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Droplet breakup of micro- and nano-dispersed carbon-in-water colloidal suspensions under intense radiation

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ABSTRACT

Carbon-in-water suspensions (CWS) have unique optical properties and have received increasing interest recently for various applications. In the field of combustion science, CWS have been recommended as a substitute for the traditional fossil fuels. The idea is to suspend carbon (coke or coal) particles in water and then inject them as a spray into a gasifier or boiler. The potential benefits are lower emissions and higher combustion efficiency, in comparison to directly injecting coal particles into air or water steam. Nevertheless, few studies have examined CWS colloidal fuels. Especially, droplet breakup can occur when the droplets are exposed to radiation. The goal of this paper is to understand droplet breakup mechanism of CWS under intense radiation. An experiment was developed to visualize the breakup process and to measure the threshold radiation intensity required for explosion at varying particle concentrations and sizes as well as droplet sizes. The results show that radiation absorption by the carbon particles play a critical role in the breakup behavior. A theoretical model was also developed to determine the effects of the particle material, size, and concentration on the threshold radiation energy.

1. Introduction

Carbon-in-water suspensions (CWS) have unique optical properties and have attracted great interest recently for various applications. For example, they can be used as a nonlinear optical limiter, a protective device whose transmission is rapidly decreased with increasing of the incident radiation [1]. In the combustion field, carbon (coke or coal)-in-water suspensions have been recommended as a substitute for traditional fossil fuels for use in boilers and gasifiers. Because of its low emissions and low BTU costs, CWS can be environmental friendly and cost-effective for heat and power generation [2]. Nevertheless, few studies have examined CWS colloidal fuels. Especially, droplet breakup can occur when the droplets are exposed to radiation.

Radiation-induced droplet breakup of pure liquids or liquid mixtures has been studied previously [3–5]. The mechanism is well understood, especially for water droplets: the high intensity radiation from a laser produces a plasma; unlike water which is almost transparent to the incident radiation, the plasma absorbs much of the laser energy and converts it to heat; explosion takes place when the superheating temperature of the liquid nearby the plasma is reached. However, there are fewer studies on the breakup of colloidal suspensions under radiation (explosive boiling) [6–8], for which the breakup mechanism is completely different from that of pure liquids.

Explosive boiling has been observed for aluminum slurry [9], aluminum nanofluid [10], and coal–oil mixtures [11]. Maloney and co-workers [6–8] studied the explosive boiling behavior of CWS droplets, in which radiation was generated by a pulsed Nd:YAG laser with 1064 nm wavelength and a heating time of around 8 ms. It was proposed that the internal superheating and explosive boiling were caused by the fuel additives (the surfactant), which formed a thin film at the droplet surface [7]. The other study [8], however, suggested that the breakup was caused by the coal particles in the outer layer of the CWS droplet absorbing radiation energy, and the heat was then transferred inward through internal conduction causing droplet breakup.

Note all previous studies used coal particles of a size in the range of submicrons to a few hundred microns. Recently, nano-dispersed coal-in-water colloidal fuels have received increasing interest. They are nonsettling colloidal dispersions of nano-sized carbonaceous materials with water and have shown outstanding long-term stability, high combustion efficiency, and less soot formation [12]. No studies have examined the radiation-induced droplet breakup of nano-dispersed colloidal fuels. We believe that

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the size of the coal particles suspended in water plays a vital role in the explosive boiling behavior.

The objective of this study is to understand the mechanisms that are responsible for the radiation-induced droplet breakup of micro- and nano-dispersed CWS, especially the influence of carbon particle size. An experiment was developed to visualize the droplet breakup process and to measure the threshold radiation energy (or flux) under various conditions (droplet diameter, and particle size and concentration). Moreover, a theoretical model was developed to further understand the mechanism of radiation-induced droplet breakup and to determine the effects of the particle material, size, and concentration on the threshold radiation energy and the explosive boiling behavior.

2. Experimental method

2.1. Fuel preparation and morphology

Carbon particles of three different kinds were selected and mixed with water to generate CWS colloidal fuels: (a) diamond particles with a mean diameter of 6 nm; (b) activated carbon particles with a mean diameter of 100 nm; and (c) graphite particles with a mean diameter of 20 μm. Fig. 1 shows the Scanning Electron Microscope (SEM) photographs of these particles. For 6-nm and 100-nm particles, their shapes are mostly spherical, and the sizes are nearly uniform. For 20-μm particles, they have a size range of 1–35 μm and are more random in shape.

The carbon particles were dispersed into water using an ultrasonic disruptor (Sharpertek, SYJ-450D). It delivered a series of 4-s-long pulses 4 s apart to disperse particles evenly and to reduce agglomeration. It was turned on for about 6 min for each CWS sample. In this study, we added no surfactant, which could have enhanced the chemical stability of the colloidal suspensions. This was because adding a surfactant complicates the understanding of the mechanism that causes explosion. However, the experiments were conducted shortly after the fuel was prepared; thus the influence of particle agglomeration was minimized. A syringe pump running at a low flow rate was used to generate a droplet at a desired size (the range of the droplet size is 0.9–2.0 mm). The droplet was then transferred to the suspension point by another syringe.

2.2. Experimental setup

The schematic of the experiment is shown in Fig. 2. The CWS droplet was suspended on a silicon carbide (Si-C) fiber with a diameter of 70 μm. The droplet evaporation and explosion processes were recorded by a high-speed digital video camera (Phantom V7.3, Vision Research). A microlens was coupled with the camera to capture the magnified view of the droplet, and an LED light was also used to provide backlight for the camera.

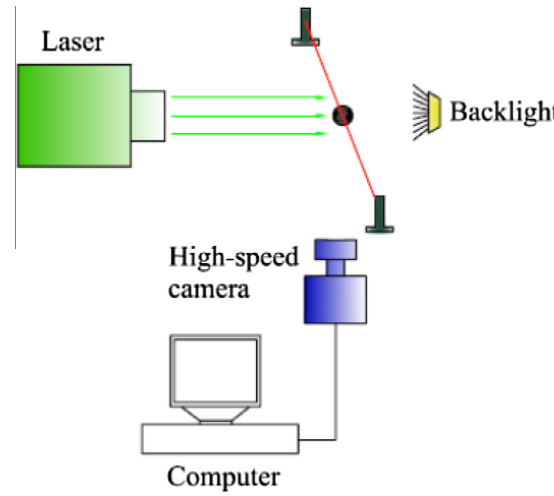

Fig. 2. Schematic of the experiment setup for radiation-induced explosive boiling of CWS fuels.

A dual-pulsed Nd:YAG laser (Evergreen 200, Quantel) with a 532-nm wavelength and 10-ns pulse width was used to irradiate the CWS droplet. At the visible wavelength, the water is weakly absorbing so that most of the radiation energy is absorbed by the particles in the droplet. The highest pulse energy of the laser is 200 mJ. The pulse energy can be adjusted from the front panel of the laser and by altering the time delay between the Q-switch and the flash lamp. The energy level from the laser was confirmed by measuring the beam energy, using an energy meter. The laser provided flattop and uniform near-field beam with a diameter of about 6.35 mm. In the experiment, the laser was controlled to last only one pulse. Therefore the heating time was fixed at 10 ns. The thresholds were determined by gradually increasing the energy intensity until the explosive fragmentation was reached. If no fragmentation had been achieved at a certain energy intensity, a new droplet with the same size was used for the next round of irradiation with increased energy intensity.

3. Theoretical modeling

3.1. Fundamental mechanism of radiation-induced colloidal droplet breakup

When a colloidal droplet is exposed under a collimated laser beam, the particles inside the droplet will move as a result of the photophoretic force. Following Tong's photophoresis model

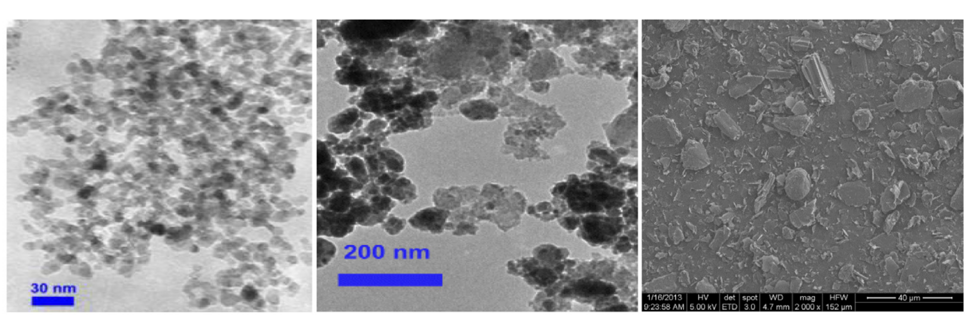

Fig. 1. SEM photographs of different carbon particles: (a) diamond particles, 6 nm; (b) activated carbon particles, 100 nm; and (c) graphite particles, 20 μm.