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Miniaturized corona flow sensor operating in drift mobility increment mode for low flow velocity measurement

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ABSTRACT

We demonstrated low flow velocity measurement with a miniaturized corona flow sensor operating in drift mobility increment (DMI) mode. The corona flow sensor consisted of a corona flow probe residing in a small diameter flow tube. The corona flow probe had an electrode gap of ~700 μm and was constructed with 50 μm stainless wire for cathode and nickel plated steel for anode. As evident in both the analytical and experimental corona current versus applied voltage curves, the corona current varied with the ozone concentration in the drift region. This also allowed the corona current to be responsive to air flow. The experimental corona current versus flow velocity trend was shown to be in agreement with the analytical trend. At an applied voltage of 1800 V, the corona flow sensor was able to measure flow velocities from 4.7 to 94.3 mm/s with a resolution of ~5 mm/s. Three configurations consisting of the corona flow probe in different orientation with respect to the flow direction were investigated. We also showed that the sensitivity and operating range could potentially be tuned by adjusting the applied voltage. Finally, the significance and limitations of the results were also discussed.

1. Introduction

Corona discharge is a partial electrical discharge. Since the late 1800s, it has been studied extensively for its behavior under different conditions and configurations [1]. Like most electrical discharges, its electrical characteristics can be highly susceptible to external perturbations such as changes in gas pressure, composition, humidity, temperature and flow rate [2–15]. This has allowed corona discharge to be harnessed as a transduction mechanism. In particular, corona discharge [16–21] has been widely employed for air flow measurement in the turbulent or unsteady flows. It has also been used to measure air flow velocities as high as 400 m/s [22].

Inspired by Wright and Gianchandani's DC plasma based gas pressure sensor [23], we have recently demonstrated air pressure sensing via a miniaturized corona device [24]. Note that miniaturized corona devices have also been previously explored for various applications that include ionization of air [25], air quality monitoring [26,27], air filtration [28,29], mechanical excitation of microfabricated structures [30–33], electronic cooling [34] and bacterial sterilization [35]. One of the key advantages of corona discharge over other types of electrical discharges is its low operating current. This often translates into minimized electrode sputtering and hence extended device lifetime.

Given the extensive prior work in corona discharge based air flow sensing and miniaturized corona devices, a marriage between them appeared to be the next natural progression. However, the existing air flow sensing mode via corona discharge is inherently limited to high velocity flows. This is because this sensing mode measures flow via the displacement of its space charge. As the space charge is displaced by flowing air, the corona current is reduced accordingly. Positive ions are often employed over electrons due to their lower drift velocities. In this case, the lower operating limit of the corona flow sensor is dictated by the drift velocity of positive ions. Therefore, in order for the corona flow sensor to measure low flow velocities, an alternative sensing mode is needed.

Országh et al. suggested that the presence of ozone in the corona discharge drift region could reduce the corona current by virtue of space charge drift mobility reduction [14]. Leveraging on the work by Országh et al., we investigated the feasibility of employing the same phenomenon for flow sensing at low flow velocities (<0.1 m/s). This alternative sensing mode (hereinafter referred to as Drift Mobility Increment mode or DMI mode) uses a confined volume to limit the diffusion of ozone away from the corona discharge drift region. This in turn increases the ozone concentration and hence reduces the corona current. When air flows past the drift region, it reduces the ozone concentration with a corresponding increase in the corona current.

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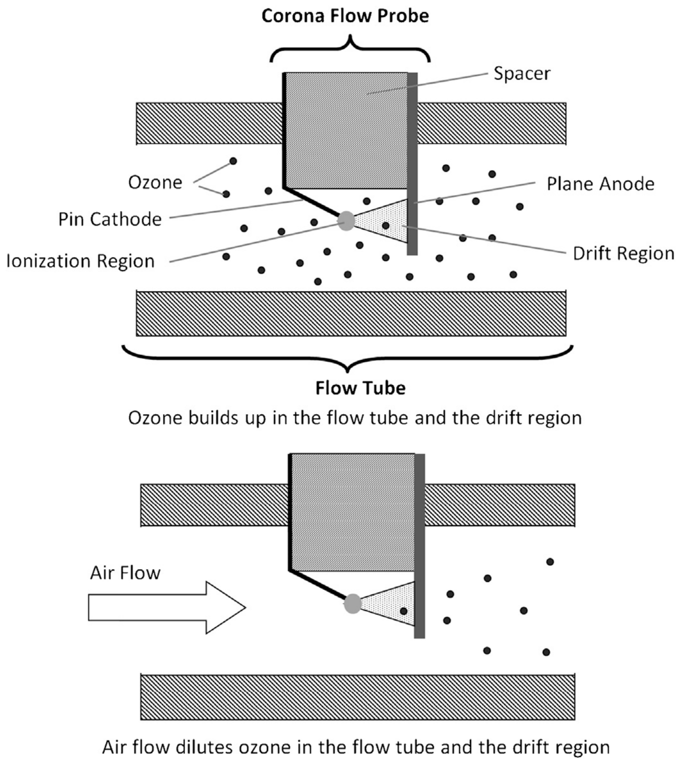

Fig. 1. Operation of the DMI mode corona flow sensor.

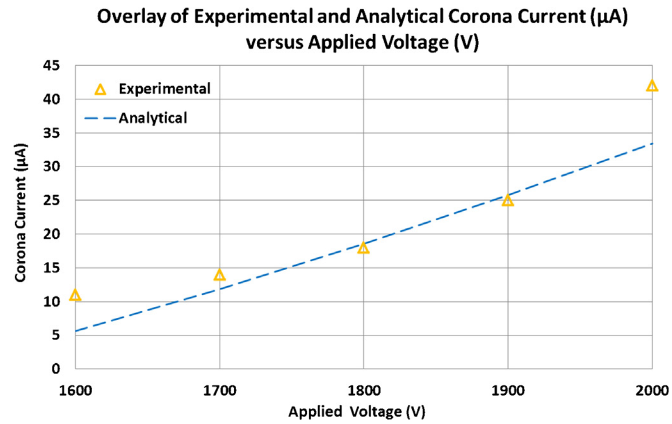

Fig. 2. Overlay of experimental corona current (μA) versus applied voltage (V) over the analytical equivalent.

At this juncture, it is important to mention that miniaturized air flow sensors, especially thermal air flow sensors, have been well-researched and successfully commercialized [36–45]. Non-thermal air flow sensors, especially the cantilever based air flow sensors [46,47], have demonstrated remarkable operating range (up to 45 m/s in wind tunnel experiments) [46] that exceeded that of thermal gas flow sensors (up to 35 m/s) [42].

Therefore the purpose of this work is to complement the existing research on miniaturized flow sensing. More importantly, it will allow us to entertain the eventual possibility of a miniaturized corona flow sensor that can potentially operate in a wide range of flow velocities from less than 0.1 to several hundred meters per second. In order to facilitate the investigation of using corona discharge in DMI mode for low velocity flow sensing, we housed a miniaturized corona flow probe with a sub-millimeter electrode gap within a small diameter flow tube.

Specifically, we measured the corona current versus voltage curve (also referred to as *I*–*V* curve) for the corona flow probe unconfined and confined by the flow tube. It was subsequently compared against the analytical *I*–*V* curves. The DMI mode corona flow sensor (corona flow probe mounted inside the flow tube) was also subjected to flow velocities less than 100 mm/s in three different configurations. The corresponding corona currents were measured and their trends were also compared against the analytical trends. In addition, the DMI mode corona flow sensor was tested and evaluated at two different applied voltages (1800 and 2000 V).

2. Principle of operation

The DMI mode corona flow sensor consists of two primary components: (i) corona flow probe and (ii) flow tube as shown in Fig. 1. The corona flow probe serves as the transducer. It further consists of a pin cathode and plane anode separated by a spacer. This allows the corona flow probe to operate with negative pin-to-plane corona discharge.

In order to incept a pin-to-plane corona discharge, the pin cathode and plane anode are electrically stressed. At a sufficiently high voltage, impact ionization by accelerating free electrons results in the formation of Townsend avalanche. By virtue of the electrical field asymmetry, the avalanche or ionization region is confined to the surface of the pin cathode. Free electrons beyond the ionization region drift toward the plane anode, thus forming the drift region. The corona current at the plane anode is a function of the drift mobilities of the electrons and negative ions.

Within the ionization region of the corona discharge, oxygen and nitrogen molecules are excited by collision with accelerating electrons. The ozone is eventually formed via a series of subsequent reactions that involve the excited oxygen and nitrogen molecules [48,49].

As mentioned earlier, the function of the flow tube is to restrict the diffusion of ozone away from the drift region. The increase in ozone concentration within the drift region reduces the free electron concentration via dissociative electron attachment process [14]. This in turn reduces the average drift velocity and hence the corona current. Therefore, in the event of an air flow through the flow tube, the ozone concentration in the drift region will be decreased. This will result in the corresponding increase of average drift velocity and hence the corona current.

The corona current can be described by Townsend's discharge equation [15,50] as follows:

$$I = \frac{8\pi\varepsilon_o \mu_i L V (V - V_o)}{R^2 \ln(R/r_o)} \quad (1a)$$

where I is the corona current, ε_o is the permittivity of free space at 8.85×10^{-12} F/m, μ_i is the effective drift mobility of charge carriers (electrons and/or ions) in the drift region, L is the active discharge length of the cathode, V is the applied voltage, V_o is the inception voltage ~ 1500 V, R is the spacing between electrodes and r_o is the radius of curvature of the cathode.

The effective drift mobility of charge carrier μ_i is in turn given by

$$\mu_i = C_1 \exp(4403a) - C_2 a^{0.6} V + C_3 a^{0.3} V^2 \quad (1b)$$

where $C_1 = 4.43 \times 10^{-4}$, $C_2 = 2.51 \times 10^{-5}$ and $C_3 = 1.1 \times 10^{-10}$.

Note that Eqs. (1a) and (1b) are prescribed for a wire-in-cylinder electrodes arrangement. However, they can be used to evaluate the corona current versus drift mobility trend for pin-to-plane electrodes arrangement. In order to estimate the values for L and r_o, we employed the approach by Chua and Son [35] which involved fitting the experimental *I*–*V* curves over the analytical equivalent as given by Eqs. (1a) and (1b).