Effect of surface roughness on the aerodynamic performance of turbine blade cascade

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Abstract The effect of surface roughness on the boundary development and loss behavior of turbine blades is investigated with different Reynolds numbers in this paper. The result shows that the velocity profile in boundary layer is plumper on rough surface than on smooth blade. The aerodynamic loss is lowered at low Reynolds number, but becomes significantly large at high Reynolds number. The total pressure loss coefficient of cascade can reach a top increase of 129% for rougher blades comparing with smooth blades at $Re = 300000$.

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1. Introduction

Surface roughness increases significantly due to erosion, corrosion, and deposition during operation under high pressure and temperature condition [1] and even exists on new made blades. After several thousands of in-service hours, roughness heights would typically drop into the range of 20–150 μm centerline on average [2]. The efficiency of turbines will be seriously affected by surface roughness. Bammert and Sandstede’s [3] measurement indicated that sand grain surface roughness on turbine blade with $K_s/C_r$ ranging from $10^{-3}$ to $10^{-2}$ could decrease the stage efficiency by 7 to 14 percent comparing with smooth blades. Boynton et al. [4] found that decreasing the surface roughness from 10.16 μm to 0.76 μm would cause a 2.5 percent increase on the efficiency of a high pressure fuel turbopump for a rocket engine. Yun et al. [5] found that in the fully rough regime (400 μm), normalized efficiency decreased by 11% with roughness only on stator vanes, 8% with roughness only on rotor blades, and 19% with roughness on both the stator and rotor blades.

Surface roughness results in aerodynamic loss through its interaction with the boundary layer. The results of
Boyle et al.'s [6,7] experiment showed that the effect of roughness on turbines is closely related to Reynolds number. Denton's [8] research indicated that low roughness has no effect on boundary layer when Reynolds number is low, while the aerodynamic loss becomes prominent at high Reynolds number. M. Montis et al. [9,10] found that the boundary layer upstream of the separation point will become thinner with the presence of roughness on blade surface, so the loss becomes significant at high Reynolds number. Q. Zhang et al. [11–13] analyzed the effect of surface roughness and turbulence intensity on aerodynamic losses. Results showed that the effects of changing the surface roughness condition on IAL values are substantial, whereas the effects of different inlet turbulence intensity levels are relatively small in general. Roughness height and roughness distribution on blade are clearly important. Suder et al. [14] found the roughness distribution on blade leading edge and the front half of the suction surface contributed to most of the aerodynamic loss. Roughness on these regions accounted for more than 70% of the performance degradation found in fully coated blade. Kind et al. [15] showed that roughness on the suction surface could cause large increase in profile loss while roughness on the pressure surface had relatively small effect.

In previous foreign studies, it has been demonstrated that the impact of roughness on the turbine cannot be ignored. Some related research of surface roughness also has been done in domestic. J. Yao et al. [16] in Tsinghua University found that the roughness effect on off-design incidence is highly significant, but different Reynolds numbers are of no sensitive. J. Wen's [17] study indicated that unsmooth blades will change the development of vortex and lower the aerodynamic loss comparing with smooth ones. However, in domestic journals, there is limited work dealing with the effect of surface roughness on boundary layer development.

In this article, simulation methods are validated at first. The boundary layer's development at different Reynolds numbers with different roughness height is analyzed in detail in the following parts.

### 2. Object and numerical methods

The simulation is carried out on the two-dimension cascade. The blade geometry parameters are listed in Table 1. The size of roughness ($K_s$) researched are 26 µm, 53 µm, 110 µm designated as SL_1, SL_2, SL_3. $K_s$ and $K$ are two parameters which describe the roughness on wall surface. $K$ is defined as the actual roughness geometry, while $K_s$ is a modeling parameter, defined to characterize and quantify the roughness on the surface. The quantity of $K_s$ represents the size of sand grains which give the same skin friction coefficients in internal passages as the roughness being evaluated.

Three-dimensional steady viscous Reynolds-averaged Navier-Stokes (N-S) equations are solved to simulate the flow in the turbine cascade using the commercial computational fluid dynamics (CFD) software CFX. The flow region is discrete using a finite volume method and convection terms are analyzed using a second-order accurate upwind scheme. The flow time is discrete using second-order rear different Euler format. Shear stress transport (SST) two-equation turbulence model, and $\gamma-\theta$ transition model are used throughout the whole work. The total temperature, total pressure and flow angle are specified as inflow boundary condition and the outlet static pressure is specified as outflow condition in this investigation. $K_s$ is used to correct the wall function in the simulation, and the function of sand grain height $K$ is pointed out to correct the transition equation to consider the roughness effect on the transition process. The outlet Mach number is 0.75.

Sixty-four thousand grid cells in computational domain are adopted. The maximum wall normal distance of the first cell center to the blade surface is less than 1, and the grid extension near the wall is less than 1.2. The computation mesh is illustrated as Figure 1.

### Table 1 Cascade parameter.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial chord/mm</td>
<td>17.3</td>
</tr>
<tr>
<td>Blade pitch/mm</td>
<td>18.32</td>
</tr>
<tr>
<td>Leading edge radio/mm</td>
<td>0.63</td>
</tr>
<tr>
<td>Trailing edge radio/mm</td>
<td>0.2</td>
</tr>
<tr>
<td>Inlet metal angel(°)</td>
<td>4.78</td>
</tr>
<tr>
<td>Outlet metal angel(°)</td>
<td>67.96</td>
</tr>
<tr>
<td>Flow turning angel(°)</td>
<td>72.74</td>
</tr>
</tbody>
</table>
3. Experiment validation of numerical methods

The experiment investigation carried out by Marco Montis is adopted to validate numerical methods in this paper. Cascade T106C is used in the experiment. The loss coefficient is showed to compare the difference between experimental data and numerical results. The distributions of loss coefficient with different Reynolds number when the roughness is at the level of $R_a = 5 \times 10^{-5}$ and $R_a = 0.8 \times 10^{-5}$ are showed in Figure 2 and Figure 3. In Figure 2, the pattern of loss coefficient is similar with the experiment's result, and its loss variation is consistent. In Figure 3, the consistency is even better comparing with $R_a = 5 \times 10^{-5}$. The roughness size and Reynolds number simulated in this paper are among the experiment's range. According to the analysis above, the numerical methods used in this paper can give reasonable results.

4. Result and discussion

The fluid on pressure side can resist the disturbance better because of the favorable pressure gradients on the blade pressure surface. Some work done in this paper also illustrates that roughness on pressure side has little effect on aerodynamic performance. So in this paper, the suction surface roughness will be mainly focused on.

The shape factor will be analyzed to illustrate the development of boundary layer. The shape factor distribution and coefficient of friction distribution with different Reynolds numbers are shown in Figure 4–Figure 8. The shape factor and coefficient of friction along the suction surface under the designed condition of Reynolds number $Re = 157000$ are showed in Figure 5 and Figure 6. First the development of boundary layer on smooth blade (baseline)
will be illustrated through shape factor. Because of the adverse pressure gradient on leading edge, the shape factor will increase significantly, and the boundary layer separates. The separation point and the separation bubble length can be clearly found from the coefficient of friction ($C_f$) in Figure 5, at which area the coefficient is negative. After the separation bubble, the boundary layer attaches when the shape factor is about 2.2, namely the boundary layer is laminar. The shape factor increase slowly with the development of boundary layer. With the presence of adverse pressure gradient near the trailing edge, the shape factor increases sharply until the boundary layer separates. The separated layer does not attach, which can be predicted from both the shape factor value and coefficient of friction. When roughness is added to blade surface, shape factor value is lower than smooth blade along the whole area of suction side, and this change becomes more obvious as the roughness size increases. The reason may be that the boundary layer velocity profile against airfoil becomes plumper since the added roughness can strengthen the boundary layer turbulent kinetic transport. A phenomenon worth to be noted is that the shape factor decreases with the presence of adverse pressure gradient on SL_3 at about 80% suction surface position. This can be explained as the transition process happens when the roughness size becomes bigger, and the boundary layer becomes turbulent so the separated bubble is absent. Separation occurs on smooth blade, SL_1, and SL_2 at about 80% percent of the arc length along the suction surface, but the increased roughness size makes the separation weak, which can be found clearly from Figure 6.

The effect of different Reynolds numbers on both smooth and rough blades are showed in Figure 4, Figure 7, and Figure 8. Under the condition of low Reynolds number, i.e., $Re=60000$, the shape factor decreases when roughness size increases, but the separated bubble is not avoided, which can be illustrated from the high value of shape factor near trailing edge. At the condition of $Re=157000$, transition happens on SL_3 blade, At the condition of $Re=300000$, the transition happens on SL_1, SL_2, and SL_3 blade. After the leading edge separation of the three blades above, the shape factor changes slowly when the boundary layer becomes turbulent.
From the analysis of shape factor, some conclusions can be obtained. Adding roughness to blade surface can weaken the separation bubble at low Reynolds number. The roughness will trigger transition process when Reynolds number increases. Especially when Reynolds number is at a very high level, the transition process will happen even at small roughness size. The reason may be that the boundary layer becomes thinner with increased Reynolds number, so the interaction between rough particle and boundary layer becomes strong. In other words, the impact of surface roughness on the flow instabilities becomes significant when Reynolds number increases.

The velocity profile distribution against suction surface at $S/S_0=80\%, 95\%$ with different Reynolds numbers and roughness size are showed in Figure 9–Figure 12. For the smooth blade, an inflection point on the velocity profile is presented at the position of 95% suction surface which indicates that boundary layer separates. On the surface of rough blade, the velocity profile become plumper compared with smooth blade. Especially, when at $Re=250000$, the inflection point disappeared for SL_2, SL_3, while $Re=300000$ the inflection point disappeared for all rough surface blade.

The difference of boundary layer development caused by different roughness size will lead to various boundary layer loss. Loss distribution downstream of the cascade, dissipation coefficient of suction boundary layer and total pressure loss will be used to analysis boundary layer loss.
Figure 13–Figure 16 show the normalized loss distribution downstream of the cascade. Loss coefficient is defined as

\[ Y_p = \frac{P_{01} - P_{local}}{P_{02} - P_2}, \]

\( P_{local} \) represents the local total pressure.

The surface roughness has a clear influence on the loss behavior and is found to produce different effects depending on the roughness size and Reynolds numbers. Under the condition of \( Re = 157000 \) (design condition Figure 14), the peak value of loss is lowered as roughness increases. This is mainly because that increased roughness weakens the separation bubble. The transition process happens on SL_3, which avoids the separation bubble on suction surface, namely the separation loss will be reduced, but at the same time thickens the boundary layer because of transition process. For the compromise SL_3 has the lowest peak value as shown in Figure 14. When Reynolds number equals to 250000, the peak value of SL_3 is the highest, while for SL_1 and SL_2, the peak value is lower than smooth blade. When Reynolds number reaches 300000, the peak values of all three rough blades were higher than smooth blade.

To describe the local loss production, the dissipation coefficients \( C_d \) defined as

\[ C_d = \frac{L_{ref}}{\rho_{ref} u_{ref}^2} \cdot \frac{\partial u_i}{\partial x_j}. \]

Under the design condition, i.e., \( Re = 157000 \), for smooth blade (baseline), \( C_d \) increases along suction surface after stagnation point because of leading edge spike and separation bubble. \( C_d \) reaches the lowest value at the reattached point after leading edge separation bubble. The \( C_d \) value changes slowly in the favorable pressure gradient after leading edge, when the adverse pressure region appears near the trailing edge, \( C_d \) value first decreases and then increases until the trailing edge.

Under the condition of \( Re = 60000 \), the dissipation coefficients of rough blades are lower than smooth blades in most of the area of suction. This is because the roughness makes the velocity profile against suction surface plumper than smooth blade which can be found from Figure 9–Figure 12. So the friction loss at boundary layer will decrease significantly. While at the trailing edge, the dissipation coefficient is higher for rough surface, especially for SL_3. With increasing Reynolds number, the boundary layer becomes thinner, so the interaction between boundary layer and roughness becomes significant, and eventually makes the transition process happen (Figure 17–Figure 20). When Reynolds number equals to 300000, the local losses for SL_1, SL_2, and SL_3 are larger than smooth blades after the leading edge. In conclusion, the local loss of boundary layer becomes significant when the Reynolds number is high with rough surface.
Total pressure loss coefficient ($Y_p$) is used to give a quantitative value of aerodynamic loss (Figure 21). For smooth blade cascades, the $Y_p$ value decreases with increasing Reynolds number. For rough blade cascades, the $Y_p$ value first decreases and then increases. For low Reynolds number such as $Re=60000$, the interaction between roughness and separated flow makes the separated loss decrease, so the $Y_p$ value of SL_3 is the lowest. When Reynolds number equals to 157000, or 250000, the transition process happens on rough blade. Although the transient process makes the loss increase, the absence of separated flow makes the loss decrease. So even at $Re=157000$, the $Y_p$ value for smooth blade cascades is still high, but at $Re=250000$, the loss of SL_3 blade cascades becomes the highest one. When Reynolds number equals to 300000, the transition happens so early that the $Y_p$ loss is significantly higher for rough blade cascades than smooth blade cascades. For SL_3, the loss becomes very large at $Re=300000$. The total pressure loss coefficient of cascade increases 129% for SL_3 comparing with smooth blade cascade at $Re=300000$.

5. Conclusions

The boundary layer velocity profile will become plumper when roughness is added to blade. Surface roughness effect on boundary layer is closely dependent on Reynolds number. The roughness on surface can weaken separation bubble at low Reynolds number, thus reduce the aerodynamic loss, while at high Reynolds number surface roughness will trigger transient progress, so the loss increases significantly. The loss is very large at high Reynolds number with rough surface. The total pressure loss coefficient of cascade increases by 129% for SL_3 comparing with smooth blade cascade at $Re=300000$.

References


