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Research paper

Effect of alternating electric fields on the behaviour of small-scale laminar diffusion flames

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HIGHLIGHTS

- The ionic wind effect on flame in small-scale was discussed.
- Flame temperature and flame height were measured.
- Flame stability was enhanced by external AC electric field.
- Active power of AC was calculated and compared with combustion thermal power.
- A new correlation of the enhancement of upper stability limit was obtained.

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ABSTRACT

The effect of Alternating Current (AC) electric field on flame behaviours of ethanol in small-scale was studied experimentally. A stainless steel tube with inner diameter of 0.9 mm was used as a burner nozzle, and the diffusion flame was established at room temperature and atmospheric pressure. The flame temperatures were measured by a thermocouple and the flame heights were measured by optical visualization method under stable combustion conditions. The ionic wind effect was considered as the dominant mechanism of AC electric field on flame. The charged particles in the flame affected by electric body force have collisions with the neutral particles and transfer the momentum. At a certain flow rate of ethanol, the flame temperature increased with electric field strength and AC frequency, and the dimensionless flame height decreased with the increase of electric field strength. The upper stability limit was enhanced greatly by AC electric field due to the increased Damköhler number (*Da*). The electric field puts a little effect on the lower stability limits due to thermal quenching and heat loss. The ratios of active power of AC electric field to combustion thermal power were from 0 to 0.202. The selection of AC frequency is very important for the design of small-scale combustion system. A new correlation between the enhancement of upper stability limit and the active power of AC electric field was obtained. The results show that the active power plays an important role in the enhancement of stability of the small-scale flame.

1. Introduction

Over the past four decades, electrohydrodynamic (EHD) enhancement of fluid flow and heat transfer including phase change heat transfer has been intensively studied and reported by a number of researchers around the world [1–5]. In recent years, the effect of electric field on flame characteristics has attracted great interest among researchers. Hydrocarbon fuel flame contains many charged particles such as CHO^+, H_3O^+, $CH_3{}^+$, e, $O_2{}^-$, OH^-, which are directly related to fluid motion

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Nomenclature

C	capacitance (F)
D	electrode spacing (mm); diffusivity (m^2/s)
Da	Damköhler number
d_i	inner diameter of stainless steel tube (mm)
d_m	outer diameter of stainless steel tube on flame image (mm)
d_o	outer diameter of stainless steel tube (mm)
E	electric field strength (V/m)
F_e	electric body force (N)
F_g	neutral gas pressure (N)
f	AC frequency (Hz)
H	flame height (cm)
H_f	calorific value of ethanol (kJ/mol)
H_m	flame height on flame image (cm)
I	the effective value of AC current (A)
$\dot{I}$	the vector of AC current
M	molar mass of ethanol (g/mol)
n_c	net charge density
P_{AC}	active power of AC (W)
P_e	electrostatic pressure (Pa)
P_g	neutral gas pressure (Pa)
P_{th}	theoretical burning thermal power of ethanol (W)
P_{re}	actual burning thermal power of ethanol (W)
Q	volume flow rate of ethanol (ml/h)
Q_{en}	enhancement ratio
Q_{max}	upper stability limit (ml/h)
$Q_{max,E}$	upper stability limit with applied electric field (ml/h)
$Q_{max,E=0}$	upper stability limit without applied electric field (ml/h)
Q_{min}	lower stability limits (ml/h)
R	goodness of fit
R_2	resistance (MΩ)
R_f	flame resistance (Ω)
T	flame temperature (K)
S	the area of the copper electrode (m^2)
U	the effective value of AC voltage (kV)
$\dot{U}$	the vector of AC voltage
$\dot{U}_2$	the vector of AC voltage on the connected resistance
V	volume (m^3)
x	axial direction
x_i	direct measured parameter
Y_f	mass fraction of fuel
y	indirect measured parameter
Z	the complex impedance

Greek Letters

α	scaling ratio
ε	electric permittivity (F/m)
ε_0	permittivity of vacuum (F/m)
ε_r	relative permittivity of air (F/m)
θ	phase difference
ρ_L	density of liquid ethanol (kg/m^3)
σ_{xi}	error of direct measured parameter
σ_y	error of indirect measured parameter
τ_s	residence time (s)
τ_c	chemical reaction time (s)
φ	phase angle of the complex impedance (rad)
ω	angular frequency (rad/s)

and chemical reaction. The number density of particles is about 10^9–10^{12}/cm^3 [6–8]. The electric field was affected by the existence of the flame and the electric body force affected the combustion behaviour in a direct current (DC) electric field under microgravity [9]. The electric and combustion fields had obvious influence on the flame shape and propagation velocity [10–18]. Marcum et al. [10] applied DC electric field above the propane/air premixed flame and found that the electric field could significantly change the flame shape and increase the flame propagation velocity. Zhang et al. [13] experimentally studied the flame shape, luminosity and NO emissions of methane/air jet flames under high-frequency alternating current (AC) electric field (10 kHz), and found that the AC electric field had less influence on flame height, while the impact on inner fuel zone height and flame luminosity was more obvious. Won et al. [14,15] carried out experimentally study of the effect of high voltage AC and DC electric field on propagation speed of tribrachial flames in laminar coflow jets, and found that the propagation speed increased linearly with the applied voltage and decreased with the distance between the flame edge and the nozzle electrode. On the other hand, experimental research and numerical simulation on the effect of electric field on flame stability were also carried out [19–25]. Wisman et al. [19] experimentally studied the combustion stability limit of propane/air premix flame under DC electric field, and the results show that an appropriate electric field can enhance the stability of the flame. Kim et al. [8,20–22] studied influence on the burning velocity and stabilization of flame with DC and the AC electric field, and reported that the electric field could significantly increase the burning velocity and enhance the flame stability. Belhi et al. [25] studied methane/air premixed flame under DC electric field using the method of numerical simulation, and confirmed that the applied electric field had effect on the flame stability. In addition, researchers also found that the electric field had influence on the flame combustion products [26,27] and soot formation [28–30]. Vega et al. [26] studied the oxygen-enriched $CH_4/O_2/N_2$ premixed combustion under electric field, and found that when the flame shape remained unchanged, there was almost no effect of electric field on NO formation. Saito et al. [29,30] studied the effect of voltage, electric field intensity, and electrodes arrangement on the formation of soot particles. Wang et al. [28] found that the applied electric field had little effect on the soot particles size, while the residence time in flame would be shortened and reduced the total mass of soot particles in the flame. Some studies were performed on micro-combustors with high energy density [31–33].

Previous studies were mainly carried out using gas fuel in micro-scale. The liquid fuel has higher energy density and smaller volume, and it was easily to store and transport [34]. Studies on the effects of AC electric field on flame behaviour using liquid fuel in small-scale remain limited. The objective of the present study is to investigate the flame temperature, flame height, flame stability of ethanol in small-scale under the effect of AC electric field. The ionic wind effect on flame behaviour was discussed. The active power of AC was measured, and a new correlation between the enhancement of upper stability limit and the active power of AC electric field was obtained based on present experimental results.