Transverse dc Glow Discharges in Atmospheric Pressure Air

Zdenko Machala, Christophe O. Laux, and Charles H. Kruger

***Abstract*—Plasma-flow interactions are investigated in transverse direct current glow discharges in atmospheric pressure air. Interestingly, the slower flow "blows out" the discharge farther than the faster flow. We find this counter intuitive result to be mainly due to gas heating in the discharge: the temperature is higher for the slower flow, thus enhancing the reduced electric field E/N and causing the discharge to extend farther downstream.**

***Index Terms*—Air, atmospheric pressure, direct current (dc) glow discharge.**

NONEQUILIBRIUM air plasmas at atmospheric pressure present considerable interest for a wide range of applications. Direct current (dc) glow discharges represent one possible way to produce such plasmas. We have previously shown that it is possible to maintain stable atmospheric pressure dc glow discharges without arcing. Such discharges can produce relatively large volumes of fairly homogeneous nonequilibrium air plasma [1]–[4]. They are obtained by applying a high voltage between a set of ballasted metal electrodes. In our previous studies, we mostly investigated discharges parallel to the axis of the gas flow [1]–[4]. In this paper, we present dc discharges perpendicular to the gas flow in order to investigate plasma-flow interactions and gas heating effects.

The present experiments were conducted in atmospheric air for two flow rate conditions, 32 and 110 standard liters per minute (slpm), with corresponding flow velocities of 45 and 160 m/s. In both cases, the air flow was preheated to approximately 2000 K with the Litmas Red microwave plasma torch described elsewhere [3], in order to facilitate a stable discharge operation at high flow conditions. The dc discharge was applied between two platinum pin electrodes spaced by 5 mm, orthogonal to the vertical axis of the upward airflow. The discharge current was 100 mA.

Fig. 1 shows photographs of the transverse discharges for the Fig. 1(a) slow Fig. 1(b) and fast flow conditions. The photographs were taken with a Nikon Coolpix 990 digital camera with no filter. We find that the discharge volume is visually larger at the low flow rate condition. The measured intensity profiles of N_2 C-B (0, 0) emission from the discharge along the centerline z-axis confirm that the discharge extends farther downstream at the low flow rate. To explain this counterintuitive result, we measured profiles of gas temperature and electric field strength along the z-axis, and we propose an explanation of the observed behavior based on the reduced field strength in the discharge.

The electric potential was measured along the centerline z-axis with a plasma probe consisting of a thin platinum wire placed inside a ceramic tube. To determine the electric field strength E from the measured floating plasma potential, we make the following approximations.

1) Since the discharge forms an arch, we assume that the current streamlines form arches as well. We make this assumption because the discharge follows the electron density distribution between the electrodes, since ionizing electrons are an essential mechanism sustaining the discharge. The electron density is directly associated with the current density, and therefore with the current. We approximate the length of an arch between the cathode surface and the probe tip by the length of a straight line.
2) We assume that the electric field is constant along a current streamline. This assumption only holds in the positive column of a glow discharge and not in the cathode layer but the cathode layer thickness is negligible with respect to the positive column at atmospheric pressure.

With these approximations, the electric field was calculated as the measured floating plasma potential minus the cathode potential fall, divided by the length of the arch extending from the surface of the (grounded) cathode to the probe. The cathode fall was measured to be about 280 V, which agrees well with the cathode fall for a glow discharge in air with platinum cathode [5]. We have also used a double plasma probe that measures the potential difference at fixed spacing. The E values measured by this technique agree with the single probe measurements.

The rotational temperature profiles along the vertical z-axis were measured by emission spectroscopy of the N_2 C-B bands. The gas temperature is assumed to be equal to the rotational temperature, owing to fast collisional exchange at atmospheric pressure. The gas density N profiles were then calculated using the state equation. In the fast flow case, the temperature increases from 2200 K at $z = 0$ to 2900 K at $z = 5$ mm. In the slow flow case, the temperature increases more steeply, from 2000 K at $z = 0$ to 3200 K at $z = 5$ mm. This effect can be explained in terms of vibrational-translational energy transfer. The discharge excites the vibrational modes of N_2, which then relax through collisions. This collisional quenching transfers energy from the vibrational to the translational modes of molecules, thereby heating the gas. There is more gas heating at low flow

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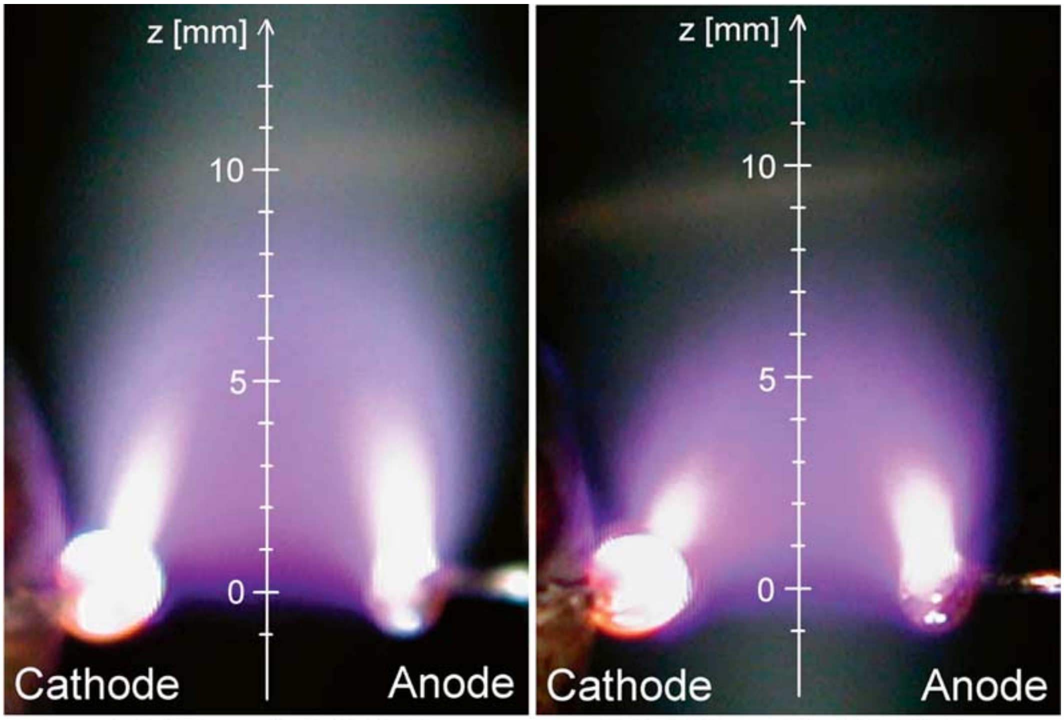

a) $Q = 32$ slpm, $v \sim 45$ m/s, $U = 1.2$ kV b) $Q = 110$ slpm, $v \sim 160$ m/s, $U = 1.33$ kV

Fig. 1. Transverse dc glow discharges in a vertical upward flow of atmospheric air preheated to ~ 2000 K. Gap spacing 5 mm, current 100 mA.

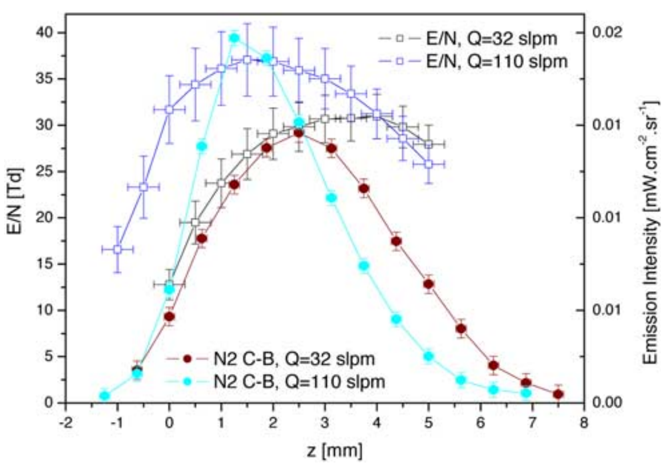

Fig. 2. Comparison of E/N profiles and N_2 C-B emission profiles in the transverse discharges.

velocity because the vibrational modes have more time to relax. Consequently, the temperature increases more in the low flow rate case.

The measured E and N profiles enable us to deduce the reduced field strength E/N profiles. E/N is the main parameter controlling the rate of electron-impact reactions in atmospheric pressure plasmas. In Fig. 2, we compare the E/N profiles with the optical emission profiles of the N_2 C-B (0, 0) band. The E/N and emission profiles peak at approximately the same locations for both flow rates. The E/N profiles are flatter after the peak than the emission profiles, which could suggest that there are chemical mechanisms that quench the N_2 C state in a region where E/N is still high, and so decrease the N_2 C-B emission. The quenching mechanisms and their temperature dependence are a subject of further investigation. Nevertheless, the counter-intuitive larger extent of the discharge at the low flow rate condition appears to be mainly caused by the higher temperature downstream. Higher temperature results in lower gas density, thereby increasing the E/N further downstream. The discharge behavior shows that the gas heating effect plays an important role in this type of atmospheric pressure air discharges and should be considered for their volume scalability.

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