of flow versus pressure ratio and compressor operation efficiency were obtained under corresponding conditions, as shown in Figure 4.



(a) Characteristic line of pressure ratio-mass flow rate



(b) Characteristic line of efficiency-mass flow rate

Figure 4: Characteristic line of models with different regular distributions along the chord direction

As shown in Fig. 4, the overall performance parameters of compressor decreased with additional roughness to the rotor blade, such as pressure ratio and efficiency. CNR3 and CNR9 correspond to the compressor performance with the least decline (peak efficiency decreased by 0.7% and 0.76%). CNR2 and CNR6 correspond to the compressor performance with the most serious decline (peak efficiency decreased by 2.15% and 2.39%). By comparing different roughness distribution laws and its corresponding numerical simulation results, we conclude that both the value of the average roughness and local distribution of rough surface on compressor played important roles in the overall performance of the compressor. When the roughness distribution rules were the same, higher average roughness value indicated more decreased compressor performance. When the average roughness value was same, a higher value of the leading edge of local roughness (before 40% along the chord direction) caused a greater effect on the compressor performance. The blade trailing edge of the local roughness exhibited a minimal effect on the performance of the compressor.

Figure 5 shows the limit streamlined on the suction side of the rotor blade when the compressor was under CNR3, CNR9, CNR2, and CNR6, which are

four different sets of the model that correspond to the peak efficiency point. CNR3 and CNR9 caused the least decline in compressor performance. CNR2 and CNR6 caused the highest decline in compressor performance.





Fig. 5 shows that the limit streamlines distribution is similar on the suction side of the blade in each condition (i.e., CNR2, CNR6, CNR3, and CNR9), in addition to the different separation zones near the blade tip. The separated airflow near the root of the blade and that along the spanwise direction in the blade tip direction in CNR2 and CNR6 were involved in the main flow before reaching the blade tip and forming a wake. To model CNR3 and CNR9, the separation of airflow rose to the blade tip and then involved into the vortex near the tip. The structure and location of the vortex differed in different conditions. On the one hand, this phenomenon is attributed to the higher average roughness of CNR2 and CNR6. On the other hand, a major factor for this phenomenon is due to the roughness areas that are mainly distributed in the leading edge (before 40% along the chord direction). The disturbance is exacerbated in CNR2 and CNR6 so that the boundary layer separates earlier than the other conditions, resulting in increased losses in the compressor and reduced work efficiency.



Figure 6: Pressure coefficient number on the middle section of the rotor blade

Figure 6 shows that the effect of surface roughness on the pressure coefficient is concentrated at the leading edge of the 40% chord region on the pressure side and 40%-70% chord region on the suction side. The flow of the boundary layer near the wall was affected by the roughness surface, subsequently increasing the pressure gradient within the boundary layer. This phenomenon led to the forward movement of the inverse pressure gradient area along the chord direction and then the advanced separation of the boundary layer, increasing the losses. The inverse pressure gradient area was closest to the leading edge in CNR2 and CNR6, which caused greatest pressure loss and the most serious performance degradation. Compared with CNR2 and CNR6, the pressure coefficient curve corresponding to models CNR3 and CNR9 was closer to the initial model (with no roughness surface model); the distance between the turning point and the leading edge was longest and caused a slight performance degradation. This result is due to the smaller average roughness of CNR3 and CNR9 and smaller roughness value close to the leading edge.

b) CFD results and analysis on non-uniform roughness distribution models along the spanwise direction

Similarly, models with different regular distributions along the spanwise direction were calculated under design speeds. Characteristic line of flow versus pressure ratio and compressor operation efficiency under corresponding conditions were obtained, as shown in Figure 7.





(b) Characteristic line of efficiency-mass flow rate



As shown in Fig. 7, the overall performance parameters of compressor decreased with additional roughness to the rotor blade, such as pressure ratio and efficiency. The working characteristic line of the compressor moved to the lower-left corner. By comparing different numerical simulation results and its corresponding roughness distribution laws, we conclude that the simulation results are different from the nonuniform distribution along the chord of the roughness model. Concentrated roughness in the hub or tip of the blade did not show a special effect on the overall compressor performance was mainly due to the value of the average roughness.

Figure 8 shows the limit streamlined on the suction side of the rotor blade when the compressor was under SNR3, SNR4, SNR5, and SNR6, which are four different sets of the model that correspond to the peak efficiency point. SNR3 and SNR4 caused the least decline in compressor performance (peak efficiency decreased by 0.86% and 0.92%). SNR5 and SNR6 caused the highest decline in compressor performance (peak efficiency decreased by 1.87% and 1.92%).





Fig. 8 shows that the limit streamlines distribution is similar on the suction side of the blade in each of the SNR3, SNR4, SNR5, and SNR6 conditions. Compared with SNR3 and SNR4, the main differences in SNR5 and SNR6 are the closer turning point near the root of the blade to the leading edge, the advance occurrence of the boundary layer separation, and more serious flow vortex in SNR5 and SNR6, which allow greater flow loss. This phenomenon is primarily attributed to the larger average roughness in SNR5 and SNR6 than in SNR3 and SNR4 and is not due to the value of the local roughness.



Figure 9: Pressure coefficient number on different heights of the rotor blade

Figure 9 shows the slight difference between SNR3 and SNR4, as well as between SNR5 and SNR6. This result is due to their similar average roughness value. The pressure coefficient curve almost coincided at the middle section of the blade although an evident difference exists in the local roughness between each model. In the 95% spanwise section, the difference in pressure coefficient curve between these four models varied widely. This difference is due to the existence of the tip clearance, which makes the flow at the tip more complex. Therefore, we conclude that in the spanwise direction, local roughness had a slight effect on the overall compressor performance. The degradation of compressor performance was mainly due to the value of the average roughness.

V. Conclusions

Models with different regular distributions along the chord and spanwise directions under design speed were calculated, and the degradation of the compressor performance was obtained. Conclusions drawn were as follows:

- Methods of wall function were used in this paper; a function that can measure the roughness of surface was added into the wall function. The wall function was used to simulate different models with different roughness distributions, and then the degradation of Stage 35 was obtained.
- 2) The numerical simulation results of models with different regular distributions along the chord direction are as follows. Both the value of the average roughness and local distribution of the rough surface on compressor played important roles in the overall performance of the compressor. When roughness was distributed from the blade leading edge to 40% of the chord, the compressor performance was greatly influenced; in severe performance, compressor efficiency decreased by more than 2%. Roughness distribution near the trailing edge had a minimal influence to the compressor and can be ignored.
- 3) The numerical simulation results of models with different regular distributions along the spanwise direction showed that local roughness, which is distributed along the spanwise direction, had a slight effect on the overall compressor performance and can be ignored. The degradation of compressor performance was mainly due to the value of the average roughness.

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References Références Referencias

- Aldi, N., Morini, M., Pinelli, M., Spina, P.R., Suman, A., Venturini, M., 2013, Performance evaluation of nonuniformly fouled axial compressor stages by means of computational fluid dynamics analyses, Journal of Turbomachinery, 136 (2), art. no. 021016
- Back, S. C., G. V. Hobson, S. J. Song, and K. T. Millsaps, 2012, Effects of Reynolds Number and Surface Roughness Magnitude and Location on Compressor Cascade Performance: Journal of Turbomachinery-Transactions of the Asme, v. 134, p. 6.
- Back, S. C., I. C. Jeong, J. L. Sohn, S. J. Song, and Asme, 2009, Influence of surface roughness on the performance of a compressor blade in a linear cascade-experiment and modeling: Proceedings of Asme Turbo Expo 2009, Vol 7, Pts a and B: New York, Amer Soc Mechanical Engineers, 239-247 p.
- Back, S. C., G. V. Hobson, S. J. Song, K. T. Millsaps, and Asme, 2010, Effect of surface roughness location and Reynolds number on compressor cascade performance: Proceedings of the Asme Turbo Expo 2010, Vol 7, Pts a-C: New York, Amer Soc Mechanical Engineers, 121-128 p.
- 5. Bons, J. P., 2010, A Review of Surface Roughness Effects in Gas Turbines: Journal of Turbomachinery-Transactions of the Asme, v. 132, p. 16.
- Bons, J. P., R. P. Taylor, S. T. McClain, and R. B. Rivir, 2001, The many faces of turbine surface roughness: Journal of Turbomachinery-Transactions of the Asme, v. 123, p. 739-748.
- 7. Bons, J. P., 2002, St and c(f) augmentation for real turbine roughness with elevated freestream turbulence: Journal of Turbomachinery-Transactions of the Asme, v. 124, p. 632-644.
- 8. Bons, J. P., and S. T. McClain, 2004, The effect of real turbine roughness with pressure gradient on heat transfer: Journal of Turbomachinery-Transactions of the Asme, v. 126, p. 385-394.
- 9. Brzek, B. G., R. B. Cal, G. Johansson, and L. Castillo, 2008, Transitionally rough zero pressure gradient turbulent boundary layers: Experiments in Fluids, v. 44, p. 115-124.
- Cardwell, N. D., N. Sundaram, and K. A. Thole, 2006, Effect of midpassage gap, endwall misalignment, and roughness on endwall filmcooling: Journal of Turbomachinery-Transactions of the Asme, v. 128, p. 62-70.
- Chen, S. W., H. Shi, C. Zhang, S. T. Wang, and Z. Q. Wang, 2012, Study on Numerical Simulation of Fouling in Compressor Rotor: International Journal of Turbo & Jet-Engines, v. 29, p. 179-188.
- Craft, T. J., S. E. Gant, H. lacovides, and B. E. Launder, 2004, A new wall function strategy for complex turbulent flows: Numerical Heat Transfer Part B-Fundamentals, v. 45, p. 301-318.

- Craft, T. J., S. E. Gant, A. V. Gerasimov, H. lacovides, and B. E. Launder, 2006, Development and application of wall-function treatments for turbulent forced and mixed convection flows: Fluid Dynamics Research, v. 38, p. 127-144.
- 14. Date, Anil W., 1995, An introduction to computational fluid dynamics, New York: Cambridge University Press, c1995.
- 15. Fouflias, D., A. Gannan, K. Ramsden, P. Pilidis, D. Mba, J. Teixeira, U. Igie, and P. Lambart, 2010, Experimental investigation of the influence of fouling on compressor cascade characteristics and implications for gas turbine engine performance: Proceedings of the Institution of Mechanical Engineers Part a-Journal of Power and Energy, v. 224, p. 1007-1018.
- Hummel, F., M. Lotzerich, P. Cardamone, and L. Fottner, 2005, Surface roughness effects on turbine blade aerodynamics: Journal of Turbomachinery-Transactions of the Asme, v. 127, p. 453-461.
- Linden D H. Long term operating experience with corrosion control in industrial axial flow compressors[C]. Proceedings of the Fortieth Turbomachinery Symposium. 2011: 93-106.
- Lu Mingliang. Research on the effects of salt spray corrosion on the compressor performance[D]. Harbin engineering university, China, 2013.
- Moore, R. D., Reid. L., 1982, Performance of singlestage axial-flow transonic compressor with rotor and stator aspect ratio respectively, and with design pressor ratio of 2.05: AIRCRAFT PROPULSION AND POWER, NASA-TP-2001, E-334, NAS 1.60:2001
- 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, 133 (7), art. no. 072402
- 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, 132 (7), art. no. 072401.
- 22. Pailhas, G., Y. Touvet, and B. Aupoix, 2008, Effects of Reynolds number and adverse pressure gradient on a turbulent boundary layer developing on a rough surface: Journal of Turbulence, v. 9, p. 1-24.
- 23. Sigal A, Danberg J E. New correlation of roughness density effect on the turbulent boundary layer[J]. AIAA journal, 1990, 28(3): 554-556.
- 24. Syverud, E., O. Brekke, and L. E. Bakken, 2007, Axial compressor deterioration caused by saltwater ingestion: Journal of Turbomachinery-Transactions of the Asme, v. 129, p. 119-126
- 25. Vera, M., X. F. Zhang, H. Hodson, and N. Harvey, 2007, Separation and transition control on an aftloaded ultra-high-lift LP turbine blade at low Reynolds numbers: High-speed validation: Journal

of Turbomachinery-Transactions of the Asme, v. 129, p. 340-347 $\,$

 Yun, Y. I., I. Y. Park, and S. J. Song, 2005, Performance degradation due to blade surface roughness in a single-stage axial turbine: Journal of Turbomachinery-Transactions of the Asme, v. 127, p. 137-143.

Nomenclature

- ho Air density
- u^+ Near surface velocity
- u_{τ} Frication velocity
- U_{t} Tangential velocity
- Δy Distance to the wall
- y^+ Dimensionless distance to the wall
- μ Viscosity coefficient
- A Total surface area
- au_w Wall shear stress
- κ Constant number of von Karman
- C Constant number related to roughness
- B Constant number of rough height
- ΔB Offset of rough height
- $h^{\scriptscriptstyle +}$ Dimensionless number of roughness
- h Average roughness of blade surface roughness
- $h_{\rm c}$ Average of roughness parameters
- $h_{\rm s}^{\scriptscriptstyle +}$ Dimensionless number of $h_{\rm s}$
- ν Dynamic viscosity
- k_s Equivalent gravel roughness
- \overline{k} Average roughness
- C_p Pressure coefficient factor $C_p = (P_0-P)/(P_0-P_{2S})$