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Full Length Article

A 1D ionic transport model for nonlinear response analysis of a counterflow laminar diffusion flame in DC electric fields

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ABSTRACT

The ionic wind effect is a well-known phenomenon in electric-field-assisted combustion in which the convective bulk flow can be modified by the collision of charged species with neutrals in the reaction region. This paper suggests an essential model based on 1D ionic transport equations to describe the ionic wind effect responsible for nonlinear responses of diffusion flame positions in a counterflow burner with DC voltage variations. The characteristics of ionized layers that substitute for counterflow diffusion flames were compared by applying the effects of one-way (unidirectional) and two-way (bidirectional) ionic wind models. The calculation results showed that the two-way ionic wind model was able to qualitatively predict the unique features of the flame positions in the present experiments and general trends in the electric current density reported in previous literature. The qualitative characteristics of the ionized layer can be classified into three regimes: (1) one-way ionic wind (OIW)-dominated regime, (2) transition regime, and (3) two-way ionic wind (TIW)-induced regime. The details are discussed in this article. The results of this study supported the importance of the two-way ionic wind effect for nonlinear responses of counterflow diffusion flames in DC electric fields.

1. Introduction

Electric-field-assisted combustion [1,2] is known to provide a practical use for controlling flame stabilization, flame propagation speed, and air pollutants. These applications can be achieved by utilizing the nature that the ions in a flame are influenced by electric fields. However, further study is required to explain the mechanism details for these advantages. Nevertheless, the ionic wind effect has been investigated extensively as one of the key factors in electric-field-assisted combustion [1,2]. As positive ions, negative ions, and electrons exist within the reaction zone of a hydrocarbon flame, the charged species will be accelerated by the Lorentz force in electric fields, which can lead to an improvement in the electric drift. Collisions between the accelerating charges and neutral molecules generate momentum transfers that can change the convective bulk flow. This is called the ionic wind effect.

In generating the one-way (unidirectional) ionic wind effect [1,2], positive ions can be dominantly acting on the momentum transfer owing to their greater concentration than negative ions as well as the electrons in the reaction zone. There exists a delay time for the momentum transfer from accelerating positive ions to neutral molecules to activate the convective bulk flow. This collision response time has been investigated by applying transient direct current (DC) and high-frequency alternating current (AC) above 50 Hz electric fields [3,4]. This has been estimated to be the order of 10 ms. The collision response time has also been investigated for premixed flames stabilized in a McKenna burner with a DC pulse [5]. For nonpremixed flames in counterflow burners with AC electric fields, as a preliminary experiment of the present study [6], the threshold frequency of the oscillation amplitude of flame displacement was demonstrated as a function of voltage strength at a frequency of the order of 10 Hz of AC electric fields, and was identified on the basis of the collision response time. Under lower AC frequencies on the order of 1 Hz, however, the oscillating flames responding to a relatively high voltage on the order of 1 kV showed a nontrivial phenomenon, which could not be fully realized by only the effect of the electric body force of the positive ions in the one-way ionic wind.

In contrast to AC electric fields where the charge flow is periodically inverted, a systematic study on flame behavior was recently carried out for the counterflow diffusion flames in DC electric fields. The axial position of the flames was experimentally investigated with respect to variations in applied DC voltage [7,8]. The experimentally measured current density was compared with numerical data predicted by a 1D ionized layer model with a stationary location [9]. In particular, double

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Nomenclature

D_-	diffusion coefficient of negative ion, [cm^2/s]
D_+	diffusion coefficient of positive ion, [cm^2/s]
D_e	diffusion coefficient of electron, [cm^2/s]
D_F	diffusion coefficient of fuel, [cm^2/s]
D_O	diffusion coefficient of oxygen, [cm^2/s]
F_-	electric body force acting on negative ion, per unit volume (q_eEn_-), [N]
F_+	electric body force acting on positive ion, per unit volume (q_eEn_+), [N]
F_b	buoyant body force acting on reaction zone, per unit volume ($\Delta\rho g$), [N]
F_e	electric body force acting on electron, per unit volume (q_eEn_e), [N]
$J_{T,d}$	total electric current density caused by diffusion, [A/cm^2]
$J_{T,e}$	total electric current density caused by electric field, [A/cm^2]
J_T	total electric current density, [A/cm^2]
K_F	strength of chemi-ionization reaction rate, [-]
K_m	strength of flow retardation, [-]
L_{FWHM}	distance between two FWHM positions, [cm]
V_0	initial electric potential, [V]
V_{DC}	applied DC voltage, [V]
cv_F	convective term of fuel $\left(v_F\frac{\partial n_F}{\partial x}\right)$, [#/cm^3·s]
cv_O	convective term of oxygen $\left(v_O\frac{\partial n_O}{\partial x}\right)$, [#/cm^3·s]
j_-	negative ion flux, [#/cm^2·s]
j_+	positive ion flux, [#/cm^2·s]
j_e	electron flux, [#/cm^2·s]
j_k	flux (current density) of charged species k, [#/cm^2·s]
k_1	reaction rate of recombination 1, [cm^3/#·s]
k_2	reaction rate of recombination 2, [cm^3/#·s]
k_B	Boltzmann constant, [g·cm^2/s^2·K]
k_{FO}	reaction rate of chemi-ionization, [-]
n_-	number density of negative ion, [#/cm^3]
n_+	number density of positive ion, [#/cm^3]
n_e	number density of electron, [#/cm^3]
$n_{F,0}$	initial number density of fuel, [#/cm^3]
n_F	number density of fuel, [#/cm^3]
$n_{O,0}$	initial number density of oxygen, [#/cm^3]
n_O	number density of oxygen, [#/cm^3]
q_e	unit charge, [C]
v_-	drift velocity of negative ion, [cm/s]
v_+	drift velocity of positive ion, [cm/s]
v_e	drift velocity of electron, [cm/s]
$v_{F,O}$	initial velocity of fuel, [cm/s]
$v_{F,S}$	base velocity of fuel, [cm/s]
v_F	average flow velocity of fuel, [cm/s]
v_M	correction velocity, [cm/s]
$v_{O,0}$	initial velocity of oxygen, [cm/s]
$v_{O,S}$	base velocity of oxygen, [cm/s]
v_O	average flow velocity of oxygen, [cm/s]
x_f	flame position, [cm]
x_{max}	$x = L$, [cm]
x_{min}	$x = 0$, [cm]
γ_-	friction coefficient of negative ion, [g/s]
γ_+	friction coefficient of positive ion, [g/s]
γ_e	friction coefficient of electron, [g/s]
μ_-	mobility of negative ion, [cm^2/V·s]
μ_+	mobility of positive ion, [cm^2/V·s]
μ_e	mobility of electron, [cm^2/V·s]
$\Delta\rho$	density difference, [g/cm^3]
E	electric field. [V/cm]
L	distance between two nozzles, [cm]
T	absolute temperature, [K]
V	electric potential, [V]
g	gravitational acceleration, [cm/s^2]
t	time, [s]
x	x-coordinate. [cm]
ε	permittivity, [C/V·cm]

Subscripts

−	negative
+	positive
0	initial
e	electron
F	fuel
k	charged species
O	oxygen

Superscripts

~	dimensionless quantity

flow stagnations accompanied by flow separation at a central flow stagnation were found though flow visualization using the Mie scattering technique [8]. The results emphasized the effect of a two-way (bidirectional) ionic wind considering both the positive and negative ions. That is, positive ions such as H_3O^+, $C_3H_3{}^+$, $CH_3{}^+$, and CHO^+ exist on the order of $10^{9–11}$ ions/cm^3 in the reaction zone [18]. In addition, negative ions such as OH^-, O^-, $C_xH_y{}^-$ hydrocarbon ions, $C_xH_yO_z{}^-$ oxygen-containing ions, and electron-attached $O_2{}^-$, H_2O^-, and electrons appeared on the order of 10^{10} ions/cm^3 [18,19]. Thus, the electric body forces on both the negative ions and electrons can be influenced in the opposite direction of those of the positive ions by the applied DC electric field.

Based on this experimental evidence [8], 2D axisymmetric simulations of the counterflow diffusion flames of methane were performed by different research groups using a skeletal chemical kinetic mechanism [10] and a detailed chemistry mechanism [11]. The predicted results agreed well with the experimental data for the flame positions and electric current densities [10]. The axial profile velocities and thermal-fluid distributions were in good agreement with the experimental results for the narrow voltage range of 0–1 kV [11]. These numerical models were progressively implemented on the basis of the modified diffusion term in the species equation for the charged particles to reflect the effect of the electric body force imposed on the ions by an applied DC electric field [12–14]. In particular, a collisional effect between the charged species and neutral molecules was taken into account in the binary diffusivity and mobility of the ion transport [15] in a freely propagating premixed lean CH_4/O_2 flame. High computational expenses were required to solve the charged species transport equation for the detailed chemical kinetics, but the flow separation phenomenon [8] in the counterflow diffusion flame by applying DC electric fields has not yet been numerically reproduced.

In the present study, the diffusion flame behavior of methane diluted with nitrogen in a counterflow burner is reexamined experimentally by applying DC electric fields. To explain the nonlinearity of the flame responses, a simple 1D model of the ionic wind effect was suggested for the counterflow laminar diffusion flame. This was inspired by an ion production and consumption model [16], and was qualitatively compared for one-way and two-way ionic wind effects.

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