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Evaporation characteristics of acetone–butanol–ethanol and diesel blends droplets at high ambient temperatures

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HIGHLIGHTS

- Evaporation characteristics of acetone–butanol–ethanol (ABE) and diesel blends.
- Droplet lifetime of ABE is shorter than that of diesel at all test conditions.
- Droplet evaporation process of ABE–diesel blends varies with ambient temperature.
- For ABE–diesel droplets, bubble formation and rupture are seen at high temperatures.

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ABSTRACT

In order to decrease the production cost of butanol, acetone–butanol–ethanol (ABE) as the intermediate product of butanol production has drawn increased attention recently because of its possibility to be a renewable fuel. In this study, the evaporation characteristics of ABE and diesel blends droplets have been investigated experimentally through droplet suspension technique at different ambient temperatures (423–823 K) under normal gravity and atmospheric pressure. The results show that the droplet lifetime of ABE is always shorter compared to diesel. However, the difference in droplet lifetime between ABE and diesel decreases with increasing ambient temperature. The ABE–diesel blends also evaporate faster than diesel. The droplet evaporation characteristics of ABE–diesel blends vary with ambient temperature. At high temperature, the droplets exhibit the expansion and shrinkage phenomena due to bubble formation and rupture. Thus the droplet evaporation shows the three-phase evaporation characteristics. The bubble formation and rupture are strengthened at higher temperature. Strong puffing is observed during the ABE–diesel blends evaporation process at 823 K.

1. Introduction

In recent years the world is confronted with the twin crises of fossil fuel depletion and environmental degradation. In this context, the research for alternative renewable energy has been drawn increased attention in the past few decades [1]. For example, China has pledged to decrease 15 million tons of conventional fossil fuel consumption by adopting renewable fuels.

Among various renewable fuels, alcohol is considered to be a promising renewable fuel because of its low boiling point, high latent heat of vaporization and oxygen content [1–4]. The application of alcohol as a supplementary compression ignition engine fuel could promote air–fuel mixing, increase the combustion efficiency, reduce the peak combustion temperature, and thus lead to lower exhaust emissions. Methanol and ethanol are two common types of alcohol, which are widely investigated. However, several factors prohibit the use of methanol and ethanol in diesel engines, including their solubility in diesel, as well as low cetane number and heat value, etc [5,6]. Compared to methanol and ethanol, butanol is an appropriate renewable fuel that has a number of desirable properties for its application in diesel engines, because it is less hydrophilic, has a higher cetane number and heat value, a lower vapor pressure, and a much greater miscibility with diesel [7]. The previous studies have reported that butanol–diesel blends show the satisfied exhaust emissions and engine performance [8–10].

Butanol is mainly produced by acetone–butanol–ethanol (ABE) fermentation from biomass feedstock. The fermentation products contain acetone, butanol and ethanol with the volumetric ratio of approximately 3:6:1. Based on the production data of an average industrial ABE plant in 2008 in China, the production cost of ABE

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was about $1440/ton [11]. However, the separation of butanol from dilute fermentation broth requires high cost and extra energy consumption [12], which reduces the economic value of butanol as an alternative fuel. In addition, acetone, ethanol and butanol are oxygenated compound. If ABE could be directly used for spray combustion, the separation cost would be eliminated. It is in this respect that the related investigations of ABE as a renewable fuel have been conducted. Chang et al. [13] investigated the ABE–diesel blends and water-containing-ABE–diesel blends in both diesel engine generator and diesel engine dynamometer. They found that the ABE–diesel blends even with small amount of water (0.5–1.0 vol.%) were stable in the stability tests. The water-containing-ABE–diesel blend could overcome the trade-off between particulate matter (PM) and nitrogen oxides (NOx), such as ABE20W0.5 (a diesel emulsion with 20 vol.% ABE-solution and 0.5 vol.% water). Meanwhile, ABE20W0.5 showed better break thermal efficiency. That might be caused by micro-explosions, which enhanced the atomization of fuel spray and allowed more complete combustion. Zhou et al. [14–16] investigated the spray combustion characteristics of ABE and diesel blends in a constant volume chamber under both conventional diesel combustion and low temperature combustion conditions. They found that ABE–diesel blends had longer ignition delay and soot lift-off length compared with pure diesel. The ABE–diesel blends presented better combustion efficiency and lower soot emission especially at low temperature combustion conditions. In addition, the authors indicated the drastically different volatilities of components in ABE–diesel blends that greatly favored the occurrence of micro-explosion might result in better atomization and air–fuel mixing, which partially explained the superior combustion performance of ABE–diesel blends at low temperature combustion conditions. As the above studies mentioned, ABE–diesel blends is a type of multi-component fuel with drastically different volatilities, which may produce micro-explosions and thus promote combustion performance. However, we still lack the fundamental understanding of the evaporation characteristics of ABE–diesel blends, and the effect of fuel properties on the ABE–diesel blends evaporation characteristics has not been revealed. Moreover, as the spray combustion is essentially the evaporation and combustion of a large number of droplets, given the complexity of studying the evaporation of droplets in a spray, one alternative approach used is to study the evaporation of a single droplet of fuel to analyze the effect of fuel properties on the evaporation process [17]. Motivated in this regard, the droplet evaporation characteristics of ABE–diesel blends were investigated in this study. As far as the authors know, such a study has not been performed.

Meanwhile, the droplet suspension technique is widely used to investigate the evaporation characteristics of fuel droplet. A very small droplet is usually suspended on an extremely fine suspension wire and quickly places it under specified environment to study the evaporation characteristics of the droplet by recording changes in certain aspects of the droplet during evaporation process. Morin et al. [18] investigated the vaporization of rapeseed and sunflower oil methyl ester droplets at high temperatures (473–1020 K) by suspending the droplet at the tip of a quartz fiber. Watanabe et al. [19] used the droplet suspension technique to investigate the characteristics of puffing of an emulsified fuel saturated with CO_2. They found that puffing behavior of the carbonated emulsified fuel was more violent than that of the degassed emulsified fuel because the dissolved CO_2 caused a reduction in the bubble nucleation energy. 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 at low convection temperatures (300–380 K). It showed that the pure liquid droplets evaporation followed the classical d^2 law. However, the blended droplets exhibited a departure from the classical d^2 law at low forced convection temperatures. Ghassemi et al. [21] studied the evaporation characteristics of single and multicomponent droplets hanging at the tip of a quartz fiber at elevated pressures and temperatures. Heptane and Hexadecane were selected as the experimental fuels. They found that the binary droplet evaporation showed the three-staged evaporation, which was completely different from a single component droplet. The evaporation of the binary droplet was accompanied with bubble formation and droplet distortion at elevated temperature and low pressure. In the subsequent works, they studied the evaporation characteristics of HAN-based monopropellants, kerosene and heptane with the addition of aluminum nanoparticles using the same experimental apparatus at elevated temperature and atmospheric pressure [22–24]. Hashimoto et al. [25] investigated the evaporation characteristics of a palm methyl ester (PME) droplet at high temperatures. They found that the droplet lifetime for PME was longer than that for diesel, and the droplet lifetime decreased with increasing ambient temperature for all fuels.

In this study, the evaporation characteristics of ABE and diesel blends droplets at high ambient temperature and atmospheric pressure were investigated in detail. Droplet evaporation experiments were conducted on a high-temperature chamber by the fiber-suspended droplet technique.

2. Experimental methods

2.1. Fuel preparation

In this study, ABE, diesel and their blends have been examined. The ABE solution was first prepared at a volume ratio of 3:6:1 (A:B:E). Analytical grade acetone (99.5%), n-butanol (99.5%) and ethanol (99.8%) were selected. Then the ABE solution was blended with the commercial diesel to obtain different mixing ratio of ABE–diesel blends. For ABE–diesel blends, ABE10, ABE20 and ABE30 represent the 10%, 20% and 30% volumetric percentages of ABE in blends. Furthermore, the previous studies have suggested that ABE–diesel blends remain stable without any surfactant addition [13]. Some fundamental physical properties of the acetone, butanol, ethanol and commercial diesel employed in this present paper are compared in Table 1 [14–16].

2.2. Experiment apparatus

Fig. 1 shows a schematic diagram of the droplet evaporation experimental apparatus. A droplet was suspended at the tip of a quartz fiber of 120 μm diameter with an enlarged extremity of 200 μm by a micro syringe. To control the size of a suspended droplet, the micro syringe with range of 2 μL and precision of 0.04 μL was chosen. The initial diameters of the suspended droplets were generally at the range of 0.8 mm to 0.91 mm. After the suspension

Table 1
Fuel properties.

Properties	Diesel	Acetone	Butanol	Ethanol
Molecular formula	C_{12}–C_{25}	C_3H_6O	C_4H_9OH	C_2H_5OH
Cetane number	53.1	–	25	8
Density at 288 K (g/cm^3)	>0.8335	0.791	0.813	0.795
Oxygen content (%)	<0.2	27.6	21.6	34.8
Kinematic viscosity at 313 K (mm^2/s)	2.293	0.35	2.63	1.08
Low heat value (MJ/kg)	42.77	29.6	33.1	26.8
Flash point (K)	337	290.8	308	281
Boiling point (K)	453–613	329.22	390.88	351.8
Critical temperature (K)	–	508.10	563.05	513.92