Droplet Evaporation Behavior of Kerosene/Nano-Aluminum Fuels at High Pressure Environment

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Abstract

This experimental study investigated the effects of nanoparticles on evaporation rate of kerosene-based nanofluid fuels in high pressure environment. The base liquid fuel was kerosene and aluminum (Al) nanoparticles with average 70 nm diameter were used. Evaporation behaviour was recorded and investigated by suspending the droplet on the silicon carbide (SiC) fiber with 0.1 mm diameter in high pressure chamber. Oleic acid was used as a surfactant to synthesize the stable nanofluid fuels and the effect of oleic acid, of course, was investigated for comparison. The concentrations of aluminum nanoparticles were 0.1 % and 1.0 % by mass fraction and the ambient pressure was increased from 0.1 MPa to 2.5 MPa. The temperature ranged from 300 ℃ to 700 ℃. The results showed that in high temperature region the pure kerosene droplet vaporized faster with pressure increase but in low temperature region the evaporation rate of pure kerosene droplet decreased with pressure increase. For all aluminum-kerosene nanofluid fuel droplets, regardless of the concentration, the evaporation rate was higher than that of pure kerosene droplets.

Keywords

Aluminum nanoparticles; Evaporation rate; Nanofluid; Heat of vaporization; Diffusion coefficient

Introduction

Recently several studies have been conducted about solid fuels and liquid fuels containing nanoparticles and they have shown multiple advantages of adding nanoparticles such as shortened ignition delay, increased energy density and high burn rates. The addition of nanoparticles to fluids can also enhance its physical properties such as thermal conductivity, mass diffusivity and radiative heat transfer. As a result, it is possible in principle to achieve the desired properties and performance of liquid fuel by adding some energetic material nanoparticles.

However, study of evaporation of droplets will be required prior to ignition, combustion study or any other further applied studies due to its importance. Evaporation phenomenon can be found easily around us such as evaporation of rain drops, sweat evaporation and so on. Also evaporation phenomenon is used in several engineering and industrial fields such as spray combustion system.

Nanofluids are stable suspensions of solid nanoparticles (10 – 100 nm) in conventional heat transfer fluids. They are used to show different thermophysical properties from their base fluids such as thermal conductivity, mass diffusivity, surface tension, radiative property and non-Newtonian viscosity. Tyaig et al. conducted hot-plate experiments and observed that with addition of small amounts of Al and Al2O3 nanoparticles, the ignition probability for nanoparticle laden diesel fuel was significantly higher than that of pure diesel fuel [1]. Jackson et al. measured ignition delay time in a shock tube and observed that an addition of aluminum nanoparticles could substantially decrease the ignition delay time of n-dodecane above 1175 K [2]. Using an aerosol shock tube, Allen et al. found that an addition of 2 % aluminum nanoparticles in ethanol and JP-8 could reduce their ignition delays by 32 % and 50 % respectively [3]. Jones et al. experimentally determined the heat of combustion of ethanol with various volume fractions of aluminum nanoparticles and aluminum oxide particles [4]. The results showed that 5 %, 7 % and 10 % of aluminum nanoparticles increased the heat of combustion by 5.82 %, 8.65 % and 15.31 % respectively. Gan and Qiao studied the effects of nanoparticles and micron sized particles on the burning characteristics of n-decane
and ethanol fuel droplets [5].

**Experimental Methods**

**Materials and Instruments**

Kerosene was obtained from Junsei Chemical company in Japan and its boiling point range was 180 °C - 270 °C and specific gravity was 0.8 at 15 °C. Aluminum nanoparticles were purchased from US Research Nanomaterials in Houston, Texas. Its average diameter was 70 nm with 99.9 % aluminum basis. Oleic acid, OA, was purchased from Sigma-Aldrich. It was technical grade and chemical formula was C$_{18}$H$_{34}$O$_2$. All materials were used without any treatment and a PM-100 planetary ball mill obtained from Retsch company was used to modify the surfaces of the aluminum nanoparticles.

**Synthesis of Nanofluid**

Successful synthesis of nanofluid means nanoparticles are dispersing stably and homogeneously in fluid. There are two primary methods for preparation of nanofluid; one-step method and two-step method. In this work two-step method was applied for synthesis of aluminum-kerosene nanofluid fuels. Ball milling, ultrasonic disruptor and addition of surfactant were used as physical and chemical methods for improvement of stability. In nanofluids the repulsive and attractive forces exist between particles and between particles and molecules of based liquid and the stability of nanofluids depends on the balance of these two forces. By addition of surfactant, it helps in balancing these two forces between the particles and base fuels by modifying the surface of aluminum nanoparticles. The amount ratio of nanoparticles and oleic acid was decided to 2:1 which was that ratio 2 was aluminum nanoparticles and ratio 1 was oleic acid from various suspension tests with different ratios. Oleic acid and aluminum nanoparticles were put in the zirconium oxide jar of ball mill with the ratio of 2 to 1 to coat the surfaces of the particles by surfactant. After operating ball mill for one and half hours they became a paste. Then the resulting paste was dispersed in kerosene by ultrasonic disruption. Ultrasonic disruptor supplies electrical energy with 20 kHZ high frequency and this electrical energy is converted to mechanical energy at the probe. The probe generates vibrations, resulting microscopic vapor bubbles and these bubbles make the solution homogeneously. Final aluminum-kerosene nanofluid was stable for 20 hours without agglomeration and sedimentation of the nanoparticles.

**Experimental Apparatus and Procedure**

The experimental apparatus in this study already had been used in several studies of evaporation and ignition behavior of droplet with nanoparticles or without nanoparticles. [7,8,9]. A schematic view of the experimental apparatus is shown in FIG. 1. First, the nanofluid fuel was filled in micro-syringe and electric furnace was lifted up from the droplet suspension system. Then temperature was maintained to an experimental condition using thermocouple and temperature controller. At the same time, the high pressure vessel was purged by pressurized dry nitrogen. Once temperature and pressure were set up, then single droplet of nanofluid fuel was suspended on silicon carbide fiber using micro syringe. The diameter of droplet was carefully controlled 1.0 mm ± 0.1 mm. The electrical furnace was moved to downward to cover the droplet. Quartz glass window enabled us to observe the evaporation process of droplet using a high speed camera and its pictured images were recorded on a computer.

**Results and Discussions**

**Evaporation of Pure Kerosene Droplet**

The evaporation rate of pure kerosene droplets was evaluated first as a baseline to compare the evaporation rates of kerosene-based nanofluid fuel droplets. FIG. 2 showed the variation in the normalized diameter squared ($d^2/d_o^2$) with the normalized time ($t^2/d_o^2$), where $d_o$ is the initial droplet diameter, for different ambient temperatures and
pressures. This normalization parameter was suggested by classical droplet evaporation theory [10]. 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, following the $-d^2 - law$. FIG. 3 is also showing the variation of squared diameter of the droplet at high pressure. At high pressure the droplet behavior followed the general behavior and $-d^2 - law$ could be applied to measure the evaporation rate. FIG. 4 is showing the comparison of the results from other previous researches. The evaporation rate was measured at atmospheric pressure and it showed similarity with other researcher - 's' results and confirmed a reliability of the experimental apparatus. FIG. 5 represents the evaporation rate of pure kerosene liquid fuel. The evaporation rate had different trends depending on the ambient temperatures. A relatively low temperature region, 300 °C to 600 °C, the evaporation rate was diminished as the pressure increased but at high temperature the evaporation rate was enhanced with the ambient pressure. The reason of this opposite trend was considered due to effects of heat of vaporization and diffusion coefficient. As the temperature and pressure increases both heat of vaporization and diffusion coefficient are decreased and the evaporation rate is determined by interactions of these two factors. Decrease of heat of vaporization induces faster evaporation but decrease of diffusion coefficient makes slower evaporation. At high temperature and high pressure environments, decline of heat of vaporization of kerosene became much dominant than diffusion coefficient so the droplet vaporized faster.

Evaporation of Nanofluid Droplet

FIG. 6 and FIG. 7 is showing the evaporation rate of kerosene-based nanofluid droplet at different temperatures and pressures. In low temperature region, evaporation rate was declined as the pressure increased same as the evaporation behavior of pure kerosene droplet. In high temperature and high pressure region, decline from the peak of the evaporation rate was bigger than pure droplet evaporation's and it was considered due to higher thermal conductivity of aluminum nanoparticles. Furthermore, evaporation rate of 1.0 % concentration of aluminum nanoparticles was not decreased but increased at high pressure region. This behavior was totally opposite from that of the pure kerosene droplet and 0.1 % concentration droplet and this behavior was also considered due to higher thermal conductivity of aluminum nanoparticles inside the droplet.

Conclusions

The aim of the current experimental research work was to develop the fundamental understanding of evaporation of kerosene based nanofluid fuel droplets at elevated temperatures and pressures. The effects of two different concentrations of aluminum nanoparticles on evaporation were investigated. This research work provides basic phenomenological understanding and some useful data about the evaporation of nanofluid fuels droplets. The classical $-d^2 - law$ was valid for kerosene and kerosene-based nanofluid fuel droplets containing dilute concentrations of aluminum nanoparticles between 300 °C and 700 °C. The ambient temperature and pressure significantly affects the evaporation rates of kerosene-based nanofluid fuel droplets. At relatively low temperatures, from 300 °C to 500 °C, the evaporation rate was decreased as the pressure increased. However, in high temperature region the evaporation rate was increased as the pressure increased.

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Appendices

FIG. 1 Schematic Diagram of Experimental Apparatus

FIG. 2 Variation of Squared Diameter of Droplet at Atmospheric Pressure

FIG. 3 Variation of Squared Diameter of Droplet at 2.0 MPa
FIG. 4 Comparison of Evaporation Rate

FIG. 5 Comparison of Evaporation Rate of Pure Kerosene Droplet at Different Temperatures and Pressures

FIG. 6 Comparison of Evaporation Rate of 0.1 % Nanofluid Droplet at Different Temperatures and Pressures
FIG. 7 Comparison of Evaporation Rate of 1.0 % Nanofluid Droplet at Different Temperatures and Pressures

REFERENCES


