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Evaporation characteristics of heptane droplets with the addition of aluminum nanoparticles at elevated temperatures

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ABSTRACT

The evaporation characteristics of n-heptane droplets with varying concentrations of aluminum (Al) nanoparticles (NPs) hanging at a silicon carbide fiber were studied experimentally at different environmental temperatures (100–600 °C) under normal gravity. The evaporation of pure and stabilized heptane droplets has been also examined for comparison. The characteristics of the shell formation due to evaporation of the NPs suspensions and its effects on evaporation rate were also investigated. The results show that the evaporation of suspended heptane droplets containing Al NPs follows the classical d^2-law at all temperatures. The phenomenon of bubble formation in stabilized heptane droplets is reduced with the addition of Al NPs. For all Al NPs suspensions; regardless of their concentrations, the evaporation rate obtained was lower than pure heptane droplets from 100 to 300 °C, but it monotonically increased and became higher than the evaporation rate of pure heptane droplets above 400 °C. However for 2.5% (by weight) Al NPs suspension, the increasing trend in evaporation rate is exponential above 400 °C. At relatively low temperatures the formation of large agglomerates results in a compact shell development which suppresses the evaporation. On the other hand, at high temperatures a highly porous shell was formed by small agglomerates so that Al NPs lead to evaporation enhancement. Maximum reduction of ~15.5% in the evaporation rate at 200 °C with 5% Al NPs and maximum increase of ~50% in the evaporation rate at 600 °C with 2.5% Al NPs suspension was observed.

1. Introduction

The design of high-energy-density fuels is an area of significant interest for high speed propulsion systems. There is a tremendous need to augment the energy content of conventional and future synthetic fuels. One possible approach to accomplish this is the addition of highly exothermic and energetic NPs to liquid fuels. Energetic NPs are usually metallic with a passivated oxide layer, offering high reactivity, fast ignition, and high rate of energy release [1]. The metallic NPs have potential to enhance the volumetric energy density of the liquid fuels, which is an utmost requirement of high-speed propulsion systems.

Nanofluids are stable suspensions of solid NPs (10–100 nm) in a base fluid. They used to show different thermo-physical properties from their base fluids such as thermal conductivity [2], mass diffusivity [3], surface tension [4], radiative property [5] and non-Newtonian viscosity [6]. The alternative fuel blends containing energetic NPs are a new class of nanofluids and such nanofluid fuels have been rarely studied.

Tyagi et al. [7] conducted hot-plate experiments and observed that with addition of small amounts of Al and Al_2O_3 NPs, the ignition probability for nanoparticle-laden diesel fuel was significantly higher than that of pure diesel fuel. Jackson et al. [8] measured ignition delay time in a shock tube and observed that an addition of Al NPs could substantially decrease the ignition delay time of n-dodecane above 1175 K. Using an aerosol shock tube, Allen et al. [9] found that an addition of 2% (by weight) Al NPs in ethanol and JP-8 can reduce their ignition delays by 32% and 50%, respectively. Gan and Qiao [10] studied the effect of nano and micron-sized Al particles on burning characteristics of n-decane and ethanol fuel droplets. Their results show that for the same particles and surfactant concentrations, the disruption and microexplosion behavior of the micron suspension occurred later with much stronger intensity. Gan et al. [11] recently compared the burning behavior of dilute and dense suspensions of boron and iron NPs in ethanol and n-decane. A simultaneous burning of both the droplet and the particles was observed for dilute suspensions and in dense suspensions; it was found that most particles were burned as large agglomerate after the consumption of liquid fuel.

A basic mechanism in spray combustion is vaporization of a liquid fuel droplet at high temperature environments, which must be taken into account in design and optimization of various practical

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combustion systems such as liquid propellant rocket engines, diesel engines, gas turbines and oil fired furnaces. The liquid fuels are injected into combustor as spray of droplets; the vaporization and oxidation characteristics of these droplets demonstrate the combustion performance. In fact, droplet evaporation is an important process in the combustion of liquid fuels and knowledge of the laws governing the rate of droplet vaporization, induction times and combustion is an utmost importance for the design of efficient combustion systems. Droplet vaporization is also important in highly complex phenomenon of combustion of nanofluid fuels which is a multiphase, multicomponent and multiscale process [11]. However studies on droplet evaporation behavior of nanofluid fuels are rare.

Chon et al. [12] studied the effect of NPs size on evaporation and dry-out characteristics of a strongly pinned water droplet on a heated substrate and identified three periods: liquid dominant evaporation, dryout progress, and NPs strain. The pattern of formation of NPs strain strongly depends upon the NPs size. Sefiane and Bennacer [13] investigated the influence of Al NPs on evaporation kinetics and wetting dynamics of ethanol sessile droplets on rough heated substrates. A reduction of evaporation rate compared to the base fuel was found during the pinning phase. Chen et al. [14] studied the effect of three different types of NPs (laponite, Fe_2O_3 and Ag) on the evaporation rate of deionized water under natural convection at room temperature. The results show that these nanofluid droplets evaporate at different rates from the base fluid. The evaporation rate of various Ag and Fe_2O_3 nanofluids goes through a transition from one constant value to another during the evaporation process. The authors explained the effect of various NPs on evaporation from the perspective of apparent heat of evaporation. Gan and Qiao [15] recently studied the effect of Al NPs on evaporation characteristics of ethanol and n-decane fuel droplets under natural and weak forced convections at temperatures up to 380 K. They observed a deviation from classical d^2-law under these convections at 300 K and 320 K. This is the only study reported in literature so far regarding the vaporization of nanofluid fuels, in-spite of their practical importance. To the best of our knowledge, no report has been available about the evaporation behavior of nanofluid fuels under the elevated temperatures which is the real environment in the practical combustors. Therefore, an experimental investigation about the evaporation characteristics of nanofluid fuel droplets at elevated temperatures was highly desirable from practical point of view.

The main purpose of this work is to experimentally determine the evaporation behavior of a hydrocarbon-based nanofluid fuel with varying concentrations of Al NPs at elevated temperatures. The n-heptane is selected as a suitable fuel due to its high purity, high volatility and abundant availability of experimental data regarding its evaporation rate at widest ranges of temperature and pressure. Experiments were performed with an isolated suspended droplet at a fine silicon carbide fiber. The initial diameter of the droplets was 1.0 ± 0.11 mm. The ambient temperature varied from 100 to 600 °C, higher than the boiling point of heptane and below the melting point of Al NPs and ambient pressure was kept constant at 0.1 MPa. High temperature environment has been provided by a falling electric furnace. The evaporation process was recorded by a high-speed charge-coupled device (CCD) camera. Droplet evaporation histories were obtained from the measured temporal variations of droplet diameter to calculate evaporation rates. A brief description of materials and characterization methods is presented in the next section, after which the nanofluid fuel preparation and experimental apparatus are discussed. Data reduction/analysis methods and a discussion about sources of error are presented in the following sub-section. In the section of results and discussions, the general evaporation behavior of pure fuel droplets, the effects of surfactant at elevated temperature on evaporation process, and a comprehensive discussion about the effects of NPs addition on evaporation at high temperature environments are presented.

2. Experimental methods

2.1. Materials

Al NPs (99.9%, metal basis, 70 nm) were purchased from US Research Nanomaterials (Houston, Texas). Heptane (99% pure) was obtained from Junsei Chemical Co., (Japan) and Sorbitan Trioleate ($C_{60}H_{108}O_8$, better known as Span 85) was purchased from Sigma–Aldrich. Silicon carbide (SiC) fiber (100 μm diameter) was obtained from Goodfellow (England). These materials were used in their as-received form without further treatment.

2.2. Characterization methods

The morphology of Al NPs was studied using high resolution transmission electron microscope (HRTEM, F30, FEI Company Eindhoven, Netherlands). The residues were examined by a field emission scanning electron microscope (FESEM, Nova 230, FEI Company Eindhoven, Netherlands). Quantitative analysis was carried out with energy-dispersive X-ray spectroscopy (EDX) attached with the FESEM. Ultrasonic disrupter (Fisher Scientific sonic dismembrator, model 505, Pittsburg, PA) was used to disperse Al NPs in the base fuel homogeneously.

Figure 1a is a TEM image of Al NPs which clearly shows that NPs are spherical in shape with smooth surface. Most of the NPs are well separated from each other. This TEM image has been analyzed using ImageJ software and the obtained plot is also shown in Fig. 1a. The plot shows that NPs vary in diameter from 30 to 250 nm with average diameter of most probable particles of 70 nm. High resolution TEM image of a single NP is shown in Fig. 1b. An oxide layer of thicknesses 2–3 nm can be clearly seen in the image. The active Al contents in the 70 nm sample were estimated to be 65–76%.

2.3. Nanofluid fuel preparation

A liquid hydrocarbon fuel, n-heptane, was considered as the base fuel with normal boiling temperature of 98 °C, critical temperature of 276 °C and critical pressure 2.74 MPa. Al NPs were used as energetic material additives. Agglomeration and clusters formation of NPs, due to their high surface energy, in a base fuel is the major drawback which limits the application of nanofluids. However, homogenous dispersion of NPs in the base fuel can be obtained by using ultrasonic dispersion and addition of some appropriate surfactants [16].

An ultrasonic disrupter generates alternating high and low pressure cycles, applies mechanical stress to the attracting forces between the individual NPs and thus breaks down the agglomerates and suppresses forming clusters of NPs. Addition of surfactant can improve the stability of NPs in suspensions by changing the hydrophobic surfaces of NPs to hydrophilic and vice versa which helps to overcome the van der Waals force of attraction between the NPs and thus reduces the agglomeration [17]. In addition the surfactants can also significantly affect the evaporation behavior of the fuel suspension, which will be discussed later.

Al NPs were stirred and mixed with base fuels by hand and an ultrasonic disruptor was used to disperse NPs homogeneously. The ultrasonication was performed in an ice bath to quickly dissipate heat from the system to avoid agglomeration of NPs. The ultrasonic disruptor was turned on for 5 min which generates 4 s-long pulses 4 s apart and ultrasonic vibrations was set at 40%