Measurements of heat transfer and pressure in a trailing edge cavity of a turbine blade

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Abstract An experimental investigation is conducted to obtain the heat transfer and pressure drop data for an integral trailing edge cavity test section that simulates a novel turbine blade’s internal cooling passage with bleed holes. Local heat transfer is measured on both the suction and pressure sides by a transient liquid crystal technique, while pressures at six positions are recorded by pressure calibrators. Moreover, flow characteristic and its effect on heat transfer are analyzed for conditions with or without bleed flow. The experimental results show that, in the cases with bleed flow, local heat transfer on the pressure side exceeds that on the suction side in the first and second channels. In the cases without bleed flow, in the first and third channels, local heat transfer on the suction side weakens whilst it increases significantly on the pressure side. For the second channel, non-bleed condition leads to a more balanced heat transfer distribution between the upstream and downstream channel. Besides, after the bleed holes are blocked, heat transfer in the first bend region on the suction side declines sharply, while the opposite phenomenon occurs for the second bend region on the pressure side. In both bleed and non-bleed cases, the total pressure of six measurement positions decreases continuously along the channel at the same Reynolds number and it promotes for higher Reynolds number. Among all the measurement points, under the same flow rate condition, the highest speed occurs at Position 5, which also shows the maximum difference between the total and static pressures. When the bleed holes are blocked, the total pressure at each measurement position appears to increase.

1. Introduction

As important heat components of aeroengines, turbine blades could easily be damaged or even fatigued to rupture under conditions of high temperature, high rotation speed, and high pressure. Therefore, the overall heat transfer conditions on the inner surface of a blade are demanded as references for blade design and breakdown diagnosis. An important part of a turbine blade, the trailing edge, has narrow internal space and is
easily eroded by high temperature gas. Consequently, it needs adequate and efficient cooling.

A real-world turbine blade channel contains many cooling structures, such as pin fins, blockage with holes, ribs, bleed holes, trailing edge exit slots, and so on. A special cooling layout which is composed of several structures takes on the heat transfer task in the trailing edge cavity.

Pin fin, suitable for heat transfer in a narrow space, is a typical cooling geometry in trailing edge passages. Metzger et al. and van Fossen started research on circular pin fins early in 1982. Chyu et al. experimentally investigated the effects of pin fin shape in staggered arrays on heat transfer enhancement. The results revealed that at the same Reynolds number, the cubic and diamond pin fin arrays performed better in heat transfer than circular ones did. However, the circular pin fin array yielded the least pressure loss among the three arrays. To reduce flow resistance further, Jaswal and Ames chose a rounded diamond pin fin array as their object of study. Bianchini et al. studied a circular pin fin array by numerical and experimental methods. More than one hundred pin fins, arranged into seven rows of staggered arrays and an innovative pentagonal layout, respectively, were inserted in a trailing edge duct to improve the heat transfer.

Simply arranging pin fins cannot sufficiently supply the heat transfer demanded in a trailing edge duct. Hence, blockages with holes often appear in cooling layout designs to further increase the heat transfer coefficient. Lau et al. investigated the heat transfer of blockages with holes in an internal cooling passage near the blade trailing edge by conducting naphthalene sublimation experiments. The results showed that the heat(mass) transfer was higher in the downstream part of the second rather than the first blockage. Taslim and Nongsaeng measured the local and average heat transfer coefficients in a trailing edge cavity by a steady-state liquid crystal technique and investigated two test sections with different jet angles. In Ref., the conjugate heat transfer in a blade channel near the trailing edge was measured experimentally, with the Reynolds number set at 67500. Distributions of non-dimensional temperature and Nusselt number were obtained using infrared thermography and finite element analysis.

In view of the trailing edge encountering the impingement from high temperature gas, bleed holes are usually punched on the pressure side to form cool films as a gas barrier. Meanwhile, bleed flow produces effect on the flow in the trailing edge duct and changes the local heat transfer distribution. Amano et al. laid 90° and 45° rectangular pins in a square channel, with bleed holes between adjacent ribs. Three different turbulence models were used for heat transfer simulation and comparison with experimental results. Ekkad et al. presented local heat transfer coefficient distributions in a two-pass square channel with a 180° turn. Though 20–25% of the inlet mass flow leaked out of the bleed holes, regional-averaged heat transfer result showed that the heat transfer enhancements were similar on the surfaces with or without bleed holes. Thurman and Poinset obtained the distributions of heat transfer and mainstream temperature in a simple three-pass serpentine channel to investigate the influence of the interaction between ribs and different bleed conditions on internal cooling. Chanteloup and Bölcs studied the flow in stationary two-pass internal cooling passages by a stereoscopic PIV technique. Bleed holes existed in the bend and second pass and the total bleed flow accounted for 50% of the inlet mass flow. The bleed flow altered the flow field near the film holes and the upstream part of the first pass. It also affected the secondary flow motions greatly.

In addition, Lee et al. experimentally studied the local heat(mass) transfer distribution in a two-pass trapezoidal channel with a 180° bend. Metzger and Sahn measured the heat transfer coefficient and distribution in the 180° bend of a smooth rectangular channel. Up to nine models were employed to examine the effects on heat transfer from two factors: the ratio of inlet to outlet channel widths and the clearance between the divider and top wall. Metzger et al. considered the geometry factor in a trailing edge and found that the flow acceleration in a wedge-shaped cavity reduced the effect of Re on Nu.

Recently, Eifel et al. presented the functions of major geometric configurations inside a turbine blade and conducted flow analysis experimentally via a flow visualization method that injected dyes into water. Flow and heat transfer were simulated by the shear stress transport (SST) turbulence model. The Reynolds number at the baseline model inlet was set at 50000. The results showed that, with the substitution of crossed ribs for parallel staggered ones in the leading edge channels, the cooling effectiveness was increased by 12.5% and the maximum wall temperature gradient declined by 33.5%. Meanwhile, a combination of staggered ribs in the first channel and pits in the second resulted in a 10% higher cooling effectiveness and 32% lower maximum temperature gradient than those from crossed ribs.

In the past, researchers used to separate local flow channels from a complete blade cavity in their studies. The flow conditions at inlet or outlet may deviate from the real conditions and this could affect the results. For the purposes of meeting the needs of engineering applications and providing more experimental results as references, it is necessary to analyze the local flow and heat transfer in an independent and integral blade channel. The experimental model in this paper, based on the integral trailing edge cavity in a blade, is novel and complex in its internal cooling structure, which contains staggered ribs, bends, bleed holes, pin fins, and trailing edge exit slots. By analyzing flow and heat transfer characteristics of these geometries experimentally and mainly investigating the effects of bleed holes on pressure drop and heat transfer in the cavity, an in-depth comprehension of the significance of internal cooling blade channel design could be gained.

2. Experimental facility

Fig. 1 displays a few views of a test model at different angles. The model consists of a cover and a base, which are both made of transparent Perspex. Fixed and sealed by bolts and rubber gaskets, respectively, these two parts form the whole trailing edge cavity, which connects to an air duct via a circular flange. In the trailing edge cavity, the inner surfaces of the cover and base are the suction and pressure sides, respectively. Fig. 2 illustrates the layout of geometric structures inside the test model without cover. Besides that a small amount of flow passes through the bleed holes in the second passage, the majority of air flow enters the test channel via the circular flange connector, then flows through a ribbed passage, a bend, a pin fin area, and eventually goes out from the exit slots.
Fig. 3 shows the lateral and top views of the base. The pressure side width $W_p = 190.5$ mm. The suction side width $W_s = 234.2$ mm. The maximum passage length $L = 368.0$ mm. The hydraulic diameter of the model inlet $D_h = 24.3$ mm. The square rib width $d = 3$ mm. And the rib spacing to height ratio is 7. On the suction side, there are merely some ribs. 17 bleed holes with a 3 mm diameter locate on the pressure side of the second passage. During the heat transfer experiment, the air temperature needs to be measured by thermocouples inserted into the cavity. Hence, six holes with a 2 mm diameter are drilled in the cover and their projection positions on the base are showed in the top view.

Fig. 4 demonstrates the layout of the experimental equipment, where high pressure air pumped by a compressor gathers in the tank, then goes through the flowmeter and flows into the fast heater to raise its temperature. Before entering the test model, the heated air is rectified with grid. The mainstream is adjusted by control valves and the flowmeter displays the magnitude of air flow rate. The history of the mainstream temperature is recorded by a temperature acquisition module and six thermocouples. The suction and pressure surfaces of the test model are monitored separately by digital cameras and the video data is transferred to a computer via a data line. In order to reduce the interference from thermal radiation imposed on the heat boundary of testing surfaces, two electro-luminescent lamps with high electro-optical conversion efficiency are chosen as lighting sources.

In the pressure measurement experiment, total and static pressures at six positions, for five flow rates and with or without bleed flow conditions, are recorded by pressure calibrators and probes.

3. Experimental principle

This experiment measures heat transfer coefficients on the inner surfaces of the suction and pressure sides of each channel by the transient liquid crystal method, considering multiple steps during gas temperature rise. According to Ref.18 and the semi-infinite solid assumption, wall temperature is found to depend on mainstream temperature at a certain extent. By use of the recorded time history of temperature, heat transfer coefficient on the wall can be solved. The relevant one-dimensional heat conduction equations are as follows:

$$T_w - T_i = \sum_{j=1}^{N} U(t - \tau_j)\Delta T_{\infty}$$  \hspace{1cm} (1)

$$U(t - \tau_j) = 1 - \exp \left[ \frac{h^2}{kL} \tau(t - \tau_j) \right] \text{erfc} \left[ \frac{h}{k} \sqrt{\tau(t - \tau_j)} \right]$$  \hspace{1cm} (2)

where $T_w$ is the wall temperature, $T_i$ the initial temperature, $\Delta T_{\infty}$ the change in every step of mainstream temperature rise,
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This paper focuses on the detailed local heat transfer distribution in an integral trailing edge cavity. Herein the $Nu$ contours at some areas on the suction and pressure sides are presented to analyze the laws of flow and heat transfer. Experiments under five flow rate conditions are conducted. The Reynolds numbers based on the inlet hydraulic diameters are $Re = 49808, 39846, 34865, 29884, 24904$. In addition to the research on heat transfer under the original geometry condition, some investigations on bleed holes of the second passage are also carried out. The channel outflow condition is changed by insertion of bleed holes. The experimental results are compared with the data obtained under the original condition. Then the effect of the holes between the ribs on heat transfer in the trailing edge cavity could be analyzed. Local heat transfer on the inner surface of the channel, as well as the average heat transfers and pressure distributions at six measurement positions, are analyzed subsequently.

4.1 Local heat transfer characteristics

From Figs. 7 and 8, it is seen that the heat transfer is stronger when $Re$ is higher. After the passage flow has fully developed, the periodic distribution characteristic of the heat transfer between the ribs becomes very clear. Since the first passage owns smaller flow cross-section than the second one does, average velocity in the first passage is higher when flow rate is constant. As a result, the heat transfer magnitude in the first passage is higher than the latter’s. Besides, as the temperature difference between flow and wall in the second passage is lower than that in the first one, this reduces the $Nu$ value in experimental results to some extent.

In Fig. 9, when the mainstream flows into the third passage, the shrinkage of the cross-section along the channel chord direction accelerates the flow. This results in a leap for heat transfer in this area, especially there existing a heat transfer enhancement region between the first and second pin fins in the first row. In addition to the high flow speed, strong turbulence disturbance is also a reason for the increase of heat transfer and it helps to maintain efficient heat exchange until the downstream part of the passage.

In Fig. 10, due to the flow impact against the end wall of the bend, very strong heat transfer appears in this area. In the

$t$ the time from the start of the test, $\tau_i$ the time at the moment of $j$, $h$ the heat transfer coefficient on the wall, $k$ the solid thermal conductivity, $x$ the solid thermal diffusivity, and $U$ a function with independent variables $t$ and $\tau_i$.

Fig. 5 shows the temperature trend of air mainstream during the heating process. For different flow rates, the voltage of the fast heater is regulated by a transformer to control the temperature curves so that they tend to coincide with each other. However, under the same flow rate condition, at the same time instant, the mainstream temperature continuously decreases along the flow path. Since there are only limited measurement positions, the assumption that the air temperatures between two adjacent measurement positions comply with a linear distribution is employed to facilitate data processing.

R30C0.8W style narrow band liquid crystal is chosen for this experiment. The red to blue color range corresponds to the actual temperature boundaries of 29.5–30.5°C. Liquid crystal is calibrated to obtain the relationship between hue value and temperature before the experiment. Fig. 6 shows the curve which covers the effective liquid crystal color range. Before the experiment, several layers of liquid crystal are sprayed on the inner surfaces of the cover and base by an air gun. Then black matte paint is sprayed on the liquid crystal layers for the purpose of providing a high-quality background on which liquid crystal presents colors.

The inlet Reynolds number for this experiment is defined as $Re = \rho u_0 D_h / \mu$, where $\rho$ is the air density, $\mu$ the dynamic viscosity, and $u_0$ the average velocity of airflow at the entrance. The local Nusselt number $Nu_h = h D_h / \lambda$, where $\lambda$ is the air thermal conductivity.

Errors of instantaneous measurement are mainly resulted from the errors in temperature, time, and physical property parameters of the testing surfaces. According to Ref. 19, when adiabatic wall temperature and heat transfer coefficient are known, the relative uncertainty of heat transfer coefficient can be calculated. The uncertainties of relevant parameters in this experiment are listed as follows: $\delta T_1 = \pm 0.2 ^\circ C$, $\delta T_{\text{in}} = \pm 0.2 ^\circ C$, $\delta T_{\text{out}} = \pm 0.2 ^\circ C$, $\delta t = \pm 0.1$ s, $\delta \sqrt{k^2 / x} = \pm 24$. Taking all measurement errors into consideration, the relative error of heat transfer coefficient is evaluated through the error transfer formula to be 9.6%.

For the pressure measurement, precision of the pressure calibrator is 0.05%. Hence the maximum relative error of the measured pressure value can be controlled to be within 5%, considering various factors.

![Fig. 5 Air mainstream temperature curves at six measuring positions.](image)

![Fig. 6 Calibration curve of liquid crystal.](image)
downstream part of the first bend, the heat transfer on the side away from the partition is more powerful than what is on the side near the partition, because of the centrifugal effect caused by the high speed flow that travels through the bend. Powerful inertia causes uneven velocity distribution perpendicular to the flow direction, with low and high flow velocities inside and outside the elbow, respectively. Thus the heat transfer outside the bend is more notable. With the $Re$ declining, the centrifugal effect due to the bend weakens.

As shown in Fig. 11, owing to the reduction of average flow velocity in the passage, the level of overall heat transfer in this area is lower than that in the first bend. However, it can be seen that the heat transfer distribution here seems more balanced than that in the first bend. This is helpful to reduce the thermal stress resulted from temperature gradient between the hot and cold areas. Since the second bend corresponds to a location at the root of a real blade, this heat transfer profile can prevent blade root from thermal fatigue damage or even fracture and hence extend the work life and improve the reliability of turbine blades.

In Figs. 12–16, the local heat transfer distributions on the suction surfaces in the trailing edge cavity, with all the bleed holes blocked, are presented. The results show that, for the first passage, heat transfer at the same position decreases as compared to the case with bleed flow open and the discrepancy between two adjacent flow rates reduces. However, on the second passage’s testing surface, the maximum magnitude of local heat transfer does not change, except that the downstream heat transfer increases slightly as compared to the bleed case. The reason for this phenomenon is that after blocking the bleed holes, no signs of decay occur to the heat transfer capacity because the flow rate remains constant throughout the second passage, but if these holes are not blocked, the film outflow would make the flow rate decrease along the passage. So the
downstream heat transfer reduces due to lower speed, which results in the differences between upstream and downstream heat transfers. In the third passage, the maximum heat transfer magnitude rises under the largest flow rate condition, while the trend is opposite for the remaining four flow rates. However, the heat transfer differences between upstream and downstream in the third passage still diminish when the holes are blocked. This is because there is more hot air upstream that can be used for heat exchange on the downstream channel surface.

After the bleed holes are blocked, the heat transfer level drops significantly in the first bend with the peak $Nu$ declining by 27.8%. Meanwhile, the spatial differences of heat transfer distribution reduce in this area. This reflects a reduced wall temperature gradient. However, no big changes emerge in the second bend with the bleed holes blocked. The magnitude and distribution of heat transfer are close to the case with bleed.

As illustrated in Figs. 17–21, $Nu$ on the pressure side of the first passage is higher than that on the corresponding suction side. In the second passage, the heat transfer on the pressure side is still stronger than that of the suction side, mainly because the width of the pressure side is narrower which leads to a higher flow speed near the wall on the pressure side. Besides, due to the existence of the bleed holes, the suction effect of high speed outflow makes heat transfer around the holes extremely strong. With the mainstream velocity decreasing downstream, the suction effect weakens and the heat transfer enhancement is no longer obvious around the bleed holes.

In the third passage, heat transfer distribution on the pressure side is close to that on the suction side, except that the former is lower than the latter in magnitude. Due to the flow separation and detached vortex, a negative pressure zone arises behind the pin fin, and the heat transfer in the leeward side of the pin fin is weaker than that in the windward side. However, two rows of pin fins in a staggered array inhibit the expansion
of the negative pressure region. The pin fins with a smaller diameter in the second row cause the flow to attach to their surfaces. Whereas new negative pressure regions shrink, due to the suction effect of high speed outflow at the downstream exit slots, they have very limited influence.

The heat transfer characteristics of the first and second bends on the pressure side are close to those on the suction side except a slight difference in magnitude. The narrow inlet of the third passage accelerates the flow downstream in the second bend. This leads to an obvious heat transfer enhancement. When $Re$ declines, heat transfer differences between the two sides of the second divider reduce gradually.

In Figs. 22–26, noting the heat transfer distribution on the pressure side with bleed holes blocked, it can be seen that the heat transfer peaks increase by 7.1%–30.8% in the first passage when compared to the cases with bleed flow. When the flow rate is lower, the extent of the improvement is greater. After the bleed holes are blocked, heat transfer enhancement areas around the holes vanish in the second passage. The downstream heat transfer is intensified to be consistent with the upstream one. This indicates that the bleed holes on the pressure side reduce the downstream heat transfer in the second passage, causing an uneven heat transfer distribution between upstream and downstream. In the third passage, thanks to the disappearance of the upstream bleed flow, the flow rate here increases and the heat transfer improves obviously on the pressure side. Meanwhile, with the flow rate decreasing, except the maximum one, the relative percentage increase in $Nu$ is also greater.

After the bleed holes are blocked, the magnitude and distribution of heat transfer on the pressure side do not change distinctly in the first bend. The heat transfer peak improves by...
Fig. 14  Heat transfer contour on the suction side of the third passage without bleed flow.

Fig. 15  Heat transfer contour on the suction side of the first bend without bleed flow.

Fig. 16  Heat transfer contour on the suction side of the second bend without bleed flow.

Fig. 17  Heat transfer contour on the pressure side of the first passage.
Fig. 18  Heat transfer contour on the pressure side of the second passage.

Fig. 19  Heat transfer contour on the pressure side of the third passage.

Fig. 20  Heat transfer contour on the pressure side of the first bend.

Fig. 21  Heat transfer contour on the pressure side of the second bend.
nearly 53% in the second bend and the heat transfer enhancement mainly emerges in the area downstream of the second bend. The participation of the upstream bleed flow significantly increases the flow velocity in the narrow channel, so it promotes the heat transfer in this area greatly.

4.2. Average heat transfer characteristic

The flow and heat transfer characteristics of different cooling structures as well as their interaction are analyzed in the trailing edge cavity via local heat transfer contours. In the following, the variation and distribution of the flow and heat transfer in the cavity are discussed from the perspective of average heat transfer at specific points. In this paper, the average Nusselt numbers, i.e., $\overline{Nu}$, are obtained by applying the area average method for $Nu$’s around six measurement positions, respectively. The relationship between flow and heat transfer is investigated by analyzing these $\overline{Nu}$ values.

In Figs. 27 and 28, for all the $Re$ conditions, $\overline{Nu}$’s from all measurement positions along the flow path in the trailing edge cavity demonstrate a rising trend roughly after the first drop and form an approximate M-shaped distribution. The flow velocity constantly decreases from the narrower first passage to the wider second passage and the fluid loses part of its kinetic energy after impacting the first bend. Therefore, $\overline{Nu}$ reduces continuously from Position 2 to Position 4. At Position 5, the fluid flows into the narrow throat in the third passage and a magnitude rebound occurs to $\overline{Nu}$ because of the flow acceleration. However, this phenomenon could not be maintained at Position 6, because the outflow through the upstream exit slots accounts for a large percentage of the total flow. Finally, the lack of flow results in a slow air speed and a weak heat transfer.

![Fig. 22](image1.png)  Heat transfer contour on the pressure side of the first passage without bleed flow.

![Fig. 23](image2.png)  Heat transfer contour on the pressure side of the second passage without bleed flow.
As shown in Figs. 29 and 30, heat transfer on the pressure side is better than that on the suction side at all measurement positions. The relative deviation of heat transfer between the suction and pressure sides from Position 1 to Position 3 is 0.1% to 10.8%. From Position 4 to Position 6, the relative
deviation ranges from 11.9% to 42.6%. The relative deviation of heat transfer between the two sides at Position 4 is the largest among all measurement points. This indicates that the flow here is very complex with some discrepancy on different surfaces. Moreover, the discrepancy is more notable at lower $Re$ and is reduced by the enhancement of turbulence intensity as $Re$ increases.

From Figs. 31–34, it can be seen that, after the bleed holes are blocked, $Nu_{ave}$’s at Positions 1, 2, and 6 decline on the suction side. A rising trend occurs to $Nu_{ave}$’s at Positions 3, 4, and 5. The increase at Positions 3 and 5 is apparent when compared with a merely slight enhancement at Position 4.

On the pressure side, without the bleed flow, $Nu_{ave}$’s at Positions 1 and 3 decrease. The heat transfers at Positions 2, 5, and 6 increase and the heat transfer at Position 4 is nearly the same as what is in the case with bleed flow.

From the above results it can be inferred that the heat transfer at Position 1 without bleed flow is weakened on both the suction and pressure sides. The reason may exist in that the...
increase in downstream back pressure affects the inlet turbulence intensity in the first passage. Positions 2 and 3 are close to the first bend where the flow is complicated in its form. Blocking the bleed holes yields contrary results for heat transfer on the suction and pressure sides. At Position 6, different variations in heat transfer between the suction and pressure sides are also caused by blocking the bleed holes. However, the relative deviation of $N_u\alpha_{ave}'s$ due to these changes can be maintained within 10% under most flow rate conditions. At Position 5, downstream of the bleed holes, the heat transfer always improves and the extent enlarges with increasing $Re$. However, at Position 4, which also locates downstream of the holes, the increased flow rate from the bleed is not enough to create the effect of flow acceleration. This is due to the large passage cross section that makes changes in heat transfer difficult to occur.

4.3. Pressure characteristic

The heat transfer distribution on the studied surfaces of the trailing edge cavity has been presented previously. The flow situations at various places can be inferred from these results. In order to verify such inferences, recording of the total and static pressures at six measurement positions is carried out. Meanwhile, for the purpose of analyzing the effect of bleed flow on flow resistance, results owing to two bleed flow conditions are compared and analyzed by either blocking the holes or not. In this paper, $p^*$ is the total pressure, and $\Delta p$ is the difference between the total and static pressures.

In Figs. 35 and 37, $p^*$ declines along the flow path for the same $Re$, and $p^*$ at each measurement position enhances with increasing $Re$. This reveals that higher air speed leads to greater flow resistance.

As seen from Figs. 36 and 38, $\Delta p$ decreases continuously from Position 1 to Position 4, which indicates that the flow speed goes down constantly. However, from Position 4 to Position 5, due to centrifugal effect at the second bend and influence from the cross section contraction of the third passage inlet, an increase in velocity causes a recovery in $\Delta p$. For all the measurement positions under the same flow rate, $\Delta p$ at Position 5 is the highest, which reflects that the flow velocity here is the fastest in the channel. Besides, with $Re$ increasing, there exists a big difference for increments of $\Delta p$ at different positions. Except a very large increase at Position 5, the increments of $\Delta p$ at other positions are all small, especially at Positions 3, 4, and 6. This is because the fluid density is constant when the flow is incompressible, and the velocity produces high amplitude response to changes in the flow rate with small passage cross sections. Since $\Delta p$ is approximately proportional to the square of velocity, the greater changes in velocity brings more significant changes in $\Delta p$. Meanwhile, different flow cross sections cause diversity of sensitivity for $Re$ at each measurement.
position. Position 5 locates near the throat of the third passage, while Position 3 and Position 4 lie in the wide second passage. So the increment of $\Delta p$ at Position 5 is much higher than those at Positions 3 and Position 4. At Position 6, the cross section does not play a leading role in the increment of $\Delta p$, because most fluid passes through the exit slots upstream of Position 6, resulting in a low velocity and a small increment of $\Delta p$.

By observing Figs. 39 and 40, $p^*$ at each measurement position promotes when the bleed holes are blocked. This indicates that the flow resistance in the whole trailing edge cavity has increased. Meanwhile, the good linear relationship between $p^*$ and $Re$ indirectly manifests that some kind of association rule exists between the flow resistance and rate. In terms of $\Delta p$, blocking the bleed holes just brings relatively large changes to upstream Position 3 and downstream Position 5, compared with the almost zero impact at Position 4 and Position 6 that are downstream of these holes. The situations at Position 1 and Position 2 are slightly complicated, where blocking the bleed holes results in an increase of $\Delta p$ for the three lower flow rates and a reduction of $\Delta p$ for the two higher flow rates. In brief, the total mass flow rate increases downstream of the holes without the bleed flow, and no significant increase occurs to the velocity at Position 4 owing to the large cross section here. For Position 6, which is far from the holes, the effect of increasing the total flow on the velocity is offset by the flow from the upstream exit slots. Due to the small cross section and short distance from the holes, the velocity at Position 5 sensitively responds to the changes in the upstream flow, and the effect is more obvious for higher $Re$. At Positions 1, 2, and 3 that are upstream of the bleed holes, blocking the holes changes the flow resistance distributions downstream of these positions so that it exerts some effect on the flow.

5. Conclusions

Heat transfer on the inner surfaces and pressure drop in the trailing edge cavity of a novel turbine blade are measured for conditions with or without bleed flow and with five mass flow rates. Within the scope of parameters studied in this paper, conclusions are drawn as follows:

1. The local heat transfer on the pressure side is better than that on the suction side in the first and second passages with the bleed flow. On the suction side of the first bend, a strong heat transfer area emerges, due to the flow impingement on the end wall of the bend. Powerful inertia results in an uneven velocity distribution perpendicular to the flow direction. The heat transfer outside the bend is more notable where the flow velocity is very high. With $Re$ decreasing, the centrifugal effect owing to the bend weakens. The heat transfer enhancement is obvious on the pressure side of the second bend because the narrow inlet of the third passage accelerates the flow downstream of the bend.

2. After the bleed holes are blocked, the local heat transfer reduces on the suction side of the first and third passages, while the maximum magnitude of local heat transfer does not change in the second passage, except that the downstream heat transfer becomes a little higher than that in the case with bleed flow. Without the bleed flow, the heat transfer decreases obviously in the first bend with the largest $Nu$ declining by 27.8%, but no big changes emerge in the second bend with the bleed holes blocked. The magnitude and distribution of heat transfer are close to those for the case with bleed. On the pressure side without the bleed flow, the heat transfer enhancement is notable in the first and third passages, while the heat transfer distribution is more balanced between upstream and downstream in the second passage. Compared with no significant changes in the level and distribution of heat transfer for the first bend, the heat transfer peak promotes nearly 53% in the second bend and the heat transfer enhancement concentrates in the area downstream of the second bend. The participation of the upstream bleed flow significantly increases the fluid velocity in the narrow channel; therefore, it improves the heat transfer in this area extremely.

3. For all the $Re$ conditions, $\bar{Nu}$’s at six measurement positions along the flow path in the trailing edge cavity show a rising trend roughly after the first drop and form an approximate M-shaped distribution. $\bar{Nu}$’s on the pressure side are higher than those on the suction side for all measurement positions. The relative deviation of $\bar{Nu}$’s between the suction and pressure sides from
Position 1 to Position 3 is 0.1% to 10.8%, whereas for Position 4 to Position 6, the relative deviation falls within a certain range from 11.9% to 42.6%. $\Delta p_{ave}$ at Position 1 decreases on both the suction and pressure sides without the bleed flow, but for Position 2 and Position 3 near the first bend, as well as Position 6 next to the exit slots, blocking the bleed holes brings in the opposite effects on the heat transfer between the suction and pressure sides. $\Delta p_{ave}$ at Position 5 that is downstream of the bleed holes always promotes, and its increment becomes higher when $Re$ increases. However, blocking the holes does not produce obvious impact on the flow and heat transfer at Position 4.

(4) Under the conditions with or without bleed flow, $p^*$ declines along the flow path at the same $Re$, and $\Delta p$ at each measurement position enhances as $Re$ increases. From Position 1 to Position 4, $\Delta p$ decreases continuously. However, from Position 4 to Position 5, due to the centrifugal effect at the second bend and influence from the cross section contraction at the third passage’s inlet, an increase in velocity causes a recovery in $\Delta p$. For all the measurement positions under the same flow rate, $\Delta p$ at Position 5 is the highest because the flow velocity is the fastest at this position.

(5) $p^*$ at each position promotes without the bleed flow and a good linear relationship exists between $p^*$ and $Re$. In terms of $\Delta p$, Position 1 and Position 2 that are upstream of the bleed holes are affected to some extent. Greater changes occur at Position 3 that is next to the holes, after the bleed holes are blocked. In the downstream area, blocking the holes only produces an increase of $\Delta p$ at Position 5, compared with almost zero impact on Position 4 and Position 6.

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References


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