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Straight and curved type micro dielectric barrier discharge plasma actuators for active flow control

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ABSTRACT

We develop micro dielectric barrier discharge plasma actuators (DBD-PAs) for active flow control under low external flow conditions. Our micro DBD-PA consists of thin dielectric material and electrodes having a small width and shape variation in the span-wise direction. The fundamental characteristics of the induced flow structures and the effectiveness of the micro DBD-PAs for separated flow over an airfoil are experimentally studied. The flow structures induced by a straight and a curved type micro DBD-PAs in quiescent air are visualized by the tracer method and processed by particle image velocimetry technique. It is found that the curved type DBD-PA produces three-dimensional flow structures as the results of counter flows that impinge each other. For the separation control of the airfoil flow, the angle of attack and free-stream velocities are set to 7.5° and 2 and 3 m/s, respectively. Results present that the separation is successfully suppressed by the use of the curved type micro DBD-PA and the curved type micro DBD-PA shows better capability in comparison with that of the straight type micro DBD-PA due to the induced flow structures.

1. Introduction

Active flow control using dielectric barrier discharge plasma actuators (hereafter called DBD-PAs) has been widely studied to improve the efficiency and performance of many kinds of fluid machinery [1–6]. The DBD-PA is one of the zero net mass flow devices, which include synthetic jets [7,8]. The structure of a typical DBD-PA is illustrated in Fig. 1. The DBD-PA consists of two electrodes and a dielectric material. When high alternating-current voltage (i.e., a few kV) with reasonably high frequencies (i.e., a few kHz) is applied between two electrodes, atmospheric-pressure non-equilibrium and non-thermal plasma is generated in sequence, and induces a wall-jet-like flow above the dielectric [9,10]. This resultant induced flow plays an important role in the control of the separated shear layers [1–6] and the boundary layers [11]. The advantages of DBD-PAs are quick response, light weight, and easy installation because they have no moving parts. Recently, active flow control using DBD-PAs has been applied to the flow around airfoils [12,13], truck mirrors [14] and bodies [15], wind turbine blades [16,17], and pantographs [18].

The abovementioned examples of applications of the DBD-PA are relatively large machinery. Recently, flow control with micro-scale DBD-PAs has been studied for enhancing the local cooling of micro-channels [19]. Thus, these micro DPD-PAs have been applied to internal [20–22] and external flows [23–25] for active flow control. For example, Okochi et al. [20] have presented the development of a micro DBD-PA for active flow control based on their micro electro mechanical systems process. Pescini et al. [23] have proposed a definition of micro DBD-PAs that is characterized by an electrode having a width less than 4 mm and electrode thickness, dielectric thickness, and electrode gap smaller than 1 mm. This study follows their definition of micro DBD-PAs and calls other DBD-PAs normal DBD-PAs. Moreover, Pescini et al. [23] have demonstrated that the actuator efficiency in the conversion of input electrical power to delivered mechanical power increased by using their micro DBD-PA and shown that a maximum induced velocity can be up to 1.36 m/s by changing the applied voltage and frequency. More recently, we have developed micro DBD-PAs [24,25] for active flow control. The width of the electrodes of our micro DPB-PAs is less than 1 mm and basically corresponds to the definition by Pescini et al. [23]. We have constructed two micro DBD-PAs (see Fig. 2 and Table 1)), namely, the straight type [24] and the sinusoidal curved type micro DBD-PA [25]. We have expected that shape variation of a electrode in the span-wise direction (i.e., the curved type micro DBD-PA in this study) could obtain

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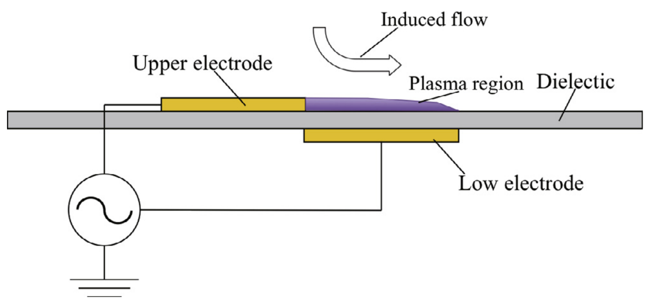

Fig. 1. Schematic diagram of a normal DBD-PA [1–6].

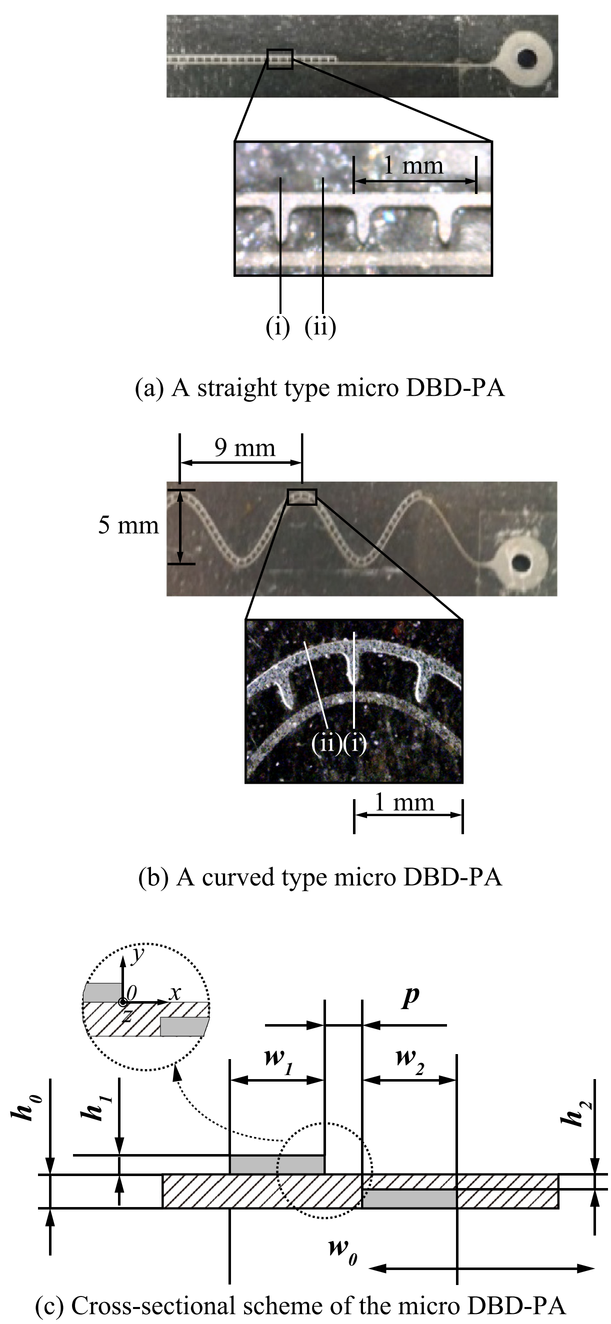

Fig. 2. Images of (a) a straight type micro DBD-PA and (b) a curved type micro DBD-PA, and (c) a cross-sectional scheme of the micro DBD-PA.

better performance of flow control due to the induced three-dimensional flow structures. This expectation regarding the induced three-dimensional flow structure has been observed by using the serpentine type normal DBD-PA in previous numerical and experimental studies [26]. The effectiveness of the serpentine type normal DBD-PA on the separated flow control over the airfoil has been presented by numerical simulations [27].

Since the micro DBD-PAs are relatively new devices for active flow control, the fundamental characteristics such as the induced flow structure in quiescent air has not been adequately understood yet. In addition, the effectiveness of separated flow control over an airfoil by using these micro DBD-PAs has not been sufficiently evaluated. Thus, we experimentally investigate the fundamental characteristics of flow induced by the micro DBD-PAs and the effectiveness of the micro DBD-PAs on moderately separated flow over the airfoil. It should be mentioned that for the airfoil flow experiment we consider a small reference length and a low speed, both of which result in a low Reynolds number condition and the conclusions could be applied to similar flow conditions considered in this study.

2. Material and methods

2.1. Description of micro DBD-PAs

Fig. 2 shows pictures of a straight and a curved type micro DBD-PAs and a cross-sectional scheme of the micro DBD-PA. The length of the electrode in the span-wise direction is about 103 mm. The material of the electrodes and the dielectric is mica. Detailed geometrical information is listed in Table 1. The manufacturing technique is mainly etching. Our micro DBD-PAs are produced by FISA Corporation. The width of the electrode is less than 500 μm and is approximately one order smaller than that of normal DBD-PAs [1] and less than half of the previously developed micro DBD-PAs [23]. The top and the bottom electrodes are connected to a high-voltage and high-frequency power source (model: PSI-PG1040F, PSI Inc.). For the curved type micro DBD-PA, the wavelength and the amplitude of the electrodes are 9 mm and 5 mm, respectively (see Fig. 2(b)). Information of the near-electrode geometry is also shown in Fig. 2. For the operational condition of the micro DBD-PAs, voltage of 5 kV_{pp} (peak-to-peak) and frequency of 12 kHz are applied. In comparison with the conditions of previous studies [1–6], lower amplitudes of applied voltage and comparable frequencies are adopted. Although it is expected that underlying phenomena governing the discharge are similar among the normal and micro DBD-PAs, here we note that the unique points of our micro DBD-PAs are their smaller size in comparison with the micro DBD-PA of Pescini et al.[23] and the normal DBD-PA [1], and the shape variation of the electrode in the span-wise direction.

2.2. Flow visualization and data processing

The flow is visualized by the smoke tracer method and the velocity fields are measured by particle image velocimetry (PIV). The incense smoke produced by burning Chinese Joss sticks (average particle diameter of 0.3 μm and particle density of 1060 kg/m^3[6]) and the smoke generated by vaporizing a liquid mix composed of water and propylene glycol (average particle diameter of 10 μm and particle density of 1036 kg/m^3) are used as seeding particles for the PIV of the flow induced by the micro DBD-PAs in quiescent air and airfoil flow, respectively. For assessing the ability of the seeding particles to follow the flow field, the Stokes number (St) is cacluated. The Stokes number represents the ratio of the