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# Influence of turbine blade leading edge shape on film cooling with cylindrical holes

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ABSTRACT

Influence of turbine blade leading edge shape, gill film, and coolant-to-mainstream density ratio and blowing ratio on film cooling with cylindrical holes has been experimentally studied using pressure sensitive paint (PSP) technique. Three leading edge models are selected including a semi cylinder of radius R = 38.1 mm, elliptical leading edges of major radius 1.5R & 2.0R with an after body. Each leading edge model has three rows of film cooling holes with 15 holes each at fixed pitch of 4 hole-diameter and located along the stagnation line (0°) and at ±30°, respectively. Additional two rows of gill holes are located at ±60° (measured from inside surface). Internal impingement cooling geometry has been used while keeping the impingement hole plate at fixed distance of 31.7 mm from the stagnation line in all three leading edge models. Two configurations, with gill film holes ON and OFF are tested separately and the effects of coolant-to-mainstream density ratios (DR = 1.0, 1.5 and 2.0) with three different blowing ratios (M = 0.5, 1.0 and 1.5) are investigated. Experiments were conducted in a suction type low-speed wind-tunnel facility at Reynolds number of 102,446 based on the mainstream velocity and leading edge diameter. The mainstream turbulence intensity near the leading edge model is about 7%. Results indicate that 1.5R leading edge model has relatively better performance over others and gill film holes benefit to achieve improved coverage with higher overall film effectiveness. Additionally, to understand the flow physics, computational simulations for 1.0R leading edge model for DR = 1.5 and 2.0 at M = 1.0 are also performed using realizable k-ε turbulence model for both gill film holes ON and OFF.



## 1. Introduction

Turbine blades are exposed to a very high-temperature environment where the leading edge experiences the highest head load and requires very effective cooling scheme. Typically, rows of film cooling holes surrounding the stagnation region are employed to form a protective film by injecting cooling air over the external surface. Many investigations related to the showerhead film cooling are well documented in the literature [1]. The trace of the history indicates that an effort has been initiated to investigate the film cooling around the stagnation region with the surface distribution for last few decades using a simple circular model. In an early stage, Mick and Mayle [2] studied the detailed film cooling effectiveness and corresponding heat transfer for such a model with 3 non–axisymmetric rows of cooling holes. They found the highest film cooling effectiveness occurs near the holes with an increase in heat transfer coefficients as much as three times. Later, similar findings were also observed from the work of Ekkad et al. [3] where they used transient liquid crystal technique to capture the local distribution of effectiveness and corresponding HTC. Computational work by Rozati and Tafti [4,5] also found a good match with the experimental results of Ekkad et al. [3]. Later, Ou and Rivir [6] employed a transient liquid crystal technique to experimentally investigate the combined effects of turbulence intensity, Reynolds number, and blowing ratio on the film effectiveness and heat transfer coefficient of a large-scale symmetric circular LE with three rows of film hole. Mehendale and Han [7,8] also studied the effects of mainstream turbulence and Reynolds number on film cooling effectiveness and heat transfer coefficient.

Taslim and Khanicheh [9] experimentally investigated the impingement effect on the leading edge internal heat transfer with and without showerhead and gill-holes. One of the major conclusions of their study was the significant enhancement of the internal impingement heat transfer due to the presence of film holes along the leading edge. Simply the presence of showerhead region holes draw the impinging jets towards the leading edge walls more effectively resulting in higher internal heat transfer coefficients.

Cutbirth and Bogard [10] studied SH film cooling performance for DR effect on a turbine vane model and suggested blowing ratio

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $C$ | mass fraction |
| $d$ | hole diameter |
| $I$ | PSP emission intensity |
| $DR$ | coolant-to-mainstream density ratio $(= \rho_c/\rho_\infty)$ |
| $L$ | hole length |
| $M$ | coolant-to-mainstream blowing ratio $(= \rho_c V_c/\rho_\infty V_\infty)$ |
| $P$ | static pressure |
| $s$ | surface distance |
| $T$ | temperature |
| $Tu$ | turbulence intensity |

*Greek Symbols*

| | |
|---|---|
| $\alpha$ | surface angle |
| $\eta$ | film cooling effectiveness |
| $\rho$ | density |
| $\theta$ | dimensionless temperature |

*Subscript*

| | |
|---|---|
| $\infty$ | mainstream |
| $aw$ | adiabatic wall |
| $blk$ | black condition |
| $c$ | coolant |
| $mix$ | mixture |
| $ref$ | reference condition |

*Acronyms*

| | |
|---|---|
| CCD | Charge Couple Device |
| GH | Gill Film Hole |
| HTC | heat transfer coefficient |
| LE | Leading Edge |
| MFR | Mass Flow Rate |
| PSP | Pressure Sensitive Paint |
| RKE | Realizable K-epsilon |
| SH | Showerhead |

as an appropriate scaling parameter. Karni and Goldstein [11] studied the effects of blowing ratio on film cooling of a leading edge region using naphthalene sublimation technique. Colban et al. [12] measured adiabatic effectiveness for the showerhead region and showed that increasing the blowing ratio changed the direction of the jets and reduced the amount of lateral spreading. Gao and Han [13] studied the influence of blowing ratio (0.5–2.0) on the film hole shape and radial orientation on seven-row and three-row of film cooling holes designs using PSP technique. They found very important information that the radial angle holes perform better than the compound angle holes at blowing ratio between 1.0 and 2.0. Their results also indicate that seven-row of film cooling holes design offer much higher effectiveness with the same amount of coolant than that of the three- row design. Later, Li et al. [14] studied the same configuration under the influence of density ratio. They found higher density ratio makes more coolant attach to the surface with extended film protection. Additionally, Gao and Han [13] and Li et al. [14] including Reiss and Bölcs [15] also studied the effect of hole geometry on SH film cooling. Furthermore, Teng et al. [16] studied the effect of gill-hole shape on film cooling effectiveness, with one row of holes near the suction side gill-hole region of the turbine blade.

Most recently Nathan et al. [17] measured the adiabatic and overall effectiveness for the SH film cooling of a NASA C3X Turbine Vane. The model incorporated an internal impingement cooling configuration with a showerhead five rows of holes and one additional row on both pressure and suction sides. They found continuous improvement in effectiveness with increasing momentum flux ratio.

Typically, SH film cooling is a lot more intricate than the flat plate film cooling due to the strong curvature profile of leading edge. Ethridge [18] et al. considered the density ratio effects on an airfoil with strong curvature and pressure gradient effects. Schwarz et al. [19] considered a row of holes on the convex surface to measure film cooling performance using mass transfer method. Cruse et al. [20] studied SH film cooling for two different LE models including circular and elliptical. Effectiveness distributions are very similar for both models with a minor difference.

In recent years, many studies use the PSP technique to measure the film cooling effectiveness. Based on the heat and mass transfer analogy, the PSP technique is free from any thermal conduction error, and is applicable to high curvature surfaces. As a result, film cooling effectiveness measured by the thermal methods is expected to provide a higher effectiveness value than by the mass-transfer method. The study of Goldstein and Jin [21] and Gao et al. [22] also confirmed that. Pressure Sensitive Paint (PSP) has made it possible to achieve high-quality conduction error free surface mapping of film cooling effectiveness. Therefore, PSP is chosen in this experiment to obtain detailed the film cooling effectiveness measurement.

Many researchers numerically investigated the leading edge film cooling using the realizable k-ε turbulence model. York and Leylek [23] studied film cooling on a turbine airfoil leading edge with diffused holes. Again, the augmentation of heat transfer coefficient in a three-row leading edge model with cylindrical holes was studied by Beimaert-Chartrel and Bogard [24]. Later, Rutledge and Polanka [25] considered the influence of fluid properties on a simulated turbine blade leading edge with one cylindrical hole. However, leading edge film cooling effectiveness comparisons between CFD and experiments are still limited in the open literature.

Based on the above-mentioned literature, very few studies are available that deal with the leading edge shape effect considering the gill film hole effect. For the present study, an attempt is taken to systematically investigate the influence of blowing ratio, density ratio and leading edge shape on film cooling performance. All three leading edge models are designed with three rows of cylindrical cooling holes near the stagnation region with additional two rows of cylindrical holes on two sides of the leading edge models to simulate gill-hole discharge. Detailed film cooling effectiveness distributions are investigated under typical ranges of blowing ratio ($M$ = 0.5, 1.0, and 1.5) and density ratio ($DR$ = 1.0, 1.5, and 2.0) with and without gill film holes. A fixed internal impingement cooling geometry is employed for three leading edge models. Additionally, the RKE model is used to simulate/understand the cooling flow distribution inside the leading edge models with and without gill-hole effect. It is expected that experimental measurements provided an important database for the evaluation of computational fluid dynamics simulations of the complex leading edge film cooling design.

## 2. Experimental approach

Experiments have been performed in the test section of a low-speed suction type wind tunnel facility as shown in Fig. 1. The cross-section of the test channel is 76.2 cm × 25.4 cm. An Induc-