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

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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\cite{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\cite{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.\cite{7} observed that with the addition of small amounts of Al and Al\textsubscript{2}O\textsubscript{3} NPs, the ignition probability of nanoparticle-laden diesel fuel was significantly higher than that of pure diesel fuel. Jackson et al.\cite{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.\cite{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 Deven and Anderson\cite{10} first performed tests of JP-10 catalytic combustion using soluble CeO\textsubscript{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\cite{11,12}. Gan and Qiao\cite{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.\cite{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.
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 multi-phase 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, Fe₂O₃, 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 Fe₂O₃ 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 up to 380 K. A deviation from the classical d²-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 (C₁₇H₃₄O₂, 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 (Rettsch 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 experimental 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 ambiance was provided by...
a freely falling electric furnace. The evaporation process was recorded by a high-speed charge-coupled device (CCD) camera. A flexible image-processing code was developed using Matlab to obtain the droplets’ diameters from the captured images. This code was executed iteratively for each image, resulting in the temporal variation of droplet diameter during evaporation. The evaporation rate can be expressed as the time derivative of the droplet diameter squared,

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C_v = \frac{-d(d^2)}{dt}
\]

multi-component nature of kerosene, its evaporation follows the \(d^2\)-law in the range 400–800 °C. Kerosene is a blend of relatively nonvolatile petroleum fractions. It typically consists of 60% paraffins, 32% napthenes, and 7.7% aromatics by volume [24]. As mentioned in the materials section, the kerosene used in the present study had a boiling point range of 180–270 °C. Each component vaporizes at a different rate, depending on its volatility. Therefore, a concentration gradient exists around and within a droplet. High-temperature gradients between the environment and the droplet result in faster heat diffusion compared to mass diffusion. Thus, the temperature inside a droplet remains fairly uniform during the evaporation process so that the mass diffusion due to the concentration gradient controls the evaporation rate. This explains why the evaporation process for a multi-component droplet like kerosene follows the \(d^2\)-law for elevated temperatures from 400 to 800 °C, as shown in Fig. 2, and as discussed in our previous work [23]. An increase in the ambient temperature decreases the total lifetime of the kerosene droplets.

### 3. Results and discussion

#### 3.1. Pure kerosene droplet evaporation

The evaporation rate of pure kerosene droplets was evaluated first as a baseline to compare the evaporation rates of stabilized and kerosene-based nanofluid fuel droplets. Fig. 2 shows the variation in the normalized diameter squared \((d^2/d_0^2)\) with the normalized time \((t/d_0^2)\), where \(d_0\) is the initial droplet diameter, for different ambient temperatures and at a constant pressure of 0.1 MPa for pure kerosene droplets. This normalization parameter was suggested by classical droplet evaporation theory [27]. The evaporation of each sample followed the same general behavior. After a finite heating-up period, the variation in the droplet diameter squared became approximately linear with time, while following the \(d^2\)-law during the last stages of evaporation. Despite the

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**Fig. 1.** SEM micrographs of (a) Al NPs as received from supplier and (b) Al NPs whose surfaces are coated with oleic acid in a ratio of 1:2 (ratio of OA to Al mass) and sample taken after 1 h ball milling.

**Fig. 2.** Variations of normalized diameter squared with the normalized time for different ambient temperatures and at a constant pressure of 0.1 MPa for pure kerosene droplets.

**Fig. 3.** Comparison of the evaporation rates of kerosene droplets between present study and previous study by Ghassemi et al. [23] at different ambient temperatures and constant pressure of 0.1 MPa.
The kerosene droplet evaporation rates obtained from the linear part of the evaporation data in Fig. 2 are plotted in Fig. 3. This figure clearly shows that the evaporation rate increased with the ambient temperature. A simple comparison of kerosene evaporation rates between the previous results of our group [23] and our current study at 0.1 MPa was plotted (Fig. 3) to illustrate the consistency of the experimental apparatus. The evaporation rates of the kerosene droplets obtained in the present study were lower than the values previously obtained because of the different fiber diameters that we used for the droplet suspensions. Ghassemi et al. [23] suspended droplets with an initial diameter of 1.0–1.2 mm on quartz fibers with diameters of 0.125 and 0.2 mm that were rounded at the tips with bead diameters of 0.25 and 0.35 mm, respectively. However, in our current research, each droplet was suspended on a 0.1-mm SiC fiber with no bead at its tip, and droplets having similar initial diameters ranging from 0.954 to 1.0642 mm were selected from the experimental data to minimize the effect of the initial droplet size on the evaporation rate.

3.2. Evaporation of kerosene droplets with the addition of oleic acid

To understand the evaporation behavior of kerosene-based nanofluid fuel droplets at elevated temperatures, it is essential to measure their evaporation rates with the addition of various concentrations of OA while holding the temperature constant. The evaporation rates of the stabilized kerosene droplets provide another baseline to distinguish the effect of the addition of NPs on droplet evaporation behavior.

Figure 4 shows the normalized temporal histories of the diameter squared of kerosene droplets with 0.25% and 0.5% surfactant (OA) at various ambient temperatures (400–800 °C). Here and below, mass percent values are used. To minimize the effect of the initial droplet size on the evaporation rate, droplets having similar initial diameters ranging from 0.9781 to 1.0796 mm were selected from the experimental data. The general evaporation behavior of stabilized kerosene droplets was similar to that of pure kerosene droplets, i.e., after a finite heating-up period, the droplet diameter squared decreased linearly and followed the $d^2$-law. Fig. 4a shows the lifetime history of stabilized kerosene droplets evaporated at 400 and 500 °C. With the addition of OA to the kerosene, the droplet heating-up period, as well as the linear evaporation period, increased at 400 °C. Kerosene has a boiling range of 180–270 °C, whereas OA has a boiling point of 360 °C. Due to the addition of OA to the kerosene, a monolayer of OA is produced at the surface of the droplet, which inhibits the outward diffusion of the kerosene, resulting in an increase in the evaporation period and a reduction in the evaporation rate [29]. This suppression is prominent at temperatures close to the boiling point of OA. Fig. 4b shows the lifetime history of stabilized kerosene droplets evaporated at 600, 700, and 800 °C. At 800 °C with 0.5% OA, there were sudden increases and decreases in droplet diameter ($d^2\frac{dt}{d\theta}$) during the heating-up period, indicating droplet distortion due to the entrapment of high-volatility components. These distortions in droplets’ diameters increase the heating-up period and consequently enhance the evaporation rate slightly at 800 °C.

Figure 5 compares the evaporation rates of stabilized kerosene droplets containing 0.25% and 0.5% OA with pure kerosene droplets at various ambient temperatures (400–800 °C). The evaporation rate of stabilized kerosene droplets was equal to the evaporation rate of pure kerosene droplets at all temperatures. Because only low concentrations of OA (surfactant) were in the kerosene, the evaporation rate of stabilized kerosene droplets was unaffected and remained the same as that of pure kerosene droplets at these temperatures.

3.3. Evaporation of kerosene-based nanofluid fuel droplets

Figure 6 shows normalized temporal histories of kerosene droplets containing various concentrations of OA at different ambient temperatures. There are slight differences in the evaporation rates of pure kerosene and kerosene-based nanofluid droplets that were the droplets having Al NPs required less time for evaporation. The early dry-out clearly indicates the higher evaporation rates of droplets containing Al NPs, regardless
of concentration. At 500 and 600 °C, the evaporation behavior of the 1.0% Al NP suspension droplets was slightly different. Compared to the 0.5% suspension, the droplets containing 1.0% Al NPs evaporated faster initially and then slightly slower during the later stages of evaporation; due to this slight reduction, the evaporation period was longer than that of the 0.5% suspension droplets. This was likely caused by the formation of NP agglomerates in the 1.0% Al NP suspension droplets, resulting in less evaporation rate enhancement compared to the 0.5% Al NP suspension droplets at these temperatures.

Figure 6b shows that at relatively high temperatures (700–800 °C), the general evaporation behavior of nanofluid fuel droplets was different from that of pure kerosene droplets, irrespective of the Al NP concentration. The heating-up period of the Al NP suspension droplets was shorter, and evaporation started earlier, compared to pure kerosene droplets. This was followed by a high-evaporation-rate period, which was reduced slightly in the later stages when the Al NPs were concentrated. Overall, the lifetime of the Al NP suspension droplets was shorter than that of pure kerosene droplets, which indicates a significant increase in the evaporation rate when Al NPs were added to kerosene. The other distinguishing feature of the addition of Al NPs to kerosene droplets was the onset of bubble formation and micro-explosions. Regardless of the Al NP concentration, bubble formation and micro-explosions were observed at these temperatures. Micro-explosions were identified in the later stages of the evaporation period at 700 °C (see Supplementary video) and were also observed in the earlier stages at 800 °C. It is important to note that for micro-explosions to be most effective, they must occur early in the lifetime of a droplet [30]. The least-squares method was applied to the linear part of the experimental data to obtain the evaporation rate of the kerosene-based nanofluid droplets.

As the nanofluid fuel droplets were exposed to relatively high temperatures (700–800 °C), the Al NPs present at the droplets’ surface were heated above the boiling point of the liquid fuel. These Al NPs provided multiple nucleation sites for the surrounding liquid, and evaporation started early in the heating-up period. The Al NPs present just inside the droplets’ surface may also have attained a temperature higher than the local boiling point of the high-volatility component, creating multiple heterogeneous nucleation sites that generated superheated vapors. These superheated vapors may have been the cause of droplets’ fragmentation in the early stages of nanofluid droplets’ evaporation. In contrast, the micro-explosions observed during the later stages of evaporation were due to the agglomeration of NPs at the surface of the droplets. As the liquid evaporated, the NPs were concentrated at the droplets’ surface and may have caused an increase in the droplets’ surface temperature. Thus, the low-volatility-component liquid present inside the droplets was heated beyond the local boiling point, accumulating as a superheated vapor that ruptured the droplets in the later stages of evaporation.

Figure 7 presents sequential photographs of evaporating kerosene droplets containing 0.5% and 1.0% Al NPs at 800 °C. Droplet distortion and fragmentation were clearly observed. For the nanofluid fuel droplet containing 0.5% Al NPs (Fig. 7a), droplet fragmentation occurred at 0.500 s, followed by droplet distortion, as shown in subsequent frames at 0.505, 0.510, and 0.515 s. The liquid evaporated up to 1.220 s, until an internal bubble started
to form at 1.225 s, followed by bubble rupture at 1.230 s. Fig. 7b shows that for the 1.0% Al NP suspension, droplet fragmentation first occurred at 0.670 s, along with droplet distortion before and after fragmentation, as shown in the images for 0.665, 0.680, 0.685, 0.690, 0.695, and 0.700 s. The droplet distortion indicated the presence of high-volatility-component vapors inside the droplet. Then, the liquid evaporated up to 1.165 s until the start of bubble formation. Eventually, bubble formation was completed at 1.255 s, and it ruptured at 1.260 s.

Droplet fragmentation was delayed with increasing Al NP concentration in the early stages of evaporation, whereas in the later stages the rupture of droplets occurred earlier and with greater intensity. This was because the increase in Al NP concentration caused the temperature inside droplets to rise slowly at the start of evaporation, but in the later stages of evaporation the more concentrated Al NPs caused droplet rupture to occur earlier and with greater intensity.

### 3.3.1. Effect of temperature on the evaporation rate of kerosene-based nanofluid fuel droplets

Figure 8 compares the evaporation rates of kerosene-based nanofluid fuel droplets containing dilute concentrations (0.1%,...
0.5%, and 1.0% of Al NPs with those of pure and stabilized kerosene droplets under different ambient temperatures. The trend in the evaporation rate curves of the kerosene-based nanofluid fuel droplets is similar to those for pure kerosene, i.e., the evaporation rate increased monotonically as temperature increased from 400 to 800 °C. However, the increasing trend in the evaporation rate of pure kerosene was represented by a power-law fit, whereas the evaporation rate of kerosene-based nanofluid fuels increased exponentially with temperature. This figure also clearly shows that the addition of dilute concentrations of Al NPs to kerosene enhanced the evaporation rate at all temperatures in the range 400–800 °C. At relatively low temperatures (400–600 °C), the evaporation rate of the nanofluid fuel droplets was slightly higher than that of pure kerosene droplets, whereas at relatively high temperatures (700–800 °C), the evaporation rate of the nanofluid fuel droplets was considerably higher than that of the stabilized or pure kerosene droplets.

It is possible that at relatively low temperatures (400–600 °C), the Al NPs enhanced only the heat transfer inside the droplets by increasing the liquid effective thermal diffusivity and at the droplets’ surface by raising their surface temperature. At relatively high temperatures (700–800 °C), the Al NPs present at or near the surface may have attained temperatures higher than the local liquid boiling point and may have provided multiple heterogeneous nucleation sites for the surrounding liquid, enhancing the evaporation rate substantially. It is also possible that the Al NP surfaces were modified, producing oxide-free, ligand-protected NPs [12]. This would have allowed the melting of oxide-free Al NPs present at the surface of the droplets when exposed to temperatures higher than the Al NP melting point (660 °C). The fractional melting of Al NPs may have extensively enhanced the evaporation rate of the nanofluid fuel droplets by providing their heat of fusion to the surrounding liquid.

The residues obtained at the end of evaporation were collected to confirm the physical state of the Al NPs present at the surface of the droplets and the shell formation of the nanofluid fuel droplets. Residues of the 0.5% Al NP suspension droplets were obtained at two different temperatures (600 and 800 °C) and studied using FESEM and EDX. The selected temperature values were below and above the melting temperature of the Al NPs (660 °C). The residues were collected very carefully. Initially, a nanofluid fuel droplet was exposed to these temperatures, and as the droplet started to evaporate, the furnace was lifted upward immediately to avoid exposing the residue to the high-temperature ambience. After that, nitrogen was purged to cool the residue to room temperature so that it could be removed.

Figures 9 and 10 show FESEM images of the residues obtained after evaporation at 600 and 800 °C for a suspension of 0.5% Al NPs. The residue obtained at 600 °C was soft and crumbly and broke during preparation of the SEM samples, as shown in Fig. 9a. A magnified view of the residue (Fig. 9b) indicates that most of the Al NPs maintained their original spherical shapes and did not melt. The NPs were also loosely packed, and many pores were present. When a 0.5% Al NP suspension droplet was exposed to 800 °C, the residue was sticky, and most of it remained on the SiC fiber, as shown in Fig. 10a. The residue also contained large particles at its surface. A magnified view of this residue (Fig. 10b) indicates that some of the NPs lost their spherical shape, fused together, and were converted into larger particles and lumps. This indicates that the NPs present at the surface of the droplet melted.

The composition of the residues obtained after evaporation at 600 and 800 °C was analyzed by EDX. The results indicate that the evaporative residues were composed mostly of Al and O, with small amounts of C. The O content was due to the oxidation of the Al NPs present at the surface of the residues after vaporization and during preparation of the samples for FESEM. The O contents were 5.3% and 14.6% (by weight) in the residues of the 0.5% NP

Fig. 8. A comparison of the evaporation rates of kerosene-based nanofluid fuel droplets containing dilute concentrations of Al NPs with pure and stabilized kerosene droplets at different ambient temperatures; (a) 0.1% Al NPs, (b) 0.5% Al NPs, (c) 1.0% Al NPs.
suspension evaporated at 600 and 800 °C, respectively, as shown in Fig. 11. This indicates high oxidation of Al NPs to Al2O3. Both of the residues were cooled down to room temperature in the presence of nitrogen before being taken out into air; therefore, the high oxygen content was due to the presence of elemental Al at their surfaces, which was oxidized. The EDX results imply that the residue obtained at 800 °C contained high amounts of elemental Al at its surface, which was thought to be the melted Al NPs.

These results indicate that the evaporation enhancement was due only to the addition of Al NPs to the kerosene. The surface temperature of a pure kerosene droplet cannot exceed the boiling point of the liquid (270 °C), but the presence of Al NPs allows the temperature of the NPs present at the droplets' surface to reach the temperature of the environment, resulting in local hot spots in the liquid droplets. After heating beyond the liquid local boiling temperature, the Al NPs can provide multiple nucleation sites, evaporate the surrounding liquid, and result in increased evaporation rates. The observed micro-explosions were also due to the presence of these heterogeneous nucleation sites in the droplets. Ambient temperatures of 700 and 800 °C greater than the melting point of the Al NPs resulted in fractional melting of the NPs accumulated at the droplets’ surface, which supplied additional heat to the liquid droplets by providing their heat of fusion, resulting in extensive enhancement of the evaporation rate. Further studies focusing on nanofluid fuel evaporation at high temperatures with dense concentrations of Al NPs will provide valuable insight into the occurrence of micro-explosions due to the NPs and their effects on the evaporation rate.

3.3.2. Effect of Al NP concentration on the evaporation rate

Figure 12 indicates that the evaporation rate of the kerosene-based nanofluid droplets was also affected by the concentration of the NPs. As the NP concentration increased from 0.1% to 1.0%, the evaporation rates at relatively low ambient temperatures
(400–600 °C) increased initially and then decreased. The maximum increasing effect was obtained with 0.5% Al NPs at low ambient temperatures. The evaporation enhancement for the 1.0% NP suspension at these temperatures was lower than that observed with the 0.5% NP suspension due to the high agglomeration of NPs.

At relatively high ambient temperatures (700 and 800 °C), the evaporation rate also increased with the NP concentration up to 0.5% and then decreased, becoming lower than the evaporation rates observed with the 0.1% NP suspension but higher than the evaporation rate of pure kerosene. The maximum increasing effect was also obtained with the 0.5% Al NP suspension at high ambient temperatures. When the concentration of ligand-protected NPs increased beyond a critical value (0.5% in this case), more heat was transferred to the Al NPs rather than to liquid, thereby reducing the evaporation enhancement. The maximum increase in the evaporation rate of kerosene-based nanofluid droplets with 0.5% Al NPs was 56.7% compared to the pure kerosene droplets’ evaporation rate at 800 °C (corresponding to an increment from 0.782 to 1.226 mm²/s).

4. Conclusions

The evaporation characteristics of kerosene-based nanofluid droplets with dilute concentrations of Al NPs (0.1%, 0.5%, and 1.0%) were studied at different elevated temperatures (400–800 °C) under normal gravity. Similar to heptane-based nanofluid fuel droplet[19], the kerosene-based nanofluid fuel droplets containing dilute concentrations of Al NPs were vaporized in the same way as the pure fuel droplets and followed $d^2$-law at temperatures from 400 to 600 °C. The new findings of this experimental study are summarized as follows.

1. Micro-explosions were observed at relatively high temperatures (700–800 °C) in the kerosene-based nanofluid fuel droplets. The absence of micro-explosions in pure and stabilized kerosene droplets indicates that this phenomenon was based solely on the presence of Al NPs. The added Al NPs provided multiple heterogeneous nucleation sites to promote micro-explosions.

2. The ambient temperature significantly affected the evaporation rates of the kerosene-based nanofluid fuel droplets. The Al NPs enhanced the evaporation rate of kerosene droplets at all tested temperatures (400–800 °C). At relatively low temperatures (400–600 °C), the Al NPs in the droplets increased the evaporation rate slightly. However, at relatively high temperatures (700–800 °C), the evaporation rate was enhanced substantially due to melting of the NPs present at the droplets’ surface.

3. The evaporation rate of nanofluid fuel droplets was also affected by the concentration of the NPs. The evaporation-rate enhancement increased with the NP concentration up to 0.5%, after which it decreased and became lower than that of the 0.1% NP suspension. The maximum increasing effect was obtained at 800 °C with the 0.5% NP suspension, where the evaporation rate was increased by 56.7%.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.combustflame.2013.07.007.

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