Numerical Investigation of the Effect of Plasma Actuator on the Film Cooling Effectiveness by Fan-Shaped Hole

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ABSTRACT: In the present study, the effects of plasma actuator on the flow and thermal fields of the film cooling through a single row of inclined fan-shaped hole over a flat plate model have been investigated. Numerical simulations have been conducted for analyzing incompressible, turbulent and steady fluid flow. Simulations were implemented using non uniform structured grid and Low-Re k-ε turbulence model. The present computed results have been compared with the numerical and experimental results and it can be seen that the gained film cooling effectiveness distributions on the flat plate agree very well with them. Then, at constant degree injection angle, length-to-diameter ratio and density ratio, investigation has been implemented, with different blowing ratios of 0.25, 0.5 and 1, applied voltages of 0, 16 and 24kV and different velocities of 4.5, 9 and 45m/s. Based on the results, fan-shaped injection hole creates better film cooling performance. And also, the effect of plasma actuator on film cooling effectiveness is better at lower blowing ratios and this improvement becomes more obvious at higher applied voltages. Also, its performance is better in low velocities. Finally, the best situation for improvement of effectiveness is in higher voltages, lower blowing ratios and low velocities

1- Introduction

Cooling of hot surfaces is of critical need for many engineering problems as gas turbine blades, which suffer very high thermal stresses due to hot effluent gases from the combustor. Film cooling is an advanced technology which can be applied to gas turbines in order to protect the surface of the blades [1]. Knowledge of film cooling is still in progress to gain more learning of the optimization mechanisms for the scheme of these systems. Effect of geometry variations of cooling holes on the cooling effectiveness has been studied [2,3]. Also, active cooling techniques play an important role to improve the cooling effectiveness, in contrast with common configuration design [4]. The plasma actuator as one of these methods is made of a set of electrode pairs (one electrode is exposed and another is encapsulated) separated by a dielectric medium. Applied voltage generates weak ionization of the working gas and so an electric body force is induced that is dominant inside the boundary layer [5]. This actuator can be attached to the wall near the outlet of a film cooling hole and affected the fluid flow field. The current study was conducted at 35 degree injection angle, hole length-to-diameter ratio *(L/D)* 5 and density ratio (DR) 1.2, with the present of plasma actuator. The flow and temperature fields were investigated with different blowing ratios (0.25, 0.5, 1), applied voltages (0, 16kV, 24kV) and main flow velocities (4.5m/s, 9m/s, 45m/s).

2- Geometry

Fig. 1 shows 3-D geometry of the computational domain [1] and Fig. 2 shows the cooling hole [2,3]. The geometry was built up and meshed using GAMBIT software.
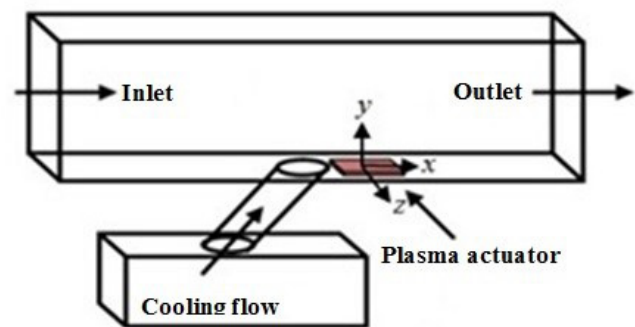

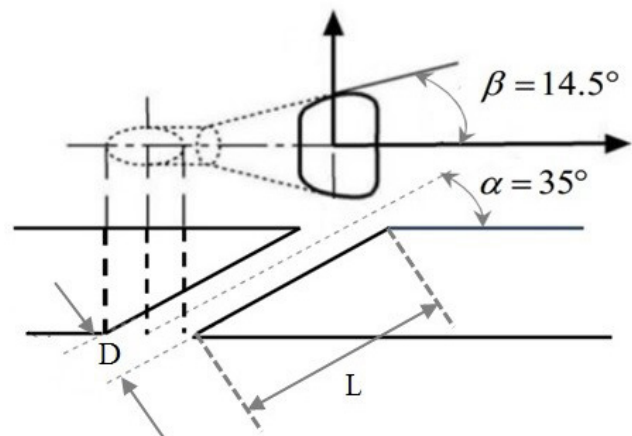**Fig. 1. 3-D geometry of the computational domain**

Fig. 2. Fan-shaped cooling hole geometry

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3- Governing Equations

The system of equations governing the flow and thermal fields including continuity, momentum and energy equations and also transport equations of k and ε, are as follows. The Launder-Sharma Low-Re k-ε turbulence model has been used. The effect of plasma actuator on the external flow is incorporated into the momentum equation as a body force vector.

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i}\left[(\mu + \mu_t)\frac{\partial u_j}{\partial x_i}\right] + \vec{f}_b \tag{2}$$

$$\frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j}\right] \tag{3}$$

$$\frac{\partial}{\partial x_i}\left[\rho k u_i - \left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] = P - \rho\varepsilon - \rho D \tag{4}$$

$$\frac{\partial}{\partial x_i}\left[\rho\varepsilon u_i - \left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_i}\right]$$
$$= \left(C_{\varepsilon 1}f_1 p - C_{\varepsilon 2}f_2\rho\varepsilon\right)\frac{\varepsilon}{k} - \rho E \tag{5}$$

4- Discussion and Results

Fluid flow velocity profile near the wall, in the vicinity of the embedded electrode which plasma is introduced, has been shown in Fig. 3.
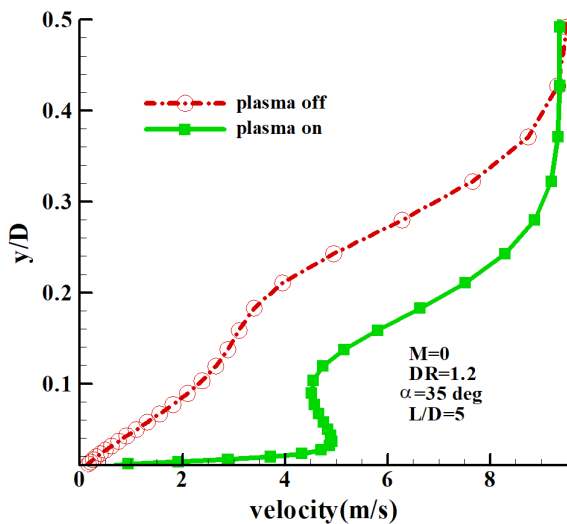
Fig. 3. Velocity profile in the vicinity of embedded electrode at *x*=0

Based on the investigations on cylindrical and fan-shepd geometries, the fan-shaped holes provide higher film cooling effectiveness than cylindrical, and plasma actuator improves the cooling performance. Temperature distribution has been shown in Fig. 4 and the results of film cooling effectiveness have been presented in Table 1.
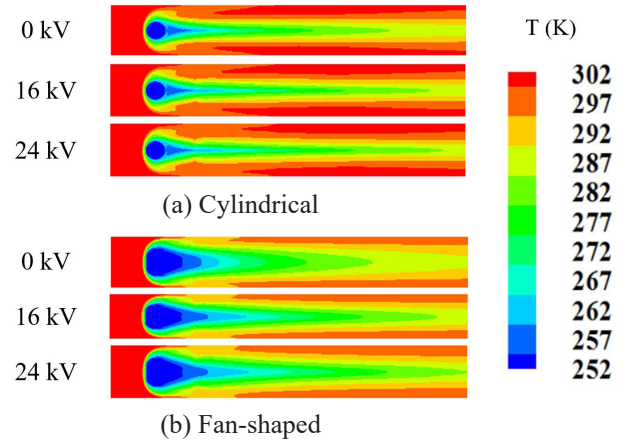
Fig. 4. Temperature distribution at *M*=0.5 and *L/D*=5

Table 1. Percentage of the average laterally film cooling effectiveness in different geometries

Cooling hole	Percentage of the average effectiveness		
	Plasma off	16 kV	24 kV
cylindrical	34.35	34.65	34.85
fan-shaped	39.72	40.83	40.76
Percentage of increasing by using a fan-shaped hole			
	15.66	17.85	16.94

Plasma actuator as shown in Fig. 5 can improve film cooling effectiveness in different blowing ratios and in higher voltages its effect is more.

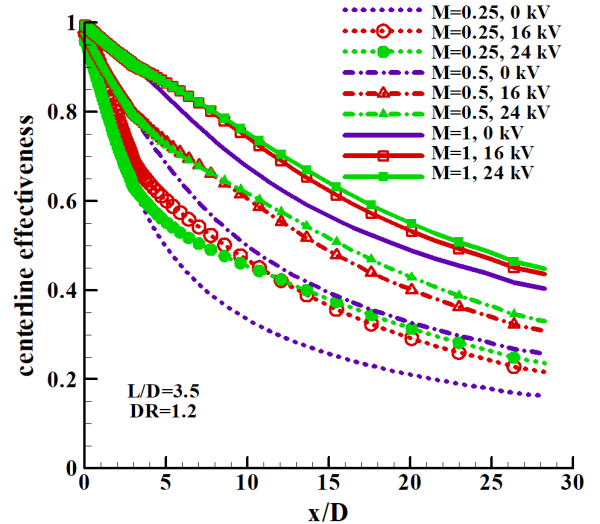The effect of the main flow velocity has been investigated for

Fig. 5. Effect of the blowing ratio on the centerline film cooling effectiveness

three values of 4.5, 9 and 45 m/s as shown in Fig. 6. Based on the results; plasma actuator performance is better in lower velocities.
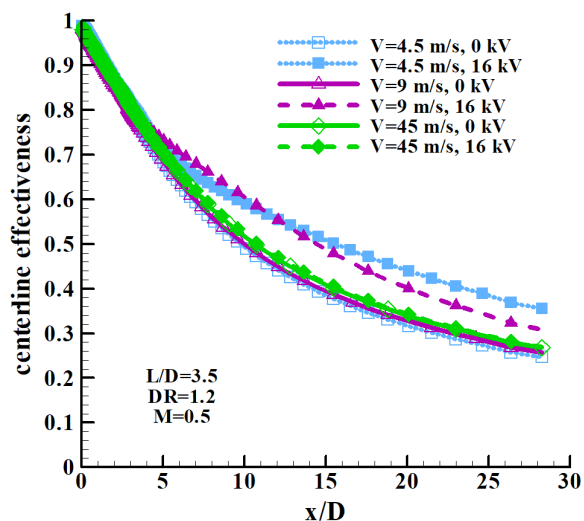
Fig. 6. Effect of the main flow velocity on the plasma actuator performance

5- Conclusions

A wide study on the effects of plasma actuator on improving film cooling performance under different blowing ratios applied voltages and main flow velocities was presented.

Based on the results, the fan-shaped hole is better than a cylindrical one and with the actuator, the cooling effectiveness is better than without. In the lower blowing ratio and higher voltage input, better film cooling effectiveness is acquired. Also, low velocities improve plasma performance.

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