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# Control of turbulent channel flow using a plasma-based body force

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ABSTRACT

A steady streamwise co-flow body force originated by plasma actuators was used to control wall turbulence. The effects of such plasma-based body force on channel flow were investigated by direct numerical simulations. We found such body force can suppress turbulence fluctuations. The underlying mechanism was proposed in the discussion of Reynolds-stress budget and turbulent structures. To explore the possibility of drag reduction, we examined the skin-friction coefficient $C_f$ in the controlled flow. Two opposite effects were identified to account for the behavior of $C_f$. The first is large streamwise velocity gradient in the normal direction at wall induced by the body force, thus large increase in $C_f$ occurs over the forcing region. The second is reduction in the Reynolds stresses, which will contributes to the decrease in $C_f$. Away from the forcing region, the skin-friction coefficient rapidly decreases, even less than that of the baseline. Furthermore, force strength and spacing were considered in the parametric study. The results showed that the plasma-based body force can reduce mean skin-friction drag by 13.4%.

## 1. Introduction

Turbulent structures such as hairpin vortices and streaks near the wall are known to be responsible for high skin friction. Many studies have been done to manipulate these structures to achieve a reduction in skin-friction drag. With the development of direct numerical simulations, many control strategies have been explored numerically. Some were accomplished with blowing and suction at wall. For example, opposition control [1], formal optimal control and suboptimal control [2,3] were proposed and significant drag reduction was reported in these studies. Micro-electro-mechanical system (MEMS) is very promising in these feedback control [4–7], however, it is still a great challenge to design durable, high-yield and low-cost devices. Other control strategies were accomplished with body force exerted on fluid particles. An idealized body force [8] was used to suppress spanwise velocity in the viscous sublayer; Implementation of such body force might be possible by using electromagnetic force. Recent research [9–11] presented a possibility of using the Lorentz force for active turbulence control in conducting fluids.

Another very promising control device is based on alternating current dielectric barrier discharge (AC-DBD). The experiments on AC-DBD plasma actuators [12,13] showed that the fluid flows can be induced by glow discharge. The role of plasma on the neutral air is commonly considered as the body force [12,14–19]. Thus, the body force might be conveniently implemented with AC-DBD plasma actuators in flow control. For example, Wilkinson [20] used plasma actuators to generate a spanwise oscillation to reduce skin-friction drag. Further work by Jukes et al. [21] suggested a drag reduction of up to 45%. Elam [22] verified this approach using direct numerical simulation at $Re_\tau = 200$, and also observed a drag reduction of more than 40%. Additionally, Whalley and Choi [23] used plasma actuators to generate spanwise travelling waves as an attempt to obtain skin-friction drag reduction. While the above work concerned on the spanwise plasma-induced flow [24], little work is reported on the role of the streamwise plasma-based body force in wall-turbulence control. The aim of this paper is twofold: first, to identify deviations from the canonical channel flow due to the manipulation of the body force, which is steady, streamwise and plasma-based. Generally, it will enhance our understanding of near-wall turbulence; second, to investigate the possibility of drag reduction by such body force.

We chose a low-Reynolds-number turbulent channel flow for our tests, since the channel flow has been well understood and sufficient data are available. The pseudo-spectral method was applied to the direct numerical simulation (DNS) of the channel flow [25]. As we know, DNS is a very useful research tool to explore turbulence control strategies [2,26]. This paper is organized as follows. In the Section 2 the forcing regions and flow geometry are

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presented. The modeling and the numerical methods are introduced in the Section 3 and validated in the Section 4. The effects of the body force on wall turbulence and skin friction are discussed in the Section 5. A parametric study is presented in the Section 6. Concluding remarks and future work are provided in the Section 7.

## 2. The forcing regions and flow geometry

As for body force generated by AC-DBD, there are models of various levels of approximation [12,14–19]. Among them, Shyy's model [16] reach a good compromise between accuracy and simplicity. Although Shyy's model does not accurately capture many of the details of DBD actuator, it has been widely used in the numerical study of DBD plasma-induced flow [27,28]. Since the spatial distribution of the body force can be approximated by Shyy's model, we also adopted this model in present work.

Shyy et al. [16] suggested the body force was linearly distributed in a triangle ABC (see Fig. 1), which is referred to as the forcing region in present paper. To be compatible with the pseudo-spectral method, we slightly modified Shyy's model in our study. The edge AC extends to AC′. The maximum force is still located at point C. From edge AC to edge AC′ or AB, the body force is linearly decreased to a constant, which is determined by the breakdown electric field strength on edge AC′ or AB. Thus it makes smooth transition from forcing region to no-forcing region. This modification can significantly attenuate the Gibbs phenomena when computation transformed from wave-number space into physical space.

Our results showed that the maximum deviation of the body force due to Gibbs' error is 0.0006. The skin-friction coefficient $C_f$ is defined as $C_f = \tau_w / \left(\frac{1}{2}\rho U_m^2\right)$, where $\tau_w$ is wall shear stress, $U_m$ is the bulk mean velocity, and $\rho$ is air density. For the no-control case, $C_f = 0.0082$. Consequently, the maximum error of the skin friction due to Gibbs phenomena is less than 7.3%. Therefore, Gibbs' error can be neglected when the overall skin-friction drag is calculated.

The body force is steady and roughly in streamwise direction when imposed on the channel flow (see Fig. 2). The two forcing regions are symmetrically placed on the upper and lower wall, which are indicated by two triangular prisms. The origin of the coordinate OXYZ lies at the center of the entrance of the channel. The non-dimensional channel height is 2 when normalized by channel half-height $H$. The non-dimensional height of the forcing region (edge AC) equals 0.5, and its width (edge C′B) is 1.2. Note that the forcing region may be placed anywhere since periodicity assumed in streamwise direction. The forcing region is located from $x = 2.7$ to $x = 3.9$ in present paper. Furthermore, it may be assumed that the forcing regions are placed in tandem due to periodical condition in $x$ direction. Thus the streamwise spacing between the two consecutive forcing regions is indicated by *Gap*, which is just the streamwise size of the domain. Symbols ST1–ST4 are four positions in $x$ direction, which represent $x = 5$, 7, 9, 11, respectively. The turbulent statistical quantities are examined in these four positions.

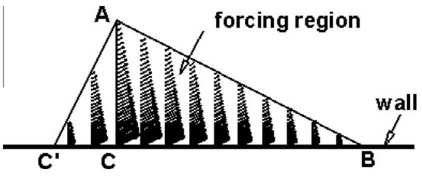

**Fig. 1.** The forcing region is triangle ABC according to Shyy's model, and changes into triangle ABC′ in our study. The body force vectors are shown in the forcing region.

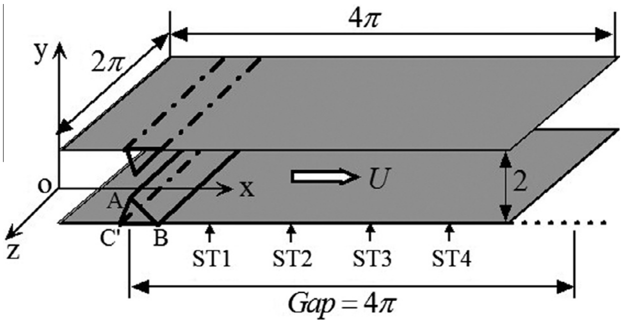

**Fig. 2.** The layout of the forcing regions (indicated by two triangular prisms) in the channel.

## 3. Modeling and numerical methodology

The Navier–Stokes equations are made non-dimensional by the bulk mean velocity $U_m$ and half channel height $H$. Reynolds number $Re_m$ is defined as $Re_m = U_m H/\nu$, where $\nu$ is molecular kinetic viscosity coefficient of air. $\nu = 1.37 \times 10^{-5}$ m$^2$/s, $U_m = 12.8$ m/s, $H = 3$ mm, $Re_m = 2800$ in this study. Both $Re_m$ and flow rate are kept constant in all cases. Reynolds number $Re_\tau$ is defined as $Re_\tau = u_\tau H/\nu$, where $u_\tau$ is wall friction velocity. In our baseline flow, $Re_\tau = 176$, very close to $Re_\tau = 180$ in the classic paper by Kim et al. [25].

The non-dimensional force strength is indicated by $Dc$, which represents the ratio of electric field force to inertial force. Following the definition in Ref. [27], it is written as

$$Dc = \frac{\rho_c e_c E_0 H}{\rho U_m^2} \tag{1}$$

where $\rho_c$ is charge density of electrons, $e_c$ is elementary charge, $E_0$ is the strongest electric field. Considering magnitudes of these parameters in practice [12,16], $Dc$ is set to be 5.14, 2.57, 1.28, respectively. For example, $Dc = 5.14$, corresponding to $\rho = 1.29$ kg/m$^3$, $\rho_c = 1.0 \times 10^{11}$/cm$^3$, $e_c = 1.602 \times 10^{-19}$ C, $E_0 = 226.27$ kV/cm.

The non-dimensional momentum equation is given by

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\nabla p + \frac{\nabla^2 \vec{u}}{Re_m} + \vec{F} \tag{2}$$

The plasma-based body force $\vec{F}$ is a time-averaged force during the period of applied voltage, and defined as

$$\vec{F} = \vartheta \Delta T Dc \vec{E} \tag{3}$$

where $\vartheta$ is frequency of applied voltage, $\Delta T$ is discharge time. In our study, $\vartheta = 3$ kHz, $\Delta T = 67$ μs. The dimensionless electric field $\vec{E}$ is given by

$$\vec{E} = \left( \frac{Ek_2}{\sqrt{k_1^2 + k_2^2}}, \frac{Ek_1}{\sqrt{k_1^2 + k_2^2}}, 0 \right) \tag{4}$$

The electric field $E$ is a linear function of $x$ and $y$, written as follows:

$$E = 1 - k_1 x - k_2 y \tag{5}$$

$$k_1 = \frac{1 - E_b/E_0}{b/H} \tag{6}$$

$$k_2 = \frac{1 - E_b/E_0}{a/H} \tag{7}$$

The breakdown electric field strength $E_b$ is 30 kV/cm. $a$ and $b$ in Eqs. (6) and (7) are characteristic length scales of the forcing region.