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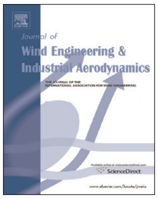

Separation control by means of plasma actuation on a half cylinder approached by a turbulent boundary layer

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ABSTRACT

The flow around a half cylinder (*i.e.* an immersed cylinder in a flat plate) approached by a turbulent boundary layer is studied, with the aim to control separation via steady Dielectric Barrier Discharge (DBD) plasma actuation. The electric wind induced by a single DBD plasma actuator is studied in quiescent air to understand the role of the different driving parameters and how the cylindrical shape influences the downstream development of the induced electric wind. A double DBD plasma actuator is then placed on the cylinder and the influence of the position of the actuator is studied in order to find the best achievable control. Comparison of the controlled and uncontrolled cases, using both hot-wire anemometry and pressure measurements, shows that a reduction of the separation bubble is possible. By optimizing the position of the double actuator, a reduction of up to 30% of the drag is achieved. The present geometry is chosen as a generic model of the flow around the front corners (A-pillars) of a truck cabin and the work is performed with the long-term vision to be able to reduce drag on trucks.

1. Introduction

When considering a 40 ton truck–trailer combination driving at 80 km/h on a level road, the aerodynamic drag counts for more than 20% of the total energy loss of the vehicle and 50% of this drag is induced by the tractor when considering a zero degree yaw angle.[1] One of the contributions to the aerodynamic drag comes from the flow separation from the truck's surface while passing the A-pillars (front corners) of the tractor. Since the 80s, solutions to decrease the drag of the tractor, such as rounded corners, have been extensively investigated and developed. It has been shown that rounded corners with a radius of about 0.3 m are optimal to delay this separation (Barnard, 2009). However this value is only appropriate for a zero degree yaw angle. Active control methods with potential feedback control loop can improve the separation delay when considering that trucks on the road are subjected to varying yaw angles. The present project focuses on the study of Dielectric Barrier Discharge (DBD) plasma actuators with the objective of using the induced electric wind to investigate whether turbulent boundary layer separation can be controlled with such devices.

Research on plasma actuators for flow control started about 20 years ago (Roth et al., 1998) when the so-called electric wind was identified as a possible candidate able to produce a wall jet with a substantial streamwise momentum that could be used for flow control purposes. Flow control areas to which DBD plasma actuators are applied to and show promising results are nowadays numerous including noise control (Thomas et al., 2008; Inasawa et al., 2013), skin-friction drag reduction both controlling laminar (Grundmann et al., 2007; Hanson et al., 2010; Duchmann et al., 2013; Osmokrovic et al., 2014) and turbulent boundary layers (Choi et al., 2011) and vortex shedding manipulation (Nati et al., 2013; Munday and Taira, 2013; Kotsonis et al., 2014). Separation flow control by means of DBD plasma actuation also already gave interesting results on geometries such as the inclined flat-plate (Greenblatt et al., 2012), airfoils (Post and Corke, 2004; Corke et al., 2011; Jukes et al., 2012) and cylinders (Thomas et al., 2006; Jukes and Choi, 2009; Benard and Moreau, 2013).

DBD plasma actuators are made of two electrodes asymmetrically placed on each side of a dielectric material as schematically shown in Fig. 1(a). They present, among others, the advantage of not having any moving parts making them potentially more robust than other types of actuators. By applying a high-frequency, alternating-current (AC) high-voltage signal between the electrodes a plasma region is formed on the surface of the dielectric. This plasma is a consequence of accelerated electrons which ionize the surrounding medium: repulsion of ions during the ionization process induces momentum similar to a wall jet which is called

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[1] Personal communication with Dr. Per Elofsson, Senior Technical Manager, Aerodynamics, Scania CV AB.

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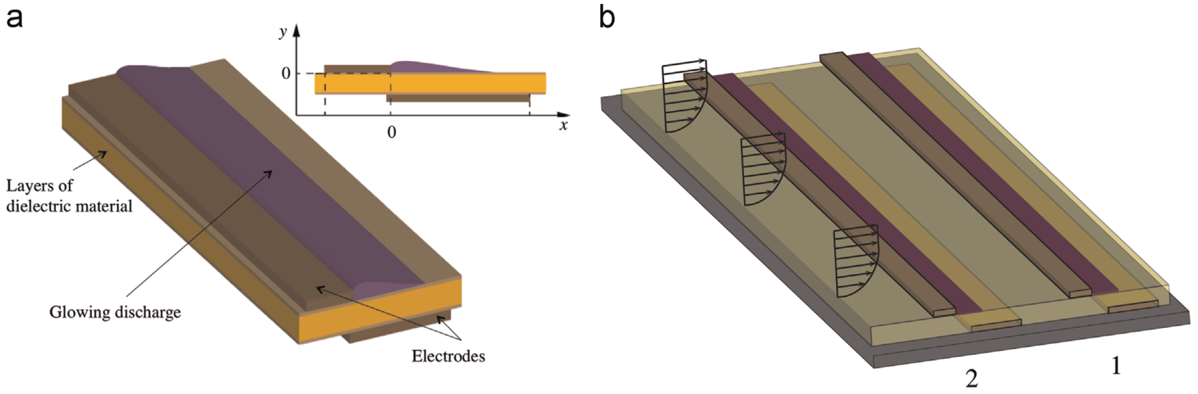

Fig. 1. (a) Schematic of a single DBD plasma actuator (thickness of the electrodes and dielectric material have been emphasized for clarity). (b) Schematic of a double DBD plasma actuator mounted on a flat plate (with embedded grounded electrode) and numbering of the plasma actuators according to the flow direction; Actuator 1 is the downstream actuator, Actuator 2 is the upstream actuator.

the electric wind. The electric wind induced by DBD plasma actuators has previously been investigated in the case of actuators placed on a flat surface (Forte et al., 2007; Kotsonis et al., 2011). For a more detailed review of both the mechanism of DBD plasma actuators and their applications, the reader is referred to review articles by Moreau (2007) and Corke et al. (2010).

In the present study the capability of DBD plasma actuators to delay separation and reduce the drag in the case of a separated turbulent boundary layer on a cylindrical 2D bump is investigated. In this case the flow encounters a strong adverse pressure gradient compared to the flow around airfoils making the ability to control the separation more challenging and is not subject to a strong vortex-shedding street as it is the case for flow passing a full cylinder. A parametric study is conducted on the location of the actuator but also on the driving voltage to optimize drag reduction. Additionally, a study of the electric wind produced by a single DBD plasma actuator in quiescent air on top of a cylinder is carried out whereby the relative location between the actuator and measurement plane is varied by rotating the cylinder to get insight into the development of the produced wall jet. The obtained experimental database is also utilized in a companion numerical project with the aim of calibrating a model for the body force induced by DBD plasma actuators (Futrzynski et al., 2013).

2. Experimental setup and measurement techniques

2.1. In-house built DBD plasma actuators and electrical arrangements

The in-house built DBD plasma actuators used for this study were manufactured using 66 μm (including adhesive) thick copper tape for the rectangular electrodes. Previous work, among others (Enloe et al., 2004), showed that the important geometric parameters for the electrodes concerning the efficiency of the actuators are the thickness of the exposed electrode that should be kept as thin as possible and the width of the grounded electrode that should be wide enough (in the streamwise, *i.e.* x, direction; *cf.* Fig. 1(a)) not to limit the expansion of the plasma; the latter can only develop on the dielectric surface where the grounded electrode is present below. Here, the grounded electrode was 8 mm wide thereby ensuring that the plasma expansion was self-limited. A small overlap of about 0.5 mm was kept between the electrodes to induce a more homogeneous plasma along the actuator length (in the spanwise, *i.e.* z, direction) as suggested by Post and Corke (2004). The electrodes were overlapping along 0.14 m in the spanwise direction for the study of the electric wind in quiescent air and along 0.26 m for the separation control study. The dielectric sheet was made of different layers of polyimide and polytetrafluoroethylene (PTFE) tape with a nominal total thickness of 434 μm for the electric wind study and 396 μm for the separation control study.

In a proof-of-concept study it was found that a single DBD actuator worked to some extent but only gave a moderate control effect on the separation and in order to achieve a stronger effect (*cf.* Appendix), a double DBD actuator was used for the flow separation control study; as Forte et al. (2007) showed, double actuators increase the electric wind velocity but do not necessarily double it. The double actuator consists of two single actuators mounted in tandem as can be seen in Fig. 1(b). Special care was taken to build this actuator and ensure that no plasma was induced between the exposed electrode of Actuator 1 and the grounded electrode of Actuator 2. As discussed in Forte et al. (2007), this could induce an electric wind in the opposite direction and therefore decrease the efficiency of the double DBD actuator. A gap of 6 mm between the grounded electrode of Actuator 2 and the exposed electrode of Actuator 1 was found to be sufficient to avoid a counter-directional electric wind.

For both studies the AC high-voltage was provided to the single or double plasma actuator using a high-voltage generator of type *Minipuls2* (*GBS Elektronik*). This generator was connected to a laboratory low-voltage generator and fed the exposed electrodes of the actuators with a high-frequency sine-like wave with an amplitude of several kilo Volts. A high-voltage probe (*Pintek Electronics HVP-39PRO*) connected to an oscilloscope (*Tektronix TDS 2014C*) was used to measure the sine-wave amplitude and frequency between the high-voltage generator and the exposed electrodes. Peak-to-peak driving voltages (V_d) between 6 and 10 kV$_{p-p}$ with a driving frequency (f_d) of 6 kHz were tested.

2.2. Setup of the electric-wind experiment

Since the geometry of a half-cylinder has been selected for the flow separation control study, first the electric wind induced by a single DBD plasma actuator placed at the apex of a Plexiglas cylinder as shown in Fig. 2 has been measured. The cylinder was placed in a large Plexiglas box to be able to measure only the airflow induced by the actuator and limit disturbances from the surroundings.

Laser Doppler Velocimetry (LDV) was employed to record the electric wind velocity using a single-component Dantec Dynamic LDV FlowLite system with a BSA 60 processor. The measurement volume is created by the intersection of two 632.8 μm wavelength laser beams. The nominal focal length of the laser optics is 160 mm and the part of the box separating the laser head from the plasma actuator was built in glass in order to minimize optical distortions.