Large Eddy Simulation of the Effects of Plasma Actuation Strength on Film Cooling Efficiency

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Abstract In this article, numerical investigation of the effects of different plasma actuation strengths on the film cooling flow characteristics has been conducted using large eddy simulation (LES). For this numerical research, the plasma actuator is placed downstream of the trailing edge of the film cooling hole and a phenomenological model is employed to provide the electric field generated by it, resulting in the body forces. Our results show that as the plasma actuation strength grows larger, under the downward effect of the plasma actuation, the jet trajectory near the cooling hole stays closer to the wall and the recirculation region observably reduces in size. Meanwhile, the momentum injection effect of the plasma actuation also actively alters the distributions of the velocity components downstream of the cooling hole. Consequently, the influence of the plasma actuation strength on the Reynolds stress downstream of the cooling hole is remarkable. Furthermore, the plasma actuation weakens the strength of the kidney shaped vortex and prevents the jet from lifting off the wall. Therefore, with the increase of the strength of the plasma actuation, the coolant core stays closer to the wall and tends to split into two distinct regions. So the centerline film cooling efficiency is enhanced, and it is increased by 55% at most when the plasma actuation strength is 10.

Keywords: large eddy simulation, plasma actuation strength, film cooling, flow characteristic

PACS: 47.85.Gj, 47.85.L−

DOI: 10.1088/1009-0630/18/11/08

(Some figures may appear in colour only in the online journal)

1 Introduction

Turbine blades bear serious heat load due to the hot gases from the combustion chamber. This problem worsens as the turbine inlet temperature increases to obtain a high thermal efficiency aero-engine. Therefore, efficient cooling techniques such as film cooling are often taken to cool the blades to extend their lifetime. In film cooling the coolant is injected into the hot crossflow and then forms a thin layer of cooling film over the wall, protecting the wall from direct contact with the hot crossflow [1]. However, the interaction of the coolant with the crossflow causes the formation of complicated vortical structures that include horseshoe vortices, jet shear layer vortices, wake vortices, and counter-rotating vortex pair (CRVP). Among the four vortices, the CRVP dominates the mixing process downstream of the cooling hole. The CRVP entrains the hot crossflow towards the wall and lifts the cold jet off the wall causing greatly reduction of the film cooling efficiency [2]. Consequently, a larger amount of the coolant is necessarily drawn from the compressor stage resulting in lower gas turbine cycle efficiency. Hence, a study of the active flow control technology to improve film cooling efficiency is crucial and significant.

According to the researches, the film cooling efficiency could be enhanced by altering the geometric parameters of the cooling hole. In Refs. [3, 4] the experimental and numerical results showed that shaped hole had a higher film cooling efficiency than cylindrical hole. Lu et al. [5] reported that the optimal trench could significantly reduce the jet momentum, and thereby the cold jet stayed closer to the wall. Li et al. [6] placed triangular tab along the upstream edge of cooling hole to enhance the adherence of the cold jet. Kusterer et al. [7] and Heidmann and Ekkad [8] designed anti-vortex film cooling geometries to counteract the detrimental vorticity of standard cylindrical hole flow, and the film cooling efficiency was improved accordingly.

As one of the promising active flow control technology, the dielectric barrier discharge (DBD) plasma flow control technology has advantages of small size, quick response, no moving part and low power requirement, and it has been used for flat plate drag reduction, airfoils lift enhancement and separation control, etc [9,10]. Thus, its development provides new thought and approach to further improve film cooling efficiency. As shown in Fig. 1, the DBD plasma actuator consists of two electrodes that are installed on a body surface. When the high voltage AC at a high frequency is enforced to the two electrodes,
the nearby air is ionized, generating a plasma layer. Under the effect of electric field, the plasma results in a body force inducing the cold jet stays closer to the wall and flows faster. Meanwhile, the plasma also alters the boundary layer distribution behind the cooling hole wall and flows faster. Meanwhile, the plasma also alters the body force inducing the cold jet stays closer to the wall and flows faster.

It is well known that RANS failed to accurately predict the film cooling flow, and the lateral spreading rate of the cold jet was usually underestimated and the penetration of the jet into the crossflow was usually overestimated. Therefore, in order to gain further insight into the influences of the plasma actuation on the film cooling flow characteristics, it is essential to adopt a more precise turbulence description such as large eddy simulation (LES) and direct numerical simulation (DNS) to predict the evolution process of the film cooling flow. LES requires less computational resource than DNS, and previous studies show that LES can capture more detailed film cooling flow structures and predict the film cooling efficiency more precisely than RANS.

![Fig.1 Sketch of the plasma actuator and its induced wall jet](image1)

To the knowledge of the authors, this is the first study reported in the open literature that large eddy simulation is applied to investigate the effects of the plasma actuation on the flow field and the film cooling efficiency. In this paper, the plasma actuator is installed at just downstream of cooling hole exit, and the film cooling flow field under different plasma actuation strengths are simulated by LES. Subsequently, flow field parameters that include Reynolds stress, time-averaged velocity and temperature, and kidney shaped vortex are analyzed in detail, to better understand the mechanism of the plasma actuation on the improvement of film cooling efficiency.

2 Governing equations and numerical method

The phenomenological model used in this article is proposed by Shyy et al. This model is based on experimental observations and empirical parameters, and cannot address the collisional momentum transfer between ionized particles of plasma and neutral gas perfectly. But this model can capture the key features of plasma structure and require less computational effort, and thereby it is suitable for preliminarily exploring various new flow applications. This model assumes that the electric force acts only on the triangular area OAB, just as shown in Fig. 2. The electric field intensity decreases linearly as moving away from the point O and it reaches the minimum value at the edge AB. The magnitude of the electric field intensity at O is defined by \( E_0 = V/l \) where \( V \) is the maximal voltage between the two electrodes and \( l = 0.25 \text{ mm} \) is the space between the two electrodes. In Ref. [17] the electric field intensity in the triangular region can be written as \( E = E_0 - k_1x - k_2z \), and the components of electric field along the \( x \) and \( z \) direction are given by

\[
E_x = \frac{Ek_2}{\sqrt{k_1^2 + k_2^2}}, \quad E_z = \frac{Ek_1}{\sqrt{k_1^2 + k_2^2}},
\]

in which \( k_1 = (E_0 - E_b)/b \) and \( k_2 = (E_0 - E_b)/a \). \( E_b \) is the breakdown electric field intensity. In Ref. [17] the body force components along the \( x \) and \( z \) direction are calculated as

\[
F_{ex} = \rho_e e E_x f \Delta t, \quad F_{ez} = \rho_e e E_z f \Delta t,
\]

where \( \rho_e = 10^{17}/\text{m}^3 \) is the number density of electrons, \( e \) is the elementary charge, \( f = 6 \text{ kHz} \) is the frequency of the applied voltage, \( \Delta t = 67 \mu s \) is the actuation time in a period.

![Fig.2 Sketch of the phenomenological model](image2)

The time-averaged electric force is considered as body force to represent its influence on the flow field in our simulations because the plasma actuation timescales are orders of magnitude smaller than the film cooling flow field. It is well known that LES directly solves the large-scale motion equations, in which the sub-grid model is adopted to account for small-scale
dynamics, but RANS models the influences of all scale motions, and so far there is no model that can simulate all flow problems precisely without adjusting its model parameters. The governing equations for LES are

\[ \frac{\partial p}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \]

\[ \frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{T} + \rho \mathbf{f}, \]

\[ \frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\rho \mathbf{u} E) = -\nabla \cdot (\rho \mathbf{u} \mathbf{u} E - \rho \mathbf{f} - \rho \mathbf{u} \cdot \nabla \mathbf{u}), \]

where the viscous stress term and the sub-grid scale stress term are defined by

\[ \sigma_{ij} = \frac{2}{3} \rho \mathbf{u}_i \mathbf{u}_j + \frac{\nu}{\delta_i} (\mathbf{u}_i \mathbf{u}_j - \rho \mathbf{u}_i \mathbf{u}_j), \]

\[ \mathbf{T}_{ij} = \mathbf{T}_{ij} - \frac{2}{3} \rho \mathbf{u}_i \mathbf{u}_j, \]

respectively. The LES model is based on a modified grid scale to account for the grid anisotropies in the wall-modeled flow. In the WMLES model, the eddy viscosity is calculated as

\[ \nu_{sgs} = \min[\{(k d_w)^2, (C_{Smag} \Delta)^2\} \cdot S \cdot \{1 - \exp[-(y^+ / 25)^3]\}], \]

where \( d_w \) is the wall distance, \( S \) is the strain rate, \( k = 0.41 \) and \( C_{Smag} = 0.2 \) are constants. The LES model is based on a modified grid scale to account for the grid anisotropies in the wall-modeled flow. The non-dimensional parameter \( D_c = \rho_e E_0 d / \rho \eta U_\infty^2 \) is the scaling of the electrical force to the inertial force, which represents the strength of the plasma actuation.

3 Physical model and boundary condition

As shown in Fig. 3(a), the geometry of the computational domain consists of a crossflow channel and a film cooling hole. The cooling hole inclines at \( \alpha = 35^\circ \) along the streamwise direction and its diameter \( d \) is 12.5 mm, its length is 5.2d. The crossflow channel is 38.6d long, 3d wide, and 5d high. The origin of the Cartesian coordinate system is located at the trailing edge of the cooling hole exit. The \( x, y, z \) axes represent the streamwise, spanwise and normal direction, respectively. The colored bar parts in Fig. 3(b) are the plasma area, whose width \( b = 0.5d \) and height \( a = 0.025d \) (see Fig. 2). Fig. 3(b) also demonstrates the block-structured mesh in the vicinity of the cooling hole. This mesh was generated with grid points clustered in the region near the walls of the flat plate and the hole. There are in total 3.5 million cells in the computational domain and the \( y^+ \) of the wall surface is less than 1.

\[ \text{Fig. 3 Schematic of the film cooling flow. (a) Computational domain of film cooling, (b) Adiabatic flat plate with plasma actuator.} \]

The freestream inlet is located at \( x/d = -8.6 \) where the velocity \( U_\infty = 20 \text{ m/s} \), the temperature \( T_\infty = 298 \text{ K} \), the boundary layer thickness \( \delta = 12.5 \text{ mm} \) and the density \( \rho_\infty \) of the crossflow are defined. The exit at \( x/d = 30 \) where a constant static pressure is set. The periodic boundary condition is imposed in the spanwise direction (at \( y/d = \pm 1.5 \)) in the computational domain. An even velocity is applied at the inlet of the cooling hole where the temperature \( T_j = 188 \text{ K} \), the velocity \( U_j = 12.5 \text{ m/s} \) and the density \( \rho_j \) of the coolant flow are also defined. Then, the density ratio \( \rho_j / \rho_\infty = 1.6 \) and the blowing ratio \( M = \rho_j U_j / \rho_\infty U_\infty = 1 \) are adopted. All walls are adiabatic and non-slip.

The non-dimensional parameter \( D_c = \rho_e E_0 d / \rho \eta U_\infty^2 \) is the scaling of the electrical force to the inertial force, which represents the strength of the plasma actuation.
4 Validation

The experimental result \cite{21} is used to validate the reliability of the phenomenological model, and the strength of plasma actuation $D_c=1.2$ in the experiment, and a wall jet type of flow is induced by the plasma actuator in Fig. 4, this is consistent with the experimental observation. In Fig. 5, it can be found that the numerically predicted flow is in good agreement with the experimental data, although a slight quantitative disagreement is visible, this mismatch may be due to the basic deficiency in the model or the inadequacy of the two-dimensional assumption.

Furthermore, to verify the feasibility of the numerical method, the centerline film cooling efficiency $\eta = (T_{\infty} - T_w)/(T_{\infty} - T_j)$ is compared with the experimental result by Sinha et al \cite{22}. The simulation model is the same as that in Ref. [22] and the blowing ratio is 0.5. From Fig. 6, it can be seen that the numerical result agrees excellent well with the experiment data. This reveals that the numerical method used in the present study is feasible.

5 Results and discussions

Fig. 7 shows the time-averaged streamwise velocity and static pressure at the centerline of $y/d=0$. It is clear that the maximum jet exit streamwise velocity and the minimum jet exit static pressure are shifted to the trailing edge of the cooling hole due to the blocking effect of the crossflow. When the plasma actuation is imposed, the jet is induced to be closer to the wall by the plasma actuation. As a result, with the increase of the strength of the plasma actuation, the maximum jet exit streamwise velocity becomes larger, but the minimum jet exit static pressure becomes smaller. Downstream of the cooling hole, the jet separates at the trailing edge, resulting in a low pressure reverse flow region, but not far from the trailing edge the jet reattaches and then the streamwise velocity and the static pressure increase to zero or larger. Since the plasma actuation also adds energy into the reverse flow region, the streamwise velocity and the static pressure become higher in this region with the increase in the plasma actuation strength.
Fig. 8 demonstrates the profiles of the dimensionless streamwise velocity in the symmetry plane. At $x/d = 0$, the jet emerges into the crossflow and the boundary layer is lifted, and the streamwise velocity near the wall increases when the plasma actuation strength enlarges. But the plasma actuation has no significant effect on the streamwise velocity in the region at about $z/d > 0.5$ due to that the plasma actuator is relatively far away from this region. In the $Dc=0$ and $Dc=1.5$ cases, very near the wall, the jets separate at $x/d = 0.25$ where the streamwise velocity is negative, thus the film cooling efficiency extremely drops in this reverse flow region. Whereas in the $Dc=5$ and $Dc=10$ cases, at $x/d = 0.25$, the positive streamwise velocity near the wall emphasizes the disappearance of the separation region. Consequently, the plasma actuation adds streamwise momentum into the boundary layer fluid and then the fluid in the separation region is accelerated. The jet reattaches at $x/d = 1$ and gradually shifts away from the wall by the kidney shaped vortex while evolving downstream. As the plasma actuation strength increases, the streamwise velocity near the wall signally rises. Further downstream at $x/d = 3$, only when $Dc=10$, the plasma actuation has remarkable effect on the streamwise velocity in the boundary layer.

Fig. 9 shows the Reynolds stress $u'v'$ profiles in the $y/d = -0.5$ plane at different streamwise locations. Andreopoulos and Rodi [23] stated that the Reynolds stress $u'v'$ was an indication of the lateral turbulent mixing. The production of the Reynolds stress $u'v'$ is partly attributed to the streamwise velocity gradients in all three directions. Among these gradients, the velocity gradient $\partial u/\partial y$ is the dominant one which produces a positive contribution to the Reynolds stress $u'v'$, since it is negative for $y<0$. The production of the Reynolds stress $u'v'$ is also closely associated with the spanwise velocity gradients in all three directions, in which the velocity gradient $\partial v/\partial z$ is the most important one, especially in the near wall region. It can be seen that the Reynolds stress $u'v'$ is negative in the near wall region at about $z/d = 0.2$, so it is mainly related to the velocity gradient $\partial v/\partial z$. The velocity gradient $\partial v/\partial z$ is positive in the near region and thereby makes a positive contribution to the production of the Reynolds stress $u'v'$. However, the velocity gradient $\partial v/\partial z$ is negative in the outer region at about $z/d > 0.2$. So the velocity gradients $\partial v/\partial z$ and $\partial u/\partial y$ contribute to the production of the positive Reynolds stress $u'v'$ in the outer region, and when the plasma actuation is applied, the Reynolds stress $u'v'$ greatly decreases in the outer region. This reveals that the plasma actuation suppresses the lateral mixing process of the jet and improves the lateral spreading rate of the jet. Moreover, it is important to note that the absolute values of the Reynolds stress $u'v'$ can be seen to decrease while approaching downstream.
The dominant vortical structure in the film cooling flow is the kidney shaped vortex, which has an adverse influence on the film cooling efficiency. Fig. 10 shows the contours of $z$-velocity ($W$) and streamlines in the cross-sections under different plasma actuation strengths. It is clear that the kidney shaped vortex is evident in the $x/d=0.5$ plane. While approaching downstream, the cores of the kidney shaped vortex are lifted off by the entrainment and move closer to each other, causing the cold jet to shift away from the wall. Meanwhile, the kidney shaped vortex entrains the hot crossflow, resulting in an increase in its size and a reduction in its strength. Further downstream at $x/d=4$, a smaller and weaker wall vortex is formed near the wall due to the inducing effect of the kidney shaped vortex. When plasma actuation is applied, the downward force and energy injection effect of the plasma actuation weaken the interaction between the jet and the crossflow. At $x/d=0.5$ and $x/d=1$, as the plasma actuation strength increases, the strength of the kidney shaped vortex and the spacing of the cores of the kidney shaped vortex decrease, the kidney shaped vortex also stays closer to the wall, but the size of the kidney shaped vortex somewhat grows. The decrease of the jet vertical velocity weakens the lift-off effect of the kidney shaped vortex when the plasma actuation strength enlarges. Downstream of the jet exit at $x/d=2$, the kidney shaped vortex grows in the size and loses its strength. Further downstream at $x/d=4$, as the plasma actuation strength rises, the kidney shaped vortex becomes closer to the wall, and the tendency of the breakdown of the kidney shaped vortex is more pronounced. Accordingly, the kidney shaped vortex grows in size and loses its strength due to the breakdown of the kidney shaped vortex. In addition, the size and the strength of the wall vortex decrease as the plasma actuation strength increases.

Fig. 11 shows the contours of the dimensionless temperature in the cross-sections under different plasma actuation strengths. The dimensionless temperature $\theta$ is defined as $\theta = (T - T_j) / (T_\infty - T_j)$, where $T$ represents the fluid temperature. The jet penetrates into the crossflow, and then a kidney shaped vortex is formed downstream of the cooling hole. The hot crossflow is entrained underneath the coolant by the kidney shaped vortex and lifts the cooling fluid off the wall, the temperature of which has to be reduced. Accordingly, the adherence of the cooling fluid is weakened and the film cooling efficiency is degraded. Furthermore, while moving downstream, under the effect of the kidney shaped vortex, the coolant core tends to split into two distinct regions on either side of the center-plane. When the plasma actuation is applied, the plasma actuation depresses the penetration of the jet into the crossflow and weakens the lift-off effect of the kidney shaped vortex, therefore the coolant flow can effectively cover the surface. The lateral sides of the coolant core are closer to the wall because the downward effect of the plasma actuation is more pronounced at the lateral sides of the coolant core. Moreover, as the plasma actuation strength grows, the coolant core is increasingly closer to the wall, and the tendency that the coolant core is split by the kidney shaped vortex into two regions is more pronounced.
Fig. 10  Contours of time-averaged $z$-velocity and streamlines in the cross-sections ($y$-$z$ plane)

Fig. 11  Contours of dimensionless time-averaged temperature in the cross-sections ($y$-$z$ plane)
Fig. 12 shows the three-dimensional streamlines in the vicinity of the jet exit. An adverse pressure gradient is formed just upstream of the leading edge of the jet, due to the blocking effect of the jet, causing the separation of the crossflow boundary layer upstream of the leading edge. Some separated fluid forms the horseshoe vortex and then spirals downstream along the flat plate. More importantly, some crossflow boundary layer fluid wraps around the base of the jet and is observed to be entrained into the reverse flow region just downstream of the cooling hole. The fluid in this reverse flow region moves upstream, is lifted away from the wall by the cold jet, and washed downstream in the shear layer between the jet and the crossflow [1]. It is clear that the reverse flow is formed mainly by the crossflow boundary layer fluid, which intensely drops the film cooling efficiency. When the plasma actuation is applied, the momentum injection effect of the plasma actuation results in an increase in the streamwise velocity and the static pressure of the reverse flow. As a consequence, with the increase in the plasma actuation strength, less and less of the crossflow boundary layer fluid is entrained into the reverse flow region, thereby the reverse flow region obviously reduces in size and even disappears. So the film cooling efficiency is enhanced downstream of the cooling hole.

Fig. 13 depicts the distributions of the centerline film cooling efficiency. Obviously, just downstream of the cooling hole, the centerline film cooling efficiency sharply drops first due to the occurrence of the reverse flow, and then the film cooling efficiency reaches the maximum because of the reattachment of the jet. When $x/d>3$, the centerline film cooling efficiency prominently decreases with further downstream evolution. This results from the lift-off effect of the kidney shaped vortex and mixing between the jet and the crossflow. When the plasma actuation is applied, the centerline film cooling efficiency obviously becomes higher with the increases in the plasma actuation strength. As the plasma actuation strength rises to 10, the centerline film cooling efficiency is increased by at most 55%. This is due to the downward force and the momentum injection effect of the plasma actuation, which makes the cooling fluid much closer to the wall, as shown in Fig. 11.

6 Conclusion

DBD plasma flow control technology is introduced in the film cooling, large eddy simulation has been conducted to investigate the film cooling flow characteristics of a flat plate with various plasma actuation strengths. Based on the above numerical results and discussions, the conclusions are summarized as follows.

a. Since the plasma actuation has a momentum injection effect on the boundary layer just downstream of the cooling hole, the streamwise velocity and the static pressure in the recirculation region continuously grow larger with increasing the plasma actuation strength. Therefore, the size of the recirculation region is gradually reduced and the film cooling performance is improved.

b. The plasma actuation actively alters the distributions of the velocity components, thus the production process of the Reynolds stresses is affected, and the absolute values of the Reynolds stress $u'v'$ observably decrease when the plasma actuation strength is applied.

c. When the plasma actuation strength increases, the strength of the kidney shaped vortex decreases and the cores of the kidney shaped vortex move closer to each other due to the downward force and energy injection effect of the plasma actuation. Moreover, the kidney shaped vortex stays closer to the wall and has a tendency to breakdown as the strength of the plasma actuation increases.

d. The plasma actuation weakens the lift-off effect of the kidney shaped vortex, so that as the plasma actuation strength enlarges, the coolant core stays closer to the wall, and the tendency that the coolant core is split by the kidney shaped vortex into two regions is more pronounced.

e. As the plasma actuation strength enlarges, the centerline film cooling efficiency obviously increases, and when the actuation strength reaches 10, the maxima increment of the centerline film cooling efficiency is 55%.
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(Manuscript received 21 December 2015)
(Manuscript accepted 15 March 2016)
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