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Superheat limit and micro-explosion in droplets of hydrous ethanol-diesel emulsions at atmospheric pressure and diesel-like conditions

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ABSTRACT

Micro-explosion of emulsified fuels has been studied on promoting the secondary break-up and improving fuel-air mixing. However, most studies are limited to atmospheric conditions, and experimental observation of micro-explosion under diesel-like conditions is rarely reported. The predictive model for the superheat limit of hydrous ethanol-diesel emulsion needs to be re-examined. In this study, firstly, with the molecular kinetics theory a mathematical model for predicting the superheat limit of hydrous ethanol diesel emulsions are established. Then, the model is verified by the experimental results of micro-explosion in the emulsion droplets. The superheat limit is independent of volume fraction of hydrous ethanol in the emulsions. The intensity of micro-explosion obeys the parabolic rule when changing volume fraction of the hydrous ethanol. The intensity of micro-explosion with the homogeneous nucleation is higher than with the heterogeneous nucleation. The emulsions of 30% and 40% hydrous ethanol exhibit the higher probability for the homogeneous nucleation than the other emulsions. Finally, the droplet behaviors of the emulsions under the diesel-like high-pressure conditions are experimentally observed. While the micro-explosions can be clearly observed for some droplets, neither the micro-explosion nor puffing are observable for most other droplets. The mechanism behind the phenomena is discussed.

1. Introduction

Given growing population and stringent emission regulations, utilization of clean alternative fuel is becoming more urgent and attractive. Therefore, a number of research works have been conducted to focus on development and application of bio-fuels and their blends. Yang et al. [1,2] utilized nonedible biomass, such as cedar sawdust, coffee bean residue, and rice straw, to produce the bio-oil, and they investigated the spray combustion characteristics of the bio-oil and their blends. Chauhan et al. [3] conducted a comparative analysis on the performance, emissions and combustion characteristics between the commercial diesel fuel and the biodiesel derived from non-edible Karanja oil. The results suggested that the biodiesel from non-edible Karanja oil and its blends with diesel could be a potential alternative fuel in the future. Lee et al. [4] investigated the effects of blending ratio of the Karanja biodiesel on the engine performance and exhaust emissions. Mahla et al. [5] carried out the engine test under the dual fuel mode with fueling the Jatropha biodiesel (B20) and the compressed natural gas (CNG) and with the exhaust gas recirculation (EGR) technique. Their results indicated that use of biodiesel or CNG could improve the trade-off between the NOx and smoke emissions at the higher engine loads without significant sacrifice of the performance of the engine.

Bo-ethanol, as a carbon-neutral bio-fuel and renewable energy, has been also considered to have great potential for use in diesel engines as a clean alternative fuel [6–8]. As limit of the production, bio-ethanol is commonly used by blending with diesel fuels. Therefore, pure ethanol is required owing to the high hydrophilicity of ethanol. Shapouri et al. [9] pointed out that the energy consumption during the bio-ethanol refining processes reach to about 37% in the total input energy with the raw material of corn. Martinez-Frias et al. [10] concluded that it can strike a better balance between the energy gain and consumption through use of the hydrous ethanol instead of the highly purified absolute ethanol. To solve this problem, studies found that surfactants can be added into

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blends to form emulsions, which can maintain a stable state for a longer period of time [11,12]. Thus, hydrous ethanol-diesel emulsions have received greater attention in recent years. Chandra et al. [13] carried out an experimental study to find stable micro-emulsions of 200° and 190° proof ethanol to be compatible with the diesel and can be used as an alternative to diesel in CI engines. Lei et al. [14] developed a novel emulsifier "CLZ" and found that the use of ethanol diesel blends with a CLZ can improve the brake thermal efficiency and reduce the equivalent brake-specific fuel consumption. Megaritis et al. [15] investigated the effect of various fractions of water blended bioethanol on the HCCI combustion. They pointed out that the fixed ratio of water-ethanol blending was disadvantageous for reducing the pressure rise rate at higher loads, and the effective load range decreased while the exhaust emissions increased with increasing the water content in ethanol. Gnanamoorthi et al. [16] investigated the influence of compression ratio on the performance, combustion and emission characteristics of a diesel engine by using the ethanol diesel blend added with 1% ethyl acetate plus diethyl carbonate. Noorollahi et al. [17] carried out a full load motor test to examine the effect of various diesel-biodiesel-ethanol blends on the engine performance and exhaust emission. Their results revealed that a best combination in terms of the fuel efficiency, performance and exhaust emissions could be achieved with the D91B6E3 fuel blend. Li et al. [18] carried out a profound investigation on the characteristics of non-evaporating, evaporating and burning sprays of the hydrous ethanol diesel emulsified fuels in a high-temperature high-pressure constant-volume vessel. They revealed that the reduction in the soot particles in the spray flames of hydrous ethanol diesel emulsions is attributed primarily to increases in the ignition delay and fuel-borne oxygen content. The liquid phase penetration in the evaporating spray jet increases drastically with increased hydrous ethanol addition in the emulsions, while the cone angle and tip penetration of the two-phase jet are almost not changed, suggesting little or adverse effects of mixture formation on the soot reduction. However, whether micro-explosion of the emulsion droplets, which may improve the local fuel-air mixing, occurs or not under the diesel-like conditions is still not clear.

Micro-explosion is a phenomenon in the evaporation and combustion processes of multicomponent fuel droplets [19,20]. It has been proved to be beneficial on improving the mixing of dispersed fuel spray by promoting secondary break-up of the mixture. Zeng et al. [21] presented a numerical model of micro-explosion for multicomponent droplets, and they found that the optimum composition and high ambient pressure could be beneficial on the droplet micro-explosion and secondary break-up. Lee et al. [22] conducted a numerical analysis of micro-explosion in multi-component droplets of the ethanol blended bio-fuel. Their results indicated that the secondary atomization of the bio-fuel can occur in the diesel-like condition, and micro-explosion could promote the engine performance by improving the mixing of fuel and air. Watanabe et al. [23] investigated the breakup characteristics of secondary atomization of emulsified fuel with a single droplet experiment. Shinjo et al. [24] pointed out that the degree of breakup can be largely due to interactions among multiple explosions. Mattiello et al. [25] found the micro-explosion can reduce solid particulate emissions in the water-oil emulsion flames. Wu et al. [26] investigated the characteristics of combustion products of kerosene/aqueous phase bio-oil and kerosene/oil phase bio-oil droplets by using thermogravimetric analysis and gas chromatography-mass spectrometry. Their results indicated that the droplet diameter of the pure kerosene changed with the d^2-law, whereas that of the KBO05 varied inconsistently, indicating the occurrence of puffing or partial micro-explosion. Kadota et al. [27] carried out an experimental study on the micro-explosion of an emulsion droplet on a hot surface during the Leidenfrost burning, and investigated the delay and rate of micro-explosion. Jeong et al. [28] investigated the characteristics of auto-ignition and micro-explosion behaviors of one-dimensional arrays of fuel droplets suspended in a chamber with the high surrounding temperature. Most of these studies are focused on the droplets of fuel blends by hanging on the thin thread under atmospheric pressure. Lasheras et al. [29] carried out the experiments to investigate the disruptive combustion of free droplets of multicomponent fuels. Wang et al. [30] studied the combustion and micro-explosion of freely falling two-component droplets, and they found that the micro-explosions can reduce the amount and size of cenospheres.

However, so far almost all the studies on the micro-explosion are limited to relatively low-pressure conditions, the experimental evidence of occurrence of micro-explosion under the diesel-like high-pressure conditions are rarely reported. Until now, it is still controversial about the occurrence of micro-explosion in the spray combustion processes in diesel engines. Wang et al. [31] reported that the possibility of micro-explosion increases with the ambient pressure, but their results were obtained with the ambient pressure below 5 bar, which is far lower than the in-cylinder pressure of diesel engines near top dead center (TDC). They commented the higher cylinder pressure might suppress the occurrence of micro-explosion. Sheng et al. [32,33] claimed that they observed the droplet group micro-explosion in the water-in-oil emulsion sprays under the diesel-like conditions by the holography technique. However, the injection pressure of 20–30 MPa in their study was far lower, resulting in remarkably larger droplets, than those by the modern common-rail high-pressure injection system. The droplet size has been reported to influence significantly on the occurrence of micro-explosion [34]. Fu et al. [35] investigated the water and fuel evaporation rate of the droplets, and they claimed that there is no micro-explosion in the diesel engines fueled with the emulsified fuel as the water evaporated much quickly than the diesel fuel.

On the other hand, relatively little attention has been paid to the mathematical model of micro-explosion, and there is no a general mathematical model for micro-explosion of fuel blends. Avedisian and Glassman [36] proposed a mathematical model in the early days, which has been frequently employed in modeling the micro-explosion till now. Zeng [37] numerically investigated the multi-component fuel vaporization in internal combustion engines based on the Avedisian-Glassman model. Li et al. [38] casted a question on the validity of the nucleation rate (i.e. $J = 106$) in the Avedisian-Glassman model. They argued that the free energy of molecules should not be calculated by the surface tension that is far smaller than that of the experimental results.

Hou et al. [39] examined the micro-explosion characteristics of a single droplet of pyrolysis bio-oil/fuel oil blends using a suspended-droplet heating device. Califano et al. [40] investigated the combustion characteristics of water-in-diesel emulsions in a single drop combustion chamber. Lee et al. [41] studied the micro-explosion characteristics of impinging droplets of water on a hot surface. Zhang et al. [42] investigated the puffing characteristics of BUT50 using the droplet suspension technology under 638, 688 and 738 K. The transient heating duration, fluctuation evaporation duration and total lifetime of the droplets were examined. Khan et al. [43] examined the micro-explosion evolution phenomenon of single droplets emulsions near the Leidenfrost condition. The effect of droplet size and waiting time of micro-explosion were investigated. Mura et al. [44] conducted an experimental comparison between the suspended droplets and the droplets on the surface near the Leidenfrost conditions. Rao et al. [45] investigated the combustion characteristics of various ethanol/Jet A-1 fuel droplets. They found that the secondary droplets may undergo further fragmentation,