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Full Length Article

Atomization characteristics of nano-Al/ethanol nanofluid fuel in electrostatic field

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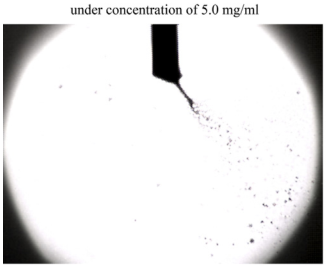
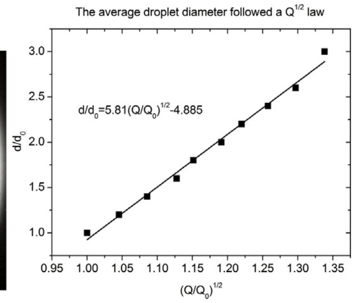
GRAPHICAL ABSTRACT

Breakup of nano-Al/ethanol nanofluid fuel under concentration of 5.0 mg/ml



The average droplet diameter followed a $Q^{1/2}$ law



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ABSTRACT

Electrostatic atomization has been widely applied in engineering, but few investigations on electrostatic atomization of liquid containing nanoparticles were carried out. This paper first presents the electrostatic atomization characteristics of nano-Al/ethanol nanofluid fuel and evaluates the contribution of nanoparticles to atomization characteristics. The physical properties of nano-Al/ethanol nanofluid were measured, suggesting that the density, surface tension and viscosity increase with enhancing the nano-Al concentration. The effects of the applied electric field voltage U, volume flow Q and nozzle size on electrostatic breakup of nanofluid jet and droplet formation were investigated in detail. It concludes that the average droplet diameter d follows a $Q^{1/2}$ law. The average diameter decreases significantly with the enhancement of the electric field voltage ranging with 17–25 kV. The decrease of nozzle size results in a reduction in average diameter of atomized droplets at critical breakup voltage. The nanofluid fuel of higher concentration exerted by the electrical field has a better atomization performance. When the nano-Al concentration reached 5.0 mg/ml, the atomized droplets became ultrafine and uniformly distributive. In comparison to 0.5 mg/ml, the average diameter can be reduced to one tenth (~9 μm).

1. Introduction

Nanofluids, dilute dispersions of nanometer-sized particles (typically < 100 nm), show anomalous enhancement of thermal conductivity, optical and heat radiation capabilities [1–4]. With the development and application of nanofluids, nanofluid fuels have been widely interestingly investigated in recent years. Nanofluid fuels are stabilized colloidal suspensions containing energetic nanoscale additives less than 100 nm size mostly in dilute concentrations (< 5 vol%) that act as combustion promoters. Energetic nanoscale additives (called

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nanofuels), such as metallic aluminum, boron, iron and graphene etc., possess some advantages over micrometer scale additives. The reduction in the size of energetic nanoscale additives has enabled to overcome the issue of long ignition delay and achieve higher burning rate [5,6]. Energetic nanoscale additives can be also considered as a potential secondary energy carrier [7]. The addition of these nanoscale additives to liquid fuels has a catalytic effect to enhance the burning rate [8], shorten the ignition delay [9,10], and improve combustion performance [11,12]. Nanofluid fuels have a potential in reducing the carbon footprint and minimizing the formation of toxic and dangerous emissions [13,14].

As compared to the host liquid fuels, combustion of nanofluid fuels exhibits extraordinary characteristics since energetic nanoscale additives are transported from the suspension to the gas-phase reaction zone and distributed homogenously along with the fuel charge [15,16]. Basu et al. [17] reported that secondary atomization is crucial to disperse homogenously nanoscale additives into liquid fuels during combustion. In automotive diesel fuels, colloidal nanocatalysts can be dispersed homogenously through atomization to reduce ignition delay and enhance combustion characteristics. In monopropellant and bipropellant propulsion systems, such effective use of nanocatalysts may allow the use of dispensable catalysts thereby eliminating the need for elaborate structural catalysts [18]. It is highlighted that the significance of secondary atomization in burning nanofluid fuel droplets. The interaction between atomization and combustion has a strong function of droplet size, nanoscale additives type, nanoscale additives concentration and the type of base fuel.

In a spray environment of nanofluid fuels, the droplet level transport significantly affects the final combustion efficiency. Excellent primary atomization is key to guarantee high surface to volume ratio of droplet level. Although many investigations have been conducted to explore the combustion behavior of nanofluid fuels, the atomization of nanofluid fuels was sparsely investigated. Kannaiyan et al. [19] demonstrated that the influence of nanoparticles' dispersion on the physical properties of aviation fuel and its spray performance by controlling injection pressure. It has been testified that the effect can become more when the nanoscale additives concentration is significantly increased. In order to obtain better atomization performance, one of solutions is that an electric field is applied to enhance secondary breakup of the droplets.

The electrostatic atomization is a liquid fuel atomization technique relying solely on electric charging. It is of ever-increasing importance in an extensive range of industrial and scientific processes, like pesticide spraying in agriculture, plating, printing, material preparation, fuel oil combustion, dust precipitation and desulfurization in industry, ionization mass spectrometer and electric propulsion etc. [20–25]. Generally, the liquid fuel in capillary (called nozzle) can be extruded into jets by pressure. As the instable jet is again applied by an electric field, the tangential stress induced by the electric field accelerates the breakup of jet and forms droplets. Simultaneously, the corona charging makes the instable droplets experience secondary breakup. Fuel physical properties (like density, surface tension and viscosity, permittivity, conductivity etc.), flow and electric field conditions comprehensively contribute to the jet diameter and the diameter of breakup droplets [26–28]. Mechanism of electrostatic atomization of pure liquid fuels has been widely investigated and revealed, however, for binary or trinary mixtures, the atomization characteristics relating with the mixture physical properties like density, surface tension and viscosity keep still unveiled. Ejim et al. [29] reported that groups of biodiesels and blends have negligible difference in drop size, and the reduce of viscosity, density and surface tension of binary blending can produce the best atomization performance. For nanofluid fuels, their physical properties are significantly different with host liquid fuel [30–33]. Herein, the key point is that the change in physical properties of nanofluid fuels can potentially alter the atomization characteristics. Besides physical properties, flow and electric field conditions are crucial to influence atomization performance. Considering the key roles played in spraying process, it is essential to have a perspective understanding of the atomization characteristics of nanofluid fuels and recognize their true merits. This triggers the motivation for the present work.

Nanometer sized aluminum (nano-Al) is a high energetic metallic fuel and has been considering as an additive widely used in propellants and vehicle fuel [14,34,35]. Also, ethanol is a common fuel. Therefore, in this work, the nano-Al/ethanol nanofluid fuel was selected as the research object to understand the effect of physical properties, flow and electric field conditions on the atomization performance.

The present work focuses on experimental investigation of the electrostatic atomization characteristics of nano-Al/ethanol nanofluid fuel. The objectives will be involving: (1) to measure the physical properties of nano-Al/ethanol nanofluid fuel including density, surface tension, and viscosity and analyze the influence of nano-Al concentration on the physical properties; (2) to test the effects of the applied electric field voltage, volume flow Q and nozzle size and nano-Al concentration on electrostatic breakup and droplet formation of the nanofluid jet; and (3) to find the rules among the voltage, flow, nozzle size and droplet diameter and to evaluate the contribution of nano-Al concentration to atomization performance by calculating the dimensionless parameters in detail.

2. Materials and methods

2.1. Material preparation

Nano-Al powders were commercially purchased (Dk Nano technology Co., Ltd, Beijing, China). They were synthesized by plasma vapor deposition method, and then passivated with a thin layer of Al_2O_3 (3–5 nm). The purity of nano-Al powders is up to 99.9% (Inductively Coupled Plasma (ICP) analysis). Its volume density is 0.23 g/cm^3 by powder density tester analysis and specific surface area is 20 m^2/g (Brunauer, Emmett & Teller (BET) method). Scanning electron microscopic photography was obtained under the conditions of 15 kV and magnification of 100 k×, as shown in Fig. 1. It can be observed that the nano-Al powders have spherical appearance and the size distribution of nanoparticles is nonuniform. The size distribution ranges from 30 nm to 70 nm, and the average diameter is ~50 nm. Moreover, due to the interaction of Van der Waals' force and Coulomb force, the nanoparticle agglomeration can be also observed. However, the agglomeration is relatively weak and can be dispersed into the host liquid fuel by sonication bath.

The X-ray diffraction (XRD, CuKα = 0.9, radiation λ = 0.154056 nm) profile was recorded in the range of 10°–80° in 2θ unit at 30 min, as shown in Fig. 2. The four sharp diffraction peaks

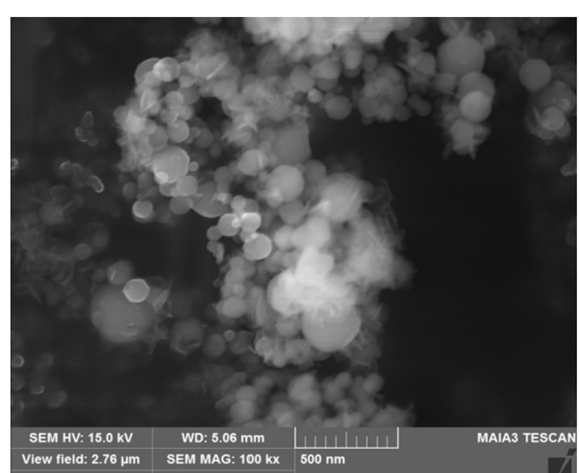

Fig. 1. SEM photography of nano-Al powders.