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Experimental and computational study of the flow induced by a plasma actuator

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ABSTRACT

A complementary experimental and computational study of the flow field evoked by a plasma actuator mounted on a flat plate was in focus of the present work. The main objective of the experimental investigation was the determination of the vector force imparted by the plasma actuator to the fluid flow. The force distribution was presently extracted from the Navier–Stokes equations directly by feeding them with the velocity field measured by a PIV technique. Assuming a steady-in-mean, two-dimensional flow with zero-pressure gradient, the imbalance between the convective term and the momentum equation's right-hand-side terms reveals the desired resulting force. This force-distribution database was used afterwards as the source term in the momentum equation. Furthermore, an empirical model formulation for the volume-force determination parameterized by the underlying PIV-based model is derived. The model is tested within the RANS framework in order to predict a wall jet-like flow induced by a plasma actuator. The Reynolds equations are closed by a near-wall second-moment closure model based on the homogeneous dissipation rate of the kinetic energy of turbulence. The computationally obtained velocity field is analysed along with the experimental data focussing on the wall jet flow region in proximity of the plasma actuator. For comparison purposes, different existing phenomenological models were applied to evaluate the new model's accuracy. The comparative analysis of all applied models demonstrates the strength of the new empirical model, particularly within the plasma domain. In addition, the presently formulated empirical model was applied to the flow in a three-dimensional diffuser whose inflow was modulated by a pair of streamwise vortices generated by the present plasma actuator. The direct comparison with existing experimental data of Grundmann et al. (2011) demonstrated that the specific decrease of the diffuser pressure corresponding to the continuous forcing was predicted correctly.

1. Introduction

The term plasma actuator denotes a flow-control device based on dielectric barrier discharges (DBDs). A radio-frequency high voltage applied between a surface-flush mounted electrode and a buried grounded electrode generates an unsteady electric field strong enough to periodically create weakly ionized plasma. The charges moved during generation and quenching of the plasma collide with the neutral surrounding gas molecules and transfer their momentum. By this mechanism a periodic body force is created above the electrodes of the actuator that can be used for numerous flow control applications. If operated in quiescent air this body force creates a wall jet (Fig. 1 left). If applied in an existing flow, such as a laminar boundary layer, the body force can be applied for a beneficial modification of the mean flow (Fig. 1 right) as well as for a modification or creation of velocity fluctuations, see e.g., Grundmann and Tropea (2009) and Benard et al. (2011). Advantages and disadvantages of discharge based devices are discussed alongside other actuators for (active) flow control by Cattafesta and Sheplak (2011). An excellent review of the actuators' working principle is provided by Moreau (2007).

The determination of the magnitude and distribution of the force imparted from the plasma actuator to the external flow is of crucial importance for any advanced prediction of discharge-based flow-control scenarios by means of numerical simulations. The typical spatial and temporal scales of gas-discharge processes are four to eight orders of magnitude smaller then those of the resulting flow-control applications. To resolve this discrepancy for CFD (Computational Fluid Dynamics), several so-called phenomenological plasma actuator models arose in recent years (see

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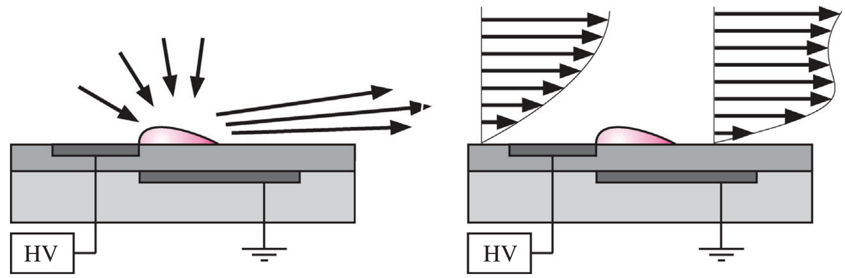

Fig. 1. Sketch of the airflow behavior generated by plasma actuator operation; (left) wall jet formation under quiescent air conditions, and (right) manipulation of an existing boundary layer.

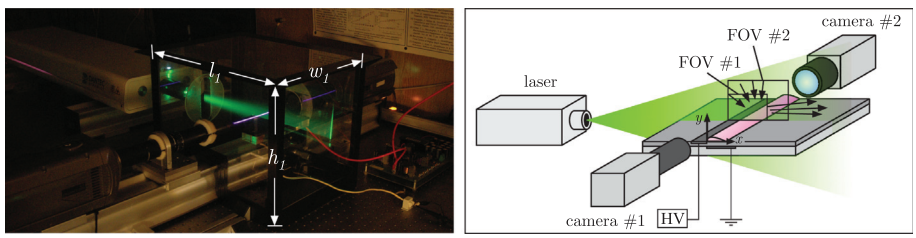

Fig. 2. Experimental setup for the PIV measurements according to Kriegseis (2011).

e.g. Jayaraman and Shyy (2008)), each of which providing a temporally constant volume-force distribution $f(x,y)$. Based on the necessarily strong simplification, the spatial distribution of these models typically result in rather artificial and non-physical shapes of the momentum-transfer domain. Therefore, the computational studies performed in the past resulted in a moderate success.

A promising alternative to provide an appropriate source term in the momentum equation within a CFD solution procedure, therefore, is the retroactive estimation of the volume force from experimental results. In the present work the PIV measurements of Kriegseis et al. (2013) in close proximity to dielectric-barrier discharge plasma actuators are utilized to provide such a velocity data base. This velocity information is then used for the force-estimation purpose and the development of an empirical model for the prediction of DBD plasma actuator momentum transfer in numerical simulations. The major advantage of the proposed approach is the successful combination of the accurate spatial resolution of velocity-information based force-distribution determination with an efficient straight forward implementation of simple functions as used for phenomenological models.

2. Experimental setup

To investigate the flow behavior and especially the momentum transfer to the flow, PIV measurements have been conducted in close proximity to the actuator's discharge region (see Fig. 2 left). For orientation purposes the wall jet direction as well as the *x*-coordinate origin are included in the sketch of the setup (see Fig. 2right).

A commercial high-speed PIV system comprising a Litron Nd:YLF ($\lambda = 527$ nm) dual-cavity laser and two Phantom V12 high-resolution cameras (12 bit, maximum resolution 1280 × 800 pixels) were utilized, which was operated in single-frame mode at a repetition rate of 10 k frames per second (fps) and a pulse duration of 150 ns. This high repetition rate with $\Delta t = 100$ μs required the reduction of the spatial resolution down to 800 × 600 pixels. A maximum number of $N = 10$ k images per run per camera was recorded, exploiting the available buffer capacity of 8 GB. The cameras were mounted facing one another perpendicular to the laser-light sheet as shown in Fig. 2. This arrangement allowed the simultaneous observation of two different fields of view (FOV). This choice provided the highest possible spatial resolution (81.3 pix/mm) in the plasma's immediate vicinity, suitable for force calculations (FOV #1). In addition, the spatial distribution of the resulting wall jet downstream of the discharge domain can be characterized for identical experimental realizations with FOV #2, which has approximately half the spatial resolution (42.2 pix/mm) but spans twice the physical domain compared to FOV #1. A reversely mounted[2] 120 mm SKR SYMMAR lens and a 105 mm Nikon Nikkor lens were fitted to span the observation dimensions 10 × 7 mm^2 (FOV #1) and 19 × 14 mm^2 (FOV #2) respectively.

The test section was enclosed in a closed plexiglass containment ($L \times W \times H = 450 \times 325 \times 345$ mm^3) with quartz-glass windows to assure best possible quality of optical accesses for laser-light sheet and cameras. Di-Ethyl-Hexyl-Sebacat (DEHS) aerosol (mean diameter 0.9 μm) was used to seed the containment. The velocity distribution was calculated from the raw data using commercial software (Dynamic Studio) (see Table 1). Rectangular interrogation areas (IAs) of 64 × 16 pixels and 32 × 16 pixels were chosen for FOV #1 and FOV #2, respectively. This particular setting was found to be favorable to calculate a wall jet, i.e. high wall-normal velocity gradients and wall-parallel velocities.

Although the major objective of the PIV investigations was a force (distribution) quantification and the spatial resolution of FOV/lens #1 fulfilled the corresponding requirements, the availability of a second camera (FOV/lens #2) was found to be extremely beneficial for other purposes. Based on the calculated DBD source terms from FOV/lens #1 (see Section 3), these additional velocity data from FOV/lens #2, comprising a fully developed wall jet, are available for further validation of the conducted numerical simulations as shown in the present work. For more details concerning the experimental procedure and the subsequent velocity-information based force-estimation approaches the reader is referred to Kriegseis (2011).

3. Volume-force estimation approaches

The major objective of the present study is a comparative analysis of advantages and drawbacks of different force estimation ap-

[2] This particular setting was chosen to reduce the observed domain beyond the lens' lower magnification limit of 1:1.