International Journal of Heat and Mass Transfer 90 (2015) 825–837

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Film-cooling of cylindrical hole with downstream surface dielectric barrier discharge actuators

Sheng-ji Dai [a], Yang Xiao [a,b], Li-ming He [a,*], Tao Jin [a], Qian Zhang [a], Peng-hui Hou [a], Zi-chen Zhao [a]

[a] Aeronautics and Astronautics Engineering College, Air Force Engineering University, Xi'an 710038, China
[b] Research Institute of Army Aviation, Beijing 101121, China

ARTICLE INFO

*Article history:*
Received 21 November 2014
Received in revised form 21 May 2015
Accepted 1 July 2015

*Keywords:*
Film-cooing
Vortex
Dielectric barrier discharge
Effectiveness

ABSTRACT

This paper presents a new way to improve film-cooling performance by using surface dielectric barrier discharge actuators installed downstream from film-cooling hole. Results provide insight into the flow field characteristic and film-cooing effectiveness of both primary cylindrical hole with and without actuator, and a comparison is made. The velocity field near the test surface is found to be significantly changed under the effect of actuator, resulting in a new pair of vortexes of which the rotating direction is opposite to that of counter rotating vortex pair. Under the effect of new vortex pair, the trend of hot main flow pushing jet flow up is impeded and the jet flow is induced to flow along spanwise direction. A better jet flow adherent performance and greater jet flow coverage are achieved by installing actuator downstream from cylindrical hole than from primary hole, providing an increment in the film-cooing effectiveness. The effects of each location parameter of the actuator on the film-cooling effectiveness are studied in detail. The results indicate that under different blow ratio, the actuator location parameter has various levels of influence on film-cooing effectiveness. This is mainly due to the strength of counter rotating vortex pair in the primary cylindrical hole and the induced ability of surface dielectric barrier discharge actuators.



## 1. Introduction

With the increase of turbine inlet temperature of modern gas turbines, more efficient cooling technique is required for turbine (or combustion chamber) to protect the metal surfaces from hot combustion gases. In the past few decades, film-cooling has been widely employed to protect metal surfaces [1–6]. In film-cooling progress, jet flow (coolant) is injected through rows of holes on the metal surface, as shown in Fig. 1. A layer of cool air is formed over the metal surface, thereby insulating the metal from the hot main stream flow and further reducing the metal temperature. However, the cooling film is destroyed in the downstream area of hole because of the counter rotation vortex pairs (CRVP), which are generated by the interacting between the jet flow from film-cooling hole and the main flow [7]. The CRVP enhances the mixing strength between the jet flow and the main flow, thus promoting jet flow lifting off from the metal surface and leading the main flow to enter into the bottom of jet flow, resulting in a bad film-cooing performance. So the best way to improve film-cooling performance is mitigating the effect of CRVP, for which two methods can be adopted: 1. Change the hole's shape; 2. Use auxiliary regulating measures. As for method 1, the effect of CRVP can be reduced by using expanded hole, fan-shaped hole, expansion of fan-shaped hole, laidback hole or sister hole, etc. [8–11]. As for method 2, the effect of CRVP can be mitigated by adding a neighbor hole in upstream area of the hole, placing discrete tabs or ridge-shaped tabs on holes, adding a ramp at upstream of the hole or embedding holes in trenches, etc. [12–15].

During the past few decades, the surface dielectric barrier discharge (SDBD) has been studied extensively by various groups around the world. It has been shown that the SDBD actuator has the ability to delay separation on turbine blade and airfoils, add momentum to an induced flow and control high speed jet, etc. [16–18]. The technology of SDBD actuator flow control was applied to improving film-cooling performance in the past few years. C C Wang and Subrata Roy [19,20] propose a possible way to improve film-cooling performance by putting a single SDBD actuator at the exit of hole. Jin-lu Yu and Li-ming He [21] studied the effect of actuator location, input power and actuator number on the film-cooling performance. All the studies revealed that employing the structure of film-cooling hole with SDBD actuator is an effective way to improve film-cooling performance.

* Corresponding author.
*E-mail address:* heliming369@163.com (L.-m. He).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.007
0017-9310/

**Nomenclature**

| | |
|---|---|
| $D$ | diameter of film-cooling hole |
| $DR$ | jet flow to main flow density ratio |
| $f$ | the frequency of AC supply |
| $F_b$ | plasma-induced body force |
| $L_d$ | the interval of each actuator |
| $L_l$ | the length of actuators |
| $M$ | blow ratio, $DRv_j/v_\infty$ |
| $Re$ | Reynolds number |
| $S$ | the interval of leading edge of actuator and trailing edge of hole |
| $T$ | local fluid temperature |
| $v$ | velocity of jet flow |
| $X,Y,Z$ | cartesian coordinates |
| $y^+$ | the normalized distance |
| $\eta$ | film- cooling effectiveness |
| $\varphi$ | AC voltage |
| $\alpha$ | injection angle of the hole |

*Subscript*

| | |
|---|---|
| $aw$ | adiabatic wall |
| $j$ | jet flow |
| $s$ | spanwise |
| $\infty$ | main flow |

In this study, we propose a new way to improve film-cooling performance by using a pair of SDBD actuators. Results provide insight into the flow field characteristic and film-cooing effectiveness of both primary cylindrical hole with and without actuator, and a comparison is made. The effects of each location parameter of the actuator on the film-cooling effectiveness are studied in detail.

## 2. Design concepts

The surface dielectric barrier discharge (SDBD) actuator has been widely researched in plasma active flow control field. The scheme of SDBD actuator is shown in Fig. 2. Two electrodes are separated by a dielectric and subjected to an alternating voltage. This results in a dielectric barrier discharge above the buried electrode. The ions in the plasma region are primarily responsible for the momentum transfer via the electric field generated by the two electrodes, resulting in a body force vector acting on the external flow that can induce velocity components. In this study, we install a pair of SDBD actuators at the downstream of film-cooling hole, as shown in Fig. 3. Under the effect of actuators on the flow region near the wall, the CRVP could be reduced significantly. Therefore the mixing strength of main flow and jet flow would be weakened and the jet flow would be closer to the wall, improving film-cooling performance.

## 3. Governing equations and turbulence model

The EHD phenomenon allows the direct conversion from electric into kinetic energy with response times that can be considered negligible when compared to the characteristic times of the fluid dynamics. Based on the method of Y. B. Suzen and P. G. Huang [22], by neglecting magnetic forces, the plasma-induced body force can be expressed as

$$\overrightarrow{F_b} = \rho_c \vec{E} \tag{1}$$

where $\overrightarrow{F_b}$ is the plasma-induced body force, $\rho_c$ is the net charge density and $\vec{E}$ is the electric field. The plasma-induced body force can be calculated from two independent equations: one for the potential,

$$\nabla \cdot (\varepsilon_r \nabla \varphi) = 0 \tag{2}$$

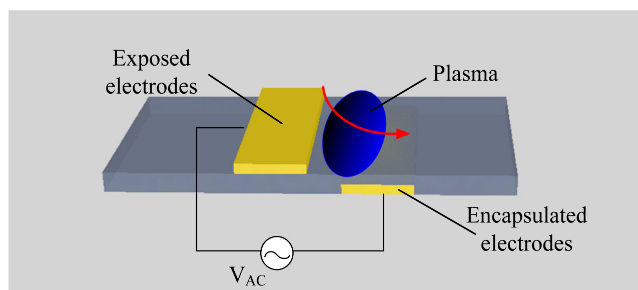



**Fig. 2.** The scheme of SDBD actuator.

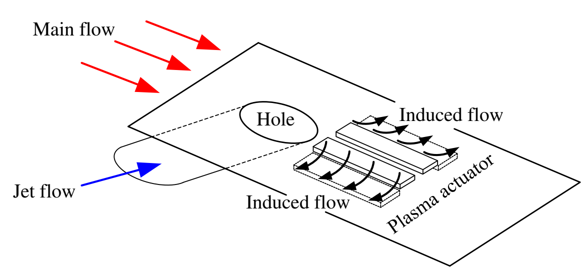
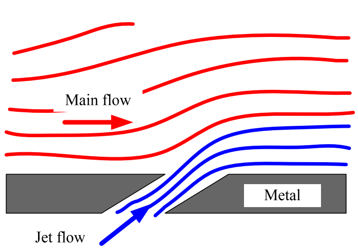
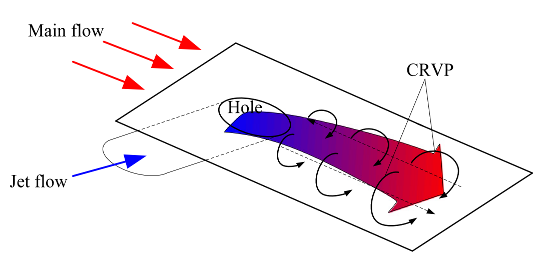



**Fig. 3.** The scheme of hole with SDBD actuator.




(a) Concept of film-cooling




(b) Counter rotating vortexes pair in film-cooing

**Fig. 1.** Scheme of film-cooing.