Flow and heat transfer characters in the integral internal cooling channel of a turbine blade

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Abstract. A scaled model of the integral internal cooling channel of a turbine blade was established for the experimental investigation. The model was made by Perspex for its transparency so that the thermochromic liquid crystal measurement could be used easily. The cooling channel is composed of 3 legs of ribbed channels. Rib with angle 45° was settled in both pressure side and suction side, which forms a cross-rib structure. Three legs were connected by two 180° turns. The main inlet and two addition inlets were arranged in the root of the model channel. Two discharge outlets were located in the tip. A row of outlet holes was distributed along the trailing edge. The channel area gradually decreases along the blade height direction, while bending and torsion occur because of the blade airfoil shape. The aspect shapes and connection methods of the channel were kept in accordance with the real blade. The inlet Reynolds number is from 10000 to 32000. Five outlet discharge ratios were alternated in this investigation. The detailed heat transfer distributions, both in the pressure side and suction side, were measured by transient liquid crystal technique. The characters of heat transfer distribution and pressure drop along the channel were displayed. The effects of flow discharge ratio on heat transfer and pressure coefficient were also described.

1. Introduction
In order to increase the specific power and thermal efficiency, the inlet temperature of gas turbine is getting higher and higher. The reasonable measure must be taken to ensure the safety of turbine. Although both the gas temperature and allowable temperature of turbine metal are increasing gradually, the gas temperature increases faster. Effective cooling method and reasonable cooling design are inevitable technical approaches.

The ribbed channel is widely used for internal cooling in turbine blades. In view of the basic flow structure in the simplified ribbed channel, J C Han et al. [1] investigated the heat transfer performance in the channel in the static state, and obtained the relationship between the heat transfer performance of the channel with structural parameters, such as the aspect ratio of the channel, the rib arrangement, and aerodynamic parameters, such as Reynolds number. Casarsa [2] and Graham et al. [3] reported more detailed flow distribution obtained through experiments and clarified the flow structure. The results revealed more intuitively the mechanism of heat transfer enhancement in the ribbed channel. Usually, the real internal cooling channel of the turbine blade is a multi-leg channel which is combined with straight passage through U-turn. Due to the U-turn connection, the flow structure is more complex, and the heat transfer performance may differ from the straight channel, which was used in heat transfer investigation. Some research studied U-shape (two legs) and S-shape (three legs) multi-leg ribbed channels, and the flow and heat transfer characteristics of each cooling unit were analyzed. S.Y. Son et al. [4] performed the experimental investigation using PIV and transient liquid
crystal measurement technology. The flow structure and temperature distribution around the bending area in the smooth and ribbed U-shape channel were measured. The results show that the heat transfer enhancement is closely related to the shape, strength, position and rotation direction of the secondary flow. The mechanism of second flow produced by the combined effect of the rib and bending of the channel, and further the influence of the second flow to heat transfer characteristics were elaborated. Smith M. A. et al. [5] studied the heat transfer characteristics of the serpentine ribbed channel with different aspect ratios, and found that the heat transfer enhancement was more significant under the high Reynolds number condition. Under the combined action of the vortex formed by turning and the secondary flow generated by rib, the heat transfer in the middle chord passage is greatly enhanced. Murata A. et al. [6] investigated the effect of rib orientation on the flow pattern in a channel with a 180° turn rectangular channel. The results show that the heat transfer distribution and performance in the bending area is directly influenced by the flow field caused by a sharp turn. In order to obtain higher heat transfer performance, the combined effect of rib orientation and bending effect should be considered together. Schuler M. et al. [7] studied the heat transfer in a U-shape trailing edge channel with lateral bleeding. Compared with the channel without lateral bleeding, the heat transfer of the side wall and the region near the bleeding holes is augmented while air flow out through lateral holes. As some fluids flowed out of the outlet hole, the cooling flow rate in the passage was reduced, and the heat transfer coefficient of the downstream passage was decreased.

Schabacker J. et al. [8] and Murata A. et al. [9] performed the flow character investigation in U-shape channel. The flow pattern affected by U-turn and heat transfer augment mechanism is presented.

The investigations mentioned above are performed in a simplified rectangular channel. In the actual blade, leading edge and trailing edge channel is usually not rectangle. The cooling channel may screw because of the blade airfoil. To consider the effect of these factors and the influence of the cooling channels connection, the heat transfer was measured by transient liquid crystal technique in a complete internal channel. The heat transfer distribution and pressure coefficient were characterized. The results may provide a useful reference for the design and improvement of turbine blade cooling structure.

### Nomenclature

| Symbol | Description                               | Greek symbols | Subscript |
|-------|-------------------------------------------|---------------|-----------|
| c     | Specific heat of model metal              |               |           |
| Cp    | Pressure coefficient                      |               |           |
| D     | The equivalent diameter of the channel    |               |           |
| h     | Heat transfer coefficient                 |               |           |
| P*    | Total pressure                            |               |           |
| Re    | Reynolds number                           |               |           |
| T     | Temperature                               |               | inlet of passage |
| t     | Time                                      |               | outlet of passage |
| U     | Velocity                                  |               |           |
| x     | Wall thickness                            |               |           |

### 2. Experiment approach and facility

The structure of the internal channel is shown in Figure 1(a). The channel is a 3-leg serpentine channel which consists of 3 ribbed passage and 2 U-shape turning. The channel is bent and screwed because of the blade airfoil shape. In the leading edge and trailing edge, the section of the passage is almost triangle. The section of the passage in the mid-chord region is approximately rectangle. The channel has 3 inlets. The most of fluid flow into the channel in the root of the leading edge. The inlet located in root near the mid-chord and trailing is for supply some coolant for trailing edge passage. At the top of the leading edge passage and trailing edge passage, there is a bleeding hole separately. A row of bleeding holes is located in the trailing edge.

The experiment model is scaled 6 times. The shape of the experiment model is the same as the generic channel. The bending and screwing characters are also kept. Transparent plexiglass was used as the material of the test model for acquiring the image of the liquid crystal. The model is split into
two parts along the blend bending direction for liquid spraying. The model can be assembled by bolts and ensure the airtightness. In order to ensure the uniformity of air intake, there is an inlet cavity at the front of inlets. The flow rate of the two outlet holes at the tip of the blade was measured by a flow meter. The 45° inclined ribs are equipped in the wall of the pressure side and suction side of the channel. The ribs in the opposite wall are arranged vertically.

Figure 2 is a schematic diagram of the experimental system. The air in the experimental system is provided by the compressor and the tank. The air flow is measured and regulated by flow meter and valve. The regulated air flows into the model through the heater and solenoid valve group. The air flow out from two top outlets is measured and regulated by a flow meter and valve for discharge ratio. The thermocouples are arranged in channel of the model. The temperature of the air flow is measured under the computer control. The color history of the liquid crystal on the inner surface of the channel is recorded by the camera.

![Diagram](image)

(a) Internal structure  (b) Assemble sketch  (c) Photo

**Figure 1.** Experiment model

Before the test, the power of the heater was shut down. The solenoid valve 1 was opened. The solenoid valve 2 was closed. The flow rate at the inlet of the model was regulated by valve in front of the model. The outlet discharge ratio was regulated by the valve at the back of the top bleeding hole. After the experimental condition are achieved, the solenoid valve 1 was closed and the solenoid valve 2 was opened. The air flow was diverted away from the model while the heater increased the air temperature to the preset value. At the beginning of the test the solenoid valve group switched the situation, the hot air flowed into the model at the desired flow rate, temperature. At the same time, the temperature of air and color are being captured.

Before of the test, the model has uniform initial temperature distribution. While the temperature of the air contacting the model rises suddenly, heat convection takes place between the air and the wall. The temperature of the wall increases and the heat conduct into the wall. The temperature change history relates to the heat transfer coefficient, the initial temperature, the thermal physical properties and the air temperature history. Therefore, under the condition that the thermal properties of the experimental model are known, as long as the initial temperature of the experimental model, the initial temperature of the model, temperature rise process of the airflow and the change history of the wall temperature are recorded, the heat transfer coefficient of the wall surface can be calculated according to the thermal conductivity
theory. In order to simplify the analysis and data processing, the experiment is usually completed in a relatively short time. At this condition, the heat conduction inside the model from one side has not reached another surface, that is, the experimental model is in a semi-infinite heat conduction state. The analysis solution can be used to calculate the heat transfer coefficient.

3. Results and discussions

3.1. Heat transfer distribution

The inlet Reynolds number is from 10000 to 32000. The heat transfer distribution at different Re and discharge ratio are similar. Figure 4 shows the flow pattern and heat transfer distribution at the condition of Re=17000, outlet discharge ratio is 28:29:43.

3.1.1. Pressure side

Figure 3(a) and (b) show the flow pattern near the pressure side and heat transfer distribution of the pressure side wall. In this side, although the shape of the inlet channel was changed before the test region, the inlet velocity is nearly uniform. The heat transfer distribution is uniform approximately. The inclined ribs are directed to the top of the leading edge. As a result in simplified channel, the second flow generated by inclined ribs interference with the side wall, the heat transfer enhancement effect is best at sharp angle region back of the rib. The high heat transfer region directs to downstream along the ribs and becomes weakened. Therefore, the heat transfer at the leading side is higher than that in the division side.

There are two higher heat transfer regions at the turning of the leading edge passage. One higher heat transfer region is formed at sharp region downstream the rib. This region is close to the sharp angle at the back of the rib and the division of channel. The shape of the region deviates to the second passage caused by the turning of the passage. The other is at the outer of this high heat transfer region. In the Figure 3(a), this region is caused by bleeding at the top of the leading edge passage. The bleeding makes more fluid flow to the wall after the rib. The experimental result shown in Figure 3(b) indicates that these two regions can be distinguished but are very close. Because of the centrifugal effect caused by turning of passage, the airflow impinges the blade tip and forms another high heat transfer region at the top of the passage. After that, the fluid continues to flow along the outer side of the bend. At the top of the second division, the high heat transfer region is formed caused by the joint action of bending and rib. In addition to the strong overall heat transfer in region 2, part of the fluid flows along the leading edge of the rib and forms a strong heat transfer region which effectively improves the heat transfer in the backflow region.

![Figure 3. Flow pattern and heat transfer distribution (Re=17000)](image)
heat transfer effect is stronger at the inlet of the second passage. This effect is almost throughout the whole passage. The overall heat transfer is stronger than that in the first passage.

Near the turning at the root, the bending effect and air supplement effect act on this region together. As the Figure 3(a) shows, the flow area is expanded. The velocity here is slow down and the centrifugal effect is small. On the other hand, the supplement effect makes the airflow from the second channel closer to the inner of the bend. This helps to reduce the low heat transfer region caused by the backflow.

The heat transfer in the trailing edge passage is the weakest among the three passages. Affect by the turning and bleeding at trailing edge, the air flow into the passage deviate to the trailing edge. Part of airflow bleeds out from the hole in trailing edge. The backflow region near the division is relatively broader. Therefore, the broader low heat transfer region is produced. The bleeding at the top of the third passage makes part of airflow to the top. This is a positive effect to reduce the low heat transfer region and improve the heat transfer performance to some extent. There is a higher heat transfer region 3 which located in the middle of the passage. This region is generated by higher velocity flow caused by air supplement of the middle inlet.

3.2. Effect of discharge ratio

The heat transfer distributions in the case of Re=21000 and various discharge ratio are shown in Figure 4. The results at other Re is similar to this. Although the heat transfer distribution is different in the suction and pressure side, the trend of heat transfer with discharge ratio is similar. All three bleeding outlets are located after the first passage. Therefore the change of discharge ratio seldom affects the first passage. Generally speaking, the flow rate of outlet 1 increase may lead to the change of flow pattern in first turning and reduce the flow rate enter into the second passage. The bleeding through outlet 1 affects these two
regions significantly. In the case of the discharge ratio is 10:36:54, the flow rate in second passage is maximum, the heat transfer is strongest. In another case, the heat transfer in the first turning and second passage become weak in various extents while the flow rate of outlet 1 increase.

But in the case of the discharge ratio is 40:24:36, the flow rate of outlet 1 is maximum, the heat transfer in the second passage is not the weakest. This means the flow pattern in the turning zone affects the second passage obviously too. The change of discharge ratio may also lead to the change of pressure distribution in the channel, then alter the enter condition of three inlets. The heat transfer in the second turning zone may be changed. In the third passage, whether bleed in the top of passage affects the heat transfer obviously. The effect of bleeding ratio on heat transfer is relatively small. The effect on average heat transfer performance is also small.

4. Conclusions
The flow character and heat transfer distribution are investigated in a real shape internal cooling channel. The conclusion can be drawn:

1) The general characteristics of heat transfer distribution in the real channel are similar to those in the ideal unit structure, but the detailed distribution characteristics are obviously different due to the influence of channel shape, inlet state and other factors.

2) The heat transfer characteristics at the junction of the channel and the mid-chord passage are most affected by the flow deflection and outflow. When the ribs in the turning zone are vertical with airflow, the heat transfer distribution in the deflection area is more uniform. The heat transfer enhancement in the second channel is also better. The bleeding at the top of the trailing edge passage is helpful to improve the heat transfer in the passage.

3) The influence of discharge ratio on heat transfer presents a general trend. But it not clear for some discharge ratio because of the complex influence factors.

4) The measurement in actual structure of internal cooling channel by transient liquid crystal testing technique can provide the detailed heat transfer distribution of the complex wall surface, which is helpful to understand the heat transfer characteristics and the heat transfer enhancement mechanism.

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