Corona Discharge Characteristics of Narrow Coaxial Wire-Pipe Discharge Tubes with Gas Flow

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Abstract -- An experimental investigation has been conducted to study corona discharge in a narrow tube. Narrow or capillary corona discharge (discharge tube diameter $d \approx 1$ to 20 mm) is used for many industrial applications such as flue gas cleaning corona induced plasma reactors, ion sources and electrohydrodynamic heat exchangers. In this work, corona discharge characteristics of narrow coaxial wire-pipe discharge tubes with gas flow are experimentally investigated. The results show that, unlike normal corona discharge, a hysteresis in the corona discharge current-voltage characteristics were observed for narrow tube discharges. The on-set of the corona discharge observed to be significantly depends on the gas temperature and gas flow rates.

I. INTRODUCTION

Narrow tube (1 mm ≤ tube diameter d ≤ 20 mm) and capillary tube (d < 1 mm) discharges are used in a plasma display [1, 2], flue gas cleaning corona induced plasma reactors [3, 4], ion sources [4], electrohydrodynamic heat exchangers [5] etc., since more intensive gas discharge will be available due to the wall stabilizing effects as well as better transport properties. However, discharge parameters and the fundamental characteristics of narrow discharge tubes are not well understood in spite of their potential for industrial applications. In this work, an experimental investigation has been conducted to study corona discharge characteristics of narrow coaxial wire-pipe discharge tubes with gas flow.

II. EXPERIMENTAL APPARATUS

Schematics of experimental apparatus is shown in Figure 1. Stainless steel wire with o.d. 0.01 cm was used as a corona wire, and 0.953 cm o.d. (0.753 cm i.d.) and 15 cm long copper tube was used as a grounded electrode. In order to measure the heat balance from the wire-pipe corona discharge system, 1.588 cm o.d. copper tube was placed coaxially outside the system. Entrance and exit gas temperature of the wire-pipe corona discharge zone and outer-grounded pipe gas cooling zone were measured by T-type thermocouples. Time-averaged current was measured by the Keithly electrometer, and air flow rate in both flow channels was measured by a rotameter. The air flow flowing through the corona discharge zone was electrically heated at upstream of the system. Experiments are conducted for the gas flow rate from 0 to 20 ℓ/min., the inlet gas temperature from 10 to 60°C, and the applied voltage from 0 to ±10 kV.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Polarity Effects

Time averaged corona discharge current-voltage characteristics for positive and negative dc applied voltages on the corona wire are shown in Figures 2 and 3, respectively, where the voltage is applied from on-set to off-set conditions via maximum value. Figure 2 shows that the current voltage (I-V) characteristics observed can be approximated by $V = k\sqrt{I}$ as expected [10,11]. However, unlike normal wire-pipe discharges, a small hysteresis was observed for a positive corona without gas flow in present narrow tube discharges. This hysteresis effect may be due to the gas being heated by corona discharge, since a small gas temperature increase was noticed when a noticeable electrical current flows. The corona current is higher from maximum applied voltage to the corona off-set transitions compared with the corona on-set to maximum applied voltage transitions. This hysteresis phenomenon becomes smaller when we sweep voltage very slowly (approximately half an hour per point) to reach a thermal equilibrium for each measuring point.

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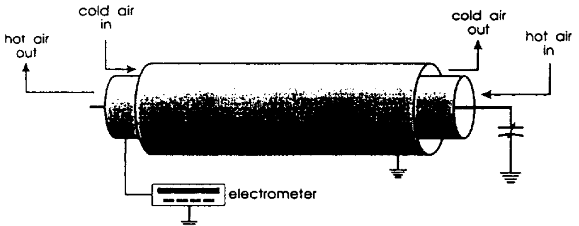

Fig. 1 **Schematics of experimental apparatus.**

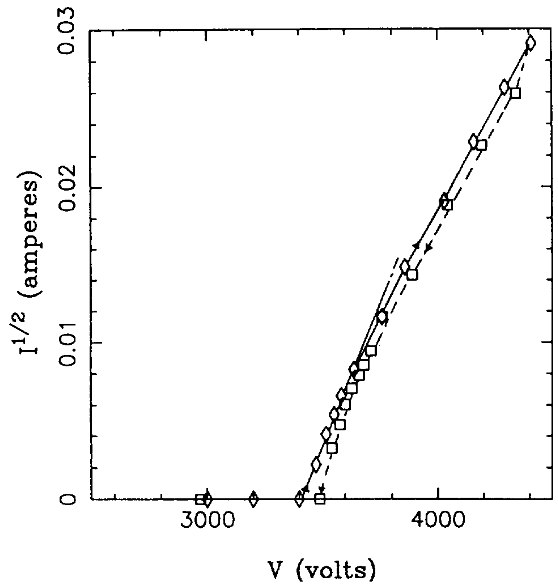

Fig. 2. **Time averaged corona discharge current-voltage characteristics for a positive corona without gas flow.**

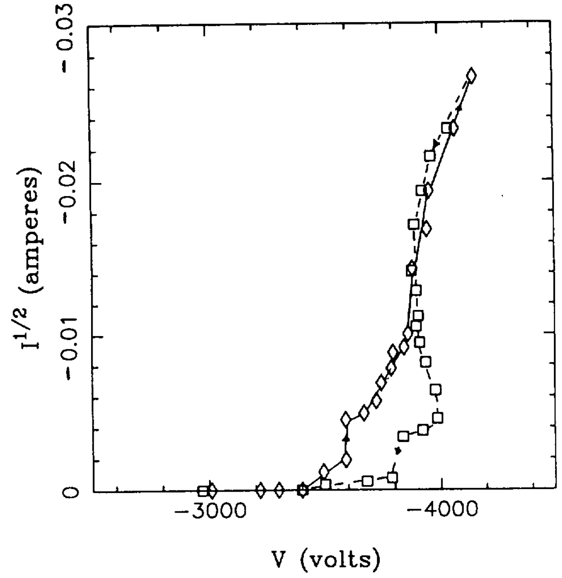

Fig. 3. **Time averaged corona discharge current-voltage characteristics for a negative corona without gas flow.**

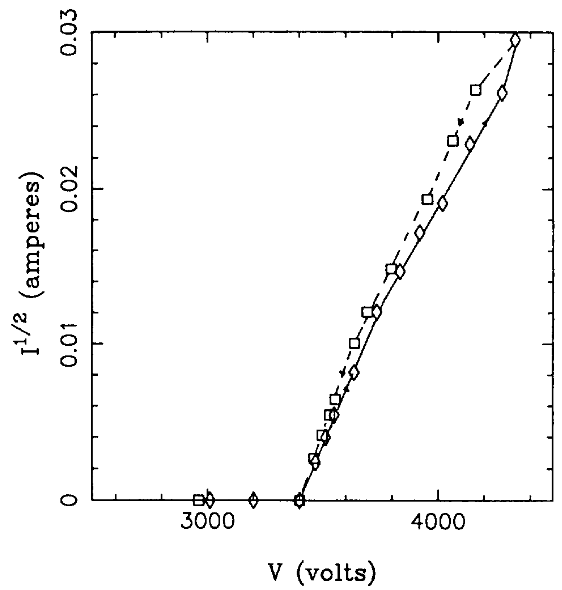

Fig. 4 **Time averaged corona discharge current-voltage characteristics for a positive corona at Q_g = 7.1 ℓ/min.**

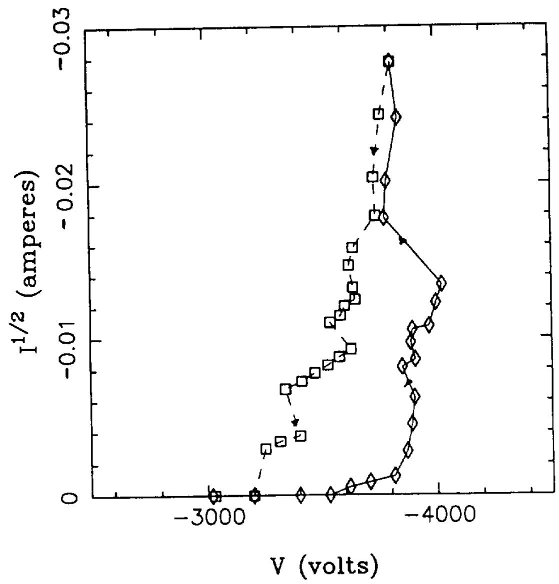

Fig. 5 **Time averaged corona discharge current-voltage characteristics for a negative corona at Q_g = 7.1 ℓ/min.**

The corona discharge current density, J, in a corona discharge field can be expressed by [9]:

$$\underline{J_i} = e\,\underline{U_g}\,N_i \pm e\,\mu_i\,N_i\,\underline{E} - e\,D_i\,\nabla N_i + e\,G_i\,N_i\,\nabla T_g \quad (1)$$

$$= < e\,N_i\,\underline{U_i} >$$

where U_g is the gas velocity, N is the number density, E is the electric field, D is the diffusion constant, μ is the ion mobility, G is the thermophoresis coefficient, T is the temperature and subscripts i and g refer ion and gas respectively. The sign in equation (1) term 2 in the right hand side depends on the polarity of ions. Since gas velocity, temperature and ion density gradient induced velocity components are not expected to be large compared with the mobility term (ion drift velocity) in the present range of the experiment. Therefore, equation (1) can be simplified to

$$\underline{J_i} = \pm\, e\,\mu_i\,N_i\,\underline{E} \qquad (2)$$

and the possible hysteresis effects may be attributed to the temperature dependence of ion mobilities. If we express the ion mobility by the Langevin equation [7,9]

$$\mu_i = 0.75\,\frac{e\,\lambda_i}{m_i\,v_i}\left(1 + \frac{m_i}{m_g}\right)^{1/2} \qquad (3)$$

both ion mean free path, λ_i, and thermal velocity, v_i, are temperature dependent [8,9] as follows:

$$v_i = \left(\frac{8\,k\,T_i}{\pi\,m_i}\right)^{1/2}; \qquad (4)$$

$$\lambda_{i1} = \lambda_{io}[T_1(T_o + C_s)/T_o(T_1 + C_s)]$$

where e is the electronic charge, k is the Boltzmann constant, m is the mass, and C_s is the Sutherland constant.

From equations (2) to (4), the corona current or positive ion mobility decreases with increasing gas or ion temperature as observed in Figure 2. As reviewed by Chang et al. [9], the experimentally observed and numerically modelled positive ion mobilities decreases with increasing ion temperature or E/p (= electric field/gas pressure) for most of the ions. For air, the ion composition consisted with N_2^+, N_4^+, O_2^+, O_4^+, CO^+, Ar^+, CO_2^+, H_3O^+ etc. [6], hence the Blac's equation [9]

$$\frac{1}{\mu_{iAB}} = \frac{f_A}{\mu_{iA}} + \frac{f_B}{\mu_{iB}}; \quad f_A = \frac{(\text{density of A})}{\text{Total density}} \qquad (5)$$

should be used. The gas temperature may also influence the ion compositions in air under corona discharges, and hence ion mobility through equation (5).

For negative corona, the time averaged current-voltage characteristics shows more significant non-monotonic hysteresis effects as shown in Figure 3, where the characteristics was obtained from the corona on-set to off-set via maximum applied voltages. The corona current in Figure 3 also shows higher current for the higher corona current region ($I > 10^{-1}$ µA) and lower current for the lower current region. Moreover, several negative current-voltage characteristics regions and significant on-set to off-set corona voltage differences were observed. Since the negative current-voltage characteristics has been observed for the bridged streamer corona discharge by other investigators for a negative tuft corona [10, 11], the hysteresis effect at the higher current region may be due to the temperature dependence of tuft spots on the corona wires, since the number of corona spots increases not only with applied voltage but also with corona wire surface temperatures [11] to enhance corona current as shown in Figure 3. This hysteresis phenomenon may also be due to the vibration mode of corona wires, since the effect of corona wire displacement is expected to be larger in a narrow tube discharge. For the lower current region, the negative ion mobility temperature dependence may reduce corona current as described before, where both the negative ion and electron mobilities decrease with increasing temperature.

The effects of gas temperature on the corona discharge current may be more significant for a negative corona compared with positive coronas, since the negative corona consisted with O^-, O_2^-, O_3^-, CO_3^- ions with electrons [6, 11]. Here the ratio between the negative ion density and electron density significantly depends on the gas temperature as well as local electric field due to vibrational and rotational excitation of molecules [6, 9].

B. Gas Flow Effect

Typical time averaged current-voltage characteristics for gas flow rate $Q_g = 7.1$ ℓ/min are shown in Figures 4 and 5 for positive and negative coronas respectively, where the voltage is applied from corona on-set to off-set conditions via maximum applied voltages. Both current-voltage character-

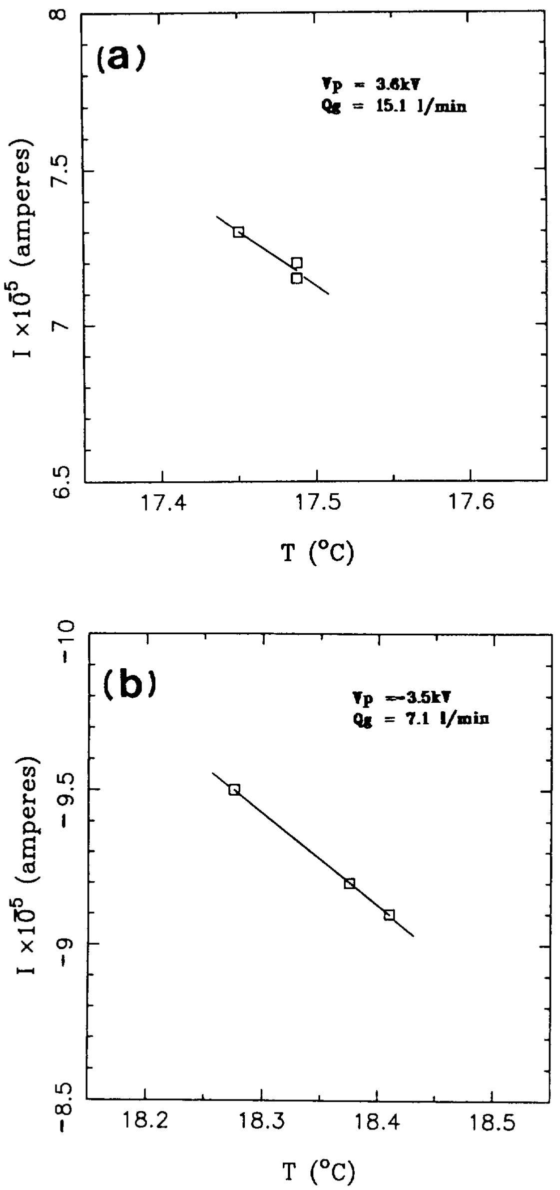

Fig. 6 Time averaged corona discharge current as a function of gas temperature at exist of corona channel at Q_g = 7.1ℓ/min: a) Positive corona; b) Negative corona.

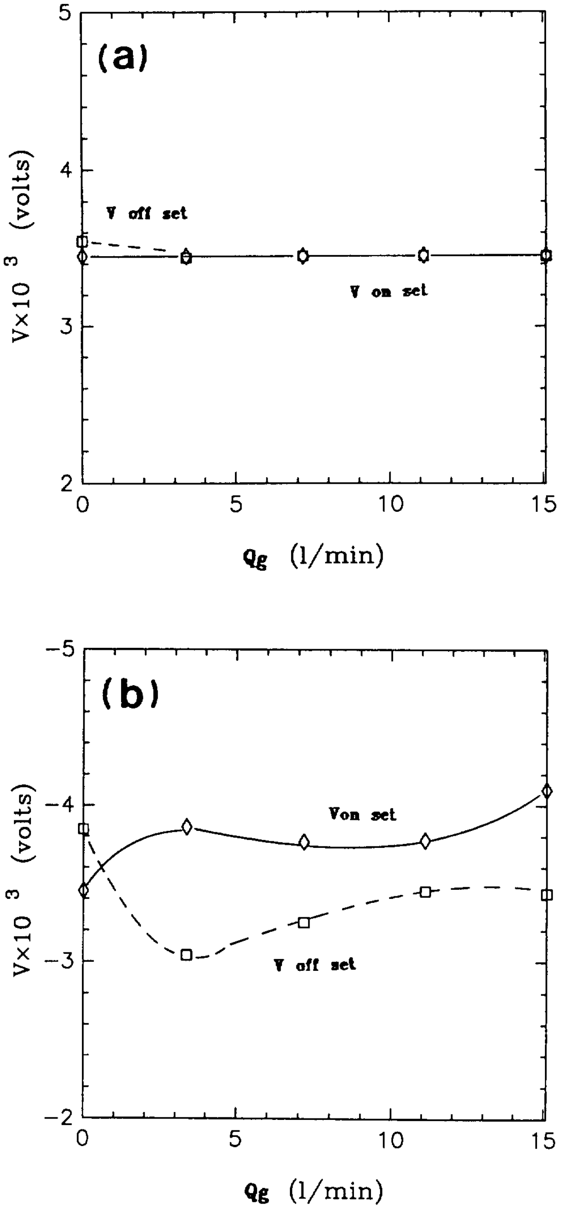

Fig. 7 Corona on-set and off-set voltage as a function of gas flow rate: a) Positive corona; b) Negative corona.

istics show hysteresis with different degree compared with zero gas flow conditions of Figures 2 and 3. For a positive corona, the corona current still can be approximated with $V = k\sqrt{I}$ type characteristics as observed by other investigators [10,11]. However, the corona current is much larger for the maximum to corona off-set voltage transitions in contrast to zero gas flow cases (Figure 2). The negative corona current also shows much higher values for the maximum to off-set voltage transitions compared with the on-set to maximum voltage transitions in contrast to zero flow cases (Figure 3).

For high enough gas flow rate, we can use gas temperature measured at exit of wire-pipe flow channel as an indication of gas temperature environment in a corona discharge zone, hence, the time averaged corona discharge current at fixed applied voltage is shown as a function of exit gas temperature in Figure 6 for both negative and positive coronas. As expected from the discussion in Section IIIB, the corona current for both polarity decreases with increasing gas temperature due to the ion mobility temperature dependencies. Therefore, the hysteresis curves observed in Figures 4 and 5 for gas flow cases may have a different mechanism other than the direct gas or ion temperature effects on the ion mobilities.

For narrow discharge tube with gas flow, the corona discharge becomes more stable compared with zero gas flow since the electrode surface was effectively cooled by the gas flow and instabilities due to the electrohydrodynamically induced secondary flow [11,14,15] will be reduced [12,13]. This flow stabilized corona discharge normally enhances corona discharge currents due to generating more uniform glow or streamer coronas discharges [13]. Hence, the enhancement of corona currents observed in Figures 4 and 5 may be due to the fact that the gas flow stabilized effect slowly overcomes the gas and electrode surface heating produced by the corona discharge. This fact also can be supported by the effect of the gas flow rate on the corona on-set and off-set voltages as shown in Figure 7. The corona on-set and off-set voltages increase with increasing gas flow rate for negative coronas since the corona discharge is normally more uniform for higher on-set voltages than that of spot type corona initiations. Figure 8 shows that the gas flow is effectively cooling the corona discharge gas and electrode heating at the on-set and off-set voltages. The exit gas temperature in a corona channel decreases with increasing the gas flow rate. Here, the exit gas temperature shown by dashed line near zero gas flow rate was measured by imposing a higher gas flow after the termination of gas discharge to obtain corona zone gas temperatures.

C. Inlet Gas Temperature Effect

In order to observe gas temperature effect on the corona discharge, a hot air is introduced in the corona channel. The time averaged corona discharge current-voltage and the average gas temperature-voltage characteristics are shown in Figures 9 and 10 respectively, for a positive corona at $Q_g = 7.1\ \ell/\text{min}$; where $T_{gav} = (T_{in} + T_{out})/2$. As we expected from the discussion in Section IIIA, an enhancement of gas temperature to ~40°C will yield more significant hysteresis effect and instabilities in the corona channel, and corona current again becomes smaller for the transition from maximum to corona off-set voltages compared with the transition from the on-set to maximum voltages in spite of gas flow. Significant gas heating by a corona discharge is noted from the observation of an average gas temperature as well as hysteresis effect as shown in Figure 10.

Time averaged corona discharge current-voltage and average gas temperature-voltage characteristics are shown in Figures 11 and 12, respectively for a negative corona at $Q_g = 7.1\ \ell/\text{min}$. Figure 11 shows that the hysteresis in the current-voltage characteristics is much larger for the higher average gas temperature (~38°C) condition than for the lower cases as expected. The average temperature-voltage characteristics also show significant hysteresis as shown in Figure 12 in spite of gas flow cooling to support the effect of temperature driven hysteresis effects and the instabilities.

IV. CONCLUDING REMARKS

Experimental investigations have been conducted to study corona discharge characteristics for a wire-pipe narrow discharge tube, and the following concluding remarks are obtained:

The results show that: 1. For positive corona, a small hysteresis in the time averaged current-voltage characteristic was observed due to the heating of the gas flow channel, where the gas temperature increases with increasing applied voltage; 2. For negative corona, a relative significant hysteresis time averaged current-voltage characteristics was observed. Since negative corona discharges in a coaxial wire-pipe are tuft coronas, this hysteresis effects may be due to the changing of corona tuft numbers with and without initial space charges in a gas flow channel; 3. The hysteresis current-voltage

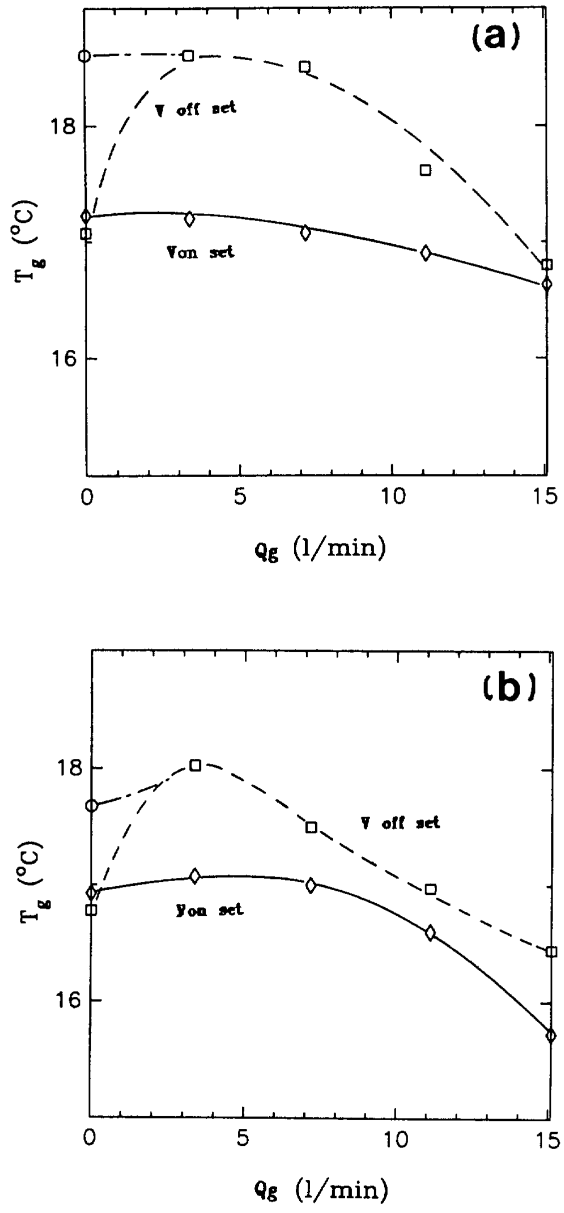

Fig. 8 Exit gas temperature as a function of gas flowrate for both corona on-set and off-set voltages: a) Positive corona; b) Negative corona. - - - temperature at corona channel.

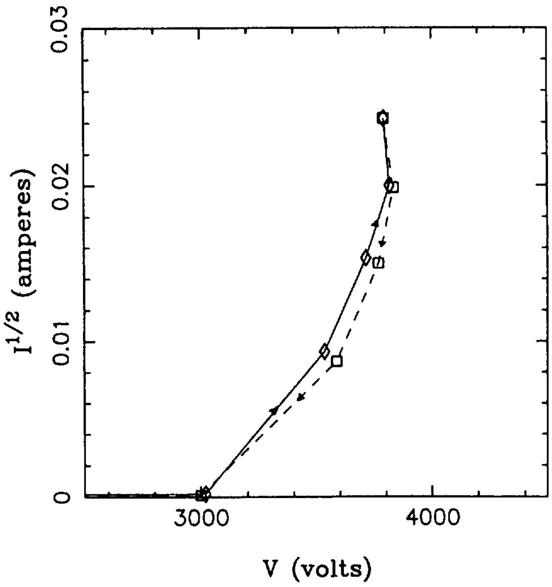

Fig. 9 Time averaged corona discharge current-voltage characteristics for a positive corona at average gas temperature T_{gav} = 39.5°C and Q_g = 7.1 ℓ/min.

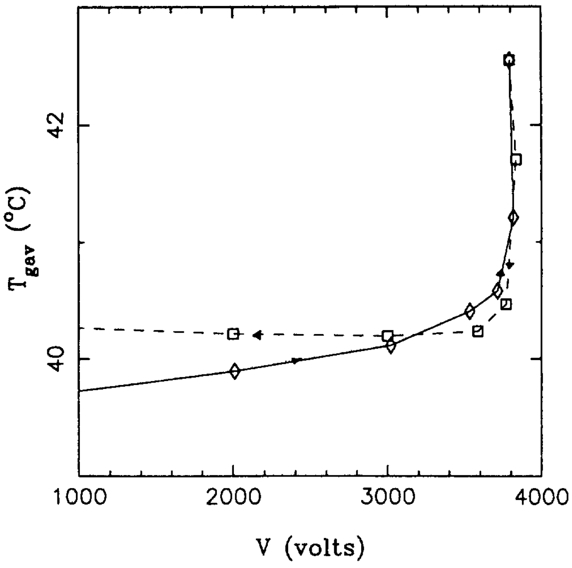

Fig. 10 Average gas temperature as a function of applied voltage for a positive corona at Q_g = 7.1 ℓ/min.

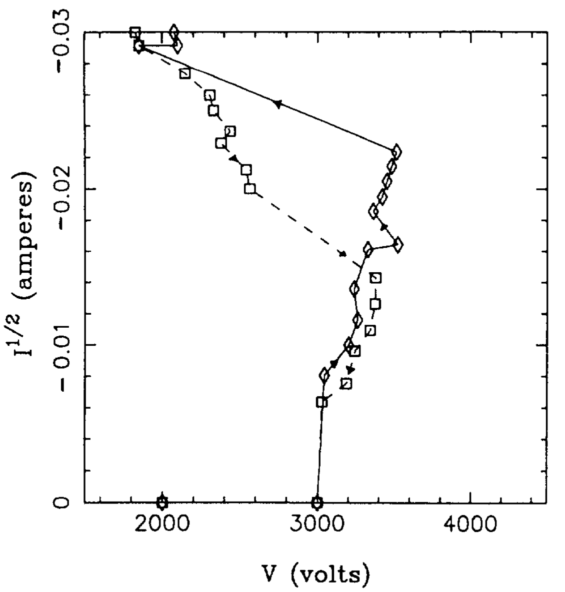

Fig. 11 Time averaged corona discharge current-voltage characteristics for a negative corona at T_{gav} = 38°C and Q_g = 7.1 ℓ/min.

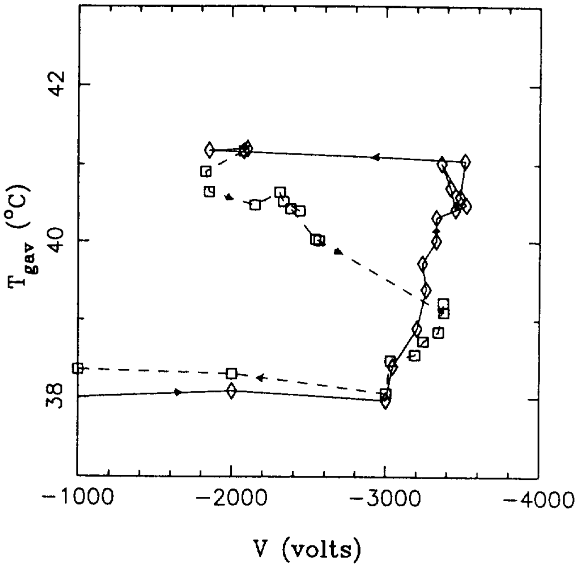

Fig. 12 Average gas temperature as a function of applied voltage for a negative corona at Q_g = 7.1 ℓ/min.

characteristics also show a slight dependence on the gas flow velocity and inlet gas temperature; 4. The corona induced secondary electrohydrodynamic flow may significantly contribute to the hysteresis effects.

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