The influence of OGV airfoil profile on the TRF

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Abstract. The outlet guide vane in a turbine rare frame plays a vital role in de-swirling the flow as well as load-bearing. This paper numerically simulates the performance of the single stage turbine with different airfoil profile design in the outlet guide vane. The result shows that the outlet guide vane with NACA65 profile has the best performance. The pressure growth in the suction side is steady and no obvious separation is found in the flow field.

1. Introduction
As the modern aero-engine design pursues higher performance design goals, the inlet flow angle of the turbine rear frame (TRF) increases dramatically, which raises design difficulty. TRF is a part of the engine load-bearing system with an outlet guide vane (OGV) inside to turn the outlet flow to an axial direction with minimum pressure loss [1]. Usually, there are fuel pipelines need to pass through OGV. This will increase the thickness of the OGV, making the design of a high-performed OGV much harder.

To improve the performance of TRF, experts at home and abroad have done plenty of work on the study of TRF. Hjärne et al. used numerical and experimental methods to compare turbulence models used in numerical calculation of TRF, suggested that a K-epsilon model with wall correction is the most accurate compared to the other model studied in the paper [2]. In 2012, Koch studied the performance of an OGV in TRF under different incidence, then validated it in tests [3]. Yahui Feng from Beihang University conducted experimental research on TRF, and optimized design of OGV by adopting the technology of large and small blades [4].

Playing a role of de-swirling and load-bearing, the airfoil of OGV blades is very important. After years of explosion, expert has compared the influence of different airfoil profiles on the compressors. The result in reference [5] shows that, in the C4 profile the pressure growth at axial position 30%-70% is slower compared to the NACA65 profile, but the low pressure area appears in the C4 profile at the leading edge is larger than the NACA65 profile.

The controlled diffusion airfoil blade (CDA), also called as prescribed velocity distribution blade (PVD), is an airfoil designed to control the pressure distribution of the suction side of the blade. The design theme of the CDA profile is to keep accelerating at the leading edge of suction side and decelerating fast firstly and then slowly to control the thickening of boundary layer as well as to avoid the separation [6]. In 2008, Sonada et al. found that under the low Reynolds number condition, the OGV with extreme front-loaded airfoil could obtain better performance, and the comparison airfoil profile is exactly a CDA airfoil [7].
Taking a single-stage turbine as an example, whose an outlet flow angle of turbine rotor is -28 degree, this paper compared the performance of different airfoil profiles to seek a best airfoil profile for the OGV in the TRF.

2. Numerical setup
The calculation of TRF is fulfilled by three-dimensional steady numerical simulation, with the turbine to provide the required inlet conditions, including the total temperature and total pressure, especially the inlet flow angle. OGV airfoil profile is designed by through-flow and airfoil design software.

| Parameter                        | Value   |
|----------------------------------|---------|
| Inlet total temperature /K       | 1197.51 |
| Inlet total pressure /kPa        | 521400  |
| Rotating speed of turbine rotor /rpm | 22000  |
| Number of NGV blades             | 25      |
| Number of ROT blades             | 52      |
| Number of OGV blades             | 10      |
| Tip clearance of ROT /mm         | 0.52    |

The grid is generated by Auto Grid 5. When the total number of grids reaches 1.28 million, the aerodynamics performance parameters of the turbine and the OGV hardly change, which validates the grid independency of the calculation. The calculation fluid type uses the same gas as in the reference [8], the maximum value wall surface $y^+$ is 5. The inlet condition is shown in Table 1. The section definition is shown in Fig. 1 and the mesh used in the calculation is shown in Fig. 2.

![Figure 1. Section definition of TRF](image1)

![Figure 2. The mesh used in the numerical simulation](image2)
3. Results

In order to compare the different aerodynamics performance of the TRF and the turbine, four kinds of airfoil profile is chosen to form the OGV blades in the TRF. They are the CDA077 profile, the Modified CDA077 profile, the C4 profile, the NACA65 profile. All maximum thickness of the airfoil is 10% chord length, the inlet flow angle is all set as -28 degree.

3.1. Analysis of different airfoil profile

As can be seen in Fig. 3, the main difference between the Modified CDA077 profile and CDA077 airfoil profile is that the blade thickness is increased at the axial position of 60%-90%. Compared with the CDA077 profile, maximum thickness position in the NACA65 profile is moved from 30% to 40% axial position, and the blades became thinner in the axial position of 10%-30% and thicker in the axial position of 40%-100%. Compared with the CDA077 profile, C4 profile is thicker thoroughly except for the maximum thickness position and has the biggest leading-edge radius. The thickness distribution of different airfoil profiles determines different pressure gradient variation rules. Therefore, changing the airfoil profile is essentially to control pressure gradient and flow by modifying blade passage width.

![Figure 3. The coordinates of different airfoils](image)

3.2. Analysis of static pressure coefficient distribution of different airfoil profile

For the current OGV flow path, the blade root is more prone to separation. Fig. 3 shows the surface static pressure coefficient distribution of different airfoil on 5% span.

It can be seen from the surface static pressure distribution map of the 5% span that, compared with the CDA077 profile, due to the thickening at the axial position of 60%-90% in the Modified CDA077 profile, the growth speed of pressure coefficient on blade surface slows down, and the acceleration in velocity on the trailing-edge of pressure surface is also alleviated. Due to the large leading-edge radius, C4 profile has an obvious low pressure region in the map, which is consistent with the description in reference [5]. Then “a platform area” appeared that static pressure coefficient has hardly any increase, which is very likely to develop into separation and should be avoid in the flow field. It’s the thickest among three kinds of airfoil profile after the position of the maximum thickness, thus the static pressure coefficient of the suction surface increases most slowly. The NACA65 profile with 10%-30% relative axial location blade thinned compared to the CDA077 profile, the passage area increases in the corresponding position. The flow there undertakes a stronger adverse pressure gradient, which is the reason why the pressure coefficient increased. Since after the maximum thickness position, the NACA65 profile is thicker than that in the CDA077 profile, which narrow the blade passage, the surface pressure coefficient increases more slowly. At the same time, the pressure side accelerating zone disappear entirely, which makes it a relevantly better design.
3.3. The suction side flow field comparisons

In this case, adopting a CDA profile in the OGV blade has an acceleration zone at the trailing edge, which is unnecessary yet good for the control of the low velocity region there. When thicken the blade near the trailing edge area, the acceleration alleviates, and the low velocity region becomes larger. The C4 profile with a large leading-edge radius has an obvious acceleration area at the leading-edge. The low velocity region in NACA65 profile appears the farrest to the leading edge, and occupies a smallest area on the suction side in the four airfoil profile designs.

![Figure 4. Static pressure coefficient distribution of different airfoil design on 5% span](image)

**Figure 4.** Static pressure coefficient distribution of different airfoil design on 5% span

![Figure 5. Static pressure coefficient distribution of different airfoil design on 5% span](image)

**Figure 5.** Static pressure coefficient distribution of different airfoil design on 5% span
3.4. Aerodynamics parameter comparison of different airfoil profile

Shown in Fig. 5, the pressure recovery coefficient distributions have a similar trend, the value of pressure recovery coefficient decrease sharply near the hub. Because of “the platform region” in C4 profile design, the pressure recovery coefficient decreases slightly on span 10%-50%. And since the acceleration reduce the low velocity area, the CDA077 and the Modified CDA077 profile have a higher pressure recovery coefficient value on the relevant zone.

![Figure 6. Pressure recovery coefficient of different airfoil design](image)

In order to make sure the inlet conditions of OGV remain the same, pressure of section 6 is set to insure the expansion ratio of turbine unchanged. Thus, the pressure on section 6 can somehow reflect the ability of OGV to turn the kinetic energy into pressure potential energy. Obviously the Modified CDA077 and the NACA65 airfoil profile are better.

As no obvious separation is found in the flow field, the aerodynamics parameter shows little difference, the best design should be chosen considering the surface pressure coefficient map as well as the flow field of suction side.

| Airfoil Profile | Pressure recovery coefficient of OGV | Isentropic turbine efficiency (include OGV) | Pressure set on section 6 /kPa |
|-----------------|-------------------------------------|------------------------------------------|-------------------------------|
| CDA077          | 0.9779                              | 0.8758                                   | 167.30                        |
| Modified CDA077 | 0.9779                              | 0.8758                                   | 167.65                        |
| C4              | 0.9772                              | 0.8753                                   | 167.45                        |
| NACA65          | 0.9777                              | 0.8756                                   | 167.65                        |

4. Conclusion

Increasing blade thickness after the position of maximum thickness can slow down the speed of surface pressure increase as well as diminish the acceleration near the trailing-edge, yet increasing the blade thickness before the position of maximum thickness will rise the adverse pressure gradient. Increasing the leading-edge radius of the airfoil profile will aggravate the acceleration feature at the leading-edge of the suction side.

No obvious separation is found in all airfoil designs, except the surface pressure coefficient map shows “a platform region” in the C4 profile on the suction side. The acceleration on CDA077 profile is beneficial for decreasing the low velocity region near the root on suction side of the OGV, it only has a tiny effect on the aerodynamics parameter of the OGV. Yet the flow field on the suction side and the
surface pressure coefficient map both shows the OGV with a NACA65 airfoil profile performs best in the TRF.

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