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Turbine tip clearance leakage flow control

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Abstract

The turbine is one of the key and core components of a gas turbine. In order to ensure the safe operation of the turbine, there must be a necessary clearance between the tip and the fixed casing to avoid friction. This clearance is generally called tip clearance or tip clearance . Due to the existence of the tip clearance, under the action of the pressure difference between the pressure surface and the suction surface of the turbine cascade, the tip leakage flow is driven. The leakage flow interacts with the main flow to form a complex flow vortex system. At the same time, it affects the aerodynamic performance of the impeller. Both efficiency and stable work have a huge impact. The hazard of the tip leakage flow is not only that the existence of the gap leads to the leakage of the working medium and the loss of work, but more importantly, the occurrence of the leakage flow will cause the flow field characteristics, heat transfer characteristics and flow loss near the blade tip and the entire cascade channel. Significant influence. Therefore, the development of tip leakage flow control technology has very important theoretical value and practical significance for improving the mechanical efficiency of the impeller and expanding the stable working range. Starting from the research background, this article introduces the research progress of this problem and several existing turbine tip clearance leakage flow control methods.

Keywords

Turbine tip; flow control.

1. Research Background

As the most important propulsion power system of aviation aircraft, aviation gas turbine engine is known as the "heart of aircraft". The improvement of the performance of aviation gas turbines is the prerequisite and foundation for the development of aviation aircraft, and has a very important impact on the aviation industry and the country's technological level. A gas turbine is a rotating machine that converts the energy in high-temperature and high-pressure gas into mechanical energy. It is the most critical component of an aviation gas turbine, and its performance has a direct impact on the performance of the aviation gas turbine.

According to the development requirements of engines, the development trend of gas turbines is mainly concentrated in the following two aspects: one is to continuously increase the temperature in front of the turbine to increase the engine thrust-to-weight ratio while reducing fuel consumption; the other is to continuously increase the aerodynamic load of the turbine and adopt transonic speed Small aspect ratio turbine design scheme reduces the number of turbine stages and blade rows. Turbines are developing in the direction of high load and high expansion ratio, and small aspect ratio turbines are more and more widely used. Since the end zone loss is inversely proportional to the blade aspect ratio, the reduction in the turbine aspect ratio causes the end zone loss in the channel to become the main source of loss. The end zone loss accounts for 60% to 70% of the total loss, and the most serious loss is Occurs in the tip area, the loss caused by the secondary flow in the tip area accounts for more than half of the loss in the tip area. In order to avoid contact between the rotor blade tip and the casing during the operation of the engine, it is necessary to leave a gap between the rotor blade and the casing, that is, the tip clearance. The existence of the blade tip clearance makes the leakage flow through the clearance inevitable. Although the size of the clearance is small, studies have shown that the clearance leakage flow affects the flow in the 20%~30% area of the cascade channel. The gap leakage flow is formed by the gas flowing through the gap under the action of the pressure difference between the suction surface and the pressure surface of the blade, which leads to the decrease of gas work near the blade tip, the blockage of the passage and the increase of loss, making the flow in the tip area extremely complicated.

The gap leakage flow exists in the form of various vortices in the blade channel, and interacts with the blade surface layer and the channel vortex, forming a complex flow and leading to increased losses. At the same time, the gap leakage flow affects the radial distribution of the blade load, resulting in a decrease in the blade load. Studies have shown that every 1% increase in the ratio of turbine tip clearance to blade height results in a decrease of about 0.8% to 1.2% in turbine efficiency, and every 1% decrease in turbine efficiency increases fuel consumption by 2%. GE's research shows that the loss of fuel consumption caused by the tip clearance leakage of the turbine rotor accounts for about 67% of the total loss. Therefore, the research on the tip clearance leakage and measures to reduce the clearance leakage loss are important for improving the performance of aero gas turbine engines. Economy has a very important meaning.

2. Research progress

The earliest research on tip clearance flow was proposed by Rains in 1954. He used flow display technology to study the gap flow between the roots of the stationary blades and the top of the moving blades of the three-stage axial flow pump, and was the first to propose a model of the gap flow. He assumed that at the top of the blade, the pressure gradient between the pressure surface and the suction surface of the blade is much greater than the pressure gradient along the chord length. Therefore, under the effect of the static pressure difference between the pressure surface and the suction surface of the blade, the interstitial fluid forms a jet substantially perpendicular to the arc in the blade. He believes that in a gap with a smaller scale, the viscosity of the fluid can be ignored due to the greater flow velocity in the gap. The strength of the gap flow is mainly determined by the static pressure difference between the pressure surface and the suction surface and the flow inertia. Therefore, in the case of small gaps, the study of gap flow can ignore the effect of its viscosity.

At the beginning of the research, the research on the turbine clearance flow was completed on the plane cascade, mainly by scaling up the clearance size and blade size, and using the three-hole/five-hole/seven-hole probe. The study found that the turbine blade tip separation vortex and reattachment phenomenon, and observed that the tip pressure side static pressure is reduced by the tip separation vortex, even lower than the tip suction side static pressure. With the advancement of measurement technology, the research on the gap flow has gradually penetrated into the actual moving blade, and the measurement methods are mainly through non-contact measurement such as PIV and LDV. Experiments have found that the movement of the turbine rotor relative to the casing has a significant effect on the tip leakage flow. The relative movement in the opposite direction to the tip leakage flow results in a low pressure area near the suction surface, and there may also be scraping vortices. From a qualitative point of view, the tip leakage flow is basically similar on the turbine rotor and the plane cascade.

In recent years, with the development of computational fluid dynamics, researchers have begun to study the complex flow in the gap through three-dimensional numerical simulation calculations. So far, although the academia has a preliminary understanding of the generation mechanism of interstitial flow and its impact, there is still a lack of in-depth research on the detailed flow inside the actual interstitial.

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3. Turbine tip clearance leakage flow control method

Since the gap height changes during the engine operation and the change is obvious, in order to avoid contact between the blade tip and the casing, the gap height must be kept above a certain value in most cases, and only rely on reducing the gap height. The method to control the gap leakage loss is unrealistic. Therefore, under the condition of constant gap height, it is necessary to study how to reduce gap leakage loss. This kind of research on taking measures to control gap leakage flow is called "gap leakage control research", and it has been a hot spot in the research of gap leakage loss in recent period.

3.1. Rib tip

The rib tip is currently the most common measure to reduce clearance flow. The study found that it can reduce the flow coefficient, weaken the gap flow, reduce the mixing loss between the gap flow and the main flow without affecting the tip static pressure distribution, and can also improve the tip heat transfer.

The ribbed tip mainly dissipates energy through the small vortex clusters that appear in the groove formed on the tip of the blade, so as to hinder the gap flow and reduce the gap flow and gap flow loss. Moreover, after the rib tip is adopted, a smaller gap height can be designed relative to the flat-top blade. Therefore, the rib tip has been widely used in industry. When the rib tip is adopted, at the top of the blade, in addition to the existing separation vortex near the pressure side, a new separation vortex is formed at the bottom of the rib, so that the fluid near the top of the blade moves in the direction of the blade thickness after entering the gap. To the rib, and then move upward in the direction of the rib height. At the same time, under the action of the relative movement direction of the shell, a clockwise rotating vortex is formed in the gap. Due to the appearance of the vortex, the gap flow is hindered to a certain extent, thereby reducing the gap flow rate and weakening the gap vortex size and gap flow loss.

3.2. Winglet

At the design speed, the wingtip can improve the performance of the turbine under all expansion ratio conditions; under the design expansion ratio, the turbine efficiency can be increased by 1.2%. At the same time, it was found that under design conditions, when the winglet is not used, the clearance vortex affects the flow within 18% of the blade height from the shell; when the winglet is used, the influence of the clearance vortex is reduced to 10% of the blade height. . The winglet not only reduces the size of the clearance vortex, but also weakens the intensity of the secondary flow in the channel. The pressure side winglet can block the mainstream fluid from entering the tip gap, thereby reducing the gap flow and the size of the gap vortex; while the suction side winglet can reduce the static pressure difference between the tip pressure side and the suction side , Can also weaken the gap flow, but the effect is weaker.

Although the winglet can reduce the gap flow, the following two serious problems exist in the use of the winglet, which makes it not feasible in industry: One is the cooling problem of the winglet. Affected by the gap flow, the winglet area will have a high heat transfer coefficient, but it is difficult to achieve cooling in this area, resulting in ablation phenomenon. The second is the problem of centrifugal stress. As the winglet increases the mass of the blade tip, the centrifugal force increases when the rotor blade rotates, the internal stress of the blade increases, and the blade life is shortened.

3.3. End wall treatment

Through the research on the first stage of GE-E3 turbine rotor blades, it is found that the heat transfer coefficient of the tip is greatly reduced after the end wall treatment, and the end wall treatment makes the phenomenon of insufficient air flow deflection alleviated. Through the irregular processing of the shell, the radius of the shell is minimized at the leading edge of the moving blade, then the radius of the shell increases smoothly, and finally the radius of the shell at the leading edge of the next row of moving blades reaches the minimum. This can accelerate the fluid near the leading edge of the rotor blade and reduce the static pressure difference at the tip, thereby weakening the gap flow. Irregular shell treatment can reduce the pressure gradient in the channel, reduce the secondary flow intensity, and the average total pressure loss of the cascade outlet section mass can be reduced by 50%. At the same time, the irregular shell can reduce the intensity of the tangential secondary flow in the flow channel and cause turbulence. The kinetic energy decreases and the channel vortex intensity decreases. In addition, increasing the shell roughness can reduce the gap flow rate, reduce the momentum loss in the gap vortex core area, and weaken the shearing effect of the gap vortex and the upper channel vortex.

3.4. Shell jet

By arranging small holes inclined to the pressure surface of the blades in different axial positions on the shells, high-pressure air is injected into the rotor blade flow passage to control the gap flow. The study found that the shell jet can affect the flow on the 50% blade height section, and reduce the blade outlet airflow angle in the range of 50~70% blade height, and increase the airflow angle in the range of 70~100% blade height.

Experiments show that the use of shell jet method can reduce the size of clearance vortex and upper channel vortex, and reduce the turbulence intensity in the vortex area by about 25%. Using proper jet position and jet volume can improve the isentropic efficiency of the turbine. The maximum efficiency occurs when the jet is 30% of the axial chord length from the leading edge of the blade, and the efficiency is increased by 0.55%. At the same time, the use of shell air jet reduces the sensitivity of gap flow loss to gap height changes. The shell jet can delay the formation of the gap vortex, and the flow through the gap can be reduced by about 11%.

3.5. Change the top shape

Foreign scholars have studied the influence of different blade tip shapes on gap flow through numerical methods. The study found that the rounding of the pressure side increases the gap flow rate. Although this part of the fluid does not participate in the formation of the gap vortex, it increases the unsteadiness of the flow and increases the flow loss; and the rounding of the tip suction side reduces the size of the gap vortex. , And has been maintained near the suction surface of the blade, and the mixing effect with the mainstream is weakened.

In addition, the researchers tried to use the method of chamfering the suction edge of the blade tip to reduce the loss caused by the gap flow, and specifically studied three different chamfer positions, including the leading edge position chamfer, the trailing edge position chamfer and the entire chord length direction. Diagonal cut. The chamfering of the leading edge increases the size of the clearance vortex and increases the flow loss. The chamfering of the entire chord length causes the gap flow to shift to the arc direction of the blade, but the flow loss increases. When the chamfer extends from the 40% chord length to the trailing edge position, the position of the clearance vortex is delayed, the size is reduced, and the flow loss caused is reduced. The reason for the reduction of the gap flow loss is that on the one hand, the secondary flow near the wall enters the gap and blocks the gap flow. On the other hand, the oblique cutting of the blade causes the gap flow to shift to the arc of the blade and the position where the gap vortex appears. put off.

4. Summary and outlook

Among the various control schemes mentioned above, the rib tip is currently the most common measure to control the gap flow. GE has adopted this technology in its aero engines and achieved certain performance.

Although the winglet can reduce the gap flow, because it is difficult to achieve cooling, high heat transfer areas will appear in the tip winglet area, which is very prone to ablation. Moreover, the centrifugal force increases when the rotor blade rotates after adopting the winglet, which leads to an increase in the internal stress of the blade and a shortened blade life. Therefore, it is not feasible in industry.

The method of controlling the gap flow loss by changing the shape of the blade tip pressure side/suction side will have completely different control effects under the influence of different blade shapes, operating conditions and other factors, so the scope of application is not large.

The end wall treatment and the casing jet solution are all realized by modifying the turbine casing. Among them, the end wall treatment scheme requires high machining accuracy in mechanical manufacturing, and although the shell air jet scheme can obtain better control effects, it also makes the housing geometry more complicated.

Therefore, more experiments and simulation methods should be explored to combine some of the above two or several independent control schemes in order to obtain a better turbine tip clearance leakage flow control effect. In addition, improving the position and arrangement of the cooling airflow holes in the turbine blades to suppress the gap flow, and arranging plasma generators inside the blades or on the end wall of the turbine to use plasma for flow control are also worth trying and exploring.

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