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Experimental investigation on spray, evaporation and combustion characteristics of ethanol-diesel, water-emulsified diesel and neat diesel fuels

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ABSTRACT

This paper explored the spray and combustion characteristics of ethanol-diesel (E10), water-emulsified diesel (W10) and neat diesel (D100), especially micro-explosion of E10 and W10. The experiments were conducted in a constant volume combustion chamber under cold (383 K, 0% O_2), evaporating (900 K, 0% O_2) and combustion (900 K, 21% O_2) conditions. Results showed that the spray expansion capacities of E10 and W10 under cold condition were much weaker than that of D100 due to the larger viscosity of emulsified diesels. Under evaporating condition, the spray volume of E10, W10 and D100 increased by 59%, 34% and 21% respectively comparing with cold spray volume. The higher increasing rates of E10 and W10 were mainly due to the micro-explosion effects of ethanol and water contents. Under combustion condition, the integrated natural flame luminosity (INFL) demonstrated that the ethanol content could accelerate the oxidation of soot, while the water content could prohibit soot generation. Therefore, both ethanol- and water-emulsified diesels could inhibit the soot emission, causing lower final residual soot emission of E10 and W10 than that of D100 by 21% and 39% respectively. Moreover, the flame lift-off length (LOL) and flame spread velocity showed that the effects of micro-explosion in E10 and W10 are different. The micro-explosion in ethanol occurred earlier, which enhanced the reaction rate in upstream flame and reduced the LOL. However, the micro-explosion in W10 occurred later, which enhanced the combustion rate in downstream flame.

1. Introduction

The research on alternative fuels in internal combustion engines (ICE) has become one of the hot spots due to the increasing serious environmental and energy problems [1,2]. Using alternative fuels can not only partially replace the traditional fossil fuels and alleviate the dependence on them [3,4], but also reduce the pollutant emissions from ICEs [5,6], making it one of the most promising methods to save energy and reduce emissions. Multi-component alternative fuel with different boiling point components could lead to a unique micro-explosion phenomenon in the spray breakup and evaporation processes [7]. Specifically, the component with lower boiling point could be superheated and experience a drastic evaporation or explosion during the fuel spray and combustion [8,9].

Ethanol gains the attention of many researchers because it is a readily available alternative fuel and has many merits such as renewability, low-pollution and nontoxicity [10–12]. However, it is difficult to use ethanol as a neat fuel directly in diesel engines becauseof its low cetane number and high latent heat [13,14]. So far, there are three methods to utilize ethanol fuel in diesel engines: (1) ethanol fumigation or ethanol injection into the intake port [15–17], (2) dual injection of ethanol and diesel into the cylinder, and (3) injection of ethanol diesel emulsified blends into the cylinder [18,19]. Methods 1 and 2 can use higher ethanol ratio while method 3 can only achieve an ethanol ratio lower than 30% due to the immiscibility. The engine performance has been intensively investigated and the results showed that all the three ethanol utilization methods could reduce soot emissions [20–23]. However, the results on brake specific fuel consumption (BSFC), NOx, CO and HC were inconsistent among publications [24].

To understand the underlying mechanisms, the effect of ethanol on the spray, atomization and combustion processes inside the engine should be investigated [25]. However, comparing to the existed many engine studies, research on the fundamental influence of ethanol on the spray, evaporation and combustion of ethanol-diesel blends is scarce

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and incomplete. Particularly, the effect of micro-explosion on spray and combustion processes of ethanol-diesel blends has rarely been explored deeply.

Diesel-water blend has become an active research topic since Sheng et al.'s study in 1995 [26]. It was reported as a potential alternative fuel to reduce harmful emissions and improve combustion efficiency simultaneously [27,28]. Diesel-water blends could be achieved by three approaches [29], including intake port water injection (WI), direct in-cylinder WI and water-emulsified diesel [30]. Water-emulsified diesel is a kind of emulsion by diesel and water [31,32]. Previous studies [33–38] showed that diesel-water blends could effectively reduce soot and NO_x emissions simultaneously in diesel engines. There are three main underlying reasons. Firstly, water has large specific heat and high latent heat of vaporization, which can reduce the peak combustion temperature and thus reduce the generation of soot and NO_x [39]. Secondly, the water-gas reactions can accelerate the oxidation of soot [40]. Thirdly, the micro-explosion of water could enhance fuel droplet break-up and fuel-air mixing, and consequently decrease the local equivalence ratio and reduce soot generation [41].

Comparing with intake port WI and direct in-cylinder WI, water-emulsified diesel can be used in the conventional diesel engines directly without major modifications. Iwai et al. [42] experimentally investigated the emission performance of neat diesel, intake port WI and emulsified diesels with 15% and 30% water. The results showed that NO_x and soot emissions of water emulsified diesels were much lower than that of neat diesel. Comparing with intake port WI, emulsified diesel with the same proportion of water also had better fuel economy and emission performance. Adopting numerical and experimental study, Samec et al. [43] found a significant emission reduction with no increase in BSFC by using water emulsified diesel. Chen [44] reported that the soot emission of water emulsified diesel was nearly 35% less than that of neat diesel.

However, there were many inconsistent results on the BSFC, brake thermal efficiency (BTE), CO and HC emissions regarding the use of water-emulsified diesel. Some researchers [45,46] reported clear decreasing trends in BSFC with the increase of water concentration in water-emulsified diesel, while some [30,33,47,48] showed that BSFC increased significantly by using water-emulsified diesel. Some researchers [49–56] reported that CO and HC emissions increased by water-emulsified diesel comparing to neat diesel due to the lower combustion temperature [49,50] and more OH radicals dissociated from water [51], while others showed that CO and HC emissions decreased slightly or nearly unchanged by water-emulsified diesel [36,57,58] because micro-explosion improved the fuel combustion process [36,58]. However, the existence of micro-explosion in spray is still in argument [59,60]. The spatial scale of engine spray droplets is very small (10–30 μm) while the spatial scale of experimental droplets for micro-explosion is much larger (larger than 200 μm). In addition, so far, no micro-explosion in spray has been directly observed.

All these inconsistency and arguments are caused by the complicated combustion behaviors of emulsified diesel fuels, including micro-explosion (or puffing), physical and chemical path of fuel emulsion, which need a deeper study. To prove the existence of micro-explosion (or puffing) and to explore the fundamental effect of micro-explosion on spray combustion of emulsified diesel fuels, a joint study on single droplet micro-explosion and spray combustion should be conducted. Our team has begun this joint research [61–64] and this paper is one study in our series research program.

As reviewed above, both ethanol and water additions have promoting effects on the spray, combustion and emissions processes of diesel engines. However, the suspended particle size and physical characteristics of dispersed phase in these two emulsified diesels are very different and thus make the onset and strength of micro-explosion vary significantly [65–68]. Moreover, direct evidence of micro-explosion in the fuel spray under real engine conditions has rarely been observed in experiments and there is still much controversy in this field. Therefore, the effect of micro-explosion on spray and combustion should be analyzed by comprehensive spray and combustion measurements. To better understand the underlying mechanisms and thus facilitate their utilization, in the present study, the spray and combustion characteristics of ethanol-diesel, water-emulsified diesel and neat diesel are optically investigated in a constant volume combustion chamber. Particularly, the possibility of micro-explosion in emulsified diesels with different boiling point additives is inferred and compared. The effects of micro-explosion on spray and combustion processes with equal mass ratio of ethanol and water addition in emulsified diesel are investigated under cold, evaporating and combustion conditions. The reported work sheds light on possible macroscopic effects of micro-explosion in spray, combustion and emission. The effect of micro-explosion in multi-component fuels on the spray, combustion and emission characteristics in this paper improves our understanding of underlying mechanisms on why emulsified diesels improve the spray atomization and reduce the soot emission. The reported work also can to some extent fill the gap on the inconsistent results on the BSFC, brake thermal efficiency (BTE), CO and HC emissions regarding the use of water-emulsified diesel. All these can guide the application of ethanol-diesel and water-emulsified diesel fuels in diesel engines in practice.

2. Preparation of ethanol-diesel and water-emulsified diesel

Ethanol and water are immiscible with diesel due to their polar molecular structures. Therefore, suitable emulsifier is needed to prepare stable ethanol-diesel and water-diesel emulsions [59,69]. In this paper, 0# diesel, 99.8% purity ethanol, distilled water and two emulsifiers, Span-80 and Op-10, were chosen to prepare the emulsified diesels. For better comparison on the effects of ethanol and water additions, same mass ratios of ethanol and water additions were adopted. Hereafter, E10 means the ethanol-diesel emulsion with 10% ethanol by mass, W10 means the water-emulsified diesel with 10% water by mass and D100 means neat diesel.

The Hydrophilic Lypophilic Balance (HLB) value is the guiding index of an emulsifying solution. Higher HLB value indicates that the emulsifier is easier to dissolve in water, while lower HLB value means the emulsifier is easier to dissolve in diesel. The stability of various compositions was tested and Table 1 shows parameters of the stable emulsifying solutions for ethanol-diesel and water-emulsified diesel. The JP300G ultrasonic emulsifier was used to prepare the E10 and W10. The solutions in Table 1 can be kept over 15 days without delaminating, which meet the requirements in this study. The dynamic viscosity measured by a NDJ-8s rotational viscometer is also shown in Table 1. E10 and W10 have greater viscosities because the viscosity of emulsifier is much higher than neat diesel.

3. Experimental setup and procedures

3.1. Constant volume combustion chamber system

Fig. 1 shows the schematic diagram of the pre-burning heated

Table 1
Parameters of E10, W10 and D100.

Fuel	E10	W10	D100
Diesel (g)	1800	1800	2000
Ethanol (g)	200	0	0
Water (g)	0	200	0
Span-80 (g)	56	57.5	0
Op-10 (g)	1.8	4.75	0
HLB	4.6	5.0	0
Density (kg/m^3 at 20 °C)	812.5	832.0	815.0
Dynamic viscosity (mPa·s at 20 °C)	6.16	6.8	2.26
Lower heating value (MJ/kg)	40.0	37.4	42.8