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# Study of discrete-hole film cooling scheme for curved wall

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## Abstract

The average discharge coefficients and overall cooling effectiveness of discrete holes with inclined angles 30°and 90°to curved walls were investigated through experiment and numerical simulation. The dependence of the average discharge coefficients on the pressure parameter was obtained. The results indicated that the inclined angle of the discrete holes exert significant impact on the discharge coefficient for a given geometrical configuration. The numerical simulations data confirmed that the flow field structures near the entrance and inside the holes influence the variation of discharge coefficient. The experiments, which were performed to study the effect of flowing ratio on cooling effect, showed that the character of flow in the curved duct can significantly affect the overall cooling effectiveness.

## Nomenclature

| | |
|---|---|
| $A_0$ | Hole area, *mm²* |
| $A$ | Curved wall area, *mm²* |
| $Cd$ | Discharge coefficient |
| $d$ | Diameter, *mm* |
| $l$ | Length of hole, *mm* |
| $M$ | Blowing ratio |
| $\dot{m}$ | Mass flow rate, *kg/s* |
| $P$ | Hole pitch in a row, *mm*. Pressure, *Pa* |
| $PS$ | Pressure parameter |
| $Re$ | Reynolds number |
| $S$ | Hole pitch in a column, *mm* |
| $T$ | Temperature, *K* |
| $v$ | Velocity, *m/s* |
| $\rho$ | Density of air, kg/m³ |
| $\alpha$ | Injection angle |
| $\eta$ | Cooling effectiveness |
| Subscript | |
| $c$ | Coolant flow |
| $j$ | Coolant jet |
| $m$ | Main flow |
| $re$ | Reality |
| $th$ | Theory |
| $w$ | Wall |
| Superscript | |
| $*$ | Total |

## Introduction

In order to improve the operational performance of gas turbine engines, high pressure ratio, increasing combustor and turbine inlet temperature are necessary technologies. Consequently, the cooling of gas turbine components is required and film cooling is widely exploited as an effective means to maintain component temperature at acceptable levels. The durability of combustor liner is regarded as an important factor in the development of the new generation combustor, especially with the increasing cooling air temperature and the decreasing cooling air flow rate. Therefore, high durability of combustor liners in future gas turbine engines depends on the development of advanced cooling technologies to induce the heat sink of cooling air. It is well known that film cooling method plays an important role in protecting the combustor liner separated from hot gas in current gas turbine engine, such as discrete holes cooling scheme as a practical and economical method for the curved duct in the reverse-flow combustor which are widely used in the turbo shaft aero-engine. The discrete holes cooling scheme is shown in Fig.1.

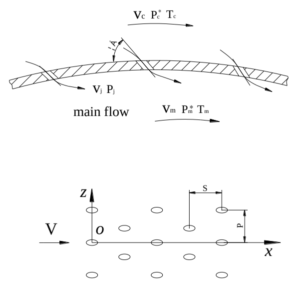



Fig.1 Discrete-hole curved wall scheme

Over the past decades, numerous research have been conducted to understand the fundamental physics of film cooling [4]. Goldstein and Yoshida [5], Schmidt et al. [10] and Yuen et al. [11] studied the film cooling effectiveness for stream wise directed holes with different angles on a flat plate. Kunlun and Richard [6] examined a discrete-hole film cooling configuration employing large eddy simulation. Peterson and Plesniak [8] studied the velocity field of multiple jets in cross flow for various jet holes and discussed the relationship between jet hydrodynamics and its implication of gas turbine film cooling applications. Numerical simulation study on film-cooling of concave plate with two staggered rows of film-cooling jets has been conducted by Miao and Ching [7]. In order to improve film cooling effectiveness, the shaped holes also have been studied. Baheri et al. [2] investigated film cooling effectiveness from a row of simple and compound-angle holes injected at 35° on a flat plate with four film cooling configurations. The results showed that shape of the hole and the trenched holes can affect the film cooling flow over the protected surface. From these cited references, the pattern of the coolant jet flow may take various forms, which can remain attached, detach and reattach, or lift off completely depending on the blowing ratio. It was also suggested that the cooling effectiveness increased along the flow direction near the holes area for a single hole or a row of holes; while the effectiveness declined as the blowing ratio beyond a certain value which the jet flow started to lift off.

In the design of gas turbine combustor, the airflow rate plays a vital role on ignition, flame stabilization, combustion efficiency and outlet temperature distribution. The knowledge of the discharge coefficients for all types of air admission holes will be required to design the airflow rate successfully. However, the geometry of the cooling holes, approach velocity and pressure drop across the liners determine the discharge coefficients of liner holes. Thus, experimental data of discharge coefficient in an analogical condition are necessary to accurately design the discrete-hole curved wall film cooling under the determinate cooling air in gas turbine combustor. Normally, the discharge coefficients of various cooling wall were obtained experimentally, and numerical simulation was adopted to study detailed dynamics in this paper. The discharge coefficient of single effusion wall with holes normal or angled to plate wall were investigated by Andrews and Mkpadi [1], Hay et al. [3] and Ren et al. [9], and the relationship of discharge coefficient with some factors, i.e., the angel to the wall surface, hole configuration and pressure parameter, was obtained.

## Theoretic Analysis

### The Discharge Coefficient

The discharge coefficient is defined as the ratio of the real mass flow rate $\dot{m}_{re}$ to the theoretic mass flow rate $\dot{m}_{th}$ through the liner holes. The real mass flow can be measured by experiment, and the theoretic mass flow rate can be calculated based on the assumption that the isentropic expansion of flow from the coolant flow to the main flow. In typical gas turbine engines the pressure drop across the combustor liners is 2%-4%, and the Mach number of air flow is 0.13-0.3, so the fluid through the liner holes can be regarded as incompressible. For the incompressible fluid, the discharge coefficient can be calculated by Eq.1

$$C_d = \frac{\dot{m}_{re}}{\dot{m}_{th}} = \frac{\dot{m}_{re}}{A\sqrt{2\rho\left(P_c^* - P_j\right)}} \tag{1}$$

The pressure drop across the cooling wall has great influence on the flow condition and discharge coefficient, and it is always described by the pressure parameter defined as Eq.2

$$PS = \frac{P_c^* - P_j}{P_c^* - P_c} \tag{2}$$

The reason causing the real mass flow rate less than the theoretic mass flow rate can be contributed to the pressure loss which may consist of separate and transition loss at pipe entrance related to the geometry configuration, friction loss caused by pipe wall roughness and dilution loss as coolant air injecting to main flow stream [1].

### Discrete-hole Film Cooling Effectiveness

Film cooling effectiveness is defined as

$$\eta = \frac{T_m - T_w}{T_m - T_c} \tag{3}$$

There are two categories of factors which determine the film-cooling effectiveness. One is the flow parameters such as the mainstream Reynolds number and blowing ratio M which is defined by Eq.4; another is configurations, such as hole-area ratio, holes pitch $P$ and $S$, and angles of injections α.

$$M = \frac{\rho_j v_m}{\rho_m v_m} \tag{4}$$

The laterally averaged film-cooling effectiveness $\bar{\eta}$ over the concave surface was calculated by laterally averaged temperature $\bar{T}_w$.

$$\bar{\eta} = \frac{T_m - \bar{T}_w}{T_m - T_c} \tag{5}$$

## Experiment

The scheme of the experiment system is showed in Fig. 2. The detailed parameters of the two experimental configurations are shown in Table 1. Air was supplied into the coolant passage, using the inlet valve 1 and outlet valve 2 to control the mass flow rate, which was measured by an orifice flow meter.

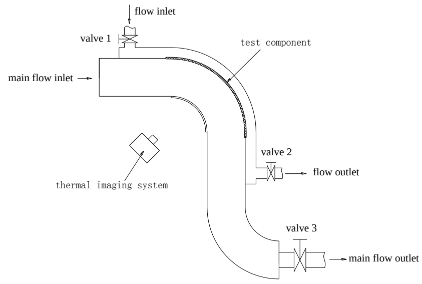



Fig.2 Experiment system scheme

The pressure drop between the coolant and main flow passages through the curved wall were controlled by the outlet valve 2 and 3. Static pressure in the coolant and main flow passage were measured by water-manometers. Then the discharge coefficients and pressure parameters were calculated by Eq.1 and Eq.2 respectively, according to a prior measured data. The effect on the discharge coefficient of concaved wall by main flow could be neglected [10]. Hence, the experiment in the present was performed under atmosphere temperature and pressure. In present experiment of the discharge coefficient, the range of operating pressure parameters was from 1.2 to 50, as shown in Table 2.

| Case | $P/d$ | $S/d$ | $\alpha$ | $d$ | $l/d$ | $A_0/A$ |
|---|---|---|---|---|---|---|
| *1* | 9.9 | 8.7 | 90 | 2.4 | 1.3 | 0.009 |
| *2* | 9.9 | 8.7 | 30 | 2.4 | 2.6 | 0.009 |

Table1 Discrete-hole cooling scheme configuration

| Case | $PS$ | $Re_m$ | $Re_j$ |
|---|---|---|---|
| *1* | 1.5-50 | $1.7\times10^4$-$4.1\times10^4$ | 900-7500 |
| *2* | 1.2-50 | $1.9\times10^4$-$4.2\times10^4$ | 1100-10000 |

Table2 Operating condition of the discharge coefficient

The film cooling effectiveness experiment was conducted base on the same discrete holes cooling configuration as the discharge coefficient experiment. The temperature on the curved wall was measured by thermal infrared imager which corrected by thermocouple imbedded on the surface of the curved wall, as shown in Fig 2. The hot gas was supplied by electric heater as the main flow, while air under atmosphere temperature as the coolant jet. The experimental operating conditions are shown in Table 3.

| case | $M$ | $T_m/T_g$ | $Re_m$ | $Re_j$ |
|---|---|---|---|---|
| 1 | 0.5,1.0,2.0 | 1.32 | $9.3\times10^4$ | 1450-6230 |
| 2 | 0.5,1.0,2.0 | 1.33 | $9.5\times10^4$ | 1650-6540 |

Table 3 Operating conditions of the cooling effectiveness

## Numerical Simulation

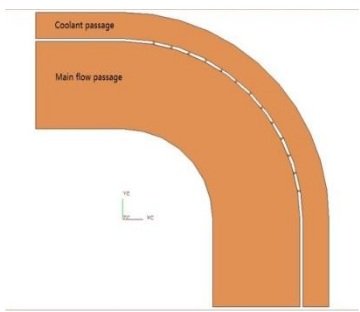



Fig. 3 Model of computation domain

For purpose of clearly display the flow characteristic and deeply explain the variety of discharge coefficient for discrete holes curved wall, CFD numerical simulations for Case1($PS$=2.2, 24) and Case2($PS$=2.2, 26) using a commercial code FLUENT were performed. The standard $k$-$\varepsilon$ turbulence model and the standard wall function, based on isotropic, incompressible and steady state fluid, have been applied in this simulation study. The computational domain was modeled by the geometry of cases, which have coolant passage, main flow passage and angled discrete holes, as shown in Fig 3.

## Results and Discussion

### The Discharge Coefficient

The relationships of the overall discharge coefficients versus the pressure parameter for two cases of discrete-hole curved wall are shown in Fig.4. The variation of overall discharge coefficients ($Cd$) of both case are similar, which increases with the $PS$ and then levels off at $Cd$=0.8 and $Cd$=0.62 roughly with specific values of $PS$, $PS$=12(α=90°) and $PS$=8 (α=30°) respectively. The main factors causing pressure loss are separation, friction and transition when coolant stream flows into the hole from coolant passage [1]. At low $PS$ value, the velocity of coolant jet is comparable to that of coolant flow in passage. Therefore, the total pressure loss which reduced the real mass flow rate $\dot{m}_{re}$ is significant to the pressure drop responding with small value of discharge coefficient $Cd$. With the $PS$ increasing, the proportion of pressure loss of separation and transition decline while the frictional loss remained same ratio to total pressure drop, which results in high value of $Cd$ and then level off at certain value. Comparing to holes which are vertical to curved wall, the discharge coefficients of holes with α=30° rise more quickly until pressure parameter reaching at $PS$=3 approximately. The variation trend of discharge coefficient for both cases could be explained by numerical simulation results as exhibited in Fig.5 which describes the flow filed of injection on the centre section of hole with different pressure parameters. It is clearly depicted in Fig. 5(a) that a recirculation zone locates in the injecting pipe, which result in the effective passage area reducing. In contrast, coolant streams can flow into pipe angled 30° more smoothly as shown in Fig 5(b). Herein, the recirculation zone is the key factor influencing the differential discharge coefficient between both cases at low $PS$ value. On the contrast, showing in Fig.5 (c) and (d), cooling stream could enter the pipe normal to surface more smoothly; while it encounter a large turning angle near the leeward side of the coolant tube entrance with angle 30°, which means more serious separation and transition loss. Meanwhile, the presence of a recirculation zone in the upper section near the leeward side of the hole angled 30° also reduce the effective passage area.

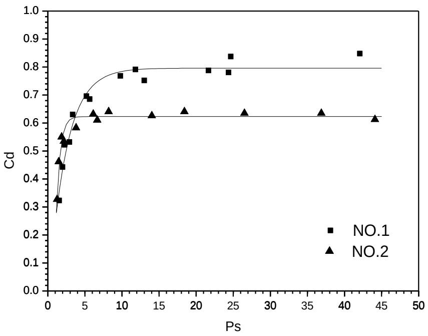
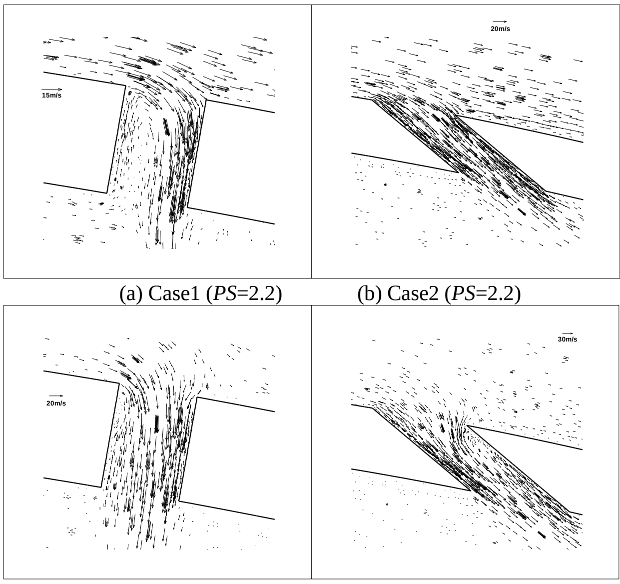



Fig.4 Curves of discharge coefficient with $PS$



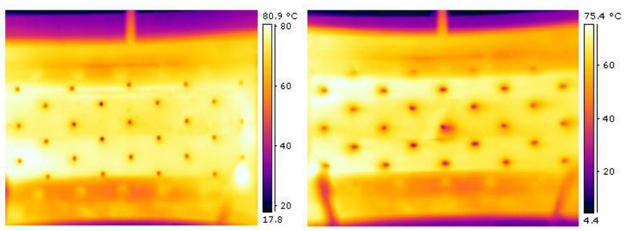

(a) Case1 ($PS$=2.2) (b) Case2 ($PS$=2.2)

(c) Case1 ($PS$=24) (d) Case2 ($PS$=26)

Fig.5 Velocity vector field of injection holes

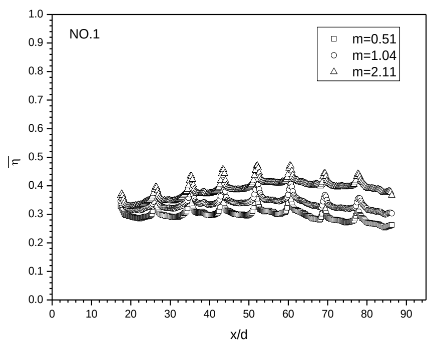
### Discrete-hole Film Cooling Effectiveness

The cooling effectiveness between both cases can be contrasted through the temperature filed of the concave wall surface as shown in Fig.6. The values of temperature were extracted from the temperature field; thus the laterally averaged cooling effectiveness can be calculated by eq.5. Fig.7 (a) and (b) plots the stream wise distributions of laterally averaged $\bar{\eta}$ at various flowing ratio for both cases respectively, which demonstrate that the cooling $\bar{\eta}$ effectiveness raise with the blowing ratio. The decline of $\bar{\eta}$ with specific blowing ratio of discrete holes with α=90° at down streaming along the direction of main flow may result from the jetting effect combining with the strong impacting and diluting by main flow stream. Therefore, the cooling film was destructed and be lift off to some extent. Comparison between both cases with specific blowing ratio is plotted in Fig.8. The evidently difference of $\bar{\eta}$ demonstrate that holes angled 30° to surface has better cooling effect than that of holes normal to surface.

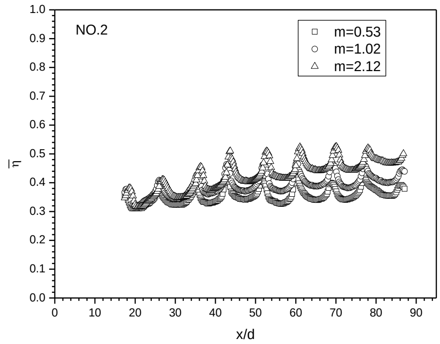



(a) Case1 ($M$=1.0) (b) Case2 ($M$=1.0)

Fig.6 Infrared image of concave wall

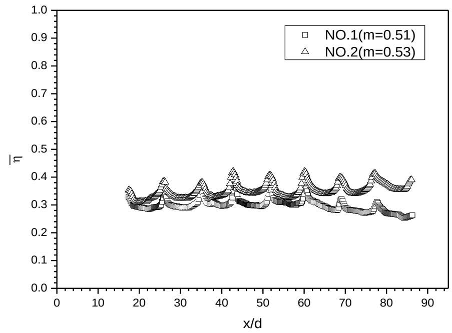



(a) Case1

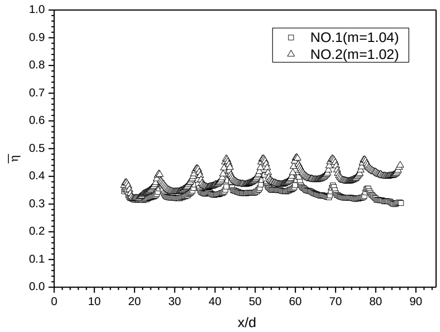



(b) Case2

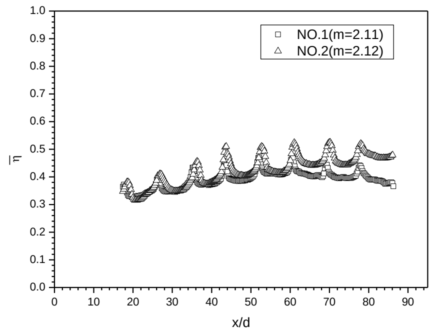
Fig.7 Lateral averaged cooling effectiveness




(a) $M$=0.5




(b) $M$=1




(c) $M$=2

Fig.8 Comparison of cooling effectiveness with various $M$

## Conclusions

A complete study of discrete-hole film cooling scheme for curved wall was conducted, including experimental and numerical simulation investigation of discharge coefficient and experimental research of cooling effectiveness. The results, under the operating condition in this paper, demonstrate that the discharge coefficient of holes normal to surface increases fast than that of angled 30°, while the differential values between them remain steady eventually, 0.18 approximately, with PS increase. The cooling effectiveness research shows that the discrete holes angled 30° performed better than that of holes normal to surface, and the main flow exerted significant influence on the overall cooling effect.

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