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Evaporation characteristics of kerosene droplets with dilute concentrations of ligand-protected aluminum nanoparticles at elevated temperatures

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ABSTRACT

The evaporation characteristics of kerosene droplets containing dilute concentrations (0.1%, 0.5%, and 1.0% by weight) of ligand-protected aluminum (Al) nanoparticles (NPs) suspended on silicon carbide fiber were studied experimentally at different ambient temperatures (400–800 °C) under normal gravity. The evaporation behavior of pure and stabilized kerosene droplets was also examined for comparison. The results show that at relatively low temperatures (400–600 °C), the evaporation behavior of suspended kerosene droplets containing dilute concentrations of Al NPs was similar to that of pure kerosene droplets and exhibited two-stage evaporation following the classical d^2-law. However, at relatively high temperatures (700–800 °C), bubble formation and micro-explosions were observed, which were not detected in pure or stabilized kerosene droplets. For all Al NP suspensions, regardless of the concentration, the evaporation rate remained higher than that of pure and stabilized kerosene droplets in the range 400–800 °C. At relatively low temperatures, the evaporation rate increased slightly. However, at relatively high temperatures (700–800 °C), the melting of Al NPs led to substantial enhancement of evaporation. The maximum increase in the evaporation rate (56.7%) was observed for the 0.5% Al NP suspension at 800 °C.

1. Introduction

Nanofluid fuels, a new class of nanofluids containing highly exothermic energetic-material (i.e., Al, B, Fe, and C) nanoparticles (NPs), have received considerable attention in recent years [1–6]. These consist of stable suspensions of energetic NPs (10–100 nm) in traditional liquid fuels. Energetic NPs are usually metallic and have advantages such as higher reactivity, faster burning rates, and lower ignition temperatures compared to micron-sized particles in solid propellants and fuels [1]. Metallic NPs have the potential to enhance the volumetric energy density of liquid fuels. However, despite this fascinating benefit, nanofluid fuels have rarely been studied. Problems such as the low dispersity of metal NPs in liquid hydrocarbons or nonpolar organic solvents and the potential emissions of metal and metal oxide particles have limited the production and application of nanofluid fuels.

In hot-plate experiments, Tyagi et al. [7] observed that with the addition of small amounts of Al and Al_2O_3 NPs, the ignition probability of nanoparticle-laden diesel fuel was significantly higher than that of pure diesel fuel. Jackson et al. [8] found that the addition of Al NPs could substantially decrease the ignition delay time of n-dodecane in a shock tube above 1175 K. Using an aerosol shock tube, Allen et al. [9] observed that the addition of 2% (by weight) of Al NPs to ethanol and JP-8 reduced their ignition delays by 32% and 50%, respectively. Van Devener and Anderson [10] first performed tests of JP-10 catalytic combustion using soluble CeO_2 NPs as the catalyst. Their results indicate that the ignition temperature of JP-10 was significantly reduced. The group later established a unique process that produced oxide-free, fuel-soluble, and air-stable boron NPs that were coated with the combustion catalyst ceria [11,12]. Gan and Qiao [13] studied the effects of nano- and micro-sized Al particles on the burning characteristics of n-decane and ethanol fuel droplets. Their results show that for the same particles and surfactant concentrations, the disruption and micro-explosion behavior of the micro-sized suspensions occurred later with much greater intensity. Gan et al. [14] compared the burning behavior of dilute and dense suspensions of boron and iron NPs in ethanol and n-decane. Simultaneous burning of both the droplets and the particles was observed for dilute suspensions, whereas in dense suspensions most particles were burned as large agglomerates after consumption of the liquid fuel.

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Evaporation of liquid fuel droplets is an important process during combustion. Liquid fuels are injected into a combustor as sprayed droplets, and the vaporization and oxidation characteristics of these droplets are related to combustion performance. The design and optimization of various practical combustion systems, such as liquid propellant rocket engines, diesel engines, gas turbines, and oil-fired furnaces, require accurate knowledge of the vaporization of these liquid fuel droplets. The evaporation behavior of nanofluid fuel droplets is more complex than that of pure liquid fuel droplets due to their multi-component, multi-scale, and multiphase nature, which is more difficult to predict. Experimental studies, which are very rare, are required to provide the evaporation characteristics of nanofluid fuel droplets.

Chen et al. [15] studied the effect of laponite, Fe_2O_3, and Ag NPs on the evaporation rate of deionized water under natural convection at room temperature. These nanofluid droplets evaporate at different rates from the base fluid. The evaporation rates of various Ag and Fe_2O_3 nanofluids transition from one constant value to another during the evaporation process. The authors explained the effects of various NPs on evaporation based on the apparent heat of evaporation. Gan and Qiao [16] investigated the effect of Al NPs on the evaporation of ethanol and n-decane fuel droplets under natural and weak forced convection at temperatures up to 380 K. A deviation from the classical d^2-law was observed under these conditions at 300 and 320 K. Gan and Qiao [17] demonstrated that the evaporation rates of ethanol-based nanofluids containing multi-walled carbon nanotubes (MWCNTs) or carbon nanoparticles (CNPs) are both higher than the evaporation rate of pure ethanol. They have also shown that radiation absorption can be significantly enhanced by adding a small amount of Al NPs to ethanol, which increases the nanofluid droplet temperature and enhances the droplet evaporation rate [18]. More recently, we have shown [19] that the addition of Al NPs to heptane increases its evaporation rate at relatively high temperatures (above 400 °C). At relatively low temperatures (below 400 °C), the formation of large agglomerates results in a compact shell that suppresses the evaporation of heptane.

In our previous work [19], we used a single-component liquid hydrocarbon (heptane) as a base fuel. In the present study, we used kerosene, which is a multi-component liquid hydrocarbon. Kerosene was selected because most aviation fuels (e.g., JP-5, JP-7, JP-8, or Jet A/A-1) and liquid hydrocarbon propellants (e.g., RP-1) can be described generically as kerosene [20]. The evaporation and combustion behavior of NP-laden kerosene droplets will provide us with an improved understanding of the effects of adding NPs to such multi-component hydrocarbon fuels. Surface-modified Al NPs were added to the kerosene to suppress the formation of large agglomerates (residues). Oleic acid (OA) was selected for surface coating of the Al NPs, instead of the previously used Span 85 surfactant, because of its lower molecular weight and its boiling point (360 °C), which is closer to the boiling point of the base fuel (180–270 °C). Due to this surface modification technique, unoxidized, ligand-coated, and fuel-soluble NPs were obtained that were more stable in suspension and had high active metal contents [12]. We then experimentally investigated the evaporation characteristics of multi-component hydrocarbon-based nanofluid fuel droplets with the addition of dilute concentrations of ligand-protected Al NPs at elevated temperatures.

2. Experimental methods

2.1. Materials and characterization instruments

Al NPs (99.9%, metal basis, 70 nm) were purchased from US Research Nanomaterials (Houston, Texas). Kerosene (extra pure, boiling range 180–270 °C, specific gravity 0.8 at 15 °C) was obtained from Junsei Chemical Co. (Japan), and OA ($C_{18}H_{34}O_2$, technical grade, 90%) was purchased from Sigma–Aldrich. Silicon carbide (SiC) fiber (100 μm diameter) was obtained from Goodfellow (England). All these materials, except the Al NPs, were used in their as-received form without further treatment.

A planetary ball mill (Retsch PM100, GmbH, Germany) was used to modify the surfaces of the Al NPs. The morphology of the Al NPs, as received and after coating with OA, was studied using field-emission scanning electron microscopy (FESEM, Magellan 400, FEI Company Eindhoven, Netherlands). The residues were also examined by the same instrument. Quantitative analysis was carried out with energy-dispersive X-ray spectroscopy (EDX) in combination with the FESEM.

2.2. Nanofluid fuel preparation

The stable nanofluid fuels were prepared using a two-step method, which is the most economic method to produce various types of nanofluids with various concentrations of NPs, either in the laboratory or at a large scale, because the metal NP synthesis techniques have already been scaled up to industrial production levels [21]. A post-synthesis surface modification concept was applied to the purchased Al NPs to improve their dispersion stability in liquid hydrocarbons. Using a ball mill, the surfaces of the NPs were coated by OA to prepare oxide-free and fuel-soluble Al NPs. The procedure adopted here has been described elsewhere [12], except for the following amendments.

A planetary ball mill (PM100) was used with a 12-mL stainless steel (SS) milling jar and 3-mm-diameter SS grinding balls. The Al NPs were added to the milling jar along with OA, which was used to coat the surfaces of the Al NPs. The amount of OA was optimized to 1:2 (ratio of OA to Al mass) by conducting a series of experiments with different ratios (1:2, 1:1, and 2:1) and studying the stability of the suspensions in kerosene. The time of ball milling was also optimized to 1 h. The charge ratio (ratio of the ball to the sample mass) was kept low (~2:1) to minimize excessive grinding of the Al NPs. The resulting NP/OA paste was dispersed in kerosene through vigorous agitation by hand. A homogeneous suspension was obtained in this way, which remained stable for 10 h with no obvious sedimentation of the NPs.

Figure 1a shows an SEM image of the Al NPs as received from the supplier, which clearly indicates that the NPs were spherical in shape with smooth surfaces. Most of the NPs were well separated from each other. An SEM micrograph of the Al NPs coated with OA is shown in Fig. 1b. This figure indicates that the Al NPs maintained their shapes and sizes during the coating process.

2.3. Experimental procedure

An experimental apparatus was previously fabricated and installed to study the evaporation, autoignition, and combustion behavior of a single suspended liquid-fuel droplet at elevated pressures and temperatures, as described in [22–25]. The same exprimental setup has also been used to study the evaporation of heptane-based nanofluid fuel droplets [19]. The experimental procedure, and the data reduction and analysis, were also described in detail in that study. The experiments were performed with an isolated nanofluid fuel droplet suspended by a fine SiC fiber (100 μm diameter). The heat loss from the fiber can be neglected during most of a droplet's lifetime for fiber diameters of less than 100 μm [26]. The initial average diameter of a droplet was 1.0 ± 0.10 mm. The ambient temperature was varied from 400 to 800 °C, which is higher than the boiling point of kerosene and the melting point of the Al NPs, and the ambient pressure was kept constant at 0.1 MPa. High-temperature ambience was provided by