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Plasma actuator: Influence of dielectric surface temperature

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ABSTRACT

Plasma actuators have become the topic of interest of many researchers for the purpose of flow control. They have the advantage of manipulating the flow without the need for any moving parts, a small surface profile which does not disturb the free stream flow, and the ability to switch them on or off depending on the particular situation (active flow control). Due to these characteristics they are becoming very popular for flow control over aircraft wings. The objective of the current study is to examine the effect of the actuator surface temperature on its performance. This is an important topic to understand when dealing with real life aircraft equipped with plasma actuators. The temperature variations encountered during a flight envelope may have adverse effects in actuator performance. A peltier heater along with dry ice are used to alter the actuator temperature, while particle image velocimetry (PIV) is utilised to analyse the flow field. The results show a significant change in the induced flow field by the actuator as the surface temperature is varied. It is found that for a constant peak-to-peak voltage the maximum velocity produced by the actuator depends directly on the dielectric surface temperature. The findings suggest that by changing the actuator temperature the performance can be maintained or even altered at different environmental conditions.

1. Introduction

There are various classes of actuators derived from the class of electrical discharge such as: direct discharge, microwave discharge, DBD, corona discharge, spark, etc. [1,2]. In the past 10 years single dielectric barrier discharge (SDBD) actuators have shown remarkable promise for various flow control applications. The benefit of converting electrical energy into kinetic energy without the need for any moving parts, having near instantaneous response, consuming relatively low power, and a wide range of operational frequencies have made these devices an attractive alternative to other active flow control methods such as piezoelectric actuators, synthetic jets, and vortex generators [3]. A new kind of surface plasma called OAUGDP™ was introduced by Roth et al. [4]. Their investigations showed the ability of the new configuration of plasma actuator in changing drag and varying the thrust direction of flat panels [5] and re-attachment of flow in a NACA 0015 aerofoil [6]. Furthermore, the actuator can be operated at atmospheric pressures and does not require a sophisticated power supply. SDBDs have the ability to manipulate the boundary layer [7–11], film cooling [12] and delaying separation on turbine blades [13] and aerofoils [14], and manipulate the transition point [15], control separation on stationary [16] and oscillating aerofoils [17] leading to reduced noise levels [18]. However, to date, they have only been used at micro air vehicle Reynolds numbers (e.g., on small unmanned aircraft [19,20]). Their benefits have not been fully utilised on large scales since the effectiveness of plasma actuators is limited by the maximum induced velocity they can achieve.

The SDBD consists of a linear asymmetric arrangement of two electrodes separated by a dielectric material. One electrode is exposed to the air, while the other is encapsulated in the dielectric [21,22]. The electrodes are long and thin and are arranged spanwise on an aerodynamic surface. A high voltage alternating current (AC) input, with typical voltages of 2–40 kV_{p-p} (peak to peak) and frequencies of 300 Hz to 1 MHz are supplied to the exposed electrode while the encapsulated electrode is grounded. Such a high potential difference weakly ionises the surrounding gas over the hidden electrode.

Using plasma actuators in aviation as a flow control device and internal flow applications [23] in gas turbine engines [24] will result in the actuators being exposed to many environmental temperatures. This makes the examination of the effect of temperature necessary to fully characterise plasma actuator performance [25–27]. Segawa et al. [27] showed a decrease in performances of circular plasma actuators by increasing the temperature of the surrounding. Schlieren photography was employed to monitor the deflection of a CO_2 tracer jet by the DBD wall normal jet. Versailles et al. [25] implemented force measurements on the conventional SDBD actuator and observed that the induced force on the fluid increases almost linearly with increasing the surrounding temperature. This paper presents results of an experimental study of the induced jet of a single dielectric barrier discharge under three

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different temperatures, at atmospheric pressure. The temperature of the dielectric surface was varied directly as opposed to changing the environmental temperature, as has been the case in previous studies.

2. Experimental setup

2.1. Plasma generation and power measurements

A schematic illustration of the actuator is shown in Fig. 1. The electrodes are made of 74 μm-thick tinned copper foil tape, and 100 mm in length. The widths of exposed and hidden electrodes are 3 and 40 mm, respectively. Layered Kapton tape (with each layer having a 60 μm thickness) was used as a dielectric material with the total thickness of 300 μm. The actuators are mounted on a Perspex substrate.

An 8-channel Multiphase high-voltage generator by Electrofluid Systems is used to generate voltages up to 10 kV_{p-p} and frequencies up to 20 kHz. The circuit board is monitored via National Instruments (NIs) Data Acquisition device (DAQ) by means of the LabView program working as an oscilloscope. A LeCroy 1:1000 high voltage probe, calibrated up to 40 kV peak has been used for input voltage monitoring while the current output is monitored using a Tektronix current probe. Data was collected at a rate of 100 MHz. A high bandwidth oscilloscope was necessary to record the plasma discharge due to the high frequency nature of the discharge events. Both the voltage and current probes are connected to a Picoscope 3206, 200 MHz digital oscilloscope and the signals are recorded onto a PC terminal. The input voltage supplied to the exposed electrode has been varied from 2 kV_{p-p} up to 8 kV_{p-p} while the frequency is kept constant at 10 kHz. This driving frequency gave a pure sinusoidal input waveform.

2.2. Particle image velocimetry

Particle image velocimetry (PIV) uses the displacement of particles to determine various flow field parameters. A laser beam is manipulated into a thin sheet using an arrangement of lenses to illuminate the region of interest. Fig. 2 shows a schematic of the experimental setup. Using two successive laser pulses separated by a known time, statistical analysis can be performed to measure the instantaneous velocity of the tracer particles captured with a high-speed camera. The PIV measurements were performed using a LaVision system with an NDYAG 532/1064 nm, Litron 200 mJ, pulsed laser. The laser pulsed with a repetition rate of 15 Hz, and a pulse width of 4 ns. In these experiments the duration between pulses was set at 700 μs. This value is set based on the field of view size and expected induced velocity, of the order of 1 m/s. The laser was delivered using a laser arm mounted above the actuator to produce a laser sheet that ran along the centre-line of the actuator span, normal to the electrodes. The actuator was located in a sealed chamber were seeding was introduced using a six jet atomizer that produced light-scattering olive oil particles with a size of approximately 1 μm. After the chamber was filled with particles the seeding was stopped and the particles were allowed to reach a quiescent state before commencing the experiments.

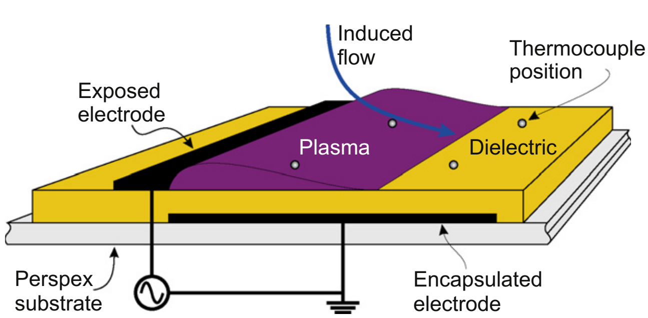

Fig. 1. Standard SDBD actuator configuration.

2.3. Temperature variation and control

For cooling and heating the surface temperature of the actuator to −40 °C and 120 °C, dry ice and a peltier heater were used, respectively. To achieve a uniform temperature over the surface, in the hot-case, the actuator was placed on top of the peltier heater. By changing the voltage supplied to the peltier the temperature was varied until the desired value was reached. In the cold-case, the actuator was put in a dry ice fridge immediately before doing each set of experiments. The time interval between removing the actuator from the dry ice fridge and placing it within the PIV chamber was approximately 10 s. The actuator was switched on for 5 s to reach stable run time before commencing the PIV measurements which lasted for approximately 6 s. Using thermocouples placed at different positions along the dielectric surface the uniformity of the temperature distribution was continuously monitored before conducting the experiments and the creation of the plasma strip (see Fig. 1 for thermocouple locations). This ensured no electrical interference and eliminated the chances of sparking between the thermocouple probe and the exposed electrode. The surface temperature was recorded after each run and was found to be within ±1.5 °C and ±1 °C of the initial conditions for the cold and hot cases, respectively. When performing repeats of each temperature case, it was ensured that the initial temperature was identical to the previous case tested.

The hot and cold cases were performed on different days so that the actuator could return to ambient conditions over night.

3. Results and discussion

Fig. 3 compares the voltage and current graphs of the standard SDBD at different temperatures for 8 kV_{p-p} and 10 kHz. The ambient, cold, and hot labels in the figures refer to temperatures of: 20 °C, −40 °C, and 120 °C, respectively. The consistent repeatability of the input voltage to the actuator in different temperatures is illustrated in Fig. 3a. However, the current trace varies depending on the dielectric surface temperature. The current peaks such as those visible in Fig. 3b are due to the presence of the microdischarges, and correspond to the creation of plasma. The number of discharges present in the figure does not appear to change with increasing temperature, however, the magnitude of the peaks increases. It is believed that by having stronger microdischarges deposited on the surface, the momentum coupling between the plasma and the neutral air increases leading to a faster induced jet as will be shown in the following sections. Based on the current and voltage measurements, the power consumption by the actuator is calculated using Eq. (1), where T and N represent the time period and the number of cycles, respectively.

$$Power = \frac{1}{NT}\int_{NT} V(t)\cdot I(t)dt \qquad (1)$$

The effect of dielectric temperature on actuator power consumption for the range of voltages is depicted in Fig. 5. The lines in the figure represent the power law fit in the form of $f(x) = ax^b$ similar to that used by Enloe et al. [28]. It can be seen that at lower temperatures less power is consumed by the actuator and at high voltages, the power consumption of the hot case is slightly more than that of the ambient case.