Numerical study of the flow structures in flat plate and the wall-mounted hump induced by the unsteady DBD plasma

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Abstract
In this work, the dielectric-barrier-discharge plasma actuator was employed to study the flow structures induced by the plasma actuator over a flat plate and a wall-mounted hump. A phenomenological dielectric-barrier-discharge plasma model which regarded the plasma effect as the body force was implemented into the Navier–Stokes equations solved by the method of large eddy simulations. The results show that a series of vortex pairs, which indicated dipole formation and periodicity distribution were generated in the boundary layer when the plasma was applied to the flow over a flat plane. They would enhance the energy exchanged between the near wall region and the free stream. Besides, their spatial trajectories are deeply affected by the actuation strength. When the actuator was engaged in the flow over a wall-mounted hump, the vortex pairs were also produced, which was able to delay flow separation as well as to promote flow reattachment and reduce the generation of a vortex, achieving the goal of reducing dissipation and decreasing flow resistance.

Keywords: DBD plasma, flow structure, large eddy simulations, fluid dynamic

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

1. Introduction

The dielectric-barrier-discharge (DBD) plasma actuator [1] is currently of considerable interest as one of the active control techniques [2, 3]. When sufficient voltages are applied to the actuator, plasma would be generated on the surface of the actuator. This plasma-based technique has been proved to be effective in enhancing lift [4], exciting the boundary layer instabilities [5], controlling dynamic stall [6] on the airfoils and so on [7]. Compared with other active control methods, the DBD plasma actuator has its own distinct advantages such as no moving parts, withstanding high g-loading and a high dynamic response. It can be also easily placed at most receptive locations [8, 9].

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The DBD was first figured out in the context of ozone generation in the 19th century [10, 11]. From then on, the DBD plasma has been widely used in various applications such as surface treatment and the excimer ultraviolet lamp [12]. In recent decades, researchers have used the DBD to generate surface electro-hydrodynamic (EHD) flows which have been demonstrated to have potential in the aerodynamic flow control applications [13]. Regarded as one of the active flow control techniques, the DBD plasma actuator now is applied to the area of enhancing lift on the airfoils, exciting 3D boundary layer instabilities, and controlling separation of low-pressure turbine blades and so on [2]. Rich physics have been observed during its application as mentioned above. However, our knowledge still seems to be insufficient to provide an adequate quantitative theoretical description for the DBD system under consideration [14]. The explanation of the experimental observations and further optimization of
plasma actuators need a deeper understanding of the mechanism of plasma flow control based on numerical simulation. Therefore, to investigate the rich physics observations shown in the applications efficiently, significant research should be continuously conducted to develop the computational capabilities.

So far, scientists have worked out many simulation approaches for the DBD plasma. They are mainly divided into First principles based modeling approaches and the simplified modeling approaches [15]. Although the first principles based modeling [16, 17] could be sufficient to address the fundamental physical mechanisms during the process of the plasma, it is too complex from a computational point of view to be solved for real plasma applications. The simplified modeling approaches are unable to predict and describe the plasma physics compared with the other ones. Nevertheless, the body force term acted by the plasma on the plasma boundary and is obtained using linear approximation; $b$ and $a$ correspond to the $x$-coordinate of point B and $y$-coordinate of point A, respectively [6]. The electric field strength outside the line A-B is not strong enough to ionize the air to generate plasma. Therefore, the value of the body force outside the triangular region is assumed to be zero.

\[ K_1 = (E_0 - E_b)/b, \quad K_2 = (E_0 - E_a)/a \] (4)

The electric force $\vec{F}_e$ can be obtained in equation (5)

\[ \vec{F}_e = \vec{E} \rho_n e_c = |\vec{E}| \rho_n e_c (K_0, K_2)/\sqrt{K_0^2 + K_2^2} \] (5)

where $\rho_n$ is the charge density and it is the same with the Shyy’s computation, $e_c$ means the elementary charge. Therefore, by coupling the electric force into the governing equations as a source term, the numerical simulation for the flows is realized [19].

Until recently, direct numerical simulation (DNS) methods, Large-eddy simulation (LES) methods and Reynolds-averaged Navier–Stokes (RANS) methods were mostly used for the computational fluid dynamics (CFD) analysis for practical engineering problems [20]. DNS based techniques and RANS based techniques are on a different side of the spectrum of turbulent calculation methods, respectively. In RANS based techniques, all turbulent fluid dynamic effects are replaced by a turbulence model, which would lead to some limitations associated with the turbulence modeling. On the other hand, the DNS methods resolve the all turbulent motions, which can avoid the limitations caused by the turbulence modeling. It will be the ultimate answer for all the turbulence flows in the foreseeable future. But they only keep the computationally practical for the simplest configurations at present. LES methods adopt a filtering function to separate the flow structure according to their scales. Then large-scaled structures are solved directly, while small-scaled structures are modeled. This leads to better prospects for improving the fidelity in the simulations for the turbulent flow.

In this work, all of the simulations described are computed with the ANSYS Fluent which provides a user-defined function (UDF) to define the source term for the flow regime. Meanwhile, the large eddy simulation method is employed with the subgrid-scale model of WALE [21].

2. Plasma model

The Shyy’s simplified model [18] is employed in the present work as shown in the figure 1. It is built on the assumption of the charge density and distribution of the electric field. Besides this, the influences of the plasmas heating and viscosity are ignored, only the effectiveness of the electric force which replaced by the plasma-induced body force is taken into consideration in the model. The electric field strength is given in equation (1).

\[ |\vec{E}| = E_0 - K_1x - K_2y \] (1)

\[ \vec{E} = |\vec{E}|(K_0, K_2)/\sqrt{K_0^2 + K_2^2} \] (2)

where $E$ is the electric field strength around actuator and decreases linearly as $x$ and $y$ increase. $E_0$ stands for the value at the coordinate origin which is set to be the maximum.

\[ E_0 = \varphi/L \] (3)

$K_1$ and $K_2$ are defined in equation (4). $E_b$ is the electric field strength on the boundary line A-B which constitutes the plasma boundary and is obtained using linear approximation; $b$ and $a$ correspond to the $x$-coordinate of point B and $y$-coordinate of point A, respectively [6]. The electric field strength outside the line A-B is not strong enough to ionize the air to generate plasma. Therefore, the value of the body force outside the triangular region is assumed to be zero.

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In this work, all of the simulations described are computed with the ANSYS Fluent which provides a user-defined function (UDF) to define the source term for the flow regime. Meanwhile, the large eddy simulation method is employed with the subgrid-scale model of WALE [21].
The governing equations are represented as follows:
\[
\rho (\partial \vec{v} / \partial t + \vec{v} \cdot \nabla \vec{v}) = -\nabla p + \mu \nabla^2 \vec{v} + f(t) \hat{F}
\]  
(6)
where the \( \rho \) is the density of the fluid, the \( \vec{v} \) refers to the velocity, \( p \) represents the pressure, and \( f(t) \) is the unsteady actuation function.

3. The discussions in the plate plane

The physical model of the flat plate (figure 2) is firstly investigated in the influence of the plasma actuator with the free stream \( U_\infty = 10 \text{ m s}^{-1} \). Shown in the figure 3, the \( x \) and \( y \) coordinates are normalized by \( b \), while the \( z \) coordinate is set to be \( 4b \). The actuator is located at \( x = 0 \). And the boundary layer thickness \( \delta \) is \( \delta = 5 \text{ mm} \). To describe the flow structure in the area of the boundary layer and the actuator clearly, the height of the first grid to the wall is defined as \( y = 0.02 \text{ mm} \).

A non-dimensional parameter \( D_c \) [22, 23] which represents the ratio of electrical force to inertial force is defined to scale the strength of the plasma actuator.
\[
D_c = \rho_c E_0 \delta^2 / (\rho U_\infty^2)
\]  
(7)
Displayed in the figure 3, the rectangular pulsed waveform is engaged to stand for the unsteady plasma actuation signal. Here, the duty cycle \( D_c \) is equal to the ratio of duration time \( T_d \) to the period \( T_p \). The unsteady actuation function \( f(t) \) is given by equation (8).
\[
f(t) = \begin{cases} 
0 \sin(2\pi ft) \geq \alpha \\
1 \sin(2\pi ft) < \alpha
\end{cases}
\]  
(8)

The actuation frequency \( f \) is 1500 Hz, while the duty cycle \( D_c \) and \( \alpha \) are 0.4 and 0.31, respectively.

In this work, the actuation strengths \( D_c \) are varied from 0 to 50. They are \( D_c = 25, D_c = 30, D_c = 35, D_c = 50 \) and the baseline case without actuation. The vorticity and velocity in the discussions are normalized by the free stream velocity: \( \omega^* = \omega / U_\infty \), \( u^* = u / U_\infty \). We also define the origin of a signal period as the zero phase angle.

Figure 4 gives the streamwise velocity of the flow field at zero phase angle with the actuation strength \( D_c = 30 \). Different stations in the streamwise are defined in the figure 4. They are \( S1 = -2.0b, S2 = 0.5b, S3 = 2.0b, S4 = 5.0b, S5 = 10.0b, S6 = 17.0b \). The velocity profile displays an inversed C shape distribution near the wall when the actuator works on the flow (figure 5). Compared with the baseline case, it can be noticed that the plasma would induce a wall jet at the location where the actuator is applied, then it leaves from the wall and decays gradually. In figure 5, the maximum induced velocity reaches nearly 1.8\( U_\infty \) at the location of \( S2 \), while it decreases to 1.2\( U_\infty \) at \( S6 \). And its location in \( y \)-coordinate grows from 0.06\( b \) to 0.40\( b \).

The contours of vorticity and streamwise velocity obtained from different cases are exhibited in figure 6. In all cases, it can be found that when the wall jet is induced, a positive vorticity would roll up. With the effect of this anti-clockwise vorticity, a negative vorticity is generated as well. They grow to be a series of vortex pairs which indicate a dipole formation and periodicity distribution. These vortex pairs can enhance the energy exchanged between the near wall region and the free stream. Due to the existence of the
fluid viscosity, the vortex pairs decay when they move downstream. Negative vorticity in the vortex pair is growing to meld with the vorticity in the boundary layer. With the increasing of the actuation strength, the vortex pair leaves the wall. The positive vorticity would be separated from the negative one and away from the wall.

Figure 7 gives the vorticity and the spatial trajectories of positive vortices in the vortex pairs along the streamwise

Figure 6. Vorticity and streamwise velocity contour at zero phase angle in different cases: (a) $D_c = 25$; (b) $D_c = 30$; (c) $D_c = 35$; (d) $D_c = 50$.

Figure 7. The vorticity of vortex pair (a) and the spatial trajectories of the positive vortex (b) with different actuation strength.

Figure 8. Mean Reynolds stress $\overline{UV}/U_{ref}^2$ profiles and mean turbulent kinetic energy $k/U_{ref}^2$ profiles comparisons in all cases: (a) $x = 0.0$; (b) $x = 0.5b$; (c) $x = b$; (d) $x = 2.0b$; (e) $x = 4.0b$; (f) $x = 6.0b$. 
direction to discuss the behaviors of the actuation strength on the vortex pair. The results also remain consistent with the discoveries in figure 6. A higher actuation strength would lead to a significantly stronger effect on the flow to induce the bigger vortices. It leads to the stronger vorticities to be maintained in the influence of the fluid viscosity and the drag of the wall.

Shown in figure 8 are the Reynolds stress profiles and mean turbulent kinetic energy profiles compared at different stations. It is known that the Reynolds stress reveals the momentum transfer by the fluctuations. At the stations of (a) and (b), the plasma draws the fluid around the plasma actuator toward the wall which causes a negative $V'$ and a positive $U'$. That is why the Reynolds stress here at the above stations is negative. And downstream from the station of (b), it pushes the fluid away from the electrode tangentially which produces a positive $V'$ and a positive $U'$. That leads to a positive Reynolds stress. It is noticed that the Reynolds stress profiles display the same basic behavior in all cases. The only difference which can be found is the magnitude shown in the different cases. With a higher actuation strength, a larger magnitude can be found at all stations. And this can be also noticed from the comparisons of mean turbulent kinetic energy profiles. Therefore, the higher actuation strength would lead to a greater momentum transfer between the near wall region and the free stream.

For the purpose of the discussion about the relationship between induced velocity and the actuation strength by the actuator, simulations are operated with the steady actuation strength $D_e$ ranging from 0 to 150 in quiescent air. Then the maximum induced velocities $U_{induced}$ in all cases at the station of $x = 0.5b$ are calculated shown in figure 9. The relationship between the the maximum induced velocities $U_{induced}$ and actuation strength $D_e$ can be obtained as follows:

$$U_{induced} = e^{0.5168 \ln(D_e)+0.9602}$$

(9)

4. The discussions in the wall-mounted hump

To examine the capability of the DBD actuator in controlling the flow separation, geometry of a wall-mounted hump is employed in this study. The grid system for the wall-mounted hump is shown in figure 10. And this grid system has been proven to be efficient in [21]. The C here stands for a chord length of 0.4200 m. Details about the geometry can be found in [24] which were released by NASA. During the investigation, a non-dimensional parameter $\chi$ which stands for the ratio of maximum induced velocities $U_{induced}$ to the free stream is defined to scale the strength of the plasma actuator.

$$\chi = U_{induced}/U_\infty$$

(10)

The free stream $U_\infty$ is 34.6 m s$^{-1}$ according to the experiments.

As shown in figure 11, four cases are conducted with $\chi = 0$ (baseline), $\chi = 0.75, \chi = 1.00, \chi = 1.25$. And the mean streamlines around the wall-mounted hump are obtained with in all cases. From the distribution of the streamline, it can be noted that without actuation, a major separation bubble exists at the downstream of the hump. When the plasma is presented, the region of separation bubble is reduced. The flow separation is also found to be delayed. Besides, flow reattachment is promoted. Especially in the case of $\chi = 1.25$, the streamline almost attaches to the wall in the near wall region.

Some instantaneous moments are chosen before the flow becomes stable. Their normalized velocity and vorticity are given in figures 12 and 13. In figure 12, a separation region is produced when the fluid flows over the hump. Velocity in this region is much less than that in the main stream. When the actuator is working on a series of fluid units, which are shown to be dipole formation, and periodicity distribution is produced. They would push the fluid in the separation region moving downstream. However, the fluid units induced by the plasma decrease when moving downstream because of the fluid viscosity. From the figure 12, it is also noticeable that the follow-up fluid unit would keep supplying the energy to the previous one. Therefore, considering figure 11, it can be concluded that with a higher actuation strength, if more energy is be added into the separation region, then separation region would be further reduced. From figure 13, the plasma can be further understood to how it works on the flow. At the early stage (a)–(e) after the actuator being active, some positive vorticities would be produced to push the negative vorticities existing in the separation region downstream. Latterly, the vortex pair would wrap the fluid upstream the actuator, keeps a higher speed moving downstream and then attaches to the wall. This leads to a smaller separation region and improving the performance of the flow.
5. Conclusions

This work discussed the flow structures over a flat plate and a wall-mounted hump induced by the dielectric-barrier-discharge (DBD) plasma. The SHYY’ model was employed to couple the plasma effect into the Navier–Stokes equations as a body force source term by the method of large eddy simulations. The results show that,

1. A series of vortex pairs, which indicated dipole formation and periodicity distribution are generated in the boundary layer when the plasma is applied to the flow over a flat plate. They would increase the mean turbulent kinetic energy of the flow to enhance the energy exchanged between the near wall region and the free stream.

2. A wall jet was produced which drew the fluid around the plasma actuator toward the wall, then ejected the fluid away from the electrode. This can be clearly noticed from the Reynold stress profiles. The distribution of $V'$ and $U'$ lead to the negative Reynold stress found before $x = 0.5b$ and positive after that.

3. At the location of $x = 0.5b$ downstream the actuator, the maximum induced velocity was found to follow a power law for the actuation strength applied. The increase of the actuation strength would result in a significantly stronger effect on the flow. More positive vorticities can be generated to have a further influence on the near wall region.
(4) When the actuator was engaged in the flow over a hump, vortex pairs were produced as well, which are in a position to delay flow separation as well as to promote flow reattachment, achieving the goal of reducing dissipation and decreasing flow resistance.

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