MODELLING OF CAPILLARY TUBE PLASMA REACTOR CORONA DISCHARGE PARAMETERS IN DRY AIR WITH TRACE VOLATILE ORGANIC COMPOUNDS

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Abstract

Corona discharge parameters of a capillary discharge tube plasma reactor in dry air with trace volatile organic compounds (VOCs) are analytically and numerically investigated. The physical model is based on the one-dimensional modified Loeb's model with experimental current-voltage characteristics as calculation inputs, where the mobility of electrons is considered as a function of local electric fields. Then the energy balance is introduced for an electron temperature calculation based on calculated electron density and electric field profiles obtained from the physical model. VOCs considered in the present model are trichloroetane, trichloetylene, toulene, carbon tetrachlorides, toluene, and EGM. Numerical results are presented for applied voltages from 5 to 12 kV, tube diameters from 1.8 to 3 mm, VOC initial concentrations from 0 to 3000 ppm, and gas flow rates from 1 to 10 l/min. Numerical results show that the corona discharge parameters significantly influenced by tube diameters, VOC concentrations, type of VOCs, applied voltages, and gas flow rates.

Introduction

Fatigued, nauseous, sore throats and watery eyes due to indoor air quality (or sick building syndrome) are often induced by the existence of volatile organic compounds (VOC), Ozone, NO_x, bacteria etc. [1].

In a paint industry, organic solvents such as toluene, xylene, methylchloride are commonly used as a paint thinner or used for cleaning of wall surfaces. More recently, these volatile organic compounds were observed to significantly affect human health for the workers via ground water contaminations and emission gases.

In a high-technology semiconductor industry, organic solvents such as Trichloroethylene, Tetrachloroethylene, Trichlorethane, EGM (Ethyleneglycolmono-ethylether) are commonly used for a cleaning of substrates before or during device processing. More recently, these volatile organic compounds were observed to significantly affect human health for people living near industrial facilities as well as factory workers via ground water contaminations and emission gases. In this work, numerical and experimental investigations have been conducted to study corona discharge induced plasmas in air with trace VOCs.

Experimental Apparatus

A schematic diagram of the testing apparatus is shown in Figure 1. To clarify the destruction process, dry air (N_2:80% vol., O_2:20% vol.) is used as a balanced gas and relatively simple and reactive VOCs such as Toluene, EGM, Carbon Tetrachotide, TCE and TCA, the major emission sources among VOCs, are used. Air supplied from the laboratory is divided into two air flows. Each air flow rate is controlled with a flowmeter. One air flow is introduced into the bubbler which contains liquid VOCs. Air with almost saturated VOC vapour is mixed with the other air flow and diluted to the prescribed VOC concentration. The initial concentration of VOC is measured by a VOC meter (VLC Snifer). Compositions of treated air are qualitatively and quantitatively analyzed by FT-IR spectrometer (Bio-Rad model FTS-40). DC high voltage is applied between electrodes. To protect the high voltage power supply, a ballast resistor is used.

The capillary tube plasma reactor [2] consists of 2.5 mm i.d. and 100 mm long tube with two needle electrodes (with 10 mm gap length) as shown in Figure 2. DC high voltage is imposed between two electrodes.

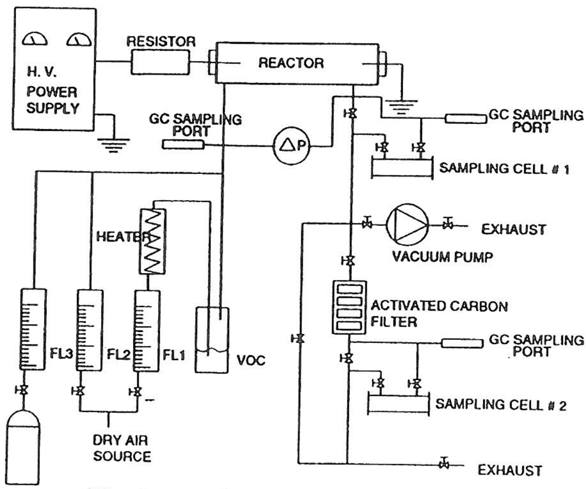

Fig. 1 Schematic of the experimental apparatus.

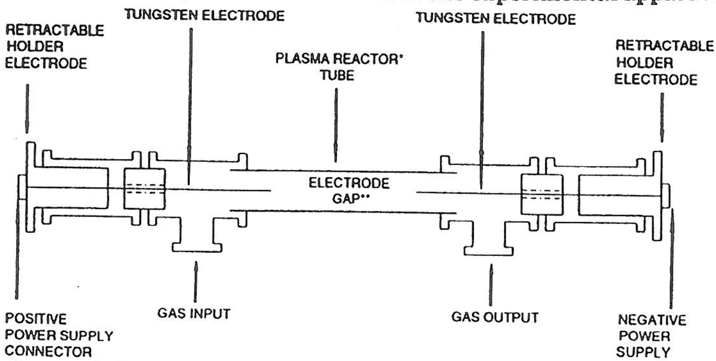

Fig. 2 Schematic of the capillary tube plasma reactor.

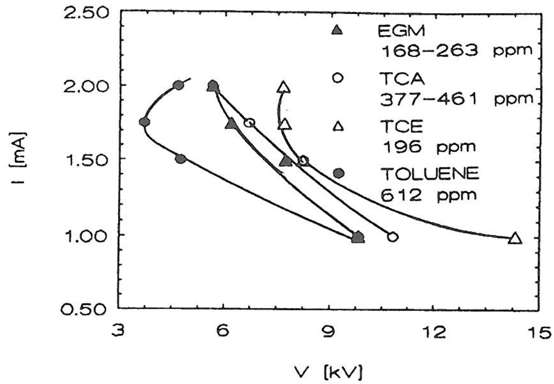

Fig. 3 Current-voltage characteristics for various VOCs in dry air.

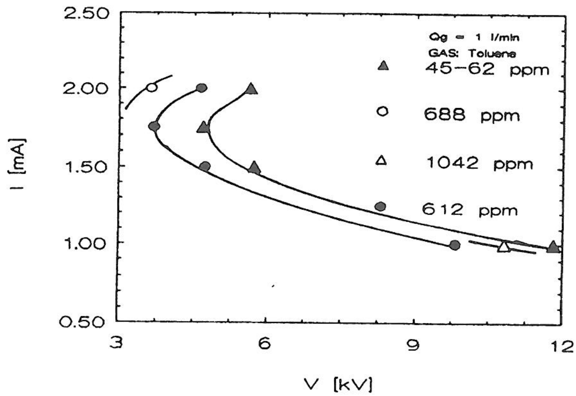

Fig. 4 Current-voltage characteristics for various initial toluene concentrations in dry air.

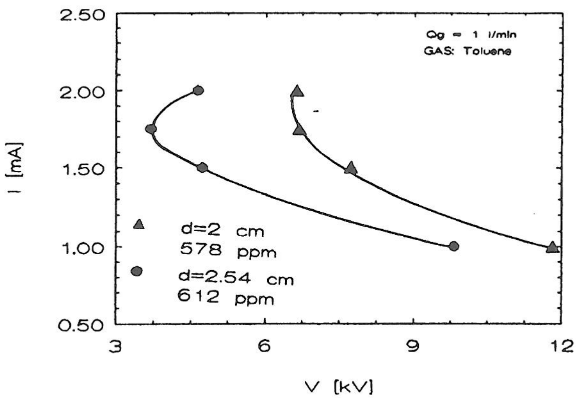

Fig. 5 Current-voltage characteristics for various tube diameters.

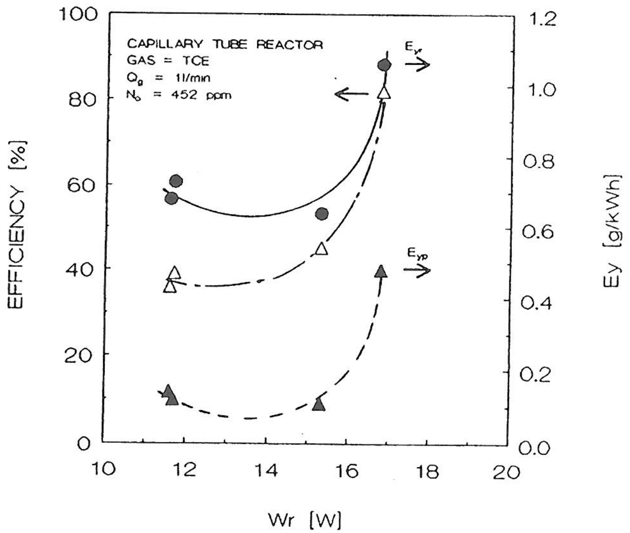

Fig. 6 Trichloroethylene (TCE) destruction efficiency, energy efficiency of destruction based on plug power E_{yp} and discharge reactor E_{yr} as a function of input power to the reactor.

Fundamental Characteristics of Capillary Tube Discharge Reactors
Current-Voltage Characteristics

Typical time-averaged discharge current as a function of applied dc voltage for various VOCs is shown in Figure 3. The time-averaged I-V characteristics show negative differential conductivity ($dI/dV < 0$) with the polarity such that the voltage is applied opposite to the gas flow (gas flows from the negative to positive electrode). Figure 3 shows that the discharge current is significantly influenced by the type of VOCs in air. The streamer corona or spark discharge I-V characteristics are negative in contrast to a low pressure glow discharge as shown in Figure 3.

The effects of Toluene concentrations and tube diameter on the current-voltage characteristics is shown in Figures 4 and 5. Figures 4 and 5 show that the capillary tube operating conditions are shifted towards lower voltage when discharge tube diameter or VOC concentration increased.

Figure 6 shows the destruction efficiency of TCE for various discharge currents. Dissociation efficiency at currents exceeding 1 mA shows some decrease likely due to falling current-voltage characteristics of gas discharge [3].

Plasma Environments of Capillary Tube Discharge Reactors

In atmospheric gas pressure plasmas, the mean free paths of ions and electrons are always much smaller compared with discharge spaces. Hence, the following charged particle transport equations [4] can be used.

$$J_c = e\,U_g N_c \pm e\,\mu_c N_c E - e\,D_C \nabla N_c + e\,G_c N \nabla T_g \quad (1)$$

$$\nabla \cdot J_c = e \frac{\partial N_c}{\partial t} + S_o - S_i \tag{2}$$

$$\nabla^2 V = \frac{- e N_{en}}{\varepsilon} \; ; \quad E = - \nabla V \tag{3}$$

where J is the current flux density, V is the velocity, N is the number density, μ is the mobility, E is the electric field, D is the diffusion coefficient, G is the thermophoresis coefficient, T is the temperature V is the electric potential, e is the electron elementary charge, ε is the dielectric constant, S_i and S_o are the sink and source reactions of species, and subscripts c, g and en are charged particles, gas and net charge, respectively.

For a capillary discharge tube as shown in Fig. 2, we can use a cylindrical coordinate system for the transport equation as follows:

$$\frac{I_c}{A} = J_{cz} = e(U_{gz} + \mu_c E_z) N_c \tag{4}$$

$$\frac{d E_z}{dz} = - \frac{e N_{en}}{\varepsilon} \tag{5}$$

when Ra_c and $F_E \gg 1$ and σ_c where Ra_c is the diffusion Reynolds number ($= U_{gs}$ d/D_c), F_E is the electric field number ($= e\ V_p\ d/L\ kT_c$), U_{gs} is the mean gas velocity, σ_c is the thermophoresis number ($= G_c\ d\ T_s/D_c$) d is the tube diameter, L is the electrode gap distance, k is the Boltzmann constant, V_p is the applied voltage, I is the current, T_s is the electrode surface temperature and A is the electrode surface area.

Hence, the plasma density can be calculated from

$$N_c = \frac{I_c}{e A(U_{gz} + \mu_c E_z)} \tag{6}$$

and the electric field can be calculated from

$$\int (U_{gz} + \mu_c E_z) d E_z = - \frac{I_c}{\varepsilon A} z + c_o \tag{7}$$

$$U_{gz} E_z + \frac{\mu_c}{2} E_z^2 = - \frac{I_c}{\varepsilon A} z + c_o \, (\text{for } \mu_c \neq f(E_z)) \tag{8}$$

where integrated constant c_o can be obtained from the current-voltage characteristics. For air, electron mobility can be approximated as follows:

$$\mu_e = 7.2 \times 10^5 (E/N)^{0.46} \text{ for } (0.1 \leq E/N\ 10\ \text{Td}) \tag{9}$$

$$= 4.6 \times 10^5 (E/N)^{0.72} \text{ for } (10 \leq E/N \leq 500\ \text{Td}) \tag{10}$$

where $N = 2.7 \times 10^{19}\ cm^{-3}$ at 1 atm. pressure [4]. Hence, equation (7) can be

Fig. 7 Typical numerical axial plasma density, electric field and mean electron temperature profiles.

integrated with the boundary conditions: $V = V_a$ at $Z = 0$ and $V = 0$ at $Z = L$, where V_a is the applied voltage and L is the electrode gap distances.

Mean electron temperature $k T_e/e$ [eV] can be obtained from the swarm parameters [5], and can be approximated for air by

$$k T_e/e = 1.45 \times 10^{-3} E^{0.72} \text{ for } (2 \times 10^4 \leq E \leq 3 \times 10^4 \text{ V/cm}) \quad (11)$$

Numerical Results

Numerical axial plasma density, electric field and electron temperature profiles are shown in Figure 7. The results show that the plasma density, electric field and electron temperature decreases along the axial direction from cathode to grounded anode, and nonmonotonically depends on applied voltages.

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