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Ignition and combustion characteristics of jet fuel liquid film containing graphene powders at meso-scale

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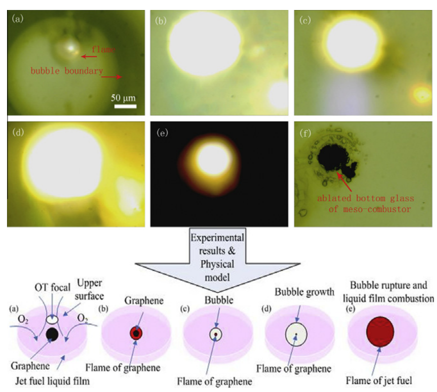
HIGHLIGHTS

- Jet fuel suspensions containing graphene powders were prepared.
- Graphene was trapped and ignited by optical tweezers prior to jet fuel.
- Ignition and combustion characteristics of jet fuel liquid film were identified.
- A schematic physical model was proposed to understand the combustion mechanism.

GRAPHICAL ABSTRACT



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ABSTRACT

At meso-scale, ignition and combustion characteristics of jet fuel liquid film containing graphene powders were investigated. Jet fuel/graphene suspensions were prepared, and sprayed to produce the liquid film. Liquid film was ignited by optical tweezers, five distinctive stages including graphene trap, ignition and combustion of graphene, bubble formation, jet fuel vaporization and bubble growth, bubble rupture and combustion of liquid film were identified. Ignition of graphene is prior to jet fuel. The combustion heat of graphene serves a heat source to accelerate the vaporization of jet fuel. The graphene serves as a nucleation point to form a bubble. Expansion of both combustion products and jet fuel vapor result in the bubble growth. The thickness of bubble boundary layer depends on graphene concentration. As the bubble escaped, liquid film ruptured and micro-explosion occurred. Jet fuel was then ignited, and combusted sustainably till burnt out. During combustion, the flame front fluctuated slightly, indicating good flame stability. Finally, a schematic physical model was presented to analyze the inductive mechanism of graphene for ignition and combustion of jet fuel liquid film by optical tweezers.

1. Introduction

As the space of energy system decreases from macro-scale to meso-scale and even till micro-scale, ignition and combustion stability of liquid fuels are becoming significant challenges due to large heat loss and short residence time [1–5]. To sustain the combustion of liquid fuels in the meso-scale combustor, Sirignano et al. [6,7] proposed a liquid film combustor. The liquid film was generated by using swirling air on the inner combustor wall, which can impede heat loss by creating a surface where the flame's heat vaporized the liquid rather than transferred directly to the walls.

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At macro-scale, recent advances in using colloidal suspension additives for improving ignition and combustion performance of liquid fuels have been shown. Tyagi et al. [8] demonstrated that the ignition probability for the diesel fuel mixtures containing nanoparticles was significantly higher than that of pure diesel. Javed et al. [9] reported that kerosene droplets with aluminum nanoparticles can automatically ignite. Nachmoni and Natan [10] found that organic metallic gellant gels can increase the heat of vaporization with increasing the gellant content in the liquid JP-5. Gan and Qiao [11] demonstrated several distinctive burning stages for liquid fuel with aluminum particles in comparison with pure liquid fuel. Ohkura et al. [12,13] and Conner and Dlott [14] reported that Al nanoparticles can be ignited by a camera flash. These studies have shown the promise of using nanoscale and micro-scale additives to enhance the ignition and combustion performance of liquid fuels. Nano-structured additives offer distinct advantages over larger scale particles due to their high surface to volume ratio and increased density of surface functionalities. Moreover, nanoscale materials also exhibit optical properties favorable to radiative heat transfer that could aid in combustion [15–18].

However, at meso-scale, ignition and burning characteristics of liquid fuels containing colloidal suspension additives have not been reported. In the present work, we investigated ignition and combustion behaviors of jet fuel at meso-scale. To upgrade ignition and burning performances, nanometer and micron-sized graphene powders were proposed to add into jet fuel. Graphene is a flat monolayer of carbon atoms tightly packed into a two-dimensional (2D) honeycomb lattice, and is a basic building bulk for graphitic materials of all other dimensionalities. It can be wrapped up into zero-dimensional fullerenes, rolled into one-dimensional nanotubes or stacked into three-dimensional graphite [19]. Graphene can be considered as an emerging high energetic material to apply widely into many fields including combustion because of its prominent intrinsic properties, such as ultrahigh thermal conductivity coefficient of 5000 W/m K at room temperature and high surface to volume ratio of 2630 m^2/g for nano single-layer sheet [20–22]. Graphene can be also considered as a fuel additive to assist ignition and as a catalyst to enhance combustion rate and efficiency. Sabourin et al. [23] demonstrated that the combustion rate was increased by 47% at a concentration of functionalized graphene sheet additive as low as 0.075%, in comparison with pure nitromethane. Gilje et al. [24] reported that photothermal deoxygenation of graphene oxide might be a promising additive as an ignition promoter for the distribution ignition of fuels.

In our work, an optical tweezers (OT) tool was used. It is not only considered as an igniter, but is also used to manipulate graphene suspended into jet fuel. The OT can exert extremely small forces via a highly focused laser beam, which is capable of manipulating nanometer and micron-sized dielectric particles. Since first demonstration of the OT appeared by Ashkin et al. [25], it has been considered as an effective tool to trap and manipulate particles in all kinds of surrounding ambiences, and applied in many fields like atmosphere, physics, micro-fluidics, medicine, bio, and life science etc. [26]. Moreover, the OT can heat the particles due to high energy density. Therefore, the OT can not only ignite the fuel, but trap the fuel particles. It is different from the spark, hot wire, camera flash and common laser igniter. Our previous studies [27,28] have already demonstrated that micron-sized active carbon particles can be effectively trapped and ignited by the OT. Generally, at micro-scale and meso-scale, gas phase hydrogen or hydrocarbon fuels were used, and their igniter is an electric spark or hot wire. These ignition sources are installed inside the combustor and immovable, and thus the ignition point cannot be optionally changed. In this study, the OT ignition system is our first effort for solving in situ ignition of a microflame outside the combustor and stabilizing the ignition at the desired location within the combustor at small scale.

The objectives of present study will be involving: (1) to investigate the dispersion performance of nanometer and micron-sized graphene in jet fuel, (2) to testify the feasibility of the OT igniter for the ignition application of liquid fuel at meso-scale, and (3) to explore ignition and combustion behaviors of jet fuel liquid film containing graphene powders at meso-scale. Moreover, a schematic physical model was built to analyze the ignition and combustion stages of jet fuel liquid film containing graphene powders.

2. Experimental

2.1. Preparation of jet fuel/graphene suspensions

Graphene powders (purchased from XFNANO Tech. Co., Ltd, Nanjing, China) typically consist of single layer graphene nanosheets. The graphene was prepared by reducing the graphene oxide, and reduced graphene oxide had many oxygen-containing groups. The oxygen content of graphene reached 7.0–7.5 at.%, indicating a large amount of defects and a more active chemical property. This tends to make the graphene sheet much easier to be oxidized than pure graphene. Graphene samples have average surface area of 700–800 m^2/g. The size of graphene powders ranges from 500 nm to 5.0 μm.

Jet fuel is a type of aviation fuel designed for use in aircraft powered by gas-turbine engines, consisting of very complex hydrocarbon mixtures [29]. Additionally, jet fuel has been identified as a potential jet propellant for various applications [30]. Due to low oxygen content and reactivity, jet fuel behaves as a fuel at ordinary pressure, requiring additional oxidizers to sustain combustion. In this work, pure jet fuel (no any oxidizers or additives) was used to prepare the suspensions. The physical properties of pure jet fuel (purchased from Fd-wzsh Co., Ltd, Hangzhou, China) were listed into Table 1.

The preparation of jet fuel/graphene suspensions is a key step. Special handling is needed to achieve homogeneous, long-term, stable suspensions and a low level of particle agglomeration. Many studies have demonstrated that sonication can reduce the coagulation of nanoparticles in liquid [31]. As the nanofluid is exposed to ultrasound, the ultrasound waves that propagate into it result in alternating high pressure and low pressure cycles. The applied mechanical stress can separate the nanoparticles from one another and reduce the agglomeration. The criteria for the selection of graphene to fuel ratio should be able to significantly enhance the evaporation rate of jet fuel, and minimize the cost of fuel additive as far as possible. Considering two aspects of evaporation rate and the cost, the graphene to fuel ratio of 0.1 mg/mL was selected in this study. Graphene powders (~1 mg) were added into jet fuel (~10 mL), and thus graphene concentration was 0.1 mg/mL (~0.013 wt.%). After bath ultrasonication about 1 h, the suspension was then allowed to settle for a couple of days. Fig. 1 shows the pictures of the suspensions after 0.5 h (left) and after 5 days (right). With sonication, suspensions of jet fuel/graphene typically can remain stable for about 0.5 h, beyond which the particles will start

Table 1
Physical properties of pure jet fuel.

Items	Values	Items	Values
Density (kg/m^3)	794.5	Net calorific value (MJ/kg)	43.30
Flashing point (°C)	46.5	Boiling temperature (°C)	156
Freezing point (°C)	−56.0	Existent gum (mg/100 mL)	<1.0
Smoking point (mm)	25	Kinematic viscosity (mm^2/s)	4.063
Specific heat (kJ/(kg K))	~2.01		