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Experimental investigation on effect of ethanol and di-ethyl ether addition on the spray characteristics of diesel/biodiesel blends under high injection pressure

Cheng Zhan, Zehao Feng, Wen'an Ma, Mingzhi Zhang, Chenglong Tang*, Zuohua Huang

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

In this work, a comprehensive experimental investigation on spray characteristics of four blended fuels, including diesel (D100), diesel-biodiesel (DB), diesel-biodiesel- ethanol (DBE), and diesel-biodiesel-diethyl ether (DBDE) has been conducted by using high pressure common rail injection system (up to 200 MPa). The transient spray behavior under various conditions was recorded by high speed photography with scattering light illumination. It is shown that higher injection pressure significantly accelerates the spray tip penetration (STP) evolution due to increased inertia of spray while increase in ambient pressure reduces the STP evolution due to higher gas resistance. With the addition of diethyl ether (DEE) into biodiesel, the STP of blended fuel tends to go down and corresponding projected area increases a lot when compared to DB. By means of particle droplet image analysis (PDIA) optical diagnostic method, spray microscopic parameters such as Sauter Mean Diameter (SMD), droplet diameter distribution probability curve, cumulative volume curve and characteristic diameter have been investigated. Results show that both the injection pressure and ambient pressure have significant influence on the spray microscopic characteristics. In addition, for fixed injection pressure and ambient pressure, when DEE is added into DB blends, the number fraction of smaller droplets increases, though the statistic diameter with peak probability is fixed at a certain value. Furthermore, SMD of the four tested fuels decreases sequentially in the order of DB, D100, DBE, and DBDE, indicating that DEE addition favors the atomization process.

1. Introduction

Diesel engines can operate at a higher compression ratio than gasoline engines without causing the issue of knock or misfire. As a consequence, diesel engines typically obtain higher torque output and thermal efficiency, making it widely used in industrial fields such as on-road and marine transportation (especially for heavy-duty carriage), as well as power generation. But diesel engines are more likely to be used in commercial rather than passenger vehicles and they only account for 1% vehicle market share in China, while this value is 60% in Europe [1]. As it is known, diesel is refined from fossil fuel such as crude oil, which has limited reserves and it has been used as conventional fuel in diesel engines for over a century. In addition, the consumption of fossil fuel by diesel engines results in tremendous environmental impact through pollutant emissions, especially the particulate matter. Rogge and Hilldeman [2] conducted an environmental investigation based on the emission of several types of vehicles in Los Angeles. Their results revealed that consumption of gasoline or diesel in internal combustion engine, contributes more than 21% of atmospheric particulate emissions. The fossil fuel depletion and public concerns on air pollution thus consequently drive the emerging needs for biofuels, which have been reported as being carbon neutral and potential for reducing fossil fuel consumption.

Hill et al. [3] pointed out that a viable biofuel should meet several criteria, including a net energy gain, environmental benefits, being economically competitive and producible in large scale without threatening food safety. However, the biofuel which perfectly satisfies above demands has not been found till now. Biodiesel [4] is typically produced from vegetable oils or animal fats through transesterification reaction process with alcohol. Because of its good solubility with diesel, biodiesel can be used as an additive into conventional diesel in any blending ratios. In addition, the presence of oxygen in biodiesel can significantly reduce soot emission [5]. Extensive engine tests on running biodiesel have been conducted and various kinds of biodiesel have been tested, including soybean oil, rapeseed oil and waste cooking oil based biodiesel. Specifically, Rakopulos et al. [6] evaluated the exhaust emission levels and engine performance of cottonseed biodiesel/diesel blends in a single-cylinder, four-stroke diesel engine. They found that

* Corresponding author.
E-mail address: chenglongtang@mail.xjtu.edu.cn (C. Tang).

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Nomenclature

DEE	Diethyl-ether
D100	Neat diesel
DB	Diesel-biodiesel (80–20% vol.)
DBE	DB-ethanol (80–20% vol.)
DBDE	DB-diethyl ether (80–20% vol.)
PDIA	Particle droplet image analysis
SMD	Sauter mean diameter(μm)
STP	Spray tip penetration (mm)
SCA	Spray cone angle (deg)
ASOI	After start of injection
PDF	Probability density function
CDF	Cumulative volume distribution function

when diesel is blended with biodiesel, higher thermal efficiency and higher brake mean effective pressure is achieved. In addition, their emission measurements showed that burning cottonseed biodiesel leads to reduced emission of unburned hydrocarbon, carbon monoxide and particle matter. Additionally, Lapuerta et al. [7] pointed out in their review that NO_x emissions will be slightly increased when using biodiesel fuels, which can be effectively compensated by injection delay strategy. Zhang et al. [8] compared the combustion characteristics of biodiesel-diesel blends and pure diesel in a turbocharged diesel engine. The similarity of diffusion burning rate was found between blends and diesel, while blends experimented a shorter ignition delay time.

On the other hand, however, biodiesel is bound to several limitations. First of all, running pure biodiesel in engines is not cost-effective. The cost of biodiesel production is higher than that of diesel, and financial support from the local government is required to stimulate its emergence. In addition, considering the higher viscosity and surface tension of biodiesel, the spray and atomization process can't match the same level of diesel under identical experimental conditions, which could results in bad performance of combustible mixture formation. Wang et al. [9] studied the spray characteristics of two kinds of biodiesels blended with basal diesel, and they found that, with the addition of biodiesel into basal fuel, longer spray tip penetration (STP), poorer ambient air entrainment and larger Sauter Mean Diameter (SMD) were found, which is expected to deteriorate the mixture formation process. It gets even worse in cold weather because of the poor cold flow behaviors of biodiesel [10,11], which definitely leads to deteriorated engine cold start performance. As a consequence, in previous engine studies [12,13], biodiesel has typically been blended into diesel with a volume fraction no more than 20%. In addition, it is suggested that blending other biofuels with better mixture formation potential is possibly useful to compensate the deteriorated cold flow behaviors and atomization characteristics by biodiesel blending.

Ethanol is a promising renewable fuel candidate for internal combustion engine. The viscosity and surface tension of ethanol is lower than that of diesel and biodiesel, which favors its spray and atomization behaviors. In addition, the high oxygen content in ethanol can significantly promote oxidation process of unburned hydrocarbon and PM [14]. Fernando et al. [15] evaluated the physical properties of diesel-biodiesel-ethanol (DBE) blended micro-emulsions. They found that the blends could be stable for a long time at a sub-zero temperature and have the similar energy density and better lubricity performance than diesel-biodiesel blends. Shi et al. [16] investigated the emission characteristics of DBE fuel in a four cylinder commercial diesel engine, and their results indicated that DBE shows an average 30% reduction in PM emissions, a general reduction of unburned hydrocarbon, and however, a 5.6–11.4% increase of NOx emissions at their test conditions.

Recently, diethyl ether (DEE) has been reported to be easily produced through industrial dehydrogenation technique by using acid clay catalyst with 90% conversion of hydrous ethanol. The physical properties of DEE, together with neat diesel, soybean biodiesel, ethanol, are presented in Table 1. Considering the high vapor pressure of DEE (approximately 110.2 kPa at 293 K), it is expected that DEE is more likely to result in even better atomization and mixture formation process. This behavior is beneficial for engine starting, especially at cold conditions [17]. In addition, the evaporation latent heat of DEE is higher than that of diesel and biodiesel. Thus blending DEE into either diesel or biodiesel will reduce the highest temperature in combustion process, which is expected to reduce the NOx emission. Bailey et al. [18] did a comprehensive literature review on DEE application in diesel engines. They claimed that the cost of fuel-grade DEE would be only slightly higher than that of anhydrous ethanol and the fuel property varies drastically. The cetane number of DEE is approximately twice that of diesel, and ten times that of ethanol. Presence of DEE in the blended fuels will significantly accelerate the auto-ignition process. What's more, DEE's Reid vapor pressure is much higher than that of ethanol, which implies that DEE possesses better volatility characteristics. The experimental results of Weberdemenezes et al. [19] shows that the mixtures with 5% DEE as additive possesses low fuel density, viscosity and surface tension at a low temperature compared to neat diesel. As to its combustion characteristics and engine performances, Rakopoulos et al. [20,21] evaluated the effect of DEE addition with different blending (8, 16, and 24% in volume) in a standard, single-cylinder, four-stroke diesel engine. They showed that with the increase of DEE blending ratio, the brake mean efficient pressure (BMEP) slightly goes down and brake specific fuel consumption (BSFC) shows a gradual rise due to the lower heating value of DEE. Additionally, Cinar et al. [22] investigated the effect of DEE addition on the regular emissions of a diesel engine fueled with diesel-biodiesel mixtures. When DEE is added into diesel and biodiesel mixture, a significant reduction in PM and CO was observed, with only slight increase in hydrocarbon and NOx emissions accompanied.

Regardless of these mentioned superiorities of DEE, both in engine performances and exhaust emissions, fundamental research work on the basic physical and chemical effects that induced by DEE addition is still quite inadequate. To understand the gas phase chemical oxidation process of DEE, Werler et al. [23] developed a DEE mechanism, which was validated against the measured ignition delay times data from 500 to 1300 K via a shock tube and a rapid compression machine. Considering the modern high-pressure common rail injection systems [24], the quality of mixture formation and injection system are becoming more and more important for a better engine performance and lower emission. We have recently investigated the effects of biofuel such as dibutyl ether, ethanol and bio-diesel blending on the spray characteristics of diesel [25,26], and results show that the spray characteristics such as the spray tip penetration evolution process, the spray cone angle, and

Table 1
Main physical-chemical properties about neat fuels.

Property	Diesel	Soybean Biodiesel	Ethanol	Diethyl ether
Density (g/ml)	0.84	0.87	0.789	0.715
Reid vapor pressure (kPa) @ 25 °C	< 0.2	–	15.8	110.2
Latent heat of evaporation (kJ/kg)	250	200	840	350
Lower calorific value (MJ/kg)	42.5	38.8	26.8	36.8
Cetane number	40–55	> 48	< 8	> 125
Boiling point (°C)	179–329	181–337	77	33
Viscosity (mPa.s) @ 25 °C	2.61	6.79	0.95	–
Oxygen content (wt%)	0	10	34.8	21.6
Carbon content (wt%)	87	78	52.2	64.9
Hydrogen content (wt%)	13	12	13	13.5
Molecular weight	170	296	46.1	74.1