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Skin-friction drag reduction in a channel flow with streamwise-aligned plasma actuators

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ABSTRACT

Direct Numerical Simulations in a turbulent channel flow at a moderate Reynolds number are performed in order to investigate the potential of Dielectric Barrier Discharge (DBD) plasma actuators for the reduction of the skin-friction drag. The idea is to use a sparse array of streamwise-aligned plasma actuators to produce near-wall spanwise-orientated jets in order to destroy the events which transport high-speed fluid towards the wall. It is shown that it is possible to reduce the drag by about 33.5% when the streamwise-aligned actuators are configured to generate appropriate spanwise-orientated jets very close to the wall so that the sweeps which are mainly responsible for the skin-friction are destroyed. We demonstrate that it is possible to achieve significant drag reduction with a sparse array of streamwise-aligned plasma actuators, with one order of magnitude less actuators than previous experiments in a similar set-up.

1. Introduction

One of the most challenging tasks for turbulent flows is how to achieve skin-friction drag reduction due to an evident practical significance for engineering applications and related global impact on the sustainability challenges that we are facing today. It is now well-established that skin-friction drag reduction requires a disruption and weakening of the large-scale wall-normal motions that are associated with quasi-streamwise vortices, responsible for the formation of alternately high-speed and low-speed streaks near the wall (Virk, 1975; Kravchenko et al., 1993; Orlandi and Jiménez, 1994; Touber and Leschziner, 2012). In the last few decades, fundamental research efforts in skin-friction drag reduction have had a considerable success, and several viable strategies to reduce drag have been introduced, although often only proofs-of-concept based on numerical simulations or laboratory experiments are available. In particular, spanwise oscillation is one of the most effective techniques in wall-turbulence control, with as much as 45% reduction in skin-friction drag observed in the literature. Many experimental and numerical studies have been performed to examine the underlying mechanisms responsible for drag reduction by spanwise oscillations (Bradshaw and Pontikos, 1985; Moin et al., 1990; Choi et al., 1998; Jukes et al., 2006; Touber and Leschziner, 2012). It was shown in those studies that imposing a constant transverse strain near the wall can progressively reduce the turbulent kinetic energy, Reynolds stresses and associated skin-friction drag. The authors in Choi et al. (2002) argued that negative spanwise vorticity are produced as a result of wall oscillations, thereby modifying the vortex-stretching mechanism responsible for the production of turbulence. Experiments in a water channel demonstrated that the near-wall flow is dragged laterally by wall oscillations, with a reduction of the length of the streaks and an increase of the spacing between them (Ricco, 2004). More recently it was shown numerically that wall oscillations are strongly altering the near-wall streaks and are reducing the contribution of turbulence to the wall shear stress (Touber and Leschziner, 2012).

There are a mainly two different strategies to achieve spanwise oscillations. The first option is to enforce the oscillations by directly imposing an oscillatory motion for the wall (Choi et al., 1998; Quadrio and Ricco, 2004; Touber and Leschziner, 2012). The second option is to use actuators to modify the flow very close to the wall. Several methods are available such as electro-magnetic (Lorentz force) oscillation (Berger et al., 2000; Du et al., 2002; Pang and Choi, 2004), local oscillatory blowing (Tardu, 2001; Segawa et al., 2007) and plasma actuators (Jukes et al., 2006; Choi et al., 2011; Whalley and Choi, 2014). All of these methods result in a similar amount of drag reduction for low Reynolds numbers turbulent flows. Actually, the authors in Iwamoto et al. (2002) showed numerically that the performance of skin-friction drag reduction techniques is gradually deteriorated when the Reynolds number is

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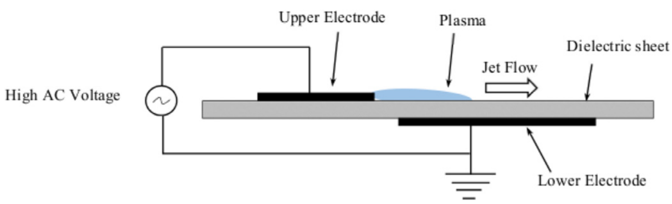

Fig. 1. Schematic diagram of an asymmetric DBD plasma actuator.

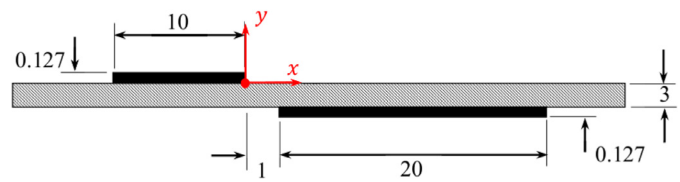

Fig. 2. Sketch of the plasma actuator used in the experiments of Benard et al. (2015). The dimension are in mm (not to scale).

increased. However, it was estimated theoretically that it should be possible to achieve a substantial drag reduction at very high Reynolds numbers (of the order of 10^5), providing that you can remove the turbulence from the buffer layer to the wall (Iwamoto et al., 2005). Finally, it should be noted that there is an open issue concerning the global energetic balance of the oscillating wall as a skin-friction drag reduction technique. The external power required to induce the spanwise oscillations can be one order of magnitude larger than the power saved owing to the skin-friction drag reduction (Quadrio and Ricco, 2004). On the positive side, it was demonstrated that net energy savings of the order of 10% are possible for low wall-oscillation velocities and low Reynolds numbers (Baron and Quadrio, 1995; Jung et al., 1992).

Following the experiments of Jukes et al. (2006), Choi et al. (2011) and Whalley and Choi (2014) the present study aims to investigate numerically a skin-friction drag reduction technique based on dielectric barrier discharge (DBD) plasma actuators. The main advantages in using these actuators are their special features that include being fully electronic with no moving parts, a fast time response for unsteady applications, a very low mass and a low power consumption. DBD plasma actuators consist of two electrodes, one exposed to the ambient fluid and the other covered by a dielectric material as shown in Fig. 1. The two electrodes are supplied with an A.C. voltage which causes the ambient fluid over the covered electrode to ionize. This ionized fluid is called the plasma and results in a body force vector which exchanges momentum with the ambient, neutrally charged, fluid. In a quiescent fluid, a DBD plasma actuator creates an induced flow towards the edge of the exposed electrode in the direction of the covered electrode and a jetting of the flow towards the far edge of the covered electrode. Extensive reviews of plasma actuators for aerodynamic applications can be found in Moreau (2007) and Corke et al. (2010). When streamwise-aligned in opposing pairs (see Fig. 7), DBD plasma actuators can be used to generate oscillating wall-jets very close to the wall, mimicking the effect of spanwise wall oscillations (Jukes et al., 2006; Choi et al., 2011; Whalley and Choi, 2014).

The first objective of the present study is to reproduce numerically, with a simple phenomenological model, the underlying physics responsible for the skin-friction drag reduction observed in the experiments of Jukes et al. (2006), Choi et al. (2011) and Whalley and Choi (2014) in a turbulent boundary layer at a moderate Reynolds number. In order to minimise the energy input, the second objective is to design a sparse array of actuators by comparison to the experiments of Jukes et al. (2006), Choi et al. (2011) and Whalley and Choi (2014), with a reduction of the number of streamwise-aligned plasma actuators by at least by one order of magnitude, while still achieving a significant drag reduction.

The organisation of the paper is as follows. First, we describe and compare three different phenomenological models used to generate a forcing term in the Navier–Stokes equations to reproduce the effect of DBD plasma actuators on the ambient fluid. Then we implement the model in our high-order flow solver and compare the effect of streamwise-aligned DBD plasma actuators in a fluid at rest with the experimental data of Jukes et al. (2006), Choi et al. (2011) and Whalley and Choi (2014). Drag reduction investigations are then carried out with pairs of streamwise-aligned actuators with and without spanwise oscillations. The underlying mechanisms for drag reduction are discussed thanks to 2D and 3D instantaneous snapshots of the flow as well as with virtual probes and the VITA technique. The paper is ended with a discussion about power balance and a conclusion.

2. Modelisation of DBD plasma actuators

Attempts at modelling DBD plasma actuators can be divided into two groups: first-principle based models and simplified phenomenological models. The first-principle based models are aiming at modelling the physical mechanisms of the actuator. They require the solution of complex transport equations for both charged and neutral species and a Poisson equation for the electric field. They are very expensive and can cost up to several orders of magnitude more than simplified models (Boeuf et al., 2007; Singh and Roy, 2008; Rogier et al., 2014; Parent et al., 2016; Nishida et al., 2014; 2016).

Simplified phenomenological models attempt to capture the ionization effects of the plasma actuator without directly modelling the species transport equations. Those models are based on the assumption that the plasma formation and fluid flow response can be decoupled due to the large disparities in the characteristic velocities associated with each process (Mertz and Corke, 2011). Among the most popular of those models are the Shyy model (Shyy et al., 2002) and the Suzen & Huang models (Suzen et al., 2005; 2007) because of their relative simplicity and ability to mimic the time-averaged effects of a DBD actuator on the ambient fluid. Even if those models are time-independent, they are widely used and have been validated in a turbulent channel flow (Ibrahim and Skote, 2014; Li et al., 2015) for single spanwise-aligned actuators.

Because this is the first attempt to achieve numerically drag reduction using streamwise-aligned pairs of plasma actuators in a turbulent channel flow, simplicity and easiness of implementation are essential starting points. Our objective here is to be able to generate spanwise-orientated jets close to the wall and this can be achieved without expensive first-principle based models. In this section, three DBD plasma actuator models among the most popular simplified phenomenological ones are tested and validated against the experimental data of Benard et al. (2015): The Shyy model (Shyy et al., 2002) (Shy02), the Suzen and Huang model of 2005 (Suzen et al., 2005) (S&H05), and the Suzen and Huang Model of 2007 (Suzen et al., 2007) (S&H07). The dimensions of the plasma actuator to be modelled are indicated in Fig. 2. The plasma actuator is made of a 10 mm air-exposed and a 20 mm grounded electrode (with an inter-electrode distance of 1 mm), these two electrodes are placed on both side of a 3 mm thick PMMA plate acting as dielectric barrier. The reference experimental time-averaged velocity profiles were obtained in an ambient fluid at rest, at the spanwise centre of the actuator with an applied voltage V_{rms} equals to 20 kV, and an applied frequency of 1000 Hz. More details about the experimental set-up can be found in Benard et al. (2015).