

Experiments of flow and heat transfer performances for air-cooling laminated turbine vane

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Abstract: Flow resistance and heat transfer coefficients of typical double wall laminated film cooling configuration within a turbine vane were experimentally studied. The specimen was in large scale, and made of transparent organic glass. Laminated configuration consisted of double wall laminates, pin-fins, staggered arrays of impingement and film holes. The number ratio of impingement holes, pin-fins and film holes was 2 : 1 : 1. Five experiment vanes were installed in static cascade, and experiments were carried out under constant heat flux. Re of internal cooling air in the experiment was from 10^4 to 2×10^5 , and Re of external fluid was from 10^5 to 3×10^5 . The experiment results show that flow resistances of front channel and back channel of the vane are in the same level, and both of them decrease as Re of cooling air increases. Nu of front channel is slightly higher than that of back channel. Both of them increase as Re of cooling air increases. And experiment results were obtained from experiment vanes were compared with that obtained from laminated flat plates, and the tendency of the results agrees well.

Key words: lamilloy; turbine vane; flow performance; heat transfer; static cascade

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Nomenclature

A	Wetted area (m^2)	Re	Reynold number
d	Diameter of impingement hole (m)	ξ	Flow resistant coefficient
G	Mass flow (kg/s)	ρ	Density of cooling air (kg/m^3)
h	Heat transfer coefficient ($W/(m^2 \cdot K)$)	v	Average velocity of cooling air (m/s)
Nu	Averaged Nusselt number	λ	Conductivity of cooling air ($W/(m \cdot K)$)
p^*	Total pressure of cooling air (Pa)	μ	Dynamic viscosity ($Pa \cdot s$)

Subscripts

c	Cooling air	in	Inlet
g	Main stream	out	Outlet

The development of modern aero-engine always requires higher thermal performances of turbine vanes and blades, and a reduction of the amount of cooling air. Highly effective laminated film cooling design is a kind of cooling tech-

nology meeting these needs. Lamilloy integrated impingement cooling, pin-fin cooling and film cooling devices into one body^[1-4]. Investigations based on internal flow and heat transfer characteristics of various laminated flat plates have

been made commonly. George, Vershure et al.^[5-6] studied heat transfer characteristics of an integrated cooling configuration for ultra-high temperature turbine blades. They constructed a large-scaled experiment model of this cooling system to measure its internal heat transfer distribution. And they numerically studied heat transfer characteristics and fluid dynamics inside several impingement cooling devices combined with pins. Funazaki et al.^[7-9] investigated the local heat/mass transfer characteristics with circular pins in the impingement/effusion cooling with an initial cross flow. The local heat/mass transfer coefficients on the effusion plate were measured with a naphthalene sublimation method. Coutandin et al.^[10] used the standard integrated design methodologies to study the thermal behavior of advanced double wall cooling system development for turbine vanes numerically. They compared the measured thermal efficiency with the theoretical ones. In China, QUAN et al.^[11-15] investigated cooling performance of an integrated impingement and pin-fin cooling device. They established a one-dimensional heat transfer model to analyze the effect of various parameters on cooling effectiveness. TAO et al. investigated flow resistance and heat transfer characteristics of typical lamilloy models^[16-17]. WANG et al.^[18-19] investigated cooling performance of a laminated configuration with infrared thermal image technique and numerical methodologies. LU, WANG et al.^[20-21] numerically studied the influence of impingement holes on heat transfer of leading edge in lamilloy.

Most of the investigations above were studied in the laminated flat plates, and the references about lamilloy turbine vane and blade were rare to see. This study focused on experiment of a laminated turbine vane, and the experiment model was designed as a real high pressure turbine vane with two channels supplied cooling air. The average flow resistance and heat transfer characteristic were experimented in a five-vane static cascade.

1 Experiment facility

Experiment was conducted in a static cascade facility. Fig. 1 showed schematic layout of the facility. It consisted of a bypass line, steady surveying segment, experimental segment, air release segment with a valve on it to adjust the pressure after the experiment cascades, and a secondary air supplying tube to provide cooling air.



Fig. 1 Experiment facility

2 Experiment model and measurement

The experiment model was designed as a high pressure turbine vane, and the airfoil of the blade vane was straight and sections were equal. Fig. 2 showed the schematic of the specimen. The turbine vane had two central channels, and cooling air was provided through these two channels. There were several laminates on pressure side and suction side, and the internal flow passages of each laminate were not connected with the others. The leading edge used impingement cooling combined with film cooling. The trailing edge used vortex matrix cooling. The specimen was ten times as large as actual engine scale. And it was made of transparent organic glass. First, using machining method to produce several parts separately, and then make them together with special glue. Radial height of the specimen was about 400 mm. Diameter of impingement holes, pin-fins and film cooling holes was 6, 7, 5 mm respectively. Distance between inner layer and outer layer was 6 mm. Film holes injection angle was 30°.

Five experiment vanes were installed in the static cascade facility; the middle vane was the chief experiment vane, and flow pressure loss in cooling passages of laminates and local heat transfer coefficient were experimented in it. External fluid static pressure distribution was experimented in the foil vane adjacent to the chief vane (Fig. 3). The specimen was divided into several elements, and experiment was carried out in each element (Fig. 4).

A stainless sheet was installed in the chief experiment vane to heat the inner surface of outer layer. Thickness of stainless sheet was 0.05 mm and width was 100 mm. A silicon rectifier was used as a heater source, its outlet voltage being 36 V, allowable outlet current being 500 A. Thermometers were used to measure the temperature of heated sheet and secondary air.

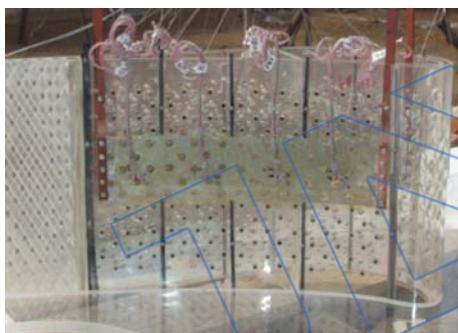


Fig. 2 Specimen

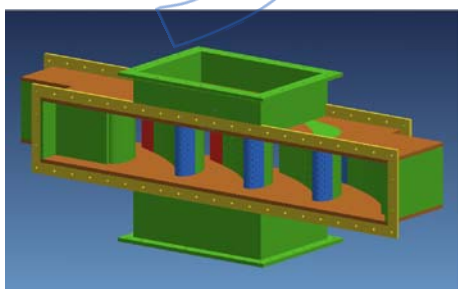


Fig. 3 Schematic of experiment static cascade facility

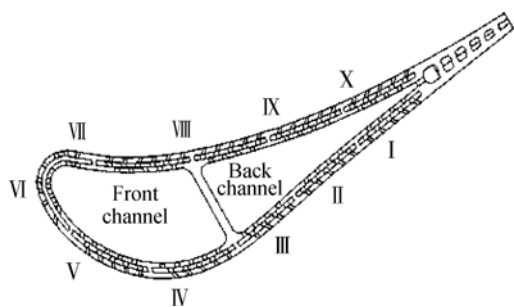


Fig. 4 Schematic of experiment element

An orifice-plate flow meter (measurement accuracy class of 1.5) and a revolving flow meter (measurement accuracy class of 1.0) were used to measure flow flux of inlet and outlet air respectively. Air tubes were used to measure pressures within cooling passages and along the blade profile. During experiment, flow ratio of front channel and back channel of the blade vane was kept constant, and the difference in average temperature of inner and outer layer wall surfaces was kept over 20 K.

3 Experiment results

Flow resistant coefficient ($\bar{\xi}$) of each experiment element was named as

$$\bar{\xi} = \frac{2(p_{in}^* - p_{out}^*)}{\rho_m u_m^2}$$

Where u_m was the average velocity of inlet cooling air.

Local Nusselt number of each experiment element was named as $Nu_i = \frac{h_i d_i}{\lambda_i}$, where h_i was the local heat transfer coefficient; d_i was the diameter of impingement holes, λ_i was the local conductivity of cooling air.

Reynolds number of cooling air was $Re_c = \frac{G_c D_c}{A_c \mu_c}$, where D_c was inlet air equivalent diameter. Reynolds number of main stream was $Re_g = \frac{G_g l_g}{A_g \mu_g}$, where l_g was blade chord.

3.1 Average flow resistance coefficient

The average flow resistance coefficient ($\bar{\xi}$) of front channel and back channel at different Re_c was shown in Fig. 5 and Fig. 6. The figures showed the results when main stream mass flow $G_g = 0.4, 1.065$ kg/s (total amount of five experiment vanes cascade). The results demonstrated that the flow resistances of front channel and back channel were in the same level, and both of them decreased as Re_c increased. Figure 7 showed that average flow resistance coefficient increased slightly when Re_g enlarged, and the numbered curves of “1-1, 1-2, 1-3” were the results of different states.

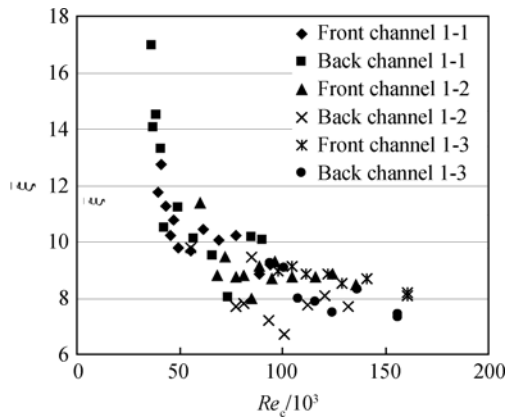


Fig. 5 ξ of front channel and back channel
($G_g = 0.4 \text{ kg/s}$)

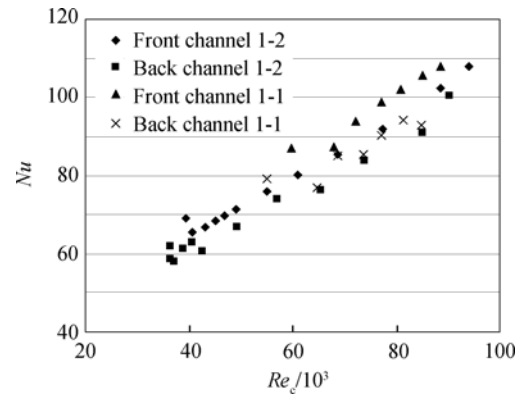


Fig. 8 Nu of front channel and back channel
($G_g = 0.4 \text{ kg/s}$)

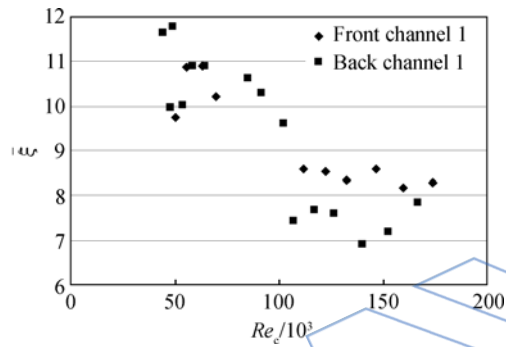


Fig. 6 ξ of front channel and back channel
($G_g = 1.065 \text{ kg/s}$)

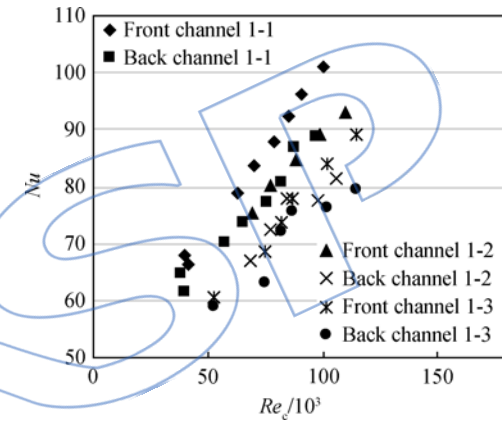


Fig. 9 Nu of front channel and back channel
($G_g = 0.7 \text{ kg/s}$)

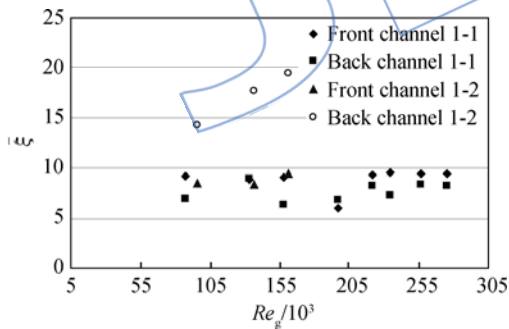


Fig. 7 Effect of Re_g on ξ

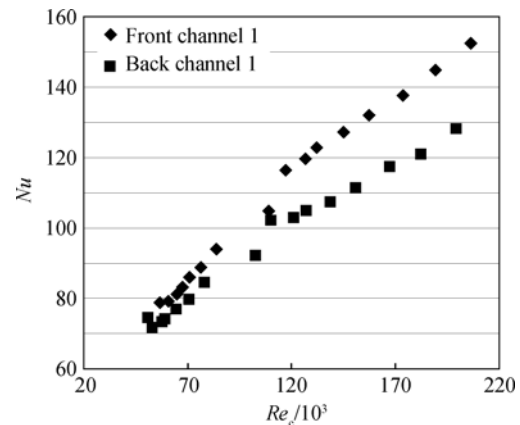


Fig. 10 Nu of front channel and back channel
($G_g = 1.065 \text{ kg/s}$)

3.2 Average heat transfer characteristic

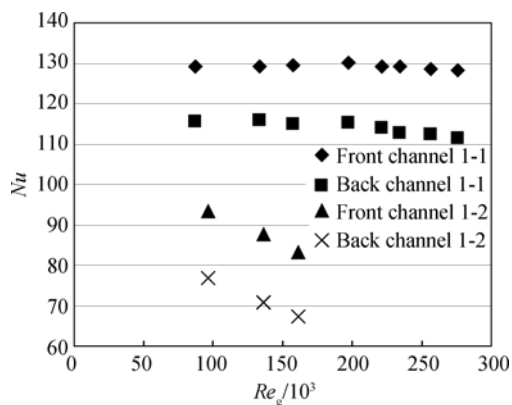
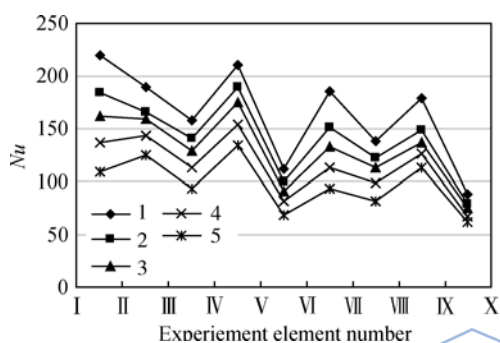
The average heat transfer characteristics of front channel and back channel were shown in Fig. 8 to Fig. 10. Nu of front channel was slightly higher than that of back channel when main stream mass flow was 0.4, 0.7, 1.065 kg/s. Both of them increased as Re_c increased.

The effect of main stream on heat transfer characteristics was shown in Fig. 11. As Re_g in-

creased, Nu of front channel and back channel both decreased.

3.3 Nu of different locations

The average heat transfer characteristics of experiment elements at different states were

Fig. 11 Nu at different Re_g Fig. 12 Nu of experiment elements at different states

shown in Fig. 12. Numbered curves of 1, 2, ..., 5 shown in Fig. 12 were the results of different states. Nu of element IV was the largest, and that of element X was the smallest. Element IV was at suction side near leading edge and element X was at pressure side near trailing edge.

3.4 Comparison with laminated flat plate

Figure 13 and Fig. 14 showed the experiment results in another investigation when the specimen was a laminated flat plate, and number

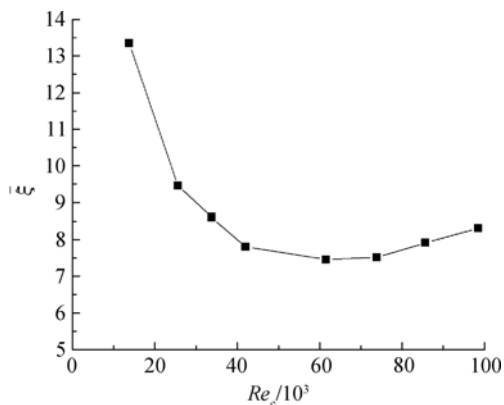
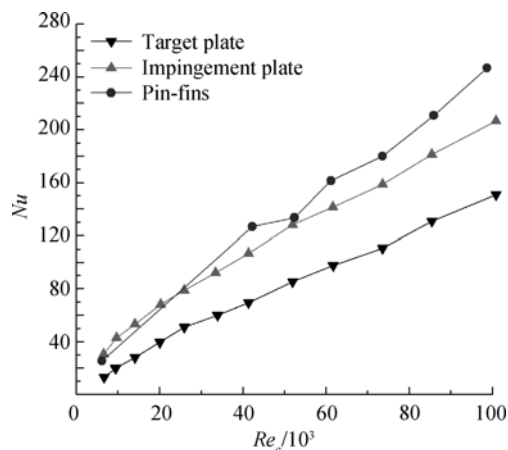
Fig. 13 Experiment result of $\bar{\xi}$ at laminated flat plate model

Fig. 14 Experiment result of heat transfer characteristic at laminated flat plate model

ratio of impingement holes, pin-fins and film holes was the same as present study (2 : 1 : 1); diameters of impingement holes and film holes both were 15 mm, and film hole injection angle was 30° .

Comparing Fig. 5 and Fig. 9 with Fig. 13 and Fig. 14, tendency of average flow resistant coefficients and heat transfer characteristics both were the same.

4 Conclusions

The experiment results of this paper demonstrate that Nu of two channels of air-cooling laminated turbine vane were in the same high level at fixed flow ratio. Nu of front channel is slightly higher than that of back channel. Nu increases evidently when the Re of inlet cooling air increases. When Re_g increases and parameters of cooling air are kept constant, the Nu of both channels are decreased. The experiment results of air-cooling laminated turbine vane agree well with the experiment results of laminated flat plate.

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