



# Autoignition and combustion characteristics of kerosene droplets with dilute concentrations of aluminum nanoparticles at elevated temperatures



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## ABSTRACT

In this experimental study, we investigated the effects of high ambient temperatures and dilute concentrations of nanoparticles (NPs) on the autoignition and combustion characteristics of kerosene-based nanofluid droplets. An isolated kerosene droplet containing 0.1%, 0.5% or 1.0% by weight of aluminum (Al) NPs suspended on a silicon carbide (SiC) fiber was suddenly exposed to an elevated temperature (in range 400–800 °C) at atmospheric pressure (0.1 MPa) under normal gravity, and the autoignition and combustion characteristics were examined. The ignition delay time, burning rate constant and combustion characteristics of pure and stabilized kerosene droplets were also observed for comparison. The results indicate that, similar to pure kerosene droplets, the ignition delay time of NP-laden kerosene (*n*-Al/kerosene) droplets also followed the Arrhenius expression and decreased exponentially with increasing temperature. However, the addition of dilute concentrations of Al NPs to kerosene reduced the ignition delay and lowered the minimum ignition temperature to 600 °C, at which pure kerosene droplets of the same initial diameter were not ignited. In contrast to the combustion of pure and stabilized kerosene droplets, the combustion of *n*-Al/kerosene droplets exhibited disruptive behavior characterized by sudden reductions in the droplet diameter without any prior expansions caused by multiple-time bubble formation and their subsequent rupture at or near the droplet's surface. This bubble pop-up resulted in droplet trembling and fragmentation and ultimately led to enhancement in gasification, vapor accumulation and envelope flame disturbance. The NPs were also brought out of the droplets through these disruptions. Consequently, the burning time and total combustion time of the droplets were reduced, and almost no residue remained on the fiber following combustion. Thus, the combustion rate of *n*-Al/kerosene droplets was substantially enhanced compared with pure kerosene droplets at all tested temperatures.

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## 1. Introduction

The volumetric or gravimetric energy contents of metals are considerably higher than the energy densities of traditional liquid fuels. Therefore, in principle, higher combustion energies can be achieved from the combustion of metallized liquid fuels. Because of this fascinating benefit, in the past, many researchers have conducted detailed research on the combustion of such fuels, which are referred to as 'slurry fuels.' Slurry fuels consist of relatively high

solid loadings (40–80% by weight) of micron-sized metallic (Al, boron (B), carbon (C) and blend of Al and C) particles in a liquid hydrocarbon carrier. The major drawbacks that limit the practical application of such fuels are incomplete combustion, lower combustion efficiency, unacceptable deposits in the combustion chamber and increased particulate emission in exhaust. The particle agglomeration (which often occurs before and/or during the ignition phase) and longer burning time of the agglomerates are the primary causes of all these side effects [1].

Nanofluid fuels, a new class of nanofluids, are stable suspensions of energetic material NPs in traditional liquid fuels. Nano-powders of energetic materials (*i.e.*, Al, B, C, Fe, and CeO<sub>2</sub>) have been used as additives and suspended in conventional liquid fuels in a proper manner that enhances their ignition and

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combustion characteristics. Previous studies have demonstrated significant improvements using such nanofluid fuels including enhanced catalytic effects [2,3], increased ignition probability [4], improved burning rate [5], shortened ignition delay [6] and higher energy release [7]. However, the applications of nanofluid fuels may be limited by the same issues that have made slurry fuels impracticable, such as particle agglomeration and potential emissions of particles. Here, it is important to note that nanofluid fuels are fundamentally different than slurry fuels. Nanofluid fuels are suspensions with relatively low loading rates ( $\sim 10\%$  by weight) of NPs, such that the physical properties (such as density and boiling point) of base fuels may not significantly change, and nanofluid fuels can be used in existing propulsion and combustion systems with slight modifications. It is expected that due to the addition of nano-scale particles, the size of the agglomerates is reduced. The agglomerates may also be shattered by the microexplosions that occur due to the addition of NPs and that have been previously observed during the evaporation of kerosene-based nanofluid fuel droplets at elevated temperatures [8,9]. These microexplosions occur early in the droplet life time and become more intense with an increase in temperature. Based on the shattering of agglomerates due to such intense microexplosions, it can be anticipated that most of the NPs will be burned during droplet combustion, which reduces particulate emission.

Although our previous research articles [8–10] have been focused on the effects of NP concentrations on the evaporation characteristics of droplets, the present study investigated the effects of NP loading rates on droplet autoignition and overall combustion characteristics. Similar to vaporization [9], the combustion of nanofluid fuel droplet is also a highly complex phenomenon compared with pure liquid fuel droplet combustion because of its multi-component, multi-phase and multi-scale nature. Several physical and chemical processes occur during the combustion of a nanofluid fuel droplet. These processes include mass and energy transport to/between the phases (solid, liquid and gas), evaporation of the liquid fuel, generation of heterogeneous nucleation sites (HNSs) within a droplet, microexplosions (transport of NPs from liquid droplet to flame), combustion of the liquid fuel in vapor phase, vapor accumulation, dynamics of the NPs (*i.e.*, particle diffusions, collisions, aggregation, agglomeration and transported out of droplet), combustion of the solid particles, and their combinations. The interaction of these processes with each other makes achieving a fundamental understanding even more difficult. In addition, the thermophysical properties of nanofluid fuels are significantly different from those of their base fuels. Moreover, these properties can also vary with time because of the continuous change in the concentration of NPs within a droplet. Furthermore, the radiation properties (by absorption) of NPs could also aid in ignition and combustion. Therefore, experimental studies, which are very rare, are required to obtain a basic understanding of the autoignition and combustion behavior of nanofluid fuel droplets.

Sabourin et al. [11] achieved a significant enhancement in the burning rate of monopropellant nitromethane through the addition of 1% (by weight) functionalized graphene sheets into it, which also reduced its ignition temperature. Gan and Qiao [12] observed the burning behavior of ethanol and *n*-decane fuel droplets after loading nano- and micro-sized Al particles into them. Their results revealed that for the same surfactant and particle concentrations, the disruption behavior occurred later and with a much greater intensity in droplets containing micron-sized particles. Later, Gan et al. [13] found a simultaneous combustion of both the droplet and the NPs in dilute suspensions of boron and iron NPs in *n*-decane and ethanol. However, in dense suspensions, most particles were combusted as large agglomerates after the consumption of the liquid fuel. Most recently, we observed [14] an intense disruptive burning behavior of Al NP-laden heptane droplets, which was

characterized by multiple expansions and ruptures or ‘microexplosions.’ Due to these intense and frequent microexplosions, almost no residue from the Al NPs remained on the fiber following combustion, and a separate Al flame was not observed. The overall activation energy obtained for dilute NP concentrations (0.5% by mass) was smaller and that for dense (2.5% and 5.0%) concentrations of NPs larger, than that of pure heptane droplets. It was also anticipated that the addition of dilute concentrations of Al NPs to a low volatile liquid hydrocarbon fuel, where ignition is diffusion limited, might reduce the ignition delay time and might also lower the ignition temperature.

In our previous work [14], we used a highly volatile, single-component liquid hydrocarbon (heptane) as a base fuel. In the present study, we used kerosene, which is a multi-component liquid hydrocarbon and a blend of relatively nonvolatile petroleum fractions. 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 [15]. The autoignition and combustion characteristics of NP-laden kerosene droplets will provide us with an improved understanding of the effects of adding NPs to such multi-component hydrocarbon fuels. Other reports [12,13] describe the simple qualitative behavior of the combustion of nanofluid fuel droplets where the droplets were ignited by a heated wire. Therefore, these reports were not able to include the effects of NPs on autoignition delay times or the droplet combustion behavior at various elevated temperatures. In addition, they could not explain the effects of NPs on combustion rate constants. To the best of our knowledge, no study has been reported regarding the effects of the addition of various concentrations of NPs on autoignition and the combustion characteristics of kerosene-based nanofluid fuel droplets at elevated temperatures.

Motivated by the above, the autoignition and combustion characteristics of kerosene-based nanofluid fuel droplets with dilute concentrations of Al NPs were investigated in this paper. The effects of particle-loading rate on droplet ignition and burning behavior were examined. The distinguishing features presented in nanofluid droplet combustion were identified through a comparative analysis with pure and stabilized fuel droplet combustion. Moreover, the key phenomenon of particle escape from the nanofluid fuel droplet is discussed in comparison to previous studies [12,14].

## 2. Experimental method

The materials and instruments used for current research work were the same as already described in previous articles [8,9]. All these materials were used in their original form as received from suppliers except the Al NPs, whose surfaces were modified before dispersing them into kerosene.

The preparation of stable, kerosene-based nanofluid fuels was also elaborated in detail previously [8,9]. Briefly, the purchased NPs were coated with oleic acid (OA) in a planetary ball mill, which improves their dispersion stability in liquid hydrocarbons. These Al/OA pastes were mixed in different proportions with kerosene, and 0.1%, 0.5% and 1.0% Al NP-laden kerosene (*n*-Al/kerosene) suspensions were obtained. In this case and for the remainder of this paper, mass percentage values are used.

The experimental apparatus used in the current research work was designed, fabricated and installed by our group in the past and is discussed in detail in previous studies [16–19]. The same experimental setup was also employed in our previous studies regarding the evaporation characteristics of nanofluid fuel droplets [8–10]. The experimental procedure was described in detail in those research articles [8–10] along with data reduction and analysis, experimental errors and reproducibility of the results. Briefly,

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