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Flow characteristics of a single stage EHD gas pump in circular tube

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ABSTRACT

Characteristics of flow induced by electrohydrodynamic (EHD) gas pumps in circular pipe have been experimentally evaluated. Two tube diameters (61.8 mm and 127.8 mm) and two electrode gap distances (25 mm and 50 mm) have been considered. The gas pumps use eight evenly spaced emitting electrodes which are flush mounted on the tube wall. As such, flows induced by the pumps have a profile with a higher velocity near the wall and a lower velocity at the tube center. Experiments are conducted using positive corona discharge with voltage varying from 17.5 kV to 30 kV. The results show that the volume flow rate increases with the applied voltage but approaches an asymptotic value before sparkover takes place. From the present results, several important implications for the practical engineering applications are presented.

Introduction

Application of high electric field between two electrodes of different radius of curvature in air can lead to discharge of ions from the electrode with a smaller radius. Under the influence of Coulomb force, ions drift from the emitting electrode to the collecting electrode. During their transit, they collide and exchange momentum with neutral molecules and induce a bulk motion of fluid. This induced fluid motion is commonly called *corona wind* or *ionic wind*. Corona discharges can be put to good use in many engineering applications such as heat transfer enhancement [1–5], drying enhancement [6–9] and flow control [10,11]. Since a pressure difference between the inlet and outlet of a pipe can be created by means of electrical body forces which act directly over the volume of fluid present between the two electrodes without any moving part, electrohydrodynamic (EHD) technique can also be used for gas pumping. This unique feature of gas pumping has received enormous attention in recent years for its potential new applications in micro-electromechanical systems (MEMS). For the latter application, the reduced length scale (and thus the gap distance between electrodes) relaxes the need for high applied voltage, which further facilitate its application.

Although various EHD gas pumps have been developed for specific applications [12–19], currently there is no general rule in design to enhance or optimize the performance of an EHD gas pump. Obviously the geometry of a gas pump, electrode polarity, electrode spacing, and electrode arrangement have all played an important role in the performance of an EHD gas pump. To address the need for a design methodology, several studies have been conducted to explore the role played by each parameter mentioned above. For example, Kocik et al. [21] investigated the electrode arrangement of an EHD gas pump with wire-nonparallel plates. They found that the flow thus generated was generally turbulent in nature with distinct vortices. The vortices formed had negative effect on the pumping capacity since they might block and suppress the flow generated. On the other hand, Richard et al. [14,22] investigated ways to increase the induced flow velocities of EHD devices using a nozzle.

While most previous studies had considered positive corona discharge for its inherent advantage of stable electric field, Komeili et al. [17] investigated flow characteristics of wire-rod type EHD gas pump operated with negative corona discharge. Similarly, Moreau et al. [20] performed a parametric study on the performance of an EHD gas pump by varying electrode polarity, collecting electrode geometry, electrode gap distance and tube diameter. Crowley et al. [23] studied the properties of a working fluid and their effect on the performance of an EHD pump. They found that a working fluid with a high dielectric constant and a low viscosity can produce high flow velocities while that with a low conductivity and mobility promotes high efficiency.

The effect of number of emitting electrodes on the performance of an EHD gas pump in a square channel has been addressed by Zhang and Lai [24]. Flow characteristics of an EHD gas pump with

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Nomenclature

D	diameter of pipe
I	corona current
L	electrode spacing
l	length of emitting electrode
R	radius of the tube
r	radial position of measuring points
V	applied voltage

four emitting pins flush mounted on a circular pipe wall have been studied by Brown and Lai [25]. Their results show that ionic wind velocity approaches an asymptotic value as the applied voltage increases. This interesting phenomenon has not been reported in previous studies. Due to the nature of asymptotic increase in the volume flow rate with the applied voltage, they have noted that operation at a higher voltage does not necessarily improve the performance of an EHD pump, but consumes more power instead. As they suggested, a further study on the effects of electrode dimensions as well as the number of electrodes on the volume flow rate of induced air flow can lead to the optimal design of an EHD pump. Hence this study is intended to further the investigation and see if the trend previously observed can be verified through other tube size, electrode number, and operating condition.

To address the role played by each design parameter, tests have been performed with two different sizes of tubes (inner diameter of 61.8 mm and 127.8 mm) with two electrode gap distances (25 mm and 50 mm). The tube diameters are roughly twice of those tested by Brown and Lai [25]. The number of emitting electrodes is also intentionally doubled to check if the previous results can be proportionally scaled up.

Experimental setup and procedure

Experimental setup

The schematic of the experimental setup used for this study is shown in Fig. 1. Basically, it consists of three major parts: an inlet section, a test section (EHD gas pump) and an outlet section, all of which are made from a clear acrylic tube. Two sizes have been considered: one with an inner diameter of 61.8 mm and the other 127.8 mm (Fig. 2). The thicknesses of the tube wall are 8 and 12 mm, respectively. The test section is 126 mm long for the small-diameter tube and 151 mm for the large tube. A mating groove of 10 mm wide and 2 mm deep has been provided at the end of the inlet section, test section and outlet section for easy assembly. Another groove of 1.2 mm wide and 1.2 mm deep, which is located 10 mm away from the top of the test section, is machined around the circumference of the inner wall of the pipe to house a copper ring which serves as a common bus for emitting electrodes. Eight emitting electrodes which are made from copper wire of 0.4 mm diameter are welded to the copper ring. They are evenly spaced at an angle of 45° around the circumference of the tube and are flushed with the tube wall. Another groove of 10 mm wide and 0.5 mm deep has been machined to mount the ground electrode. The electrode spacing is measured as the distance between the tip of the emitting electrode and the ground electrode. The copper ring is connected to a high voltage power supply while the ground electrode is maintained at the same level as that of the power supply. The high voltage power supply is custom made by You-Shang Technical Corp. in Taiwan with dual polarity and a maximum output of 30 kV. It has an accuracy of ± 1 V in voltage and 2% in current.

For flow measurement, nine sampling holes (each of 6.5-mm-diameter) are drilled circumferentially around the tube (Fig. 3). They are arranged in three rows and three columns. The first row of holes is 15 mm below the ground electrode and the rest are equally spaced in a vertical distance of 10 mm center-to-center. Similarly, each column of holes is evenly spaced at an angle of 22.5°. In this arrangement, the first and third columns of sampling holes (labeled here by axes XX and ZZ) are midway between two neighboring emitting pins and the second column (labeled as YY axis) is aligned with the emitting pins.

A hot wire anemometer (TSI 8465) has been used along with a tripod with six degree of freedom for flow measurements. The latter greatly facilitates the velocity measurement at each level downstream of the ground plate. The hotwire anemometer has an accuracy of ± 0.5% of the full scale with minimum resolution of 0.07 m/s. The sensitivity of the anemometer is 0.07% of the full scale which translates to 0.035 m/s. The hotwire anemometer is connected to a data acquisition system (NI 9207) that has 16 channels with ±20 mA and 24 bit resolution. A sampling rate of 5 Hz has been used for all measurements reported in this study. It has been determined by a systematic trial that this sampling rate is sufficient to capture the variations of electric and flow fields. The measured air velocity can be directly read out from the virtual instrument developed using LabView program.

Experimental procedure

Before each experimental run, the setup is carefully cleaned and tightly re-assembled. The emitting electrode pins are connected to the high voltage power supply while the ground electrode is grounded to the same level as that of the power supply and multimeter. After the hot wire probe is carefully aligned and placed at the sampling position, the high-voltage power supply is set to the positive polarity and turned on. The voltage is gradually increased until it reaches a threshold value, at which point a hissing sound can be heard. This threshold voltage marks the onset of corona discharge. Corona current collected from the ground electrode is recorded using a multimeter (FLUKE 287). Ambient conditions (temperature and humidity) are also recorded for reference.

The hot wire probe is carefully positioned using a camera tripod with an embedded bull's eye spirit to minimize positioning error. Since the diameter of the hot wire probe is much smaller than that of the tube, flow blockage by the probe stem is expected to be minimal. At each sampling hole, measurement was taken at six radial positions (P1 through P6) starting from the center (Fig. 4). To minimize the interference to the flow field, measurements are first taken at the pipe center and subsequently retreat from the center. At each measuring point, data are recorded for a minimum of three times and an average value is taken for all cases conducted in the experiment.

Since corona discharge is greatly affected by the ambient condition [11,26,27], the present study has been conducted under tightly control of room temperature and humidity. The ambient condition has been recorded during the course of experiment to substantiate any variation due to ambient condition. The uncertainty associated with the measurements was calculated by the method proposed by Steele et al. [28]. It has been estimated that the velocity measured by the hotwire anemometer and the average current measured by the multimeter both have an uncertainty of 5% while the pump performance has an uncertainty of 7%.

Results and discussion

Experimental observation

Depending on the ambient conditions, the threshold voltage varies slightly. When the electrode spacing is fixed at 25 mm, a faint flow is first detected at an applied voltage approximately of 16 kV