Aerodynamic Performance Analysis of the Transonic Turbine with Tip Clearance Variations for Marine Turbochargers

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ABSTRACT
Using ANSYS 17.0 numerical prediction code and SST k-ω turbulence model, a three-dimensional (3D) Reynolds-averaged Navier-Stokes (RANS) calculation of a single-stage transonic turbine of a marine turbocharger was carried out in order to understand the variation of its aerodynamic performance with tip clearance. The effects of tip clearance height and rotational speed on tip leakage flow and loss under design and off-design conditions were studied by numerical calculation. Under design conditions, as tip clearance height increases, the influence area of low pressure zone on blade trailing edge and the total pressure loss at cascade outlet increases, the formation position of leakage vortices moves to the leading edge of blade, and the intensity and size increase. The length and intensity of shock wave increase, but no strong reflection wave and shock/boundary layer interaction are found. Under off-design conditions, with the increase of rotational speed, clearance mass flow ratio increases first and then decreases, total pressure loss and total-static efficiency decreases.

INTRODUCTION
In gas turbines, as turbine loads increase and turbine stages decrease, the emergence of transonic turbine stages is inevitable, and turbine tip clearance is an important factor in increasing flow losses and reducing turbine efficiency. Previous studies on tip clearance mainly focused on subsonic, but in practice most of them were transonic.

There are numerous reports concerning the development of tip leakage vortices, the flow mechanism of leakage vortices and the variation of leakage vortices with clearance height. Newton et al. (2005) proposed that the leakage flow separated from the tip surface and reattached to the area parallel to the PS edge. As the leakage vortex becomes more intense as the gap increases, the area affected by the leakage vortex increases. O’Dowd et al. (2010) showed that the increase of tip gap leads to the increase of tip leakage vortex intensity, the increase of tip leakage mass flow, and the leakage core further away from the SS of the blade. The passage vortex not only increase in intensity, but also change in position relative to tip leakage vortex.

Gao et al. (2016) carried out a series of studies on four different tip gap sizes of RT27a turbine cascade, and then summarized the characteristics of the size, shape, position and loss of the leakage vortex core with the increase of tip gap. Tallman and Lakshminarayana (2001) numerically simulated the turbine cascades with tip clearance of 2.5% and 1.0%, and described in detail the components of the inner core of the leakage vortex, another explanation of leakage vortex roll-up and three main secondary flow forms in the passage.

Bindon (1987) studied the tip pressure distribution and found that the pressure along the very narrow strip of the blade edge is 2.8 times lower than the cascade exit pressure. His research showed that the low pressure was caused by the small radius of curvature required for the flow radially along the PS and enter the gap through 90 degrees.

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In addition, the flow field distribution on the surface of blade tip was also explored. The previous annular cascade experiment by Morphis and Bindon (1988) have indicated that the width of the separation bubble was directly controlled by the tip gap height. Key and Arts (2004) discovered a distinct separation vortex along the PS of the clearance, and a distinct
separation line on the SS in blade cascade. Stephens et al. (2008) studied the effect of tip thickness on clearance leakage flow based on low pressure turbine blade row tests. It was found that the start of the PS separation/ reattachment lines moved toward the TE as the tip became thicker.

At the same time, the effect of Mach number variation on tip clearance leakage flow and loss in transonic turbines was also investigated. Arisi et al. (2015) found that the size of the near-tip region affected by leakage vortex was not sensitive to exit Mach number/Reynolds number. Wheeler et al. (2012) pointed out that when Mach number at blade exit was greater than 0.8, the tip flow was largely transonic, and the mass flow rate at blade tip changed little with the increase of Mach number at blade exit.

Considering the complex shock wave problem in transonic turbine clearance, many scholars have studied it. By comparing and analysing the flow field of the original and optimized blade profiles in the cascade, Zhao et al. (2016) drew the conclusion that the optimized blade profile can reduce the tailing edge shock loss of the high-load transonic turbine with convergent passage. Zhang et al. (2011) found that in supersonic tip flow, oblique shock waves are generated at the PS of the blade, reflected between the casing and tip, and left the tip in the form of normal shock wave.

Moreover, the structures of flat and squealer tips are searched to study their aerothermal performance. De Maesschalck et al. (2013) compared the aerothermal performance of two new (fully carved 3D) and two conventional (flat and squealer) geometric structures turbine rotor blade tips. In this area, Mischo et al. (2008) discussed the flow field near the blade tip for different shapes of the recess cavities and presented an improved design of a recessed blade tip, highlighted its differences from the generic flat tip blade. The previous experiments by Camci et al. (2005) have indicated that partial-length squealer rims could positively affect the local aerodynamic field by weakening the tip leakage vortex.

Therefore, it is necessary to understand the aerodynamic performance of the transonic turbine tip clearance, which can provide direction for the design of transonic turbines and further improve the overall performance of gas turbines. As shown in Figure 1, the research object is a single-stage axial-flow transonic turbine of a marine turbocharger.

METHODOLOGY

In this paper, the three-dimensional (3D) numerical simulation method is used to analyse the flow mechanism of the tip clearance of a single-stage axial-flow transonic turbine in a marine turbocharger. The variation of the tip clearance aerodynamic performance with the clearance height and the rotational speed (total temperature and pressure) under design and off-design conditions is also explored. The relative tip clearance heights of 0.47%, 0.65%, 0.84%, 1.03%, 1.21%, 1.40% under design conditions and 1.12% under off-design conditions were studied.

Geometry and grids

The grid size sensitivity analysis directly involves the result error of the computation, even determines whether the result of numerical simulation is plausible. In this paper, grid sensitivity analysis is carried out with 0.5M, 1M, 1.5M, 2M, 2.5M, 3M, 3.5M, 4M grid number respectively. And the variation of leakage mass flow ratio with grid number is investigated, as shown in Figure 2.

The grid details are shown in Figure 3, which shows the cascade grid and the grid in the rotor clearance tip. The structured grid used in the numerical simulation is generated by AutoGrid5 module in NUMECA software, which has 0.5M grids in stator and 3.5M grids in rotor. There are 49 layers in the tip clearance along the spanwise direction, and 17 control points in the circumference direction. The grids use the default O4H topology, which have good quality and no negative cells.
Boundary conditions and convergence condition

In this paper, ANSYS CFX 17.0 software was used for numerical simulation. In order to reduce the calculation time, periodic boundary conditions are set on both sides of the cascade for single channel calculation. The total temperature and pressure boundary conditions are set at the inlet of cascade, the mass flow boundary conditions are set at the outlet, and the stator-rotor interface is set as Stage (Mixing-Plane). The cascade inlet and outlet mass flow are monitored to ensure calculation convergence. And the solution is considered to converge when the total mass flow of inlet and outlet is the same. Meanwhile, the RMS residuals of all numerical calculations are also reduced to less than $1 \times 10^{-3}$, which verifies the convergence of all results.

Solver validation

Before the beginning of the research work, the numerical simulation results of stator under a certain working condition are compared with the experimental data, which acquired from a plane cascade wind tunnel test in the 1.5 stage turbine Laboratory of Harbin Engineering University. The pressure distribution at 50% span of stator is compared with the experimental data, as shown in the Figure 4. Limited by the experimental conditions, some pressure taps were not measured or negative pressure was measured, so the experimental data at the TE were not consistent with the numerical simulation results. Except for the TE of the blade, they match well in remaining positions, so the numerical simulation method is credible.

Figure 4 Static Pressure Distribution at 50% Span of Stator

RESULTS AND DISCUSSION

Design condition

Flow field analysis

Figure 5 shows the isentropic Mach number distribution at 50% and 98% span for 0.47% and 1.21% tip clearance heights under design conditions.

With the increase of clearance height, the isentropic Mach number of PS and SS increased evenly at 50% span, while the isentropic Mach number increased evenly at 98% span with the increase of clearance height, and the isentropic Mach number of SS increased significantly from 10% blade length, and then returned to increase evenly at 60% blade length. This is because SS flow is affected by tip leakage flow. With the increase of clearance height, leakage flow increases and leakage vortices occur ahead of time. Comparing the isentropic Mach number distributions of 50% and 98% span, it was found that the blade tip presented a distinct form of after-loaded.

Figure 5 Isentropic Mach Number Distribution at 50% and 98% Span for 0.47% and 1.21% Tip Clearance Heights

The distribution of static pressure coefficient at tip sections with different tip clearance heights is shown in the Figure 6. It can be found that there is a high pressure area in the leading edge of the blade and a low pressure area in the trailing edge of the blade, which indicates that the trailing edge of the blade is the main area of the leakage flow. With the increase of tip clearance height, the area of blade trailing edge affected by low pressure zone increases, while the numerical value decreases, and the value of PS is even lower than that of SS.

Figure 6 Static Pressure Distribution at 50% Span of Stator
Because there are complex shock waves in the clearance of transonic turbines, the analysis of the blades with different clearance heights is shown in Figure 7. The rotor tip is the static pressure coefficient distribution, the density gradient distribution in the x direction on the two sections (The section D and E are at 30% and 77% of the blade chord length), and the white line is the flow reattachment line in the clearance. It is found that the pressure changes rapidly at the position where the re-attachment line exists, the pressure on the left side is lower, the pressure on the right side is higher, and the pressure jump occurs when the gas crosses the reattachment line. At the same time, with the increase of clearance height, the reattachment line moves from blade PS to SS.

The two sections are enlarged and displayed as shown in this figure. On the left side of the two sections, there is an arcc region with higher relative density gradient, which is due to the separation of gas through the corner of the intersection of PS and tip, forming separation bubbles. With the increase of clearance height, the separation bubble length increases until the re-attachment line disappears, which is consistent with the change rule of the re-attachment line, indicating that the reattachment line is a sign of the re-attachment of gas to the top surface of the blade. Oblique shock wave exists in the E section (shown by the red line). Close observation shows that the oblique shock wave is generated at about 40% of the separation bubble length. With the increase of the clearance height, the intensity of the shock wave increases. Unlike Zhang et al. (2011), weak reflective oblique shocks are observed only at 0.47% in this case, and strong interaction between shocks and boundary layer is not found at SS. This may be due to better blade design and reasonable load distribution.
Loss analysis

In order to better explore the development process of leakage vortices, three sections A, B and C are plotted along the blade flow direction. At 50% blade chord length and 0.47% clearance height, the leakage core at section A is very small and almost non-existent. With the increase of clearance height, the leakage core at section A can be observed obviously, which indicates that the position of leakage vortex formation moves to the leading edge of blade with the increase of clearance height. At 96% blade chord length, with the increase of clearance height, the entropy of the leakage vortex core increases at the C section, which indicates that the strength and size of the leakage vortex increase, while the leakage vortex core gradually moves away from the SS and approaches the pressure surface of adjacent blades.

Considering the interaction between passage vortices and leakage vortices, the distribution of entropy increase downstream of blades is investigated, as shown in this figure. When the clearance height is 0.47%, 0.65% and 0.84%, it can be clearly observed that the long strip passage vortex core and the circular leakage vortex core are independent of each other. With the increase of clearance height, the two vortices are close to each other. When the clearance height is 1.03%, the leakage vortices gradually merge with the passage vortices, and when the clearance height is 1.40%, the leakage vortices almost completely "engulf" the passage vortices.

At the 53.42% axial chord length downstream of blade, the distribution of total pressure loss coefficient at cascade outlet is plotted. From Figure 11, it can be seen that the total pressure loss is divided into upper and lower parts. When the tip clearance height is 0.47%, the loss of the upper part mainly
exists in the upper passage vortices. With the increase of the clearance height, the total pressure loss concentrates near the leakage vortices, and the loss and influence areas increase. The loss of the lower part is mainly caused by the lower passage vortices. With the increase of clearance height, the loss increases gradually, but it is smaller in size and numerical value than the loss of the upper part.

Figure 11 Total Pressure Coefficient at Cascade Outlet with Different Clearance Heights

(a) $\tau=0.47\%$
(b) $\tau=0.84\%$
(c) $\tau=1.21\%$
(d) $\tau=1.40\%$

Off-design condition
In order to study the overall performance of rotor under variable conditions, the turbine blades are operated at 5 different rotational speeds, in which $N_D$ is the rotational speed of design conditions. Figure 14 show the isentropic Mach number distribution at 50% and 98% span for 83.20% $N_D$ and 106.75% $N_D$ under off-design conditions. With the increase of rotational speed, the isentropic Mach number of 50% and 98% span decreases. At 83.20% $N_D$, there is a reverse pressure zone at 50% and 98% span SS, and the formation of the reverse pressure zone at 98% span is earlier than that at 50% span. With the increase of rotational speed, the reverse pressure zone disappears, and 98% span presents obvious after-loaded form.

Figure 15 and 16 show the variation of flow rate, total pressure loss and total-static efficiency with rotational speeds under off-design conditions, respectively.

With the increase of rotational speed, clearance mass flow ratio increases first and then decreases, total pressure loss decreases logarithmically and total static efficiency decreases exponentially. This is because with the increase of rotational speed, the flow inlet angle and positive incidence decreases...
gradually. As the positive incidence decreases, the total pressure loss tends to decrease, and in the process of decreasing the positive incidence to zero and increasing the negative incidence, there exists an optimum operating condition with the minimum loss. (In this case, the optimum operating condition is not calculated, but obviously there exists this characteristic).

CONCLUSIONS

In this paper, the aerodynamic performances of single stage turbine blades of marine turbocharger at different clearance heights under design conditions and different rotational speeds under off-design conditions are studied, and the following conclusions are obtained:

Under design conditions, with the increase of clearance height, the area of blade trailing edge affected by low pressure zone increases, and the PS value is lower than the SS value. The total pressure loss at cascade outlet increases gradually, and the total pressure loss is transferred from the upper passage vortices to the leakage vortices.

The formation position of the leakage vortices moves towards the leading edge, and the strength and size of the leakage vortices increase. At the same time, the core of the leakage vortices gradually moves away from the SS and approaches the PS of the adjacent blades. Upper passage vortices and leakage vortices are close to each other and gradually merge, even the leakage vortices completely "engulf" the channel vortices.

The tip reattachment line moves from the blade PS to the SS, and the separation bubble length increases continuously. The length and intensity of shock wave increase, but no strong reflection wave and shock/boundary layer interaction are found.

Under off-design conditions, with the increase of rotational speed, clearance mass flow ratio increases first and then decreases, total pressure loss and total static efficiency decreases.

NOMENCLATURE

- $c_{ps}$: static pressure coefficient [-]
- $P_{ps} = \frac{P - P_{exit}}{P_{exit} - P_{exit}}$
- $c_{pt}$: total pressure loss coefficient [-]
- $C_{pt} = \frac{P_{ps}^{2} - P_{exit}^{2}}{\frac{1}{2} P_{exit} V_{exit}^{2}}$
tip clearance mass flow
rotor inlet mass flow

\[ \Delta S = S - S_{in} \text{ (stator)} \]

\[ \Delta S = S - S_{1} \text{ (rotor)} \]

relative axial chord length

coordinate direction [mm]

pressure [Pa]

velocity [m/s]

rotational speed [r/min]

entropy [J/kg·K]

rotational speed under design condition [r/min]

Mach number [-]

tip clearance height [mm]

density [kg/m³]

total-static efficiency [-]

cascade exit

cascade inlet

isentropic
design condition

rotor inlet

rotor outlet

three-dimensional

Reynolds-averaged Navier-Stokes

root mean square

leading edge

tailing edge

pressure side

suction side

tip leakage vortex

tip passage vortex

ACKNOWLEDGMENTS

This work has been supported by the National Natural Science Foundation of China (No. 51779051), the Natural Science Foundation of Heilongjiang Province of China (No. QC2016059) and the Fundamental Research Funds for the Central Universities (No. HEUCFP201720), which are gratefully acknowledged.

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