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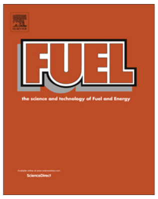

Full Length Article

Combustion characteristics of colloidal droplets of jet fuel and carbon based nanoparticles

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ABSTRACT

Addition of micro and nano-sized particles to liquid fuels has proven to be a successful mechanism to improve certain combustion characteristics such as burning rate and ignition delay. In this study, sub-millimeter size droplets of colloidal suspensions of jet fuel and different types of carbon based nanoparticles were ignited and burned at ambient conditions to investigate the effects of particle size and morphology on combustion behavior. Carbon nanoparticles, nanotubes, and nanoplatelets with dimensions in the range of 2–3 nm to 100 nm were added to jet fuel at a wide range of mass concentrations. In general, higher burning rate (7–10% increase) was achieved for all of the carbon additives but it was found that the size and morphology of nanoparticles play an important role in the extent of this increase. For each particle type, a concentration was found at which maximum burning rate was achieved. It was observed that addition of more particle beyond this concentration would result in a burning rate reduction possibly due to the formation of large aggregates. Among the three carbon additives, nanotubes resulted in the highest burning rate increase at only 0.25% particle loading. Improved thermal and optical properties of these suspensions is believed to result in improved heat transfer within the droplet and an increase in the droplet temperature and evaporation rate.

1. Introduction

A relatively new area of thermal-fluid sciences that has been explored only since the 1980s is the addition of nano-sized particles to liquids to achieve enhanced heat transfer features. This new type of fluid, known as nanofluid and typically categorized as suspensions of 1–100 nm nanoparticles in fluids, started to emerge with the work of Choi and Eastman [1] and probably is one of the very first studies that proposed the concept of nanofluids. They proposed that a new class of heat transfer fluids can be engineered by suspending metallic nanoparticles in conventional heat transfer fluids to obtain higher thermal conductivity. This unique property provides nanofluids with a great potential to be used in a wide range of new industrial technologies such as cooling for micro- and nanoelectromechanical systems (MEMS and NEMS), power electronics, and light emitting diodes (LEDs) [2]. For instance, it has been experimentally determined that adding 2% (by volume) Al_2O_3 nanoparticles to water will result in up to 57% increase in the overall heat transfer coefficient of a horizontal shell and tube heat exchanger [3].

Nanofluid-type fuels are a special type of nanofluid that have received great attention in recent years. In this type of fuel, nano-sized energetic materials and nanocatalysts are added to traditional fuel in order to improve their ignition and combustion properties. Previous studies have shown that addition of energetic nanomaterials such as aluminum and boron, and nanocatalysts such as cerium oxide could improve fuel performance by shortening ignition delay [4] and increasing energy release [5], burning rate [6,7] and ignition probability [8]. Aluminum and aluminum oxide nanoparticles have also been widely used as an energetic additive and have shown promising effects in terms of enhancing heat conductivity, increasing burning rate and reducing ignition delay [5,6,9]. Allen et al. [4] used 2% (by weight) of 50 nm aluminum nano-particles in ethanol and JP-8 and reduced ignition delay by 32% and 50% respectively. Gan and Qiao [10] showed that addition of nano aluminum particles might cause deviation from d^2-law of combustion in some circumstances and reduce burning rate. They explained that if the droplet lifetime is longer than the characteristic aggregation time, large aggregates are formed. These aggregates then will inhibit diffusion and so reduce the evaporation rate. However, there are still challenges such as particle

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agglomeration and potential emission of metal oxides that may limit the application of metallic nanomaterials as fuel additives.

Studies on the addition of carbon particles to conventional liquid fuels started before the concept of nanofluids was proposed for the first time. Due to abundant resources of coal in the world and its inexpensive cost of extraction compared to other fuels, there has always been an interest to mix coal powder with water or liquid fuels and burn it directly in turbines or other internal combustion engines. However, its poor pollution performance and its solid residue of matter has limited its practical use. Coal liquefaction technologies are still very expensive and have their own environmental issues such a high CO_2 emission from gasification process or from heat and gas input to the reactors. The idea of crushing coal into micro meter sized particles and mixing it with oil in order to directly burn in industrial furnaces became attractive in the 1970s. Miyasaka and Law [11] examined combustion of carbon in oil (COM) mixtures in furnace environment. They found it very likely that agglomerates form during the burning of COM, implying that coal burns in the form of agglomerates instead of individual particles. It was also concluded that it is unnecessary to finely crush coal unless it could be reduced to micron-size. Later, Liu and Law [12] examined the combustion of coal-water slurry (CWS) droplets and identified several stages of CWS combustion. New technologies leading to production of nano-sized particles gave rise to nanofluid application and provided an opportunity to make new types of fuels by mixing energetic nanoparticles with conventional liquid fuels. Sabourin et al. [9] examined the effects of both metallic and non-metallic additives on liquid fuel combustion and discovered that the addition of less than 1% functionalized graphene sheets to nitromethane could significantly increase linear burning rate and reduce ignition delay. Gan and Qiao [13] also studied suspensions of carbon based nanostructures in ethanol and reported higher evaporation rate and higher droplet temperature compared to pure ethanol. They found that in comparison to pure ethanol, colloidal suspensions have much lower transmittance which helps them use more of the absorbed radiation energy to heat up the droplet and enhance its evaporation. Such unique thermal and optical properties of carbon nanoparticles makes them particularly popular with low energy content fuels.

The behavior of carbon based nanomaterials in fuels is a new topic and has been studied only by few research groups during last ten years. It is now understood that carbon based nanomaterials have better thermal and optical properties and could be considered as effective and yet safe fuel additives [9,13,14]. However, the limited number of works have mainly focused on simple fuels, such as ethanol and decane, and the performance of fuels that are widely in use has not yet been studied. Furthermore, these nanomaterials come in a wide range of sizes and morphologies that may result in different combustion behaviors. The morphology of aggregates and their effect on droplet combustion has also been studied for metallic particles with different sizes [15] but the effect of particle morphology on the shape of the aggregate has not yet been explained. In this regard, the main objective of this research is to experimentally examine the effects of size and morphology of carbon nanomaterials and their aggregates on the combustion behavior of liquid fuel droplets.

2. Experimental method

The methodology used in conducting experiments and data analysis has been explained in [16]; Therefore, only a brief description will be presented here. Submillimeter-sized fuel droplets generated using a microsyringe were deployed on a set of three 16 μm SiC fibers and ignited by two symmetrical hot wire loops. The heating time through hot wires was set to 350 ms for all experiments. The heating and combustion process was captured using two high speed cameras: a black and white CCD camera aligned with a 300 W projector light to record the evolution of droplet diameter and a color camera to capture flame behavior and the changes it might undergo during combustion.

To prepare the colloidal suspensions, Jet-A and carbon-based nanomaterials were used as continuous and dispersed phase respectively. To investigate the effects of morphology, four different types of nanomaterials were considered: Carbon Nanoparticle (CNP), Multi-Walled Carbon Nanotubes (MWNT), OH functionalized Multi-Walled Carbon Nanotubes (MWNT-OH) and Graphene Nanoplatelets (GNP). CNPs are 100 nm (average) activated carbon while MWNTs are tubes with inside diameter of 3–5 nm, outside diameter of 8–15 nm, length of 0.5–2 μm and Specific Surface Area (SSA) of greater than 233 m^2/g. MWNTs-OH are MWNTs having hydroxyl groups (–OH) attached at a mass concentration of 3.52–3.89%. The CNP, MWNT and MWNT-OH for this study were purchased form Nanostructured and Amorphous Materials, Inc. (Product IDs 1211NH, 1235YJS and 1248YJF respectively). Finally, GNPs are platelets (Strem Chemicals, Catalog No. 06-0210) with an average width of 5 μm, thickness of 6–8 nm and SSA of 120–150 m^2/g. The SEM images in Fig. 1 show the morphology of these nanomaterials.

Preparing a homogeneous and stable suspension is a key step in performing any experiment with nanofluids. One of the main challenges in preparing colloidal suspensions is the coagulation of nanoparticles, which can be suppressed by the combined effect of sonication and the addition of a surfactant. In the current study and to reduce particle agglomeration, Span 80 (Sorbitan Monooleate, $C_{24}H_{44}O_6$) was added to the base fuel at a mass concentration of 1.5% and stirred on a magnetic stirrer for 30 min. Then the nanoparticles were added at different mass concentrations and the sonication was performed using a 300 W ultrasonic disruptor (Biologics 3000MP). All of the suspensions prepared for droplet combustion in this work were prepared in a 25 ml glass Erlenmeyer flask and using a 3/16 in. titanium probe (for sonication) in small volumes between 15 and 20 ml. Given the great amount of heat generated during sonication, the sonication was performed

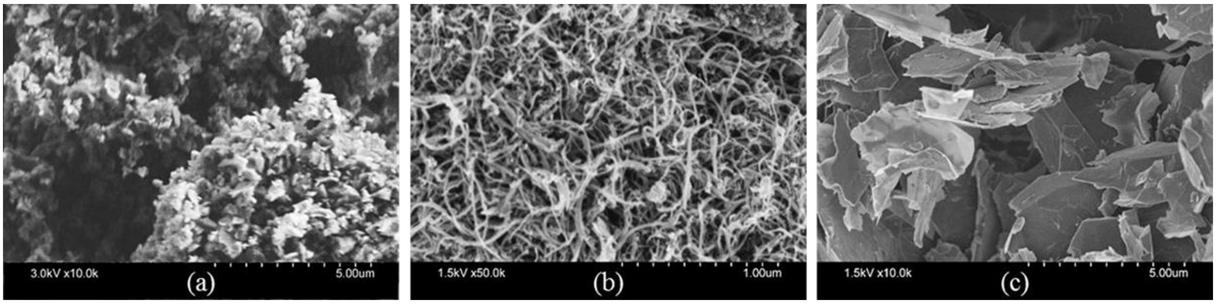

Fig. 1. SEM images of (a) CNP, (b) MWNT/MWNT-OH and (c) GNP.