

Article

Effect of Inlet Compound Angle of Backward Injection Film Cooling Hole

Yoon Seong Jeong and Jun Su Park * 

Automotive Engineering, Korea National University of Transportation, Chungju 27469, Korea;
yoonseong512@daum.net

* Correspondence: js_park@ut.ac.kr; Tel.: +82-43-841-5286

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Abstract: Backward injection film cooling holes were studied to improve film cooling effectiveness using simple cylindrical holes, and this principle was applied to an actual gas turbine. Although film cooling effectiveness was improved using a backward injection film cooling hole, the backward flow of combustion gas from the backward injection cooling hole was one of the major reasons for cracks in the hot components. To prevent cracks and backward flow in the backward injection film cooling hole, this study changed the inlet compound angle of the backward injection film cooling hole. Numerical analysis using CFX v. 17.0 was performed to calculate the flow characteristics and film cooling effectiveness of backward injection film cooling. As a result, the effect of the inlet compound angle of the backward injection film cooling hole was confirmed to prevent the backward flow, which increased upon increasing the inlet compound angle. This study shows that the backward flow and cracks in the backward injection film cooling hole can be prevented simply by changing the inlet compound angle.

Keywords: film cooling; compound angle; backward injection; gas turbine

1. Introduction

In order to enhance gas turbine output, turbine inlet temperatures were continuously increased over the past half-century. Turbine inlet temperatures currently exceed the melting point of superalloys; hence, thermal barrier coatings and diverse cooling technologies are utilized to protect high-temperature parts from combustion gas.

Among these, film cooling technology directly protects high-temperature parts from combustion gas by forming a low-temperature cooling fluid on the surface of high-temperature parts. Variables affecting the efficiency of film cooling performance include blowing ratio and blowing angle, which were examined in many studies.

Bogard et al. [1] summarized film cooling methodologies and reviewed previous film cooling studies. Walters et al. [2] and Schmidt et al. [3] studied the detailed film cooling physics and the effect of compound angle. They tried to improve the film cooling effectiveness of cylindrical holes. They confirmed that the compound angle film cooling hole was a good method to improve film cooling effectiveness. However, these studies expressed the limitation of cylindrical film cooling holes by kidney vortex.

To overcome the effect of kidney vortex, previous studies changed the hole shapes. Guo et al. [4] made grooves on the wall to prevent the kidney vortex. The grooves interrupted the development of the kidney vortex behind the film cooling hole. Sister hole arrangements were studied to reduce the effect of the kidney vortex using an anti-kidney vortex [5–8]. These studies reported an efficient film cooling hole shape and arrays with excellent cooling performance compared with existing film cooling

holes by generating an anti-kidney vortex. However, the grooved wall and the sister hole arrangements require a complex manufacturing process compared with the cylindrical film cooling hole.

The blowing ratio is the most important variable that affects film cooling efficiency/performance/effectiveness. When the blowing ratio increases, the cooling fluid momentum also increases, which causes cooling fluid liftoff from the surface of airfoil, undermining film cooling efficiency [9]. In addition, a kidney vortex develops behind the film cooling hole, and the hot combustion gas flows into the cooling fluid. These fluid mechanisms involving hot combustion gas and cooling fluid reduce the effectiveness of film cooling on the surface. One proposed method to control liftoff used a diffuser-shaped cooling hole, which reduced cooling fluid momentum at the cooling hole outlet [10–13]. However, the diffuser-shaped cooling hole and anti-kidney vortex cooling hole require a highly complex manufacturing procedure and, hence, can only be installed in limited areas. Thus, there is a need to develop a method to improve the cooling performance of the simple circular hole.

The backward injection film cooling hole was proposed to improve the film cooling effectiveness of a simple circular hole. The backward injection film cooling hole is designed to inject the cooling fluid in the direction opposite to that of the external combustion gas. The cooling fluid injected from the backward injection film cooling hole changes the flow direction immediately owing to the momentum of the combustion gas. Then, the cooling fluid is spread on the surface without the liftoff phenomenon and kidney vortex. The backward injection film cooling hole shows relatively high and uniform film cooling performance in wider areas compared with forward injection film cooling [14,15]; hence, it is utilized on combustors and vane surfaces in the turbine.

Although the film cooling effectiveness of backward injection film cooling was higher than that of forward injection film cooling, the backward flow of combustion gas from the cooling hole outlet during backward injection was observed [16]. If the combustion gas flows backward into cooling holes, then the film cooling efficiency drops, and stress accumulates inside the cooling holes. As a result, cracks develop from the inside of cooling holes, which are a major cause of high-temperature damage. For this reason, a previous study suggested the prevention of backward flow by adjusting the channel length of the film cooling hole and blowing ratio.

However, since the channel length of the film cooling hole is limited by the airfoil design and material thickness, additional studies are necessary. Therefore, this study suggests changing the inlet compound angle of the backward injection film cooling hole to prevent backward flow in the backward injection film cooling hole. The inlet compound angle of the film cooling hole influences the flow directional component, and it is expected to help prevent the backward flow from the outlet of the film cooling hole and to improve the film cooling effectiveness. This study conducted a computational numerical simulation to explore the flow characteristics inside backward injection cooling holes. Based on this study, the backward injection film cooling hole with an inlet compound angle can be applied to the hot components of an actual gas turbine. Furthermore, the life and reliability of hot components are expected to improve turbine efficiency and reduce maintenance costs.

2. Numerical Analysis

Figure 1 shows a numerical analysis model of the backward injection film cooling hole. The numerical analysis model was based on the combustor of an actual gas turbine. In the combustor of a gas turbine, a film cooling hole of about 1 mm is drilled in a large area, and a slope cooling hole is used to locally improve cooling efficiency. The wall thickness of the combustor is thin; therefore, the channel length of the cooling hole is short. In consideration of this, a model for evaluating film cooling hole performance was constructed.

The fluid region includes the mainstream channel, cooling fluid supply channel, and cooling hole. The main flow supply channel was set as 70 mm, the cooling fluid supply channel was set as 30 mm, the hole diameter was set as 1 mm, the ratio of cooling supply channel length to film cooling diameter (L/D) was set as 1.75, and the blowing angle was set as 35° , as displayed in Figure 2. To control main

flow backward flowing from the cooling hole, the cooling hole inlet angles were changed from 0° to 30° , 60° , and 90° , as shown in Figure 3. When the inlet angle of the film cooling hole was changed from 0° to 90° , the film cooling hole became nozzle-shaped.

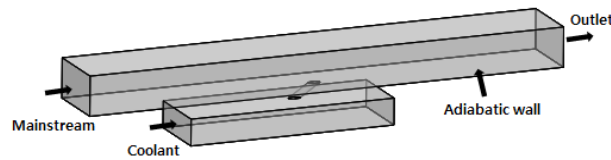


Figure 1. Schematic of the three-dimensional (3D) model of geometry.

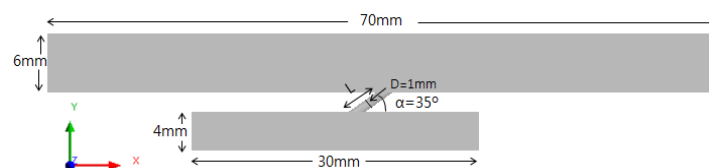


Figure 2. Size of the schematically modeled geometry.

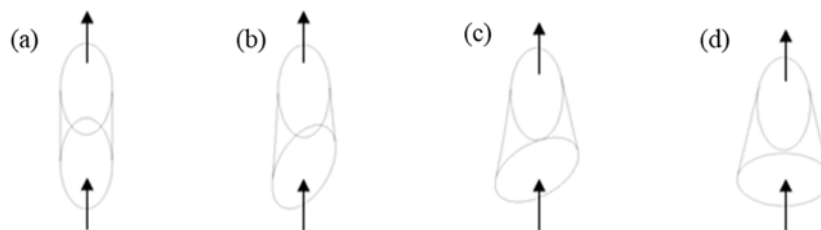


Figure 3. Schematic view of the backward injection film cooling hole: (a) 0° ; (b) 30° ; (c) 60° ; (d) 90° .

To explore flow characteristics, the three-dimensional (3D) Reynolds-averaged Navier–Stokes (RANS) equation was employed to calculate the area for analysis, and ANSYS-CFX Ver. 17.0 was utilized as a flow analysis code. A high Reynolds number was utilized for a turbulence model along with the $k-\epsilon$ model, which is appropriate when the wall viscous force is dominant. Viscosity and insulation conditions were applied to all wall surfaces. In the numerical analysis, the boundary conditions were made identical to those in the experiment [2] by setting the operating pressure at 1 atm, main flow temperature and cooling fluid temperature at 330 K and 300 K, respectively, main flow velocity at 11 m/s, and blowing ratio (M) at 1, as listed in Table 1.

Table 1. Boundary conditions of numerical analysis.

Mainstream Temperature (T_∞)	330 K	Wall Condition	Adiabatic
Coolant temperature (T_c)	300 K	Operating condition	1 atm
Mainstream velocity (U_∞)	11 m/s	Working fluid	Air ideal gas

In the film cooling technique, the blowing ratio is controlled by fluid density and velocity as expressed in the following equation:

$$M = \frac{\rho_c - U_c}{\rho_\infty - U_\infty}, \quad (1)$$

where ρ_c represents the cooling fluid density at the cooling hole outlet, U_c is the cooling fluid velocity at the cooling hole outlet, ρ_∞ is the main flow density, and U_∞ is the main flow velocity.

Film cooling effectiveness can be defined as an equation for cooling performance on the airfoil surface as follows:

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c}, \quad (2)$$

where T_∞ represents temperature of the mainstream, T_{aw} is the adiabatic surface temperature, and T_c is the coolant temperature.

As the accuracy of computational fluid dynamics results is closely related to the grid setting, an optimal grid was established by analyzing experimental data [2,3]; the results are shown in Figure 4. Due to the characteristics of the film cooling analysis, the y^+ value near the wall has more influence on the analysis results than the total grid number. Therefore, the numerical analysis model consisted of 600,000 alignment grids, and the y^+ value was set to be less than 1. As a result, the numerical analysis data tended to agree with the experimental data. The grid was set with the same conditions for all four models analyzed in this study.

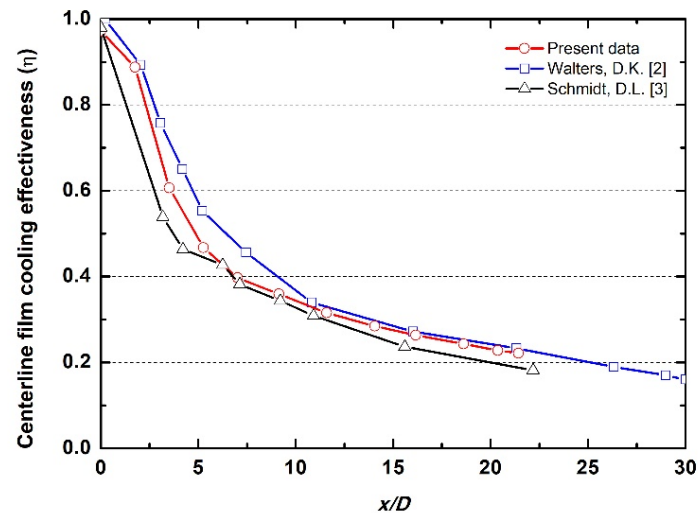


Figure 4. Centerline film cooling effectiveness comparison of present data and previous studies.

3. Results and Discussions

Figure 5 shows the velocity distribution in the flow cross-section toward the XY-direction at each position when the film cooling hole inlet angle was 0° . As the cooling fluid flowed into the channel, it leaned toward the trailing edge inside the channel owing to fluid inertia, as shown in Figure 5a–e. In particular, the cooling fluid was concentrated in the trailing-edge side of the central part of the film cooling hole channel, as shown in Figure 5b–d. As a result, the cooling fluid supply became insufficient in the leading-edge area inside the film cooling hole channel, which caused main flow influx from the leading edge of the cooling hole outlet.

When the film cooling hole inlet angle was changed, the relative angle between cooling hole inlet and outlet created rotating components of the cooling fluid. As a result, the cooling fluid further spread across the film cooling hole channel to re-attach some of the cooling fluid to the leading-edge area inside the channel, as shown in Figure 6d. This phenomenon is seen more clearly in Figures 7d and 8b,d. In contrast, Figures 6b and 7b show the re-attachment of the cooling fluid around the leading edge inside the film cooling hole channel.

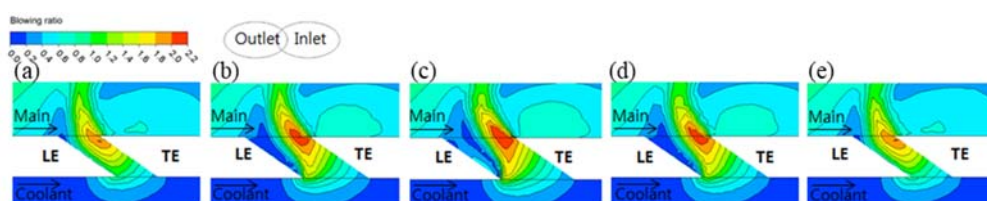


Figure 5. XY-flow cross-section contours of the 0° inlet angle of the backward injection film cooling hole: (a) $z/D = -0.4$; (b) $z/D = -0.2$; (c) $z/D = 0$; (d) $z/D = 0.2$; (e) $z/D = 0.4$.

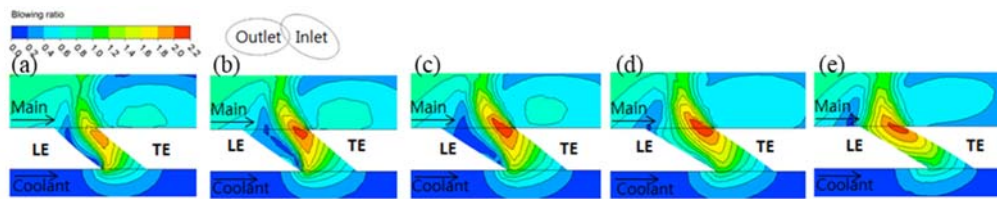


Figure 6. XY-flow cross-section contours of the 30° inlet angle of the backward injection film cooling hole: (a) $z/D = -0.4$; (b) $z/D = -0.2$; (c) $z/D = 0$; (d) $z/D = 0.2$; (e) $z/D = 0.4$.

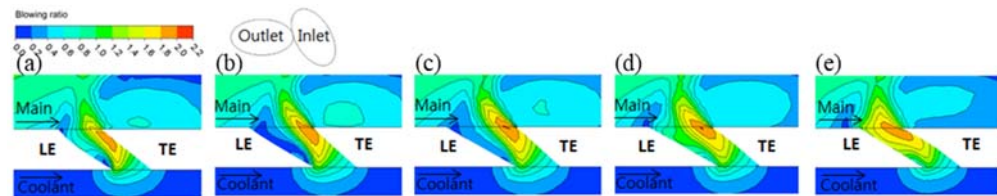


Figure 7. XY-flow cross-section contours of the 60° inlet angle of the backward injection film cooling hole: (a) $z/D = -0.4$; (b) $z/D = -0.2$; (c) $z/D = 0$; (d) $z/D = 0.2$; (e) $z/D = 0.4$.

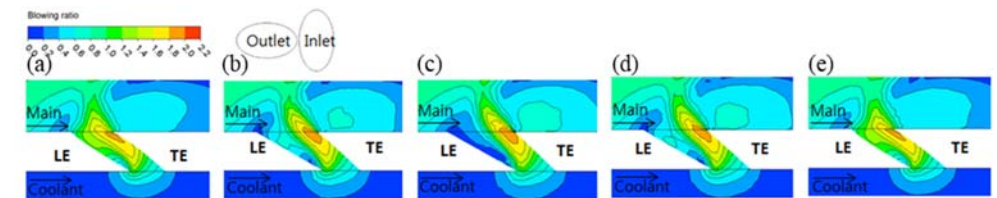


Figure 8. XY-flow cross-section contours of the 90° inlet angle of the backward injection film cooling hole: (a) $z/D = -0.4$; (b) $z/D = -0.2$; (c) $z/D = 0$; (d) $z/D = 0.2$; (e) $z/D = 0.4$.

Figures 9–12 exhibit the main flow cross-sectional velocity distribution in the XZ-direction at each position according to the cooling hole inlet angle. In general, the backward injection cooling hole showed the main flow characteristic in which the cooling fluid that developed around the leading edge of the $L/D = 0$ point moved toward the trailing edge of the $L/D = 1.75$ point of the cooling hole outlet.

When the cooling hole inlet angle was 0°, the cooling fluid distribution became intensive around the center of the film cooling hole channel. However, if the angle was 30°, the cooling hole inlet angle was twisted and, as shown in Figure 10b,c, the cooling fluid distribution was concentrated at the upper wall area. Therefore, there was no re-attachment at the $z/D = -0.2$ point in the upper wall area owing to the high momentum of the cooling fluid. In contrast, the lower wall area had cooling fluid with relatively lower momentum, which caused cooling fluid re-attachment at the $z/D = 0.2$ point in the lower wall of the film cooling hole channel.

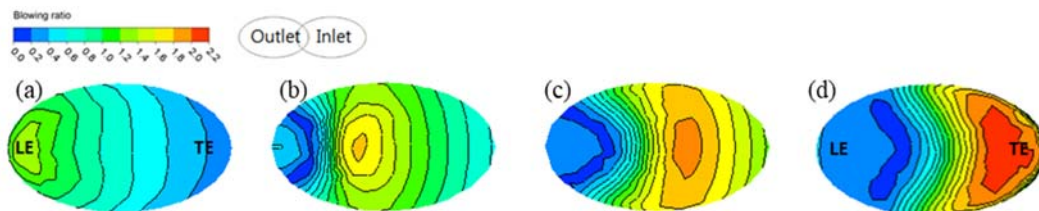


Figure 9. XZ-flow cross-section contours of the 0° inlet angle of the backward injection film cooling hole: (a) $L/D = -0.0$; (b) $L/D = -0.58$; (c) $L/D = 1.17$; (d) $L/D = 1.75$.

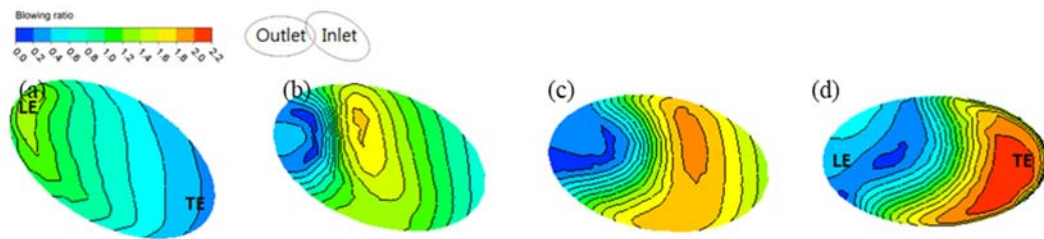


Figure 10. XZ-flow cross-section contours of the 30° inlet angle of the backward injection film cooling hole: (a) $L/D = -0.0$; (b) $L/D = -0.58$; (c) $L/D = 1.17$; (d) $L/D = 1.75$.

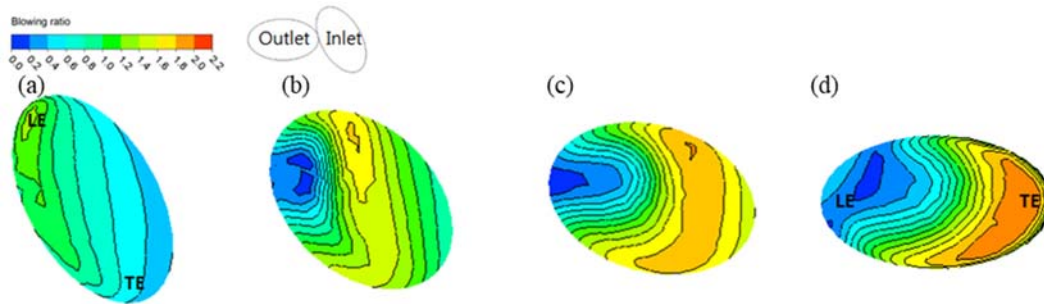


Figure 11. XZ-flow cross-section contours of the 60° inlet angle of the backward injection film cooling hole: (a) $L/D = -0.0$; (b) $L/D = -0.58$; (c) $L/D = 1.17$; (d) $L/D = 1.75$.

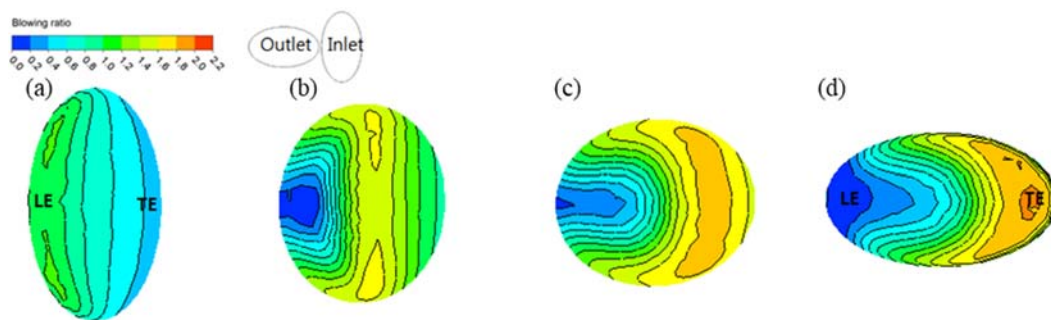


Figure 12. XZ-flow cross-section contours of the 90° inlet angle of the backward injection film cooling hole: (a) $L/D = -0.0$; (b) $L/D = -0.58$; (c) $L/D = 1.17$; (d) $L/D = 1.75$.

When the film cooling hole inlet angles were 60° and 90°, cooling fluid starting from the $L/D = 0$ leading edge point developed in a broader area. In particular, the cooling fluid developed at a low velocity around the leading edge of the cooling hole inlet when the inlet angle was 90°, as shown in Figure 12a. As a result, relatively uniform cooling fluid distribution was observed in the cooling hole outlet compared with other cases.

Figure 13 shows the streamline of cooling fluid according to the inlet angle of the hole. As mentioned above, the cooling fluid was discharged at the trailing edge of the hole in the 0° inlet angle case, as seen in Figure 13a. As the inlet angle of the cooling hole increased (Figure 13b–d), the discharged area of the cooling fluid also increased, and the maximum velocity of the cooling fluid decreased. These changes in cooling fluid flow had positive effects on film cooling effectiveness.

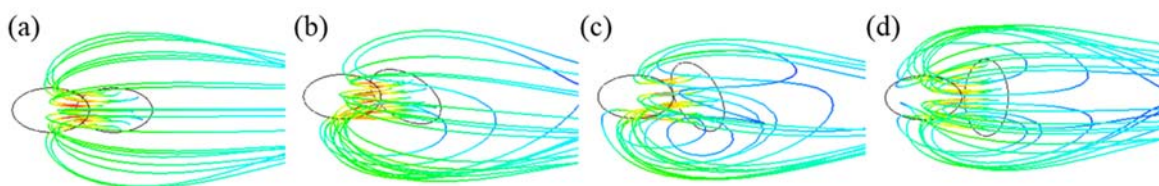


Figure 13. Streamline of cooling fluid according to the inlet angle of hole: (a) 0°; (b) 30°; (c) 60°; (d) 90°.

Firstly, it prevented the backward flow of the main flow due to increasing discharged area of the cooling fluid in the cooling hole outlet. The reduction in backward flow could be confirmed by the distribution of film cooling effectiveness at the cooling hole outlet, as shown in Figure 14 and Table 2. In general, the film cooling effectiveness at the cooling hole outlet is 1 when the main flow does not flow back into the cooling hole. However, the main flow moves back to the leading edge of the backward injection film cooling hole outlet; hence, the film cooling effectiveness is less than 1 in some areas.

In particular, the area of the main flow influx was approximately half of the cooling hole in the 0° inlet angle case. Near the leading edge of the film cooling hole outlet, the film cooling effectiveness was near 0. This means that the film cooling coolant did not spread on the whole of the film cooling hole outlet owing to the coolant moment inside the film cooling hole channel. Then, the main flow, hot combustion gas, smoothly flowed into the film cooling hole outlet, reducing the film cooling effectiveness at the film cooling hole outlet.

However, when the cooling hole inlet angle changed to 90° , rotating components were created in the coolant, and the coolant could be spread on the whole of the film cooling hole outlet. As a result, the area of the main flow influx from the cooling hole outlet decreased, and the overall film cooling effectiveness was increased.

The area-averaged film cooling effectiveness at the cooling hole outlet was calculated using Equation (3).

$$\bar{\eta} = \frac{\sum A_{outlet} \eta}{A_{outlet}}. \quad (3)$$

The area-averaged film cooling effectiveness at the cooling hole outlet increased by approximately 38%, from 0.679 in the 0° inlet angle case to 0.938 in the 90° inlet angle case. Therefore, it was confirmed that the backward injection film cooling hole with a compound inlet angle could prevent the backward flow of the main flow.

Moreover, the discharge coefficient was increased and the coolant spread widely upon increasing the inlet compound angle. The discharge coefficient presents the pressure drop in the cooling hole channel, as expressed in the following equation:

$$C_d = \frac{V_{coolant}}{\sqrt{\frac{2\Delta P}{\rho}}}, \quad (4)$$

where ΔP represents the pressure drop in the cooling channel.

A high discharge coefficient means that the coolant flows smoothly without loss in the channel. In the backward injection film cooling hole, the coolant flow direction is in the opposite direction to that of the main flow, and the different flow direction induces a high pressure drop and reduces the discharge coefficient of the backward injection film cooling hole. In addition, the backward flow of the main flow in the backward injection film cooling hole interrupts the film cooling coolant discharge and induces a high pressure drop. However, upon increasing the inlet compound angle, the backward flow of the main flow is diminished, and the film cooling coolant discharges on the whole outlet area of film cooling hole. As a result, the pressure drop decreases and the discharge coefficient increases as the smooth film cooling flow flows in the film cooling channel (Table 2). The advantage of a high discharge coefficient is to ensure a pressure margin. Therefore, a backward injection film cooling hole with an inlet compound angle can be applied in a large variety of operating conditions in an actual gas turbine due to the high pressure margin compared with the normal backward injection film cooling hole.

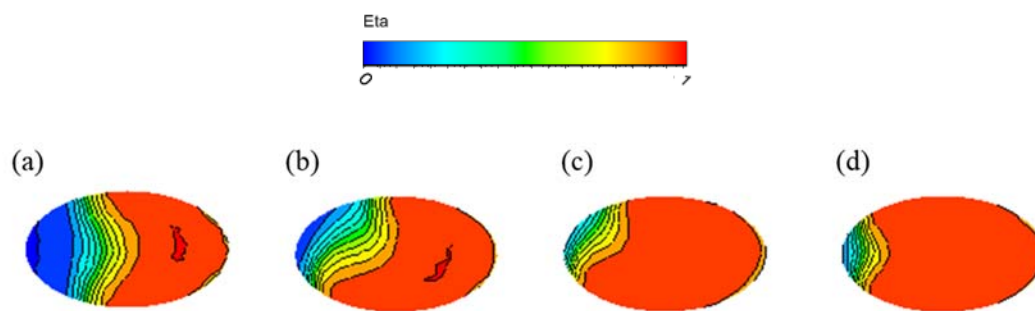


Figure 14. Film cooling effectiveness at the film cooling hole outlet according to the inlet angle of hole: (a) 0°; (b) 30°; (c) 60°; (d) 90°.

Table 2. Area-averaged film cooling effectiveness at the cooling hole outlet and discharge coefficient.

Compound Angle	Effectiveness on Outlet (η)	Discharge Coefficient (C_d)	Compound Angle	Effectiveness on Outlet (η)	Discharge Coefficient (C_d)
0°	0.679	0.58	30°	0.811	0.61
60°	0.921	0.67	90°	0.938	0.70

Secondly, as the cooling fluid was discharged to the entire area of the cooling hole outlet, the maximum velocity and local blowing ratio of the cooling fluid decreased. Furthermore, the cooling fluid spread out in the lateral direction in the process of directional change of cooling fluid flow by the main flow. As a result, the liftoff effect of the cooling fluid was reduced, and the cooling fluid was reattached to the surface relatively easily. As shown in Figures 15 and 16, the film cooling fluid affected a broader area and the film cooling effectiveness increased with increasing inlet angle of the cooling hole. The rotating component of the coolant fluid as a result of the inlet compound angle enhanced the film cooling effectiveness on both sides of the hole. Then, it helped to expand the high film cooling effectiveness area. Therefore, the average film cooling effectiveness in the inlet compound angle cases was clearly 10% higher than that in the normal case, and the film cooling effectiveness increased not only near the cooling hole but also in the region of $X/D > 5$.

Although the average values of film cooling effectiveness in the inlet compound angle cases were similar, as shown in Figure 16, the 90° case showed the best cooling performance because it prevented the backflow of main flow efficiently (Figure 14) with uniform film cooling effectiveness (Figure 15) compared with other inlet compound angle cases. Moreover, the discharge coefficient at 90° was the highest. The backward injection film cooling hole with a 90° inlet compound angle can be applied in the maximum operating range compared with other cases.

This study confirmed that changing the inlet angle of the cooling hole not only prevents the backward flow of the main flow but also achieves high film cooling efficiency in a broader area. Therefore, the backward injection film cooling hole with an inlet compound angle can be applied to improve the lifetime and reliability of hot components of an actual gas turbine. In particular, the backward injection film cooling hole with an inlet compound angle is effective when applied to the wall of a combustor or vane that requires a broader cooling area and a variety of operating conditions. Upon increasing the lifetime and reliability of the hot components using a backward injection film cooling hole with inlet compound angle, it is expected that the turbine efficiency can be improved and the maintenance cost can be reduced, which can result in lower power generation costs.

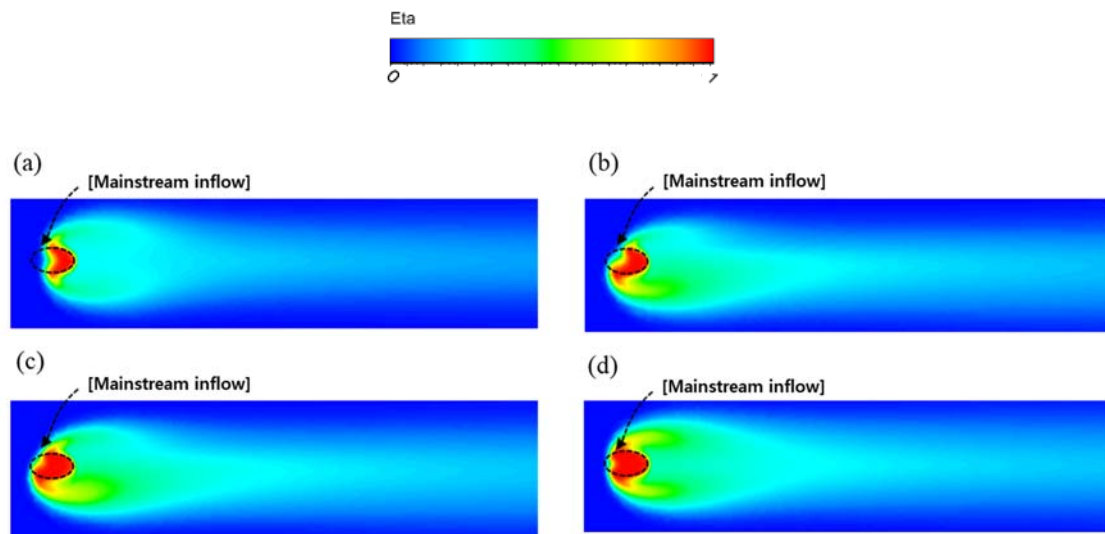


Figure 15. Film cooling effectiveness contours on the external plane according to the inlet angle of the hole: (a) 0°; (b) 30°; (c) 60°; (d) 90°.

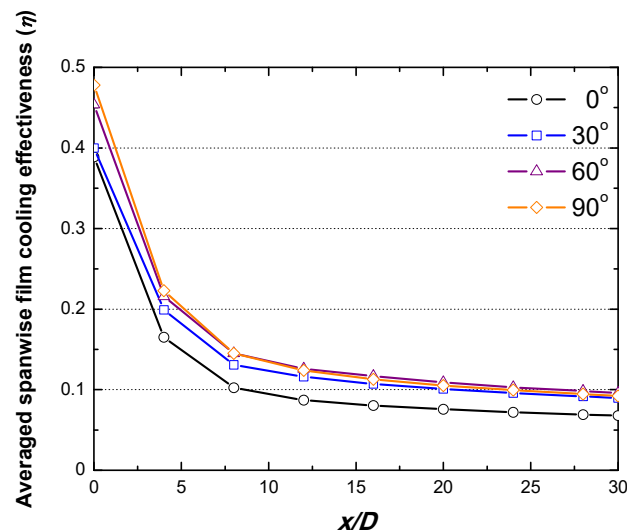


Figure 16. Averaged span-wise film cooling effectiveness according to the inlet angle of the hole.

4. Conclusions

To control the backward flow of the main flow from the cooling hole outlet in a backward injection film cooling hole, this study changed the cooling hole inlet angle to explore the flow characteristics. Based on the results of numerical analysis, the following conclusions can be drawn:

In backward injection, the cooling fluid distribution is concentrated on the tailing edge area inside the film cooling hole channel because of fluid inertia, as the cooling fluid flows in the channel. As a result, the cooling fluid supply becomes insufficient in the leading-edge part of the film cooling hole channel, causing backward flow of the main flow from the cooling hole outlet leading edge.

If the film cooling hole inlet angle is changed, the relative angle between the cooling hole inlet and outlet creates a cooling fluid rotation component, which causes cooling fluid re-attachment to the leading edge of the film cooling hole channel. In this manner, the main backward flow from the film cooling hole outlet is controlled. This is clearly observed when the cooling hole inlet angle is close to 90°.

When the cooling hole inlet angle is 90°, the cooling hole outlet has uniform velocity distribution, and the cooling fluid lies low on the external surface. Such a flow characteristic results in high film

cooling effectiveness. Furthermore, the discharge coefficient is increased upon increasing the inlet compound angle. The advantage of the backward injection film cooling hole with the inlet compound angle is not only a high cooling performance but also a wide operating range. Therefore, it is expected to contribute greatly to the improvement of turbine efficiency and to the reduction in maintenance cost by improving the cooling performance.

Based on the results of this study, it is expected that the calculation of the thermal stress around the backward injection film cooling holes with the inlet compound angle in future work can be applied to the hot components of actual gas turbines.

Author Contributions: Y.S.J. designed and conducted the numerical analysis. J.S.P. contributed to analysis and guided the writing of the manuscript. All authors analyzed the data. All authors discussed the results and commented on the manuscript. All authors read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A_{outlet}	Area of film cooling outlet
D	Film cooling hole diameter
L	Cooling supply channel length
M	Blowing ratio
T_{aw}	Adiabatic surface temperature
T_C	Coolant temperature
T_∞	Main flow temperature
U_C	Cooling fluid velocity
U_∞	Main flow velocity
x	X-direction coordinate
y	Z-direction coordinate
z	Y-direction coordinate
η	Film cooling effectiveness
$\bar{\eta}$	Averaged film cooling effectiveness
ρ_c	Cooling fluid density
ρ_∞	Main flow density

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