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Effects of water content on evaporation and combustion characteristics of water emulsified diesel spray

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HIGHLIGHTS

- The influence of micro-explosion on water emulsified diesel spray is concluded.
- Water emulsified diesel spray exhibits greater volume expansion from 383 K to 900 K.
- Ignition delay and flame lift-off length of test fuels are prolonged by water content.
- Natural flame luminosity decreases obviously with the increase of water content.

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ABSTRACT

Due to its potential of reducing NOx and soot emissions simultaneously while improving thermal efficiency, water emulsified diesel is considered as one of the most promising fuels for compression ignition engines. In this study, spray and combustion characteristics of neat diesel and water emulsified diesel with various water contents (10%, 20% and 30% by mass) were investigated. The influence of micro-explosion on high pressure spray characteristics of water emulsified diesel was optically observed and discussed. Experiments were conducted in a constant volume combustion chamber with a high-speed schlieren system to capture the spray and combustion processes. The results show that water content plays a significant role in affecting spray and combustion characteristics of water emulsified diesel. Under non-evaporating condition, the spray tip penetration increases with the water content but the corresponding spray angle decreases with the water content. Such an effect was found diminishing under evaporating condition. The spray volume of test fuels increases from non-evaporating to evaporating condition, and the relative volume increase of water emulsified diesel is at least 5 times higher than that of neat diesel. Both the ignition delay and flame lift-off length increase with water content. Consequently, the integrated natural flame luminosity decreases with the increase of water content. In addition, indirect evidences have proven that the occurrence of micro-explosion can enhance the breakup and evaporation processes of water emulsified diesel spray, and the use of water emulsified diesel can effectively reduce soot emission.

1. Introduction

Compression ignition (CI) engines have been widely used in the fields of transportation, engineering machinery, and electricity power generation due to their higher efficiency and better durability compared to sparking ignition (SI) engines [1]. However, high NOx and soot emissions from CI engine cause a serious pollution problem to the environment [2,3]. Consequently, the emission regulations become globally more stringent in order to limit the pollutant emissions from CI engines. For example, Real-Driving Emissions (RDE) requirement has been launched in Euro to further reduce the particle number (PN) and NOx emissions [4]; a more stringent Euro 6 type mandates for China and India will be implemented by 2020 [5]. More importantly, the concern of fossil fuel depletion has intensified the energy crisis over the past decades [6]. Conventional fossil fuels, such as diesel and gasoline, are expected to remain as the dominant fuels for transportation while new energy sources are being developed [7]. Consequently current researches in CI engines focus on emission control and efficiency

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improvement by new combustion mode [8,9], fuel blends [10,11], and exhaust gas treatment devices [12,13]. The use of multicomponent fuel blends, such as biodiesel/diesel [14,15], alcohol/diesel [16,17], and water/diesel [18,19], in CI engines has been considered as the most promising solutions to decrease emissions and to relieve the energy crisis.

As a promising clean fuel for CI engines, water emulsified diesel has the potential of reducing NOx and soot emissions from diesel engine simultaneously and improving the combustion efficiency without any engine modification [20–22]. Generally, there are two types of two-phase water emulsified diesel fuels, namely water-in-oil (W/O) and oil-in-water (O/W) [23,24]. The W/O emulsified diesel is widely known for its unique structure with water in dispersion phase and diesel in continuous phase. In such a fuel, the water droplets with lower boiling point can experience a rapid evaporation or even explosion under superheat environment, and this phenomenon is termed as micro-explosion [25]. On the contrary, the O/W emulsified diesel is not suitable for diesel engines as the water in the continuous phase could lead to misfire or poor combustion [26]. Experimental investigations have proven the advantages of utilizing W/O emulsified diesel in CI engines. Specifically, due to water's high latent heat and specific heat, using W/O emulsified diesel can reduce the in-cylinder temperature resulting in lower NOx emission [27]. Moreover, the decomposition of water during the combustion process produces a large amount of hydroxyl radicals, which can effectively suppress the generation of NO and promote the oxidation of soot [28,29]. Furthermore, both the evaporation and micro-explosion of water in fuel spray can lead to enhancing droplet breakup, accelerating fuel evaporation and promoting fuel-air mixing, thus reducing soot generation and improving thermal efficiency [30,31].

Past engine experiments indicated that when water emulsified diesel was utilized in CI engines, both the water content and engine load had noticeable influences on the engine performance. However, contradictory results on these two factors were reported. Experiments conducted by Abu-Zaid [32] and Elsanusi [33] demonstrated that with water content less than 20%, the brake thermal efficiency (BTE) of water emulsified diesel increased with the water content. However, Alahmer et al. [34] reported that the BTE reached a maximum value at 5% water content during tests when the water content was increased from 0% to 30%. Fahd et al. [35] showed that the BTE of water emulsified diesel with 10% water was lower than neat diesel for all engine loads and the difference of BTE between these two fuels decreased with increasing engine load. Subramanian [36] reported that the BTE of water emulsified diesel with high water content (40% by mass) was lower than that of neat diesel at low load condition, while the BTE of water emulsified diesel could slightly exceed that of neat diesel's under high engine load condition. In order to clarify the observed inconsistent engine performances with different water contents and engine loads, further research is essential to reveal the underlying mechanism of elevated water content on spray atomization, evaporation and combustion process of water emulsified fuels.

Due to its positive influences on spray evaporation, combustion, and emission processes, micro-explosion phenomenon has been investigated for decades [37,38]. Interest in this field is currently renewed with the improvement of emulsion technologies and the development of high pressure injection system in diesel engines [39,40]. An experimental investigation of emulsified fuel droplets by Watanabe et al. [41] reported that the micro-explosion phenomenon is highly influenced by superheat temperature and water content. In particular, the intensity of micro-explosion was enhanced with the ambient temperature. Huo et al. [42] investigated the effect of micro-explosion on reacting spray in a constant volume combustion chamber and the occurrence of micro-explosion was observed in the central lift-off region of a burning spray flame under higher temperature conditions. The water content of emulsified diesel is well recognized as another important factor affecting the onset and intensity of micro-explosion, which subsequently influences the physical and chemical processes of spray and combustion [43]. With the increase of water content, both the amount of dispersed water droplets and the size of dispersed water droplets increase [24]. As such, the stability of internal structure is reduced and more surfactant is needed to obtain kinetically stable emulsified fuel [44]. Consequently, increasing water content in emulsified fuel can increase the fuel density and viscosity [45], for which the radial expansion capability of fuel spray is reduced [46,47]. However, micro-explosion is intensified to some degree with the increase of water content from 10% to 30% [48,49], while excess water content in emulsified fuel is reported to have a negative effect on spray combustion [50]. Therefore, the influence of water content on spray and combustion characteristics is rather complex due to the trade-off relationship between the increased viscosity and the enhanced micro-explosion behavior. However, a comprehensive investigation concentrating on the effects of ambient temperature and water content on spray, micro-explosion and combustion characteristics, under high injection pressure diesel engine-like conditions is rarely reported.

In this study, the impact of water content on spray and combustion characteristics of water emulsified diesel was investigated. Water emulsified diesel with 10%, 20% and 30% water by mass (W10, W20 and W30) were employed as test fuels with neat diesel (W0) as the reference fuel. Experiments were conducted in a constant volume combustion chamber, and a high-speed COMS camera combined with a schlieren system to visualize the spray and combustion processes. Macroscopic characteristics, such as penetration, spray angle, and spray volume, were deduced from the schlieren images using a MATLAB based algorithm. The influences of water content on atomization, evaporation, and micro-explosion of water emulsified diesel fuel sprays from a high-pressure injection system were analyzed and discussed. These effects on spray process were then correlated with the observed combustion and emission characteristics. The current results intend to shed some lights on the observed inconsistency of the effects of micro-explosion on spray and on BTE in engine performances using water emulsified diesel.

2. Preparation of water emulsified diesel

In general, water is immiscible with diesel due to the different polarities between water and diesel molecules. Therefore, surfactant and mechanical agitation are essential to obtain kinetically stable water emulsified diesel. The surfactant molecule consists of a hydrophilic head and a lipophilic tail, and this special molecule structure can weaken the polarity between water and diesel molecules [51]. The hydrophilic-lipophilic balance (HLB) value of surfactant is a useful parameter when preparing emulsified fuel. A high HLB value indicates that the surfactant molecule is hydrophilic, while a low HLB value means that the surfactant is lipophilic [52]. In this study, two surfactants Span-80 (HLB = 4.3) and Op-10 (HLB = 14.5) were chosen and the HLB value of a combined surfactant system can be calculated by Eq. (1),

$$\mathrm{HLB} = \frac{HLB_S \times W_S + HLB_O \times W_O}{W_S + W_O}, \tag{1}$$

where W_s and W_o stand for the weight percentages of Span-80 and Op-10 respectively ($W_s + W_o = 1$). In order to obtain a stable W/O type water emulsified diesel, neat diesel, distilled water, and surfactants were mixed by an ultrasonic emulsifier for 30 min. Experimental tests indicated that water emulsified diesel with 10%, 20% and 30% water prepared by a surfactant with 5 HLB value was more stable than others and could maintain for over 15 days without layer formation at 25 °C. Detailed components of test fuels are tabulated in Table 1.

It is well known that the atomization and evaporation characteristics of a diesel spray are highly influenced by the physical fuel properties, such as density, viscosity, and surface tension. In this paper, a rotary viscometer (LVDV-1T) combined with a thermostatic water

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