Spray Visualization of Alternative Aviation Turbine Fuel embedded with Metallic Nanoparticles

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Abstract Gas-to-liquid (GTL) fuel, a liquid fuel synthesized from natural gas, is considered as a potential alternative fuel candidate for aviation engines due to its cleaner combustion characteristics. The chemical and physical properties of GTL fuels are different from those of the conventional jet fuel, like jet A-1. The effect of change in fuel properties on the spray, combustion, and emission performance of GTL fuels for aviation engines have been the subject of study for a while now. On the other hand, it is known that addition of metallic nanoparticles enhances the combustion and emission performances of conventional liquid fuels. The addition of nanoparticles also affects the fuel physical properties that change its atomization characteristics affecting combustion and emission performances. This serves as the key motivation for this study. The objective of this paper is to study the effect of change in fuel physical properties due to the addition of nanoparticles on the spray cone angle, fuel sheet breakup, and ligament characteristics of the GTL fuel. The dynamics of liquid sheet, its configuration, and atomization characteristics are studied using the optical diagnostics of shadowgraph technique for a given nozzle operating condition.

Keywords: Alternative aviation fuels, spray visualization, shadowgraph

1 Introduction

High energetic materials (EM, metals having high energy density) like aluminum, boron and iron are considered as active ingredients for solid propellants, explosives, and under water propulsion for a while now [1], [2]. The positive influence of the EM particles on combustion performance of solid propellants has paved the way for enhancing the energy content of liquid fuels with low energy density like ethanol, biodiesel etc., with the addition of EM particles. In such cases, EM particles in the size range of several micrometers were added to liquid fuels at high volumetric concentrations resulting in slurry fuels [3], [4]. However, the key challenge with the combustion of EM particles based slurry fuels was the agglomeration of metal particles which resulted in long ignition delays [5]. This aspect negated the beneficial influence of EM particles on the liquid fuel combustion performance. In the recent past, with the advent of nanotechnology to develop EM particles at nanometer scale consistently has instigated renewed interest on EM particles for liquid fuels. The reduction in size of EM particles from micrometer to nanometer scale has enabled to overcome the issue of long ignition delays and achieve higher burn rates [6]. This in turn, led to the development of stable, homogenous liquid fuels dispersed with EM nanoparticles, called as “nanofuels”, with the help of mechanical (ultrasonic) and chemical (surfactants) dispersion techniques [7]. Among other EM particles, aluminum is the most widely used due to its cost benefit and high combustion enthalpy [5].

In the past, several researchers have investigated the influence of aluminum (Al) or aluminum oxide (Al_2O_3) nanoparticles on the thermo-physical properties and heat transfer performance of aviation turbine fuel [8], ignition probability of diesel [9], and the evaporation [10] and combustion [11] characteristics of ethanol. All those studies have clearly demonstrated that the addition of Al / Al_2O_3 nanoparticles have enhanced the thermo-physical properties, heat transfer, and combustion performance of the base fuels. In addition, the effect of Al / Al_2O_3 nanoparticles on the fuel physical properties like viscosity and surface tension was also investigated. Al_2O_3 nanoparticles dispersed in aviation turbine fuel at 1% volume concentration have shown to increase the viscosity of the fuel by about 38% [8]. Furthermore, the surface tension was reported to increase with an increase in particle concentrations [12]. It is important to note that the change in fuel physical properties can potentially affect the atomization characteristics of nanofuels which in turn influence the mixing, combustion and emission aspects of the liquid fuel. Until now, the effect of nanoparticle dispersion on the atomization characteristics of aviation fuels have not been investigated. This serves as the motivation for the present study.

The key objective of this work is to investigate the influence of Al_2O_3 nanoparticle dispersion in alternative aviation fuel, gas-to-liquid (GTL) fuel, on its spray performance. The atomization characteristics like spray cone angle, sheet breakup, and ligament formation are investigated at the macroscopic level in the near nozzle region. The optical diagnostics of shadowgraph technique is used to gain insights on the above spray features.

2 Experimental facility and Methodology

The schematic of the experimental setup used in this work is shown in Fig. 1. The high pressure nitrogen gas supplied from the cylinder is utilized to pressurize the fuel inside the pressure vessel. The fuel supply to the nozzle at the desired injection pressure is controlled with the help of a two-way solenoid valve. The two-way solenoid valve and camera are synchronized using TTL signals from the computer. The injection pressure is measured continuously using the pressure transducer installed just upstream of the nozzle. The spray chamber is equipped with optical windows on all four sides. High speed camera is placed on a platform on one side and the light source is placed on the opposite side. A pressure swirl nozzle (Duesen-Schlick, Germany) with an exit diameter of 0.8 mm is used as atomizer in this study. The fuel vapor is continuously extracted from the spray chamber through the vapor exhaust at the bottom of the spray chamber.

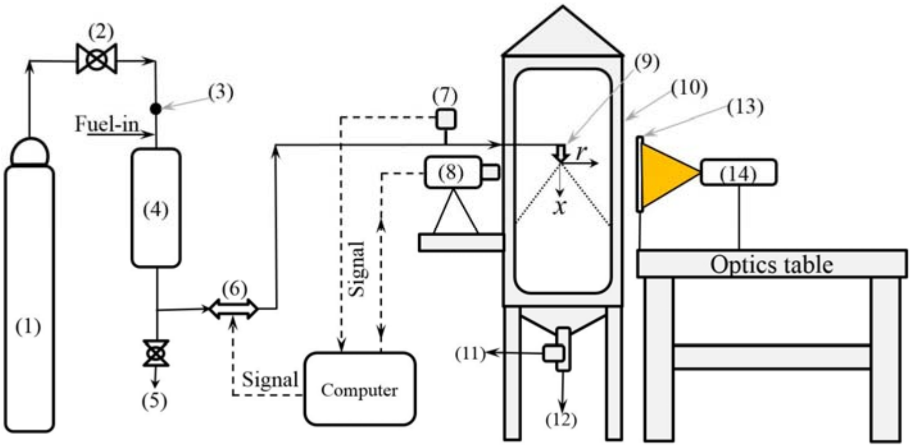

Fig. 1 Schematic of the experimental facility with components description; (1) Nitrogen gas cylinder, (2) Valve, (3) Rupture disk, (4) Pressure vessel, (5) Liquid drain, (6) Two-way solenoid valve, (7) Pressure transducer, (8) High speed camera, (9) Pressure nozzle, (10) Spray chamber, (11) fuel vapor exhaust, (12) Drain for liquid fuel, (13) Light diffusing screen, (14) Halogen light source

For each case, the experiments are performed three times to have good repeatability. When changing the measurements from one fuel sample to the other, the fuel inside the fuel supply system is drained first. Then, the system is flushed (cleaned) with base fuel (*i.e.,* pure GTL), and dried using nitrogen gas. This methodology is followed to ensure that the traces of nanoparticles adhered inside the tubes are removed and it does not affect the nanofuel concentration. Before each set of measurements, the camera is calibrated using a standard calibration target (typically used in velocimetry measurements like PIV) to obtain the conversion factor from image coordinates to real coordinates.

3 Nanofuel preparation

In this work, the alternative aviation fuel, gas-to-liquid (GTL) fuel is taken as the base fluid for dispersing the nanoparticles. Here, the nanofuels are prepared following the top-down approach *i.e.,* by dispersing the commercially available alumina (Al_2O_3) particles (from Nanostructured and Amorphous Material Inc., USA) in GTL fuels using the mechanical dispersing technique (*i.e.,* sonication). Initially, the nanoparticles are dispersed in GTL fuels without any chemical agent and found that the nanofuel is not stable even at low particle concentrations. Consequently, a stability study was performed independently and found that the non-ionic *sorbitan oleate* (commercially called as *Span80*) surfactant is essential to obtain a stable nanofuel. The surfactant is reported to reduce the surface energy of the nanoparticles and in turn the particle-to-particle attractive force [12]. This helps in stabilizing the nanofuels. Subsequently, in all the nanofuels, 4 ml of surfactant is added to 1000 ml of pure GTL fuel. In this study, the base case is a mixture of pure GTL fuel and the surfactant. Although the surfactant disperse readily in the base fuel, the base fuel and surfactant mixture is also sonicated using a bath type sonicator (VWR Ultrasonicator, 35 kHz) for about 15 minutes to ensure a homogenous dispersion of surfactant in the base fuel.

For the nanofuel preparation, the GTL fuel, nanoparticles, and surfactant is mixed in a beaker and exposed to cyclic ultra-sonication by immersing a probe type sonicator (QSonica S-4000, 25 kHz) for about 45 minutes in order to obtain a stable, homogeneous nanofuel. The sonication time used here is same as that used in the stability study. However, the sonication time is reported to have minimal influence on the nanofuel stability [8]. The nanofuel sonication process is carried out in a temperature controlled environment using a heat exchanger (Julabo, GmbH) in order to avoid any fuel vapor formation. The size of the nanoparticles used in this work is in the range of 27-43 nm. The nanoparticles are mixed with the GTL fuel at different weight concentrations (0.5% and 1.5%). The physical properties such as viscosity, surface tension, and density, of nanofuels are measured and compared with those of the base fuel in Table 1. The base fuels are supplied by Shell, Qatar.

Physical properties measured at 20°C	**Base case***	**Nanofuels§**	
		0.5 wt %	1.5 wt %
Dynamic viscosity (cP)	1.005	1.011	1.020
Surface tension (mN/m)	24.10	23.62	23.15
Density (kg/m^3)	750.9	754.9	762.9

Table 1. Comparison of fuel physical properties between base fuel and nanofuels.
(*fuel properties provided by Shell Inc. §measured.)

Table 1 highlights that the change in dynamic viscosity, surface tension, and density, due to the addition of nanoparticles are only a maximum of 1.5%, 4%, and 1.6%, respectively, from the base case. The trends exhibited by the fuel physical properties with the addition of nanoparticles are in line with those reported in the literature [8], [12]. However, the fuel physical properties measured in this work may appear to be low when compared to those reported in the literature [8]. This can be attributed to the fact that the nanoparticle concentrations used in this work are all on weight basis and the equivalent volume concentrations are about one-fourth of the weight concentrations. Consequently, the change in fuel physical properties measured in this work are low owing to very low equivalent volume concentrations.

4 Spray Diagnostics

The optical diagnostics of shadowgraph technique is employed to capture the spray images in the near nozzle region. The schematic of the shadowgraph technique employed is shown in Fig. 2.

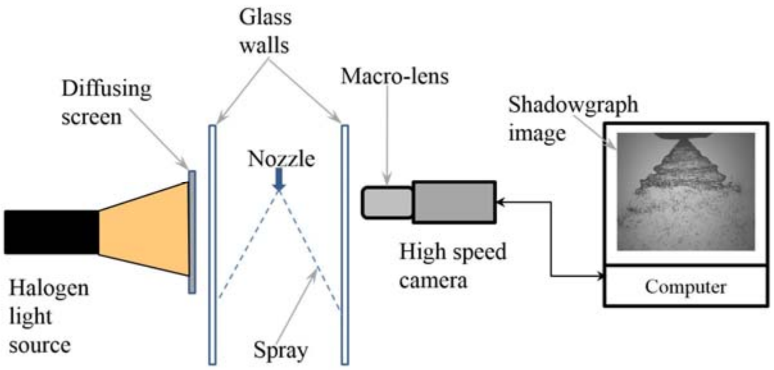

Fig. 2 Schematic of the shadowgraph technique employed in the above experimental facility

A 150W halogen lamp is used as the light source. High speed CMOS camera (Vision Research Phantom v1210) fitted with a macro lens (sigma Macro 105mm/F2.8) is positioned opposite to the light source. A diffusing screen is placed in between the light source and the spray chamber glass wall as shown in Fig. 2. The camera is operated at an image capture rate of 20,000 frames per second with an exposure time of 4µs. The size of each image is 352 x 280 pixels. A sample shadowgraph image of water spray emanating from the nozzle captured in the vicinity of nozzle exit is shown in Fig. 3. For all the results reported here, the camera is operated with the same settings and focused on the same region of spray as shown in Fig. 3.

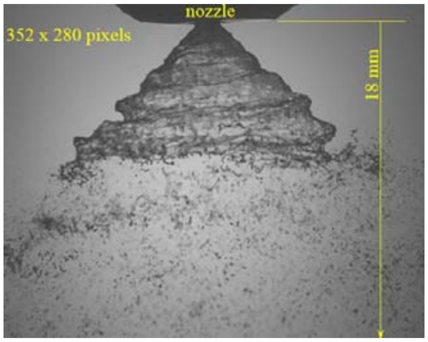

Fig. 3 Sample shadowgraph image of water spray captured in the near nozzle region at 0.3 MPa injection pressure

4 Results and Discussion

In this section, the influence of addition of nanoparticles to GTL fuel on its atomization characteristics are discussed and compared with those of the base case. The results presented here are measured at a nozzle injection pressure of 0.3 MPa. The high speed spray images are processed using the Matlab edge detection (canny) procedure to determine the spray edges and in turn the spray cone angle (2θ) as shown in Fig. 4.

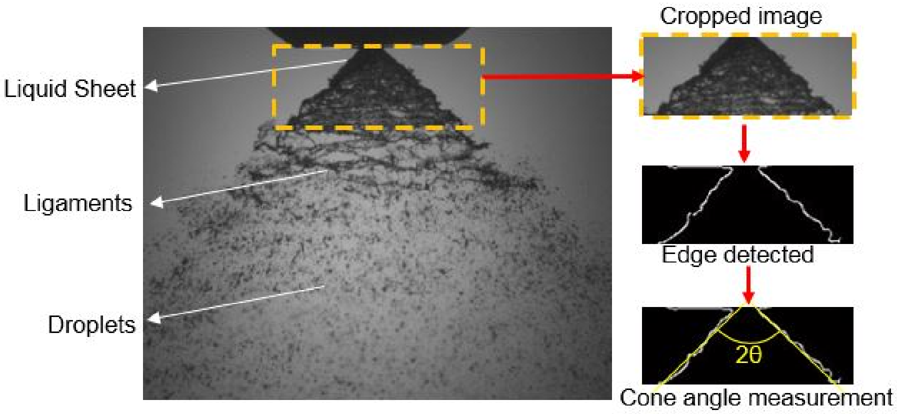

Fig. 4 Cone angle measurement methodology

Only a small region of the spray image (100x60pixels) near the nozzle exit is used for applying the edge detection procedure as demonstrated in Fig. 4. The size of this region is chosen based on a parametric study and found that this size gives the best outcome for the spray cone angle determination. In all the cases, the spray reached a steady state operation in about 150 milliseconds. For each case, a series of about 20,000 images captured during the steady operation of the spray are utilized for the cone angle determination. The spray cone angles of nanofuels (0.5% wt. and 1.5% wt.) are compared with that of the base case fuel in Fig. 5. The spray cone angle is seen to decrease by about 2-3% with the addition of nanoparticles. However, it must be interpreted with caution as the difference in spray cone angle between the base case and nanofuel sprays is within the uncertainty of the cone angle determination. The key parameters that affect the spray cone angle are the fuel physical properties like viscosity, surface tension, and density. The minimal difference in spray cone angles can be attributed to the fact that the change in fuel physical properties measured in this work is only about 3% as shown in Table 1. However, further investigation is warranted to ascertain the influence of nanoparticles concentration on the spray cone angle as seen here.

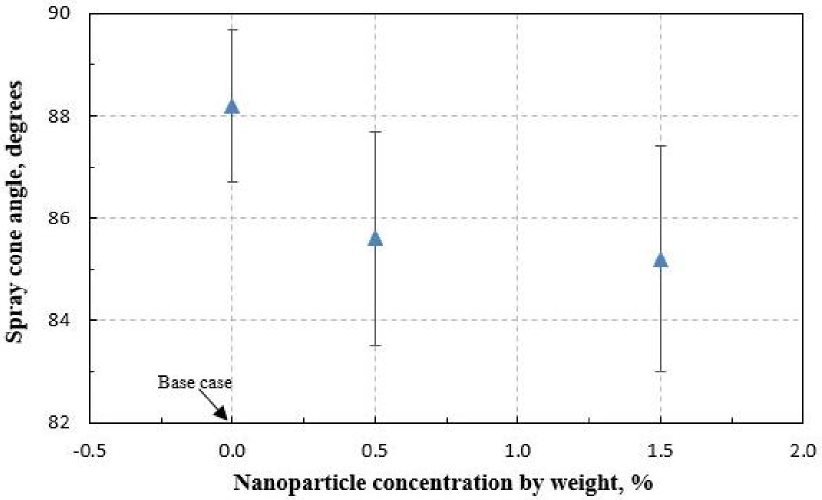

Fig. 5 Cone angle comparison between the base case and nanofuel sprays

Using the spray cone angle as a metric, the transient nature of the sprays with and without the dispersion of nanoparticles is also investigated. The spray cone angle is determined as described above from the spray initiation. As mentioned earlier, the spray reaches the steady state operation in about 150 ms in all the cases. However, during the initial transient period, some difference is observed between the cases as show in Fig. 6. With the addition to nanoparticles, the spray cone angle reaches steady state at a slower rate than the base case. The time to reach a stable spray cone angle is seen to increase with an increase in nanoparticle concentrations. This can be attributed to the small change in fuel physical properties with the addition of nanoparticles.

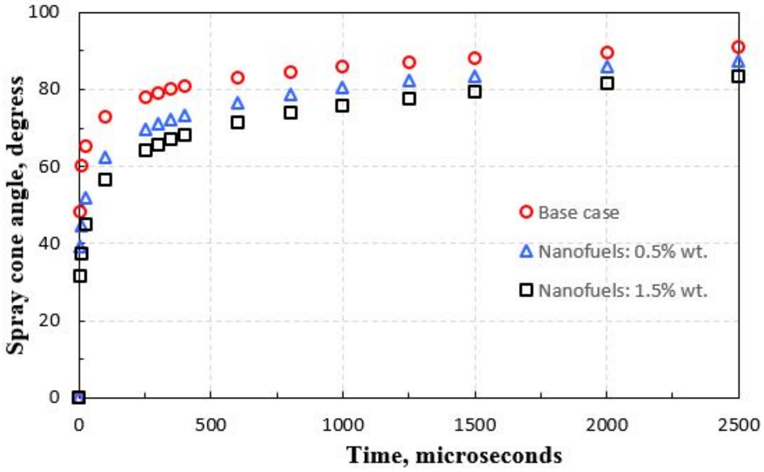

Fig. 6 Spray cone angle during the transient period

In addition to the spray cone angle, the atomization characteristics like sheet breakup distance and ligament velocity are also determined. The sheet breakup distance (or liquid film length) is defined as the vertical distance from the nozzle exit to the point where the liquid sheet begins to disintegrate in to ligaments [13]. In this work, about 25 images captured with a time difference of 50 milliseconds between each image are considered for the determination of sheet breakup length. The sheet breakup length (*l*) is determined with the visual observation of each image as shown in Fig. 7. The liquid sheet break up length is seen to decrease with the increase in the nanoparticles concentration as shown in Fig. 7.

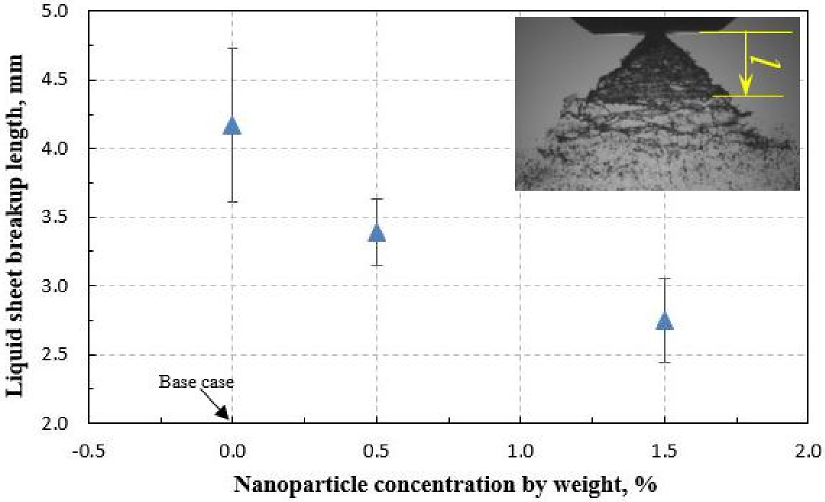

Fig. 7 Variation of liquid sheet breakup length with nanoparticles concentration

Furthermore, the ligament velocity is also determined using the high speed camera software. The ligament velocity is determined for the same set of images that are used to calculate the liquid sheet breakup length. The average ligament velocities for the base case, base fuel with nanoparticles at 0.5% wt., and base fuel with nanoparticles at 1.5 % wt., are about 18.82 m/s. 15.55 m/s, and 15.51 m/s, respectively. It is calculated at about 3 to 4 mm downstream of the nozzle exit for an injection pressure of 0.3 MPa. It must be noted that these velocities are determined from two dimensional images of a three-dimensional phenomenon. The ligament velocities reported here are not corrected for the angular movement of ligaments in the spray. However, in relative terms, these results will help to identify the change in ligament velocity with the addition of nanoparticles to the base fuel. The change in velocity could be due the change in fluid properties such as viscosity and density.

To summarize, all the results from this preliminary investigation on the addition of metallic nanoparticles to the base fuel indicate that it has an effect on the atomization characteristics. However, a detailed investigation is required to gain more insights on these trends.

5 Conclusions

In this work, the influence of nanoparticle concentrations on the atomization characteristics of alternative aviation turbine fuel, gas-to-liquid (GTL) fuel is investigated. To this end, the spray characteristics of GTL fuel with and without the dispersion of nanoparticles is studied. The visualization study is performed using the conventional shadowgraph diagnostic technique with the help of high speed camera and a light source. The nanofuels are prepared with two weight concentrations of nanoparticles with the base fuel (GTL). The macroscopic spray characteristics such as spray cone angle, liquid sheet breakup length and ligament formation are investigated. The spray cone angle is determined with the help of edge detection procedure in Matlab.

The spray cone angle of GTL fuel is found to decrease with the increase of nanoparticles concentration by about 3-4%. This marginal change in spray angle could be due the change in fuel physical properties like viscosity and density which in turn, affect the fluid dynamics of the spray. The liquid sheet breakup length is also observed to decrease with the increase in nanoparticles concentration. Furthermore, the ligament velocity is also observed to decrease with nanoparticle addition. All these results highlight that although the nanoparticles are closer to the molecular dimensions of the fuel components, the presence of nanoparticles does seem to enhance the disruption of liquid sheet into ligaments and the ligament velocity. More detailed investigation is required to confirm the results observed in this study and to gain further insights about the influence of nanoparticles on the fuel atomization characteristics.

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