IMPACTS OF FILM COOLING PARAMETERS ON AERODYNAMIC LOSS OF A COOLED TURBINE VANE

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ABSTRACT

This paper describes the experimental and numerical study on aerodynamic loss due to coolant and main flow mixing for a cooled turbine guide vane. The impacts of blowing ratio, hole shape, injection location and multi-row injection on mixing loss are investigated. Ideal isentropic mixing method is introduced to quantify the aerodynamic loss caused by film cooling. Measurements of total pressure loss due to the mixing were performed for a linear cascade with various film cooling configurations at different blowing ratios. Numerical simulations were also performed to study the mixing flow details. The results showed that aerodynamic loss increases with the increase of blowing ratio. The change of loss increment in the wake region near trailing edge is discussed and the mechanism is exposed.

INTRODUCTION

Film cooling is an effective technology to protect turbine vanes and blades from hot gas. The turbine metal temperature is reduced by film cooling, at the penalty of aerodynamic loss increment. Literature research shows that most of the experimental and computational studies of film cooling focus on increasing the adiabatic cooling effectiveness. For modern gas turbines, full coverage film cooling is commonly applied. Therefore, the additional loss due to the coolant and main stream mixing has a strong impact on the turbine aerodynamic efficiency. In the design stage of a modern gas turbine, not only the film cooling effectiveness should be considered, but also the aerodynamic mixing loss should be taken into account. Previous study of Ito et al.[1] found that the introduction of film cooling on turbine blade and vane surface will change the loss, and then influence the aerodynamic performance of the cascades. Hong et al. [2] performed experiments to study the effects of coolant injection on secondary flows. The experimental results showed that the coolant injection from the rear of the suction surface causes more energy loss compared with other locations. Haller et al. [3] studied the effects of coolant injection on the loss of vane cascade. The experiments showed that the aerodynamic mixing loss varies with the locations of film holes, and mixing loss is increased with the increase of blowing ratio. Day et al. [4] performed experiments on the aerodynamic loss of a turbine guide vane. The injection location, number of film hole rows and film hole shape proved to be influential on the aerodynamic loss. The fan-shaped holes cause generally higher mixing loss than cylindrical holes. Walters and Leylek [5] performed numerical simulations on a linear turbine airfoil cascade to study the impact of film-cooling injection on aerodynamic loss. They separated the increase in profile loss by coolant injection into two sources, the mixing loss is the main reason for loss increase at lower blowing ratio, while the wall loss changes by film cooling becomes significant at higher blowing ratio. Chappell [6] investigated the performance of suction-side gill region film cooling.
Experimental results showed that the shaped holes always cause more loss than cylindrical holes. The aerodynamic losses at trailing edge are caused by the changes of boundary layer thickness, which result from film cooling. The similar conclusion can be found in [7] and [8]. Gomes et al. [9] studied the flow separation caused by film cooling on suction surface. It is found that the flow separation appearing at low Reynolds number can be restrained by the coolant injection and the total aerodynamic loss can be reduced as a result. The effects of endwall film cooling [10,11] and trailing-edge slot [12,13] have been studied as well. The hole shapes, blowing ratio, injection location and other parameters of the coolant injection can influence the secondary flow structure. As a result, the aerodynamic loss is enlarged or even reduced.

In order to study the aerodynamic mixing loss caused by film cooling, a mixing loss evaluation method should be set up. Most of the studies [1,2,5~7,10] picked the total pressure loss coefficient as the quantization standard. Besides, thermodynamic efficiency [3], integrated aerodynamic losses [6,7] and entropy creation [8] were used as well.

Most of previous studies focused on the effects of one or two parameters on aerodynamic loss. In this paper, both experimental and numerical methods will be employed to study the impacts of blowing ratio, hole shape, injection location and multi row injection on mixing loss. A new rational method is put forward to evaluate the aerodynamic loss of a guide vane with film cooling. Both phenomenon and mechanism will be discussed. After this introduction, experimental and numerical methods, validation and main results are presented.

**Experimental Facilities and Technique**

*Wind Tunnel and Film-Cooling Injection System.* The present experiments were conducted in an open-cycle, low-speed continuously tunnel rig. Facilities are illustrated in Figure 1. The mainstream is provided by a 55kW radial-flow blower. The max pressure head of the blower is up to 8515Pa and the max mass flow rate is up to 4.5kg/s. After the blower are the transition section, settling section, contraction section and test section of linear cascade. The mainstream is accelerated in the contraction section to 15m/s, with a turbulence intensity of 3.5%, measured by hot wire anemometer.

![Figure 1 Experimental facilities](image)

The inlet size of the test section is 600mm*125mm. Four vanes are placed 250mm downstream from the inlet, numbered from 1 to 4, see Figure 2a. Vane 1 and Vane 4 are made of metal, Vane 2 and Vane 3 are 3D printed resin vanes with film cooling structures. The middle three passages are adjusted to be periodic by two guide plates placed after vane 1 and vane 4. Probe slot is placed 38mm downstream the vane trailing edge for the total pressure measurement. The coolant is provided by the film-cooling injection system, which is composed of an air compressor, air reservoir, electromagnetic flowmeters and valves. Coolant pressure is maintained up to 0.8MPa by air reservoir, and decompressed by the valve to fit the required blowing ratio. Temperature, density ratio and other operating conditions are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Temperature</td>
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<tr>
<td>Pressure</td>
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<tr>
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<tr>
<td>Blowing ratio</td>
<td>0.5~2.0</td>
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</table>

*Table 1 Test rig operating conditions*

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### Table 2: Relative positions of film cooling holes

<table>
<thead>
<tr>
<th>Location</th>
<th>SS1</th>
<th>SS2</th>
<th>SS3</th>
<th>PS1</th>
<th>PS2</th>
<th>PS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of Axial Chord</td>
<td>17.1</td>
<td>53.0</td>
<td>63.8</td>
<td>13.3</td>
<td>34.2</td>
<td>51.5</td>
</tr>
</tbody>
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Vane Profile and Hole Geometry. The vane profile models the mid-span section of a turbine nozzle guide vane in a heavy duty gas turbine. The span height, axial chord and pitch of the vane blade are 125mm, 94.1mm and 150.4mm, respectively. The vane inlet angle is 0° and the outlet angle is 74.2°. In the present study, 6 typical locations of cooling holes on suction and pressure surface are considered. Film cooling holes are located at three different locations for both pressure surface (PS1, PS2, PS3) and suction surface (SS1, SS2, PS3), the relative positions are listed in Table 2, expressed as a percentage of axial chord length. The location of the throat has been marked as well, see Figure 2b. For the convenience of internal structural design, SS1, SS3, PS1 and PS3 are set in one vane, SS2 and PS2 are set in another. Figure 2c shows a side view of the vane. For each row of holes, a separate coolant inlet is designed to control coolant mass flow rate individually.

**Figure 1 Experimental facilities**

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The inlet size of the test section is 600mm*125mm. Four vanes are placed 250mm downstream from the inlet, numbered from 1 to 4, see Figure 2a. Vane 1 and Vane 4 are
Four different hole shapes are employed in the present study, the cylindrical hole (CH), the fan-shaped hole (FSH), the laidback fan-shaped hole (LFSH) and the double jet hole (DJH). The characteristic diameter of holes is \( D = 1.6 \text{mm} \). The length of the hole is \( L = 5D \) and hole pitch is \( p = 5D \). For FSH and LFSH, see Figure 3, the length of the cylindrical inlet portion is \( l = 2D \). \( \alpha \) is the angle of hole inclination, \( \alpha = 30^\circ \) is invariant for all shapes. \( \beta_1 = 14^\circ \) is the lateral diffusion angle for FSH and LFSH. \( \beta_2 = 8^\circ \) is the forward diffusion angle for LFSH. FSH has no forward diffusion angle, which is the only difference between FSH and LFSH. For DJH, the compound angle is \( \gamma = 30^\circ \).

Fig. 3 Geometry parameters of FSH and LFSH

Measurements of Aerodynamic Mixing Loss. Total pressure measurements are carried out at the location of probe slot after the trailing edge, using a five-hole probe fixed on a shifting axes frame. The total pressure distributions of the measure plane are obtained automatically. Meanwhile the main flow total pressure, static pressure and the coolant total pressure are measured respectively. The control and acquisition system are constructed on NI PXI platform.

For an uncooled vane, the aerodynamic loss can be evaluated with total pressure loss coefficient (TPLC), defined as,

\[
\text{TPLC} = \frac{P_{\text{t,in}} - P_{\text{t,out}}}{P_{\text{t,in}} - P_{\text{t,out}}} \tag{1}
\]

Where \( P_{\text{t,in}} \) is the inlet total pressure of main flow, \( P_{\text{t,out}} \) and \( P_{\text{t,out}} \) are respectively the static pressure and total pressure at the outlet plane. For the film cooled vane, \( P_{\text{t,in}} \) should be modified to account for the effect of coolant total pressure. The mass flow averaged (MFA) method is commonly used, which defined as

\[
P_{\text{t,in,MFA}} = \frac{m_m P_{\text{t,in}} + m_c P_{\text{t,c}}}{m_m + m_c} \tag{2}
\]

Where \( m_m \) and \( P_{\text{t,m}} \) are the mass flow rates and the total pressure of the main stream.

An ideal isentropic mixing (IIM) method is proposed in this paper to modify \( P_{\text{t,in}} \). We assume that the main flow and the coolant have reached a mixed state (before the real mixing). Constraint condition is that the entropy of the mixed flow keeps unchanged. By means of this assumption, the suppositional mixing process doesn’t cause any other aerodynamic loss. And the total pressure of the mixed state is equivalent to the summation of main flow and coolant, in terms of aerodynamic loss. The averaged total pressure by IIM method can be expressed as:

\[
P_{\text{t,in,IIM}} = \frac{P_{m} (m_c / m_m + m_m)}{\left( \frac{T_{m}}{T_{m}-1} \right) (\gamma/\gamma_m)^{\gamma/(\gamma-1)}} \tag{3}
\]

The rationality of the IIM method will be discussed thereinafter.

Parameter Definition and Test Case Configurations. Define the blowing ratio as:

\[
BR = \frac{m_c / A_c}{(\rho V)_{m}} \tag{4}
\]

The metering area \( A_c \) is the cross-section of the initial cylindrical hole portion:

\[
A_c = \frac{\pi}{4} D^2 \tag{5}
\]

Test blowing ratio is selected from 0.5 to 2.0, which contained most of the real cooling conditions. For DJH, BR is from 0.25 to 1.0, due to the limitation of coolant supply. When a single row is selected to test, the coolant supply for other rows is cut off and the holes are blocked as well to reduce the interference. A full test matrix of 96 different single row cooling configurations is created and each of them has been tested, as well as the uncooled condition (NH). For the convenience of memory and use, each case has a short name, e.g. a test case of fan shaped hole at the second hole row on suction surface with \( BR = 1.0 \) can be shorten as SS2FSSH1.0. The results are analysed with control variate method, in order to investigate the influence of different blowing ratio, different hole shape and different hole location on aerodynamic mixing loss.

Two-row CH film cooling cases are tested as well. The results are compared with single row film cooling, in order to obtain the loss correlation between multi-row and single-row injection.

Measurement Uncertainty. The uncertainties were estimated using error propagation analysis:

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**Figure 2 Test section**

**Fig. 2 Test section**

- Coolant Inlet SS1, PS1, SS3, PS3
- Leading Edge

- Side view of the vane

- Main flow direction

**Figure 3 Geometry parameters of FSH and LFSH**

- Inlet total pressure, static pressure and the coolant total pressure are measured respectively.
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\[
P_{\text{t,in,IIM}} = \frac{P_{m} (m_c / m_m + m_m)}{\left( \frac{T_{m}}{T_{m}-1} \right) (\gamma/\gamma_m)^{\gamma/(\gamma-1)}} \tag{3}
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Two-row CH film cooling cases are tested as well. The results are compared with single row film cooling, in order to obtain the loss correlation between multi-row and single-row injection.

Measurement Uncertainty. The uncertainties were estimated using error propagation analysis:
\[
\Delta y = \sum_{i=1}^{n} \left[ \frac{\partial f(x_i, \ldots, x_n)}{\partial x_i} \right] \cdot \Delta x_i \tag{6}
\]

For the blowing ratio, the uncertainty is primarily dependent on the coolant mass flow rate and main flow velocity uncertainty (±0.5 m/s). According to the precision of the electromagnetic flowmeter (±0.5% of full scale range), the maximum possible variation of blowing ratio is estimated to be 4%. The uncertainties in the flowmeter, the pressure transducer (±0.05% of the full scale range), the thermocouple (±0.5°C) and the five-hole probe calibration (1% for total pressure and 0.08% for static pressure) are applied to calculate the uncertainty of TPLC, which is estimated to be 10% in the worst-case scenario.

**Numerical Method**

**Geometry and Grid.** The geometries used for CFD are the same as experimental vanes. Computational domain contains three regions, the main flow region, the film-cooling hole and the coolant plenum, as shown in Figure 4a. To reduce the consumption of computational resources, only one vane and one passage are adopted. Periodic conditions were used on the two sides of the main flow passage to simulate the experimental condition with multi-rows of vanes. Unstructured grids were generated by using ICEM CFD. The first layer height near the wall was 0.01 mm and the growth ratio was 1.2. Thus, Y+<1 was obtained for all solid walls. The grids are refined locally in the cooling hole to improve the local grid quality. For the vane with two plenums (SS2 and PS2) the grid contains 12,150,000 cells, if double the plenum number (SS1, SS3, PS1 and PS3), the grid contains 17,810,000 cells. Figure 4b shows the grid details of double jet film holes.

**Boundary Conditions and Solver.** Boundary conditions are chosen to match the experimental test cases as closely as possible. As mentioned above, periodic conditions are applied between the vanes in order to model an infinite linear cascade.

CFD simulations are conducted with Ansys CFX. The solver is based on finite volume method, and is second order accurate. SST turbulence model with scaled wall function is employed for RANS calculation. It can provide highly accurate prediction of the separation under adverse pressure gradients, which are common in the boundary layer and in the cooling hole. Several studies [14-16] showed that the SST turbulence model is suitable for the film cooling calculations.

Convergence to a steady state is reached only if the overall residuals of the primary variables are less than 1e-4 and the variables of monitor points are kept unchanged for enough iteration steps.

**Validation.** A validation simulation is performed for the uncooled vane and then compared with the present experiment result. Pressure coefficient can reflect the vane load features, as shown in Figure 5. Horizontal ordinate x/Cx is the dimensionless axial chord length, negative for PS, 0 for the leading edge and positive for SS. The numerical result is very close to the experimental results of Vane2 and Vane3, which means that the numerical method employed in this paper is feasible and reliable. The experimental results of Vane2 and Vane3 agree with each other at most positions. Only slight divergence is observed after x/Cx >0.6. It can be stated that, the experimental passages have a good periodicity.

![a. computational domain](image1.png) ![b. grid details](image2.png)

**Figure 4**

**Experimental Results**

**Rationality of the IIM Method.** The suppositional ideal isentropic mixing method mentioned above is compared with traditional mass flow average method, in terms of TPLC calculation. Theoretically, this IIM avoided the uncertain loss occurred in mass flow averaging which is not considered yet. In addition, this method considered the influence of temperature difference between the main flow and coolant. For a real gas turbine, the temperature difference can be more than 1000K, which will cause a great disparity between these two average method.

Specific to the present experimental results, TPLC of each test conditions are calculated with these two averaging method. Figure 6 shows the disparities of these two methods (TPLC\textsubscript{MFA} – TPLC\textsubscript{IIM}) with horizontal ordinate sorted by TPLC. For lower mixing loss test cases (TPLC<0.08), TPLC\textsubscript{MFA} almost equals to TPLC\textsubscript{IIM}. For higher mixing loss test cases (after TPLC>0.08), positive disparities appear and become more obvious with the increase of TPLC. That means the P\textsubscript{ave} given by MFA is higher than that given by an ideal isentropic process, which is obviously improper. The highest disparity of 0.02 appears at TPLC\textsubscript{MFA}=0.22.

The present experiments are conducted at normal atmospheric temperature with only 14K temperature
If the temperature difference increased up to 1000K, the disparities will increase enormously. Therefore the MFA method should be eliminated and replaced with IIM method. All results have been processed with IIM method in the following parts.

**Figure 6 Disparities of MFA and IIM methods**

**Aerodynamic Mixing loss.** The TPLC distributions on the measurement plane are obtained with the help of an automatic measure system, as shown in Figure 7. The horizontal ordinate donates the pitch direction of the vane, and the vertical ordinate denotes the span wise direction of the vane. For the uncooled condition (NH), good periodicity can be observed in pitch direction, which means the vane configuration in the test section is rational.

The left wake region is from the cooled Vane 3 and the right wake is from the reference uncooled Vane 2. High TPLC districts appear at the wake region of the vanes. The highest TPLC arisen at z=2cm and z=8cm is caused by the passage vortex, which is mainly determined by vane profile. It is worthwhile to note that, the TPLCs of the cooled vane decreases at higher blow ratios. In a sense, it can be stated that the film cooling with high blowing ratios will decrease the loss of the wake region, by raising the local total pressure. This phenomenon appears at local analysis may result in an incorrect conclusion, especially the total pressure of the coolant is not taken into account of TPLC, which can be found in [2]. In order to benchmark the actual aerodynamic mixing loss caused by film cooling, the TPLCs are averaged in the mid span clip (z ranges from 4cm to 6cm) for an entire passage (y ranges from 4cm to 18cm).

**Figure 7 TPLC distributions on the measurement plane**

**Effect of Blowing Ratio.** Blowing Ratio is a parameter to describe the cooling condition and the coolant injection behaviour. For a cylindrical hole, the coolant injected at low blowing ratio will stay attached to the vane surface and form
an effective film. At high blowing ratio the coolant will be blown away from the vane surface, and the metal will be exposed to hot gas temperature. Some diffuser film cooling holes have proved to be more effective at higher blowing ratios, such as FSH and LFSH [17]. As BR increasing, more coolant will be injected into the main flow, with the mixing loss increment as well. Thus, the experimental results of CH and LFSH are selected to analyse the effect of blowing ratio on aerodynamic mixing loss.

Averaged TPLCs of CH and LFSH on suction surface are compared for BR=0.5 to 2.0, see Figure 8. The uncooled vane is selected as a reference. From BR=0 to BR=2.0, TPLC increases continuously at each inject location as BR increases. The loss increment can be separated into two parts, the extra aerodynamic loss caused by the mixing process and the internal separation loss generated in the film holes. Due to the incline of the hole, separation appears near the hole inlet, which is related to the inner-hole velocity of the coolant. In a narrow sense, the inner-hole loss cannot be considered as part of mixing loss. However, the measurement of inner-hole loss will be difficult. As a matter of convenience, the inner-hole loss will be treated as part of the mixing loss, not be discussed solely. The TPLC increments at SS3 are higher than other location, especially for LFSH. It means the film cooling mixing loss at SS3 is more sensitive to blowing ratio. Diffuser shaped holes that gain the best effectiveness at high BR should be carefully considered to place at SS3 in order to avoid high aerodynamic losses.

On the pressure surface, see Figure 9, there are also increasing trends for TPLCs, though the increment is not as obvious as on the suction surface. There is an exception at PS1, the TPLC seems to be self-limited at higher BR. In other words, the mixing loss at PS1 is not sensitive to blowing ratio, which is an advantage to place diffuser shaped holes.

Effect of Hole Location. The cooling holes are scattered on both suction and pressure surface. Thus, the influence of the coolant injection to main flow may differ at each location. Figure 10 shows the averaged TPLCs of CH on various hole locations. The uncooled vane (NH, BR=0) is selected as the reference. TPLCs on the suction surface are much higher than those on the pressure surface. That is because the blowing ratio is based on the local main flow velocity. Due to the vane profile, the local main flow velocity near SS2 is more than eight times of the velocity near PS1. It needs more coolant for SS2 to obtain the same blowing ratio, compared with other locations. The more coolant, the more mixing loss. Therefore, TPLC on SS2 is the highest at most test conditions.

Figure 9 TPLCs of CH and LFSH on pressure surface.

Figure 10 The influence of injection locations on TPLC of CH.

At the trailing edge, the low velocity boundary layer will be sucked into the trailing wake, aerodynamic loss increases sharply after the trailing wake, see Figure 11. With the help of CFD simulation, the linear averaged TPLC is illustrated from the leading to the measurement plane, with clear marks of the injection location as well as the trailing wake region. For the uncooled vane, the loss increment in the trailing wake is impressive. About one third of the total loss is generated in this region. The numerical result under predicted the aerodynamic loss of the film cooling on pressure surface, which is very close to the uncooled vane. For SS film cooling, the loss is generated at both the injection location and the trailing wake. It is important to note that, the gradient of TPLC in the trailing wake region decreases obviously, especially for SS2CH2.0. According to previous studies [6-8], the loss
variety is the result of the change boundary layer thickness, caused by coolant injection. Figure 12 shows that the boundary layer on the suction surface is interrupted by the injection at SS2. After the injection, the boundary layer begins to redevelop again.

![Figure 12 Boundary layer changed by coolant injection](image)

Effect of Hole Geometry. Bunker’s study [17] showed that, hole shapes have great influence for film cooling effectiveness. They listed 30 different hole shape with cooling effectiveness, manufacturing cost, repairing difficulty and other measure items. The LFSH gained the highest scores and is ranked as one of Top 3 hole shapes. However, the aerodynamic mixing loss is not included in the ranking. The present study shows that, LFSH will cause the highest aerodynamic loss at any cooling condition on suction surface, see Figure 13.

The loss of injection at SS2 is higher than that at SS3 for CH and FSH, which is mainly because that the loss is determined by the location factor. For LFSH and DJFH, the loss of injection at SS3 is higher than that at SS2. It can be explained that, the geometry factor becomes determination for loss increment. In other words, the hole shape and hole location are in the same order in impacting the aerodynamic loss, especially at high blowing ratio. An elaborate arrangement of the hole shape and injection location will improve the cooling effect and reduce aerodynamic loss at the same time.

![Figure 13 The influence of hole shapes on TPLC](image)

Effect of Multi Rows Cooling. When multi rows of holes applied, the cooling effectiveness has been proved to be additive [18]. As the aerodynamic loss is mainly investigated in this paper, we wish to find a loss correlation for multi-row film cooling. Figure 14 shows the TPLCs when SS1 and SS3, or PS1 and PS3 are used synchronously. The loss of two-row film cooling TPLC13 is higher than single hole film cooling (TPLC1 or TPLC3) at any condition. Considering each TPLC contains the common vane profile loss TPLC_{NH}, TPLC_{13} will be compared with the actual sum (TPLC_{1}+TPLC_{3}-TPLC_{NH}). The multi-row mixing loss TPLC_{13} is slightly higher than the sum of two single row losses. A comparison of numerical result is made, as shown in Table 3. The relative error is less than 5% for the highest blowing ratio. That is to say, the upstream row injections will rarely influence the downstream injection on mixing loss, as long as the upstream mixing process completes before the next injection location.

![Figure 14 The influence of multi-row injection on TPLC](image)
Both experiments and numerical simulations have been performed. Film cooling configuration cases for various blowing ratios, injection locations, hole shapes have been tested. The effect of multi-row film cooling has been investigated as well. The main conclusions are as follows:

1) The new IIM method proved to be rational in evaluating the aerodynamic loss of a cooled vane. The influence of temperature difference between the main flow and coolant are considered.

2) Different injection locations have different sensitivity to blowing ratio in terms of aerodynamic loss. The hole shape and hole location are in the same order in impacting the aerodynamic loss, especially at high blowing ratio. An elaborate selection of the hole shape and injection location will improve the cooling effectiveness and reduce aerodynamic loss at the same time.

3) One third of the total pressure loss is generated in the trailing wake region for the uncooled vane. The gradient of TPLC in the trailing wake region decreases for suction surface film cooling at high blowing ratio, because the injection interrupted boundary layer changes boundary layer thickness.

4) The upstream row injections will rarely influence the downstream injections on mixing loss, as long as the upstream mixing process completes before next injection location.

### NOMENCLATURE

- **CH**: Cylindrical hole
- **FSH**: Fan-shaped hole
- **LFSH**: Laidback fan-shaped hole
- **DJH**: Double jet hole
- **NH**: Uncooled vane
- **D**: Diameter of cooling hole, mm
- **p**: Lateral pitch between holes, mm
- **α**: Injection angle, °
- **β₁**: Lateral diffusion angle, °
- **β₂**: Forward diffusion angle, °
- **γ**: The compound angle, °
- **L**: Hole length, mm
- **l**: Length of the cylindrical inlet portion, mm
- **P**: Static pressure, Pa
- **P₁**: Total pressure, Pa
- **T**: Total temperature, K
- **TPLC**: Total pressure loss coefficient, -
- **BR**: Blowing ratio, -
- **V**: Velocity of main flow, m/s
- **p**: Density, kg/m³
- **A₁**: Metering area
- **m**: Mass flow rate, kg/s

### ACKNOWLEDGMENTS

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### REFERENCES


<table>
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</tr>
<tr>
<td>TPLC₂</td>
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<tr>
<td>TPLC₃</td>
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<tr>
<td>TPLC₁₂</td>
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<table>
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