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Evaporation characteristics of dual component droplet of benzyl azides-hexadecane mixtures at elevated temperatures

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HIGHLIGHTS

- Evaporation characteristics of benzyl azides-hexadecane (BAH) droplet are studied.
- BAH droplet shows three-staged evaporation characteristics at high temperatures.
- Puffing and incomplete micro-explosion are observed during BAH droplet evaporation.
- Droplet lifetime of BAH is shorter than that of dodecane–hexadecane at high temperatures.
- Liquid-phase reaction of benzyl azides improves the evaporation of BAH droplets.

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ABSTRACT

The evaporation characteristics of different dual component droplets are experimentally studied through a suspended droplet device and a high-speed video camera. The droplets of hexadecane, dodecane–hexadecane mixture and benzyl azides-hexadecane mixture are studied. The initial diameter of droplet is about 1.21–1.23 mm, and the elevated temperature environment in the range of 473 and 773 K is provided by an electric furnace. The results indicate that the evaporation trend of the dodecane–hexadecane blend droplet is the same as hexadecane at the different ambient temperatures, while the evaporation characteristics of the benzyl azides-hexadecane blend droplet are completely different from that of the dodecane–hexadecane at the high temperature of 673 K. The evaporation process of the benzyl azides-hexadecane blend droplet consists of three stages: transient heating, fluctuation evaporation and steady evaporation at the high ambient temperatures. The bubble formation and expansion, droplet distortion, puffing and incomplete micro-explosion are observed for benzyl azides-hexadecane droplet due to the reactivity of benzyl azides at liquid phase. Moreover, the reduction of the benzyl azides-hexadecane blend droplet lifetime is larger than that of the dodecane–hexadecane blend droplet with increasing ambient temperature. The increase of the liquid-phase reaction rate of benzyl azides is the main reason for improving the evaporation of the binary fuel droplet. In addition, with increasing benzyl azides mass fraction, the benzyl azides-hexadecane binary droplet lifetime decreases.

1. Introduction

The increasing demand for high-power-density engines has raised researchers' interest on increasing engine speed and brake mean effective pressure (BMEP), both of which would lead to inefficient combustion due to the decrease of cycle duration and the increase of fuel demand. Thus rapid combustion has become the key technique issue that affects the engine power output.

The traditional solutions have mainly focused on using a high-pressure injection system, a high-pressure-ratio turbocharger and optimizing the combustion system parameters [1–7]. However, fuel properties also have a strong impact on the mixture formation and subsequent combustion process, and a number of attempts have been carried out. Rakopoulos et al. [8] investigated the combustion and emission characteristics of a diesel engine fueled with n-butanol diesel fuel blends. Compared to diesel, during the starting event, the n-butanol blend resulted in lower exhaust gas opacity and higher NO emission. Xiao et al. [9] dissolved liquid CO_2 into diesel, which improved the fuel atomization and significantly reduced NO_X emissions. Chang et al. [10]

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investigated water-containing acetone–butanol–ethanol diesel blends in diesel engines, and improved energy efficiency and reduced pollutant emissions. These studies have mainly focused on reducing the fuel consumption and emissions. However, Lee and Bae [11] applied JP-8 in a heavy-duty diesel engine and found that JP-8 combustion was accelerated primarily by the increase of vaporization of JP-8, which inspired us to design a fuel blend to achieve rapid combustion under high engine speeds.

Azides are a class of compound with a generalized formula of $R–N_3$ which contains high energy density. The exothermic decomposition of the middle nitrogen–nitrogen bond and the formation of nitrogen are main features of this class of compound and can result in significant energy release. Generally, the decomposition temperature of azides is in the range between 423 and 473 K [12]. Because of its high energy density, extensive studies have attempted to utilize these compounds as high power density solution. Specifically, Lee et al. [13] investigated the vaporization and combustion behavior of n-alkanes with one N_3 substitution at one end of the carbon chain, and two N_3 substitutions at both ends. Results showed that, compared with the conventional hydrocarbon fuels, droplets of azido fuels gasify significantly faster. It is believed that such strong responses are caused by the exothermic decomposition of the azides in the liquid phase. The energy released by the decomposition of azides may increase the temperature and thus the overall droplet vaporization rate, and then the released nitrogen will lead to micro-explosion within the liquids, which induces secondary atomization and promotes mixing, leading to rapid combustion. Based on the above analysis, it is clear that mixing azides with diesel fuel is a promising approach to accelerate the combustion process.

In our previous study, a diesel-benzyl azides blend was prepared with a mass fraction of 10% benzyl azides, and its physical and chemical properties were analyzed and an experimental study in a single-cylinder engine was carried out [14]. The results showed that, compared with diesel, the diesel-benzyl azides blend leads to shorter combustion duration. The heat released and the nitrogen produced through the liquid-phase reaction of benzyl azides are attributed to this combustion acceleration. Subsequently vaporization characteristics of diesel-benzyl azides blend droplets were investigated through an experiment at high ambient temperature [15], and the diesel-benzyl azides blend droplet lifetime was found to be shorter than that of diesel droplet at 933 K, and also puffing and incomplete micro-explosion were observed. However, diesel is a mixture consisting of several species with a wide range of physical properties. The degree of volatility, boiling temperature, evaporation latent heat, surface tension, and heat capacity of each component also affects the interior thermo-fluid dynamics of droplet. The evaporation of the more volatile components with lower boiling temperature produces bubbles within the droplet and leads to puffing or micro-explosion [16,17]. The mechanism of the accelerated evaporation of diesel by benzyl azides blending has not been revealed. Therefore, in order to distinguish effect of the liquid-phase reaction of benzyl azides on the mechanism of vaporization induced micro-explosion, two different blends of benzyl azides-hexadecane (bah) and dodecane–hexadecane (dh) have been examined in this paper. Normal hexadecane as a representative for diesel has been selected to eliminate its multi-component effect, and normal dodecane as a high volatile fuel has been used with normal boiling temperature 491 K, which is close to the boiling temperature of benzyl azides.

Although the droplet suspension technique has the disadvantage that heterogeneous bubble nucleation occurs on the surface of the wire, it has still been widely used to investigate the evaporation characteristics of fuel droplet because of its convenient manipulation in droplet temperature measurement. Watanabe et al. [18] investigated the breakup characteristics of the secondary atomization of emulsified fuel droplets suspended from an R-type thermocouple. Ghassemi et al. [19] studied the binary droplet evaporation characteristics at elevated pressures and temperatures by suspending the droplet from a fine quartz fiber. Gan and Qiao [20] investigated the evaporation characteristics of fuel droplets with the addition of nanoparticles under natural and forced convection by suspending the fuel droplets from a thin K-type thermocouple. Because it is important to estimate at which temperature the liquid phase reaction of the benzyl azides occurs, it is reasonable to choose the thermocouple as suspension wire.

In this study, in order to analyze the effect of liquid-phase reaction of benzyl azides on droplet evaporation, the evaporation characteristics of the binary fuel droplets with different benzyl azides mass fractions are experimentally investigated in detail. The histories of droplet temperature and size are simultaneously analyzed by droplet thermocouple suspension method coupled with photographic technique.

2. Experimental setup and materials

2.1. Experimental setup

Fig. 1 shows a schematic diagram of the single-droplet evaporation experimental apparatus. A droplet (1.21–1.23 mm) is suspended at the welding point of a thermocouple wire with a diameter of 0.127 mm, by which the temperature of the droplet is measured. The droplet is pushed into the electric furnace by the electric push device, and the evaporation process is observed through a high speed camera.

Two quartz glass windows with dimensions of 230 mm $\times$ 40 mm $\times$ 20 mm are installed in the front and rear sides of the furnace to provide the windows for the camera and backlight respectively. The temperature inside the furnace is controlled by a temperature controller, which can adjust the output power of the furnace through the temperature detected by the K-type thermocouple temperature sensor. The maximum temperature is about 1000 K. The temperature control accuracy is about ±5 K, and the internal temperature of the furnace has been tested and good stability is assured. A small hole with diameter of 8 mm is made at the top of the furnace through which the droplet is pushed to the target position, where the high-speed camera is focused.

In order to prevent the droplet from being preheated by the furnace before the droplet arrives at the target position, water jackets are designed between the outside wall of the small hole and the inside wall of the furnace. The circulation of the water inside water jackets is maintained by a water pump to remove heat from the furnace. In addition, the time taken by the droplet to arrive at the target position is minimized by controlling the speed of the stepper motor to reduce preheating of the droplet. However, a large speed of the stepper motor can induce the droplet falling off from the suspended thermocouple. The transmission speed of droplet is set about 300 mm/s in the present study to satisfy the requirements, and the speed provides the time of a droplet entering into the furnace shorter than 0.3 s.

2.2. Data analysis

The general behavior of the droplet evaporation process is recorded by a high-speed video camera (Photron brand Fastcam SA4). The different recording speed is selected at different ambient temperatures. At the low temperature, 100 fps is selected for image recoding, whereas at the high temperature, to record the partially micro-explosion, 500 fps is used. Using high-resolution image diminishes the error in droplet size extraction via image