Applied Thermal Engineering 87 (2015) 595–604

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

The electro-spraying characteristics of ethanol for application in a small-scale combustor under combined electric field

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HIGHLIGHTS

- Pulsed-jet, cone-jet, skewed cone-jet, and multi-jet were observed.
- Different electro-spraying modes for ethanol were divided into several regions.
- The driving force in jet region came from the electrostatic induction field.
- The electric field supplied driving force for the motion of liquid droplets.
- The specific charges of ethanol reached maximum value at the cone-jet mode.

ARTICLE INFO

Article history:
Received 5 February 2015
Accepted 24 May 2015
Available online 30 May 2015

Keywords:
Electro-spraying
Micro-scale combustion
Cone-jet mode
Specific charge

ABSTRACT

A small-scale combustor with electro-spraying technique was investigated. It consisted of vertical quartz glass tubes with an inner diameter of 16.0 mm. A stainless steel ring and a stainless steel mesh were used as an extractor and a collector, respectively. A capillary tube with an inner diameter of 0.9 mm was used as a nozzle. The nozzle and the steel ring were connected to the positive electrode of Direct Current power sources. The steel mesh was the droplets collector and a flame holder. Stable combustion flame was observed under combined electric fields. The electro-spraying modes of pulsed-jet, cone-jet, skewed cone-jet, and multi-jet were observed. The operating ranges were divided into several regions at various voltages and flow rates. The whole fluid field was divided into the jet region and spraying region. The driving force in the jet region came from the electrostatic induction field between the nozzle and the steel ring. The electric field between the steel ring and steel mesh supplied the driving force to move liquid droplets in the spraying region. The steel mesh is a key component for the directional movement of liquid droplets. Taylor angles measured at cone-jet mode were in the range of 75.18°–82.45°.

1. Introduction

In recent years, liquid electro-spraying has been a hot topic with growing interest due to its wide applications in such areas as fuel atomization in combustion systems [1,2], cooling for microelectronics [3–5], electro spinning process [6,7], deposition of thin functional films [8] and other areas [9–11]. There are some other researches on charge injection atomizers using dielectric liquid only [12–14]. In present study, we aim at the micro combustor applying electro-spraying technique and using liquid ethanol with low conductivity as fuel.

The crucial component in a micro energy system is the micro-combustor with stable flames, but it is very difficult to keep flames stable in the micro-combustor, due to short residence time and high heat loss rate [15–17]. Combustion using liquid hydrocarbon fuels can supply relatively high energy density but bring more challenges [18]. Electro-spraying is an ideal method in micro-scale combustion system with liquid fuels.

Kyritsis et al. [19] presented a meso-scale catalytic combustor coupled with direct energy conversion modules for power production. The jet fuelJP8 (Jet Propellant 8) was electro-sprayed at a flow rate on the order of 10 g/h and combusted under the equivalence ratios varying from 0.35 to 0.70 with estimated combustion

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http://dx.doi.org/10.1016/j.applthermaleng.2015.05.046

Nomenclature

A_q	specific charge(C/kg)
E	electric field strength(kV/m)
E_a	axial electric field strength(kV/m)
E_r	radial electric field strength(kV/m)
F	electrical field force(N)
L_1	distance from the outlet of the capillary nozzle to the steel ring(mm)
L_2	distance from the steel ring to the steel mesh(mm)
I	current (A)
I_0	initial current (A)
m	mass flux of liquid ethanol (kg/s)
m_1	mass flux of liquid ethanol evaporated into the air (kg/s)
P_{in}	internal pressure(N)
P_{ex}	external pressure(N)
Q_v	flow rate(ml/h)
R	resistance (MΩ)
r	radius of jet(mm); polar coordinates (mm)
r_{cr}	critical radius of jet(mm)
t	measurement period (s)
U	electric potential difference (mV)
V_1	voltage on the capillary nozzle(kV)
V_2	voltage on the steel ring(kV)

Greek symbols

ε_0	permittivity of air(F/m)
ε_r	permittivity of ethanol(F/m)
ρ	density of ethanol(kg/m^3)
σ	surface tension(N/m)
σ_0	initial surface tension(N/m)
φ	equivalent ratio

efficiency of 97%. Further they studied the performance of a combustor with liquid fuel electro-spray injection through a stack of catalytically coated grids [20].

The whole process of combustion using liquid fuel mainly includes electro-spraying, vaporization and combustion, it is quite important to understand the electro-spraying characteristics for better design and operation of micro-scale combustors. Mestel [21] investigated the steady flow in a cone-jet at high Reynolds number, when circulation occurs within the drop while the jet was fed by a surface boundary layer. Two models of the phenomena were presented with very different similarity scalings both agreed qualitatively with experiment. Experimental investigation was performed on electro sprays of liquids with low electric conductivity (heptane with different fractions of antistatic additive) in the cone-jet mode. The stable and monodisperse electro sprays could be established only within certain ranges of liquid flow rates and applied voltages [22]. The qualitative studies of jet structure and droplet formation in the electro hydrodynamic spraying were carried out. Ten modes had been distinguished and interpreted by considering the electrical and mechanical forces on the liquid jet [23,24]. The effect of pulsed voltages on electro hydrodynamic spraying in the cone-jet mode was investigated. Results showed that both the amplitude and the frequency of the pulsed voltage could affect the behavior of the spraying [25]. Deng et al. [26] successfully demonstrated the multiplexed electro spray systems with an unprecedented packing density of up to11,547 sources/cm^2. In order to generate fine droplets, electrostatic atomization was applied using nozzle and grounded ring with high voltage in between. Stable droplets of water and KCl solution were produced in oil without any surfactants [27]. Electro statically assisted sprays of butanol were established and compared with those of ethanol and heptane. The spray structure was characterized through measuring droplet sizes and velocities in a wide range of flow rates and applied voltages [28]. A high-speed camera with microscopic zoom lens had been used to visualize the deformation and breakup of charged droplets at the dripping mode. It was found that large surface tension could lead to low deformation of droplets and high voltage was necessary to make sprays transit from the dripping mode to the cone-jet mode [29].

Jaworek and krupa [30] gave the detailed description of main modes of electro hydrodynamic spraying of liquids in standard capillary-plane configuration. Chiarot et al. [31] studied experimentally the transient modes of an electrified fluid interface. There are several perfect involved reviews on the role of interfacial shear stresses [32], electro hydrodynamic spraying functioning modes [33], and the fluid dynamics of Taylor cones [34].

So far there are some researches on electro-spraying and micro-combustion, but the study on micro-combustion using electro-spraying technique is still in its infant stage. In order to enhance spraying and combustion in small-scale, a single capillary nozzle-steel ring-steel mesh configuration was placed inside a quartz glass tube with inner diameter of 16 mm. The stable combustion and flame was achieved under combined electric field. This research aimed to identify different electro-spraying modes and their operating ranges. The Taylor cone angles at the stable cone-jet mode and the specific charges at each mode were all measured. Our results will supply helpful guidance for design and operation of new small-scale combustors with high performance.

2. Experimental description

2.1. Test section

Fig. 1 shows a schematic of the present small-scale combustor. The combustor consisted of three pieces of vertical quartz glass tubes with inner diameter of 16 mm. A stainless steel ring as an extractor electrode and a stainless steel mesh as a collector electrode were connected among them by using a heat resistant adhesive. The inner diameter and outer diameter of the steel ring was 12.4 mm and 16 mm respectively. The whole steel mesh has a diameter of 16 mm and 98 round holes with a diameter of 1.0 mm in it.

A stainless steel capillary tube was used as a combustor nozzle, with an inner diameter of 0.9 mm and outer diameter of 1.2 mm. The nozzle was set at the center of the glass tube and the applied voltage to the nozzle was V_1using a Direct Current (DC) power source (Model 71030P, GENVOLT). The steel ring was arranged above the nozzle tip with vertical distance of L_1 and the applied voltage to the ring was V_2 using another DC power source. The steel mesh was arranged above the ring electrode with vertical distance of L_2 and was connected to the ground electrode with a standard resistance between them. In present study, the electric potential difference across the resistance is not bigger than 40 mV, so the electric potential on the steel mesh is near to zero. That is to say, the steel mesh can be regarded as setting to ground.

The working process of the combustor was divided into three regions. The fuel of ethanol jet was produced in the jet region, then