# Experiment on Effect of Tip Clearance Leakage Flow on Heat Transfer of Turbine Outer Ring

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**Abstract:** The cascade model was tested using transient liquid crystal temperature measurement technology. The effects of main flow Reynolds number, blowing ratio and tip clearance height on the convective heat transfer coefficient of the turbine outer ring were studied. Two feature lines were marked on the turbine outer ring corresponding to the position of the blade. The conclusions are as follows: The tip clearance leakage flow has a great influence on the convective heat transfer coefficient of the turbine outer ring. When the clearance height and the blowing ratio are kept constant, gradually increasing the main flow Reynolds number will result in an increase in the convective heat transfer coefficient of the turbine outer ring. When the clearance height and the main flow Reynolds number are kept constant and the blowing ratio is gradually increased, the convective heat transfer coefficient of the turbine outer ring is almost constant. The heat transfer coefficient of the turbine outer ring surface is little affected by the blowing ratio; The clearance height has great influence on the heat transfer characteristics of the turbine outer ring. Under the typical working condition in this paper, when the tip clearance height ratio is 1.6%, the convective heat transfer coefficient of the outer surface of the turbine is the highest.

**Key words:** tip leakage flow; film cooling; liquid crystal temperature measurement; heat transfer characteristics

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## 0 Introduction

In the working state of an aeroengine, due to the presence of tip clearance, the high temperature gas is driven by the pressure difference and passes through the clearance. This results in a complex leakage flow, which directly affects the air flow and heat transfer characteristics of the turbine outer ring. Factors such as the tip clearance height, the Reynolds number of the main flow and the blowing ratio of the blade can all affect the leakage flow of the tip. Predecessors have conducted considerable research via numerical simulation and experimental methods. For instance, Kou et al.[1] exhibited the influence of blade rotation, blowing ratio and film cooling hole arrangement on the cooling of the high pressure turbine outer ring by numerical simulation. And he increased the blowing ratio to strengthen the Gourd shaped air film under the action of the tip leakage vortex. Zhang[2] investigated the effects of blowing ratio and number of film cooling holes on the turbine outer ring at the blade rotation speed of 1 500 r/min. Wang[3] numerically studied the effect of the periodic conditions of turbine blades on the turbine outer ring outlet on the cooling efficiency of the film. Tang et al.[4] studied the distribution of surface temperature of the turbine outer ring at different impact distances via 3-D numerical simulation, and presented an optimal impact distance. Using the liquid crystal thermography, Tamunobere et al.[5-7] reported the heat transfer behavior of the shroud and the effectiveness of the shroud cooling of a single stage turbine at a low rotation speed. In addition, an experiment of film cooling on a gas turbine outer ring with a blade speed of 1 200 r / min was conducted, and the effects of the forward, backward and lateral injection

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on the shroud heat transfer and cooling behavior were investigated. Amerie et al.[8] investigated the heat transfer characteristics of the GE-E3 high-pressure turbine casing and the characteristics when the turbine casing was specially processed. The influence of the slotting operation on the heat transfer characteristics of the turbine casing was analyzed under different clearance height conditions. The conclusion indicated that the convective heat transfer coefficient of the upper surface of the turbine casing was slightly reduced due to the slotting of the turbine casing. Kwak et al.[9] studied the GE-E3 high-pressure turbine cascade, and the model is a two-dimensional flow channel composed of five blades. The paper focused on the influence of different tip clearance heights on the surface heat transfer coefficient of the casing. It was found that there was a high convective heat transfer zone near the blade pressure surface, which was caused by the impact of the tip clearance leakage flow on the casing. As the tip clearance height increased, the convective heat transfer coefficient on the casing decreased slightly. Chana et al.[10] obtained a certain heat transfer law of the blade and the surface of the casing via the MTI turbine test, and found that the corresponding position of the blade pressure surface was precisely the maximum convective heat transfer coefficient zone on turbine casing. Rhee et al.[11] studied the influence of the tip clearance height and inlet turbulence on the heat transfer characteristics of the casing in the flat blade tip. The study found that the convective heat transfer characteristics on the casing with tip clearance leakage flow were obviously different from those without tip clearance flow. The maximum convective heat transfer coefficient on the casing appeared at the corresponding position of the blade pressure side, and the maximum convective heat transfer coefficient increased as the gap height increased.

Up to now, most of the studies on the turbine outer ring have been accomplished via numerical simulation, and the test variables of the turbine outer ring were also relatively simple in some experiments. In this paper, the transient liquid crystal temperature measurement technology is used in the experiment, which is conducted considering three aspects: The main flow Reynolds number, the blowing ratio, and the tip clearance height. By analyzing the experimental results, the influence of the tip leakage flow on the heat transfer characteristics of outer surface of the turbine is comprehensively studied.

## 1 Experimental Devices

### 1.1 Experimental components

In this experiment, the first stage bucket of the GE-E3 high-pressure turbine is magnified three times and used as a simulation blade for the test. The specific parameters of the blade profile are the blade height of 122 mm, the axial chord length of 86.1 mm, the blade installation angle of 32.01°, and the outlet angle of 65.7°, as shown in Fig.1. The experimental section has two air inlets for supplying compressed gas to the main flow and the secondary flow separately. The main air inlet is connected to the cascade channel, while the secondary air inlet is connected to the cold air chamber, which provides cooling air for the film cooling holes. The cascade channel has an inlet height of 10 mm, a length of 310.7 mm, and a width of 125.3 mm. There are 15 film cooling holes with a diameter of 1.2 mm at 1.2 mm in front of the front line of the blade, and the distance between the holes is 15 mm. The high-speed camera is set above the cascade channel through a cold air chamber to capture the liquid crystal coloration results in the channel. The cooling gas entering the cold air chamber is provided by the compressor, and is discharged into the main flow pas-

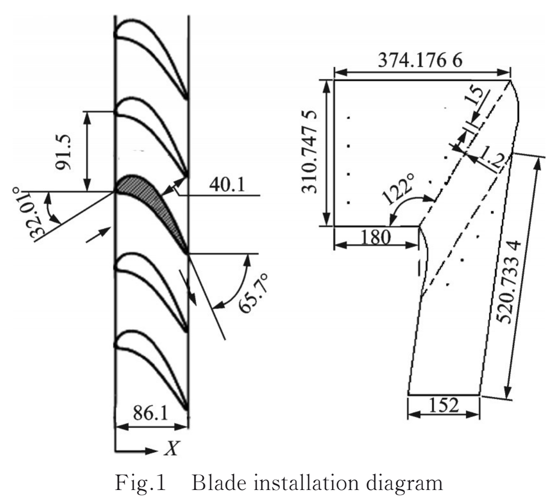


Fig.1 Blade installation diagram

sage through the air film cooling hole and converged with the main flow. The cold air chamber is connected to the cascade channel through the flange. The diameter of the inlet pipe of the cold air chamber is 40 mm, and the base area of the cold air chamber is 259.54 mm×1 258.78 mm with a height of 150 mm and a thickness of 5 mm, as shown in Fig.2.

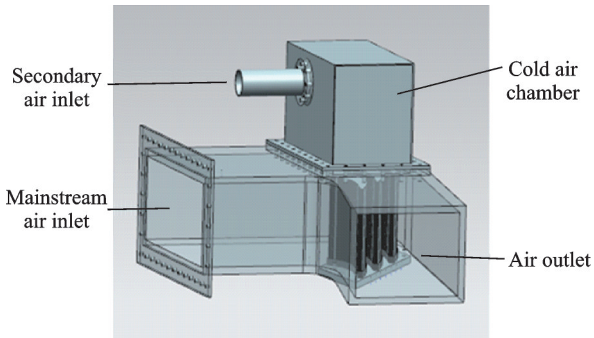


Fig.2 Schematic of experimental components

To ensure the accuracy of the tip clearance height, three blade models with different heights are machined before the experiment. The heights of the three blade models are 133.0, 134.3 and 135.0 mm[12-14].

Three holes with the same shape as the blade are machined on the lower surface of the cascade channel, and the lower plate is inserted into the cascade channel together with the fixed blades on the plate. The plate is fixed on the lower surface of the cascade channel, using bolted connections.

### 1.2 Experimental system

The experimental system is shown in Fig.3. The main air flow is supplied by the compressor of the wind tunnel. In order to ensure the drying of the compressed air, a drying device is necessarily used to remove moisture from the air. The main air flow is controlled by the valve, and the flow rate is measured by a flowmeter. After being stabilized by the pressure stabilizing device, the main flow enters the cascade channel. The flow is then adjusted until the cross-flow Reynolds number reaches the setting value. The gas source of the secondary air supply system is also provided by the air compressor. After the secondary air flows out from the air compressor, it enters the surge tank and passes through the cold air chamber after being stabilized by the pressure stabilizing chamber. The airflow then enters into the cascade channel through the cold air chamber and is discharged into the atmosphere after being mixed with the main flow[15-17].

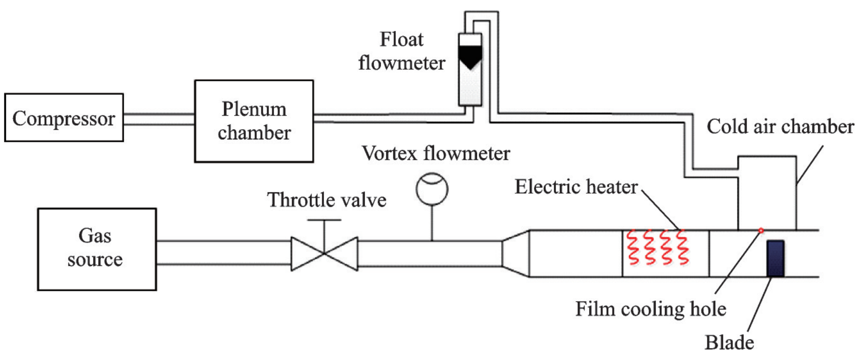


Fig.3 Schematic of experimental system

In the experiment, the inside of the electric heater for heating the main flow (Fig.4) is a resistance exothermic element inside, and the exothermic element is a combination of six carbide rods, which are uniformly distributed in the circumferential direction of the pipe. The carbon rod uses a 380 V three-phase power with a maximum power of 200 kW. The heating control cabinet is used to control the heating power, and the digital temperature controller in the control cabinet maintains the temperature control accuracy at ±1 ℃.

Fig.4 Electric heater

The main flow range of this experiment is calculated to be 0—0.6 kg/s, thus the range of vortex flow meter used for measurement is 320—2 000 /h. The flow rate of the secondary flow is measured with a float flow meter with a range of 0.25—2.5 $m^3$/h. The pressure measurement points and the temperature measurement points are set before and after the flow meter intake, and the actual mass flow rate is obtained by the compensation calculation.

During the experiment, it is necessary to measure the static pressure before and after the blades and the static pressure after the flow meter. The static pressure measurement points of the blades are distributed on the lower surface of the cascade channel, where there is a measurement hole with a diameter of 1 mm. A static pressure probe with a diameter of 0.8 mm is inserted into the hole to extract the gas and connected to the pressure sensor via a hose. The pressure sensor model number is CYG1601 with an accuracy rating of 0.25, as shown in Fig.5. At the same time, the static pressure after the flow meter is measured with a BP-801 pressure transmitter.

Fig.5 Pressure sensor diagram

The temperature is measured with a K-type thermocouple ( ±0.75%) with a range of −40 to +350 ℃ , which is used together with the multichannel temperature tester JK-48U to measure the inlet temperature of the cascade channel and the temperature of the airflow after the flow meter. The liquid crystal temperature measurement technology is used in the experiment. The pitch of the liquid crystal changes with temperature. When a beam of light is irradiated onto the surface of the liquid crystal, only that with a wavelength equal to the molecular rotation pitch can be reflected back, exhibiting different colors, and the temperature is measured due to this characteristic. A high speed camera is used to record the different colors that the liquid crystal layer displayed at different temperatures. The images captured by the camera are processed by a self programming program to obtain the temperature distribution of the turbine outer ring surface.

The temperature range of liquid crystal is 40 ℃ to 60 ℃, and therefore the total temperature of the main flow in the experiment is set to 338 K. The main flow Reynolds number is calculated based on the main flow rate, and the calculation formula is Eq.(1). The above determines all the main flow gas parameters.

$$Re_{\infty} = \dot{m}_1 d / \mu A_1 \tag{1}$$

where $\dot{m}_1$ is the the main flow rate measured by the flowmeter, $d$ the equivalent diameter of the main flow cavity, $\mu$ the dynamic viscosity, and $A_1$ the area of the main flow cavity.

The temperature of the secondary flow provided by the surge tank is 293 K, and the secondary flow rate is determined by the blowing ratio and the main flow. In the experiment, the main flow temperature and the main flow and secondary flow temperature ratio are kept unchanged[18]. The definition of the blowing ratio $M$ in the test is

$$M = \frac{\rho_2 u_2}{\rho_1 u_1} = \frac{\dot{m}_2 / A_2}{\dot{m}_1 / A_1} \tag{2}$$

where $\dot{m}_2$ is the secondary flow and $A_2$ the outflow area of the secondary flow.

The test conditions are shown in Table 1. For the typical working condition, $\tau/H$=1.6% ($\tau$ is the blade tip clearance and $H$ the blade height), and to be specific, the tip clearance is 1.97 mm, the main

**Table 1 Different experimental conditions**

| Main flow Reynolds number / $10^4$ | Blowing ratio | Gap to height ratio / % |
|---|---|---|
| 6 | 1 | 1 |
| 7 | 1.5 | 1.6 |
| 8 | 2 | 2.7 |
| 9 | 4 | |
| 10 | | |

flow Reynolds number is 80 000, and the blowing ratio is 1.5. The remaining control trials only change one type of the variables.

In the experiment, the maximum flow velocity is 11 m / s and the maximum Mach number is 0.03.

## 2 Photonic Arbitrary-Waveform Generation

### 2.1 Analysis of typical working conditions of turbine outer ring test

The typical working condition is taken as an example, of which a temperature contour is given in Fig.6 according to the experimental data processing results. In Fig.6, the heat transfer coefficient at the position of the turbine outer ring surface corresponding to the blade region is higher, and the heat transfer coefficient at the turbine outer ring surface outside the blade region is lower. This indicates that the tip clearance leakage flow has a great influence on the heat transfer coefficient of the turbine outer ring surface. While the motion law of the tip clearance leakage flow is complicated, the tip clearance leakage flow continuously impacts the tip and turbine outer ring surfaces in the clearance, and then a heat transfer coefficient increase zone of the turbine outer ring surface is formed. In Fig.6, there is a relatively low heat transfer coefficient region at the leading edge of the blade. This is because the blade is thicker at the leading edge and the pressure difference is smaller, which makes the air movement slower, and as a result, the heat transfer coefficient is lower. Two feature lines are marked on the temperature contour corresponding to the position of the blade, as shown in Fig.7. By analyzing the change of heat transfer on the feature line, the influence law of several parameters on the surface heat transfer coefficient of the turbine outer ring is found.

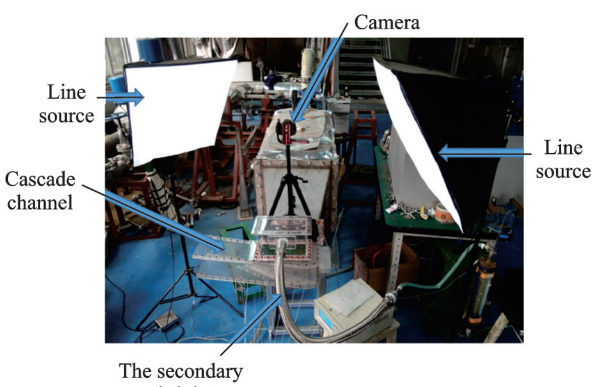


Fig.6 Physical photo of the test

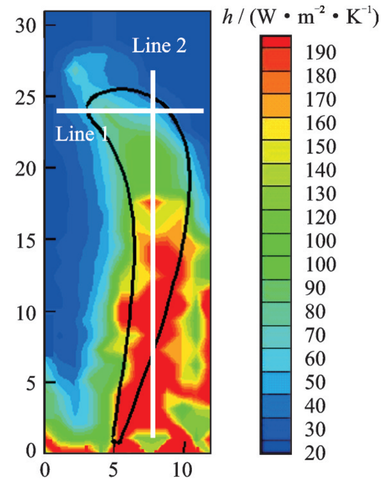


Fig.7 Schematic diagram of typical working conditions

### 2.2 Influence of main flow Reynolds number on surface heat transfer characteristics of turbine outer ring

Fig.8 shows the relationship between the heat transfer coefficient on the feature Line 1 and the main flow Reynolds number, where $X/C_{\mathrm{axial}}$ represents the relative position on the feature Line 1. The abscissa is the dimensionless axial distance and the ordinate is the turbine outer ring heat transfer coefficient. As shown in Fig.8, when the main flow Reynolds numbers are different, the heat transfer coefficient changes on Line 1 are almost the same, increasing first and then decreasing. It can be seen from the corresponding position of the blade on

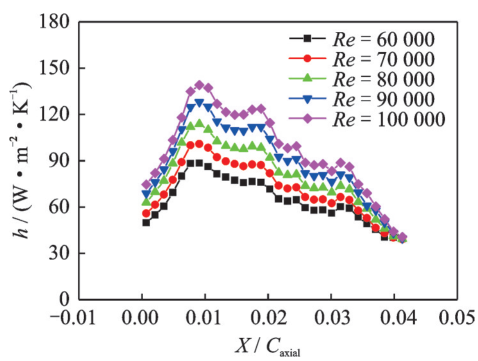


Fig.8 Influence of main flow Reynolds number on distribution of heat transfer coefficient on feature Line 1

Line1 that the heat transfer coefficient on the feature line suddenly increases to a peak at the pressure side position of the blade, and then gradually decreases. When the feature Line 1 is in the tip clearance, the heat transfer coefficient fluctuates continuously along the feature line. As the leakage flow flows out from the tip clearance, the heat transfer coefficient of the feature line at the suction side of the blade decreases rapidly. It can be clearly seen that as the main flow Reynolds number increases, the heat transfer coefficient on Line 1 also increases. This is because the larger the main flow Reynolds number is, the larger the inlet flow rate of the main passage is, and the more the flow leaking into the tip clearance becomes. When the main flow Reynolds number is 60 000, the convective heat transfer coefficient of the turbine outer ring surface is the smallest. When the main flow Reynolds number is 100 000, the convective heat transfer coefficient of the turbine outer ring surface reaches its maximum, which is 36% higher than the minimum value. And the increasing main flow Reynolds numbers increase the percentage of convective heat transfer coefficient on the feature line by 14%, 12.8%, 12.5%, and 8.6%.

Fig.9 shows the variation of the heat transfer coefficient on the feature Line 2 with the main flow Reynolds number, where $Y/C_{axial}$ represents the relative position on the feature Line 2. It can be seen that the heat transfer coefficient increases less before the airflow enters the gap. With the mixing of the main flow and the leakage flow, the leakage flow impacts back and forth between the turbine outer ring surface and the blade tip, thereby enhancing the convective heat transfer at the impact point. As the leakage flow flows out of the tip clearance, the fluctuation of the heat transfer coefficient on the Line 2 is relatively reduced. Furthermore, the heat transfer coefficient on the feature Line 2 is basically increasing when the main flow Reynolds number is increasing.

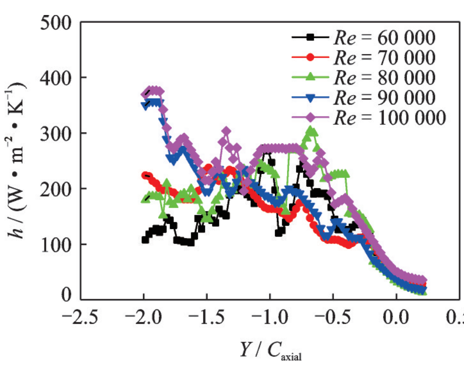


Fig.9 Influence of main flow Reynolds number on distribution of heat transfer coefficient on feature Line 2

### 2.3 Influence of air blowing ratio on heat transfer characteristics of turbine outer ring surface

Fig.10 is a curve of the heat transfer coefficient on Line 1 as a function of the blowing ratio $M$. It can be seen from Fig.10 that when the blowing ratios are different, the heat transfer coefficient on Line 1 changes almost the same. It can also be found that when the blowing ratios are different, the heat transfer coefficient on Line 1 corresponding to the area before the airflow enters the clearance is basically unchanged. After the leakage flow flows out of the tip clearance, the heat transfer coefficients are similar on the feature line when the blowing ratio is 1, 1.5 and 2, and when the blowing ratio is increased to 4, the heat transfer coefficient on Line 1 is somewhat decreased compared with those under other blowing ratio conditions, by about 27%.

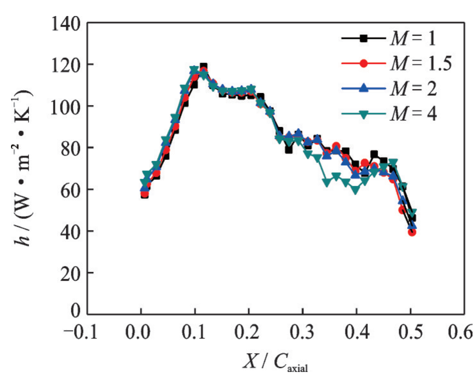


Fig.10 Influence of blowing ratio $M$ on heat transfer coefficient on feature Line 1

Fig.11 shows the curve of the heat transfer coefficient on Line 2 as a function of the blowing ratio $M$. As can be seen from Fig.11, multiple peaks of the heat transfer coefficient appear in the tip clearance because the leakage flow continuously impacts the turbine outer ring surface. In addition, in

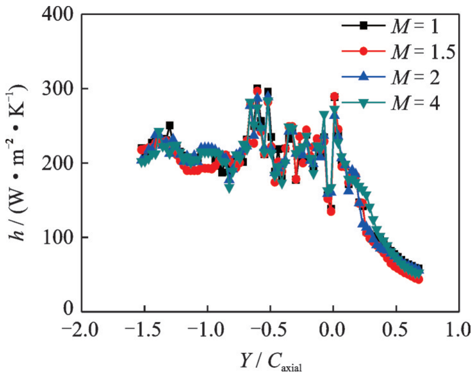


Fig.11 Influence of blowing ratio $M$ on heat transfer coefficient on feature Line 2

Fig. 11, after changing the blowing ratio, the heat transfer coefficient on the feature line is less affected. Based on a comprehensive analysis of Figs. 10, 11, the blowing ratio has little effect on the convective heat transfer coefficient of the turbine outer ring.

### 2.4 Influence of tip clearance height on heat transfer characteristics of turbine outer ring

Fig.12 is a curve of the heat transfer coefficient on Line 1 as a function of the tip clearance height. Under different clearance heights, the heat transfer coefficient of the turbine outer ring along Line1 exhibits the same change law, first increasing and then decreasing. The maximum of the heat transfer coefficient occurs at the position where the leakage flow flows into the tip clearance, and the minimum appears to be at the position where the leakage flow flows out of the tip clearance. It can also be seen from Fig.12 that the relatively suitable clearance size is $\tau/H = 1.6\%$ under this typical working condition, and the turbine outer ring surface heat transfer coefficient is increased by about 53% compared with that when $\tau/H = 2.7\%$. The reason is that when the clearance height is large, the influence of the entrance effect and the fluid acceleration is weakened, and the leakage flow rapidly flows out of the tip clearance. Hence, the influence of the heat transfer coefficient on the turbine outer ring surface is weak; and when the clearance height is reduced, the tip clearance leakage flow decreases. Therefore, the convective heat transfer coefficient on the surface of the turbine outer ring also decreases.

Fig.13 shows the influence of the tip clearance height on the distribution of the heat transfer coefficient on Line 2. When the feature line passes through the corresponding tip clearance position, the change of the heat transfer coefficient on the feature line is complicated, and a significant difference appears with different clearance heights. The heat transfer coefficient corresponding to the tip clearance region on the feature line fluctuates greatly, and there is a plurality of points with a high heat transfer coefficient. The reason is that the leakage flow and the main flow are mixed in the tip clearance, and the turbine outer ring surface is subjected to multiple impacts, thus resulting in an increase in the heat transfer coefficient at the impact point. It can also be seen from Fig.13 that when the tip clearance height ratio $\tau/H = 1.6\%$, the heat transfer effect is optimal, and the maximum heat transfer coefficient in the leakage clearance is about twice that of the other states.

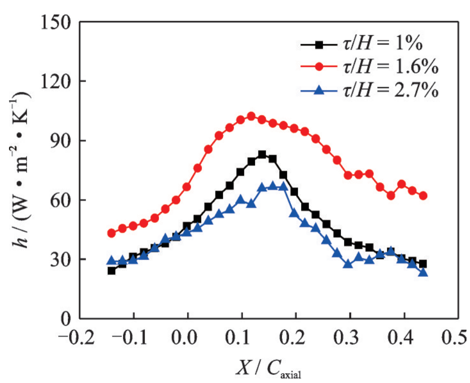


Fig.12 Influence curves of tip clearance height on heat transfer coefficient on feature Line 1

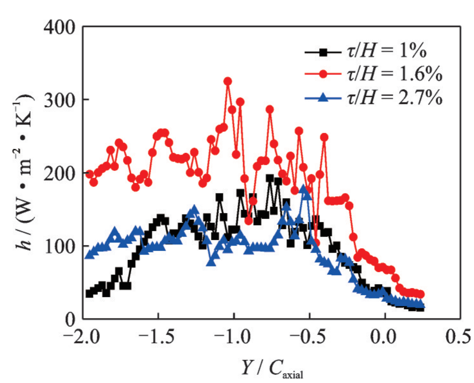


Fig.13 Influence of tip clearance height on heat transfer coefficient on feature Line 2

## 3 Conclusions

The following conclusions can be drawn from the experiment.

The heat transfer effect of the outer surface of the turbine is greatly affected by the tip clearance leakage flow. Increasing the main flow Reynolds number as well as maintaining the same gap height and blowing ratio will result in more leakage flowing into the tip clearance. At the main flow Reynolds number of 100 000, the convective heat transfer coefficient is increased by 36%, compared with that when the main flow Reynolds number is 60 000.

Under the condition of keeping the gap height and the main flow Reynolds number unchanged, by the way of comparing and analyzing the leakage amount entering the tip clearance when several sets of different blowing ratios are obtained, it is found that the tip clearance leakage is less affected by the blowing ratio. Therefore, the blowing ratio has little effect on the convective heat transfer coefficient of the turbine outer ring.

Changing different gap heights, the heat transfer coefficient of the outer ring surface of the turbine at the tip clearance changes complicatedly. Too much or too little leakage flow will result in a decrease in the heat transfer coefficient of the outer surface of the turbine. Under typical conditions with a clearance height ratio of $\tau/H = 1.6\%$, the maximum heat transfer coefficient can be twice that under other height ratio conditions, meanwhile the overall heat transfer effect is optimal.

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Dr. **JIN Feng** is an associate professor in Nanjing University of Aeronautics and Astronautics. His research interest focuses on heat transfer of aeroengine.

**Author contributions** Mr. **LIU Tianyi** carried out the experiment, collected important background information, and wrote the manuscript. Mr. **YANG Jiang** and Mr. **WEI Xin** participated in the design of this study, and they both performed the statistical analysis. Dr. **JIN Feng** contributed to the general validation and verification of the results. All authors commented on the manuscript draft and approved the submission.

**Competing interests** The authors declare no competing interests.

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# 叶尖间隙泄漏流动对涡轮外环换热影响的实验

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**摘要:**使用瞬态液晶测温技术对叶栅模型进行了实验,研究了主流雷诺数、吹风比和叶尖间隙高度对涡轮外环表面对流换热系数的影响。结果表明:叶尖间隙泄漏流对涡轮外环表面对流换热系数的影响很大。当保持间隙高度和吹风比不变时,逐渐增大主流雷诺数,导致涡轮外环表面的对流换热系数升高;当保持间隙高度和主流雷诺数不变时,逐渐增大吹风比,涡轮外环表面对流换热系数几乎不变,外环表面换热系数受吹风比的影响很小。间隙高度对外环表面换热特性的影响很大,在典型工况下,当叶尖间隙高度比为1.6%时,涡轮外环表面的对流换热系数最高。

**关键词:**叶尖漏流;气膜冷却;液晶测温;换热特性