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Experimental investigation on wall film ratio of diesel, butanol/diesel, DME/diesel and gasoline/diesel blended fuels during the spray wall impingement process

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ABSTRACT

Spray wall impingement in the early injection period has been proved be unavoidable in the diesel engine using early injection strategy. The formation of wall film directly affects fuel/air mixture formation, combustion, exhaust emissions and oil quality. In this study, experiments were carried out to investigate the wall film ratio of pure diesel, butanol/diesel, DME (Di Methyl Ether)/diesel and gasoline/diesel blended fuels. The variations of wall film ratio with different injection pressures, impingement distances, impingement angles and blending ratios were compared under both dry wall and wet wall conditions. For both dry wall and wet wall conditions, with increasing injection pressure and blending ratio, wall film ratio decreased, which is the opposite trend to impingement distance and impingement angle variations. Some dimensionless numbers also have been introduced in order to evaluate the effect of each impact factor on the variation of wall film ratio. Results showed that impingement momentum is the major impact factor on wall film ratio when varying the injection pressure or impingement distance. Impingement flow mass is the major impact factor when varying the impingement angle. For different blending ratios, the wall film ratio is mainly influenced by surface tension, followed by viscosity and saturated vapor pressure. In addition, the equations between the wall film ratio and Weber number of the impingement droplet were derived for each test fuel.

1. Introduction

To solve the NOx and soot trade-off problem of the conventional diesel engine, a number of advanced combustion technologies have been studied such as homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI) combustion. In order to realize HCCI and PCCI combustion, the early injection has been utilized widely to prolong the fuel/air mixing duration [1–3]. However, because of the lower gas temperature and density at the early injection timing, some fuel spray unavoidably impinges with the cylinder wall or piston head and formed wall film [4–5].

The wall film formed on the piston head or cylinder wall during the spray wall impingement process is a major source of excessive soot, CO (carbon monoxide) and HC (Hydrocarbon) emissions to the HCCI or PCCI diesel engines, which has been proved by previous studies [6–8]. The increasing trends of the emissions caused by the formation of the wall film could be attributed to two aspect. On one hand, it develop over-rich fuel/air mixture in the impingement region [9–10], on the other hand, pool fires also take place during the combustion process [11]. Except for the adverse impact on the engine emissions, the wall film formed on the cylinder wall also have a dilution effect on the lubricating oil, which will shorten the service life [12].

In order to reduce the wall film mass formed on the piston head of cylinder wall effectively, a better understanding of the wall film characteristics formed during the spray wall impingement process is well needed. Wall film ratio, which is defined as the ratio between the wall film mass formed in the spray wall impingement process and fuel injection mass, is a useful quantity in the analysis of the spray wall impingement phenomena. Mundo et al. [13] Bai et al. [14], Lee et al. [15] O′ Rourke and Amsden [16], and Senda and Fujimoto [17] all raised the models for estimating the wall film ratio based on the single droplet experiments. However, these models did not always provide accurate results, mostly because of their inability to allow for the complex interactions among the impingement droplets which occur in impingement process for diesel-like very dense sprays. Considering the limitation of the investigation on wall film ratio based on single droplet, Arai [18–20] did a series investigations on the characteristics of wall film ratio of real diesel spray wall impingement. The effects of injection pressure, impingement distance, and impingement angle on the wall film ratio were studied. And the empirical relationships between the wall film ratio and the Weber number of the impingement droplet were also derived.

Previous studies show that changing the diesel properties by blending some other fuel is one of the methods to improve the emission level

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of the diesel engine using early injection strategy and reduce the occurrence of spray wall impingement. Considering the cost and safety, some typical blended fuels including the butanol/diesel, DME/diesel and gasoline/diesel have drawn considerable research attention [21–25].

On one hand, the high oxygen content, lower stoichiometric air-fuel ratio and the absence of aromatic and sulfur of these fuels shows a promoting effect on reducing soot and CO emissions which provided a methods to solve the emission problem caused by spray wall impingement. Huang et al. [26], Zheng et al. [27], Lee et al. [28], and Yao et al. [29] all investigated the effects of early injection on the emission characteristics of the diesel engine fueled by butanol/diesel blended fuel. Results showed that compared with pure diesel, with the increase of butanol blending ratio further reduced soot emissions because the long ignition delay period and higher oxygen concentration. However, the variation of CO emission was not obvious. Lee [30–31] did a series of investigations into the combustion and emission characteristics of diesel engines fueled with DME or DME/diesel blended fuel using early injection strategy. Results showed that DME's superior evaporation and high oxygen content characteristics resulted the decrease of spray wall impingement and decreased soot, HC and CO emissions compared with when using diesel. Liu et al. [7] and Zheng et al. [27] researched the effect of gasoline/diesel blended fuels on the emission characteristics of the PCCI diesel engine. It indicated that increasing the blending ratio of gasoline, the soot emission decreased and was lower than the pure diesel conditions.

On the other hand, the better evaporation characteristics of the blended fuels also be proved to be beneficial for limiting the phenomenon of spray wall impingement due to the shorter spray penetration length, smaller droplets and more uniform droplet distribution.

Studies on the spray characteristics of butanol and butanol/diesel blended fuel have been carried on by Lee et al. [32–35]. Results showed that the spray penetration length and spray cone angle of the butanol and butanol/diesel blended fuels were obvious shorter and smaller than the neat diesel spray. Lim et al. [36], Cipolat et al. [37] and Li et al. [38] investigated the spray characteristics of DME/diesel blended fuel in a constant-volume combustion chamber. Results showed that the spray penetration decreased while the spray angle increased as the portion of DME increased. The Sauter mean diameter (SMD) also decreased and shifted the peak of the distribution curve toward smaller particles which made the droplet distribution more uniform. Similar variations of shorter spray penetration length and smaller droplets' SMD with the increase of the gasoline blending ratio were observed for gasoline/diesel blended fuel by *Ma* et al. [39] and Park et al. [40].

Although the blended fuels mentioned above have been used to reduce the occurrence of spray wall impingement, it still cannot be avoided in HCCI and PCCI diesel engines due to the structure design and early injection timing, so the wall film formed on the piston head and cylinder wall during the spray-wall impingement process still affects the in-cylinder mixture formation and further influences the engine emission level. And this is why a better understanding of the wall film characteristics of diesel blended fuels is needed. However considerable work published in recent years about the wall film ratio characteristics are focused on the pure diesel and doesn't include diesel blended fuels. In addition, the research on wall film ratio characteristics are limited in conditions of spray impinging with dry wall, and the conditions of spray impinging with wet wall (covered with lubrication oil film) have not been published in the literature.

Therefore, in this study, experiments were carried out to investigate the wall film ratio of pure diesel, butanol/diesel, DME/diesel and gasoline/diesel blended fuels. The variations of wall film ratio with different injection pressures, impingement distances, impingement angles and blending ratios were compared under both dry wall and wet wall conditions. In order to evaluate the effect of each impact factor on the variation of wall film ratio, some dimensionless numbers have also been introduced. In addition, the equations between the wall film ratio and Weber number of the impingement droplet were derived for each test fuel. The following conclusions can be drawn from this work:

2. Experimental apparatus and procedures

In this section, the experimental apparatus and materials used was introduced. Moreover, the experimental procedures were also explained in details including the determination of the experiment conditions and the measuring method of the wall film ratio, impingement velocity and spray penetration time.

2.1. Apparatus and materials

The constant-volume vessel was used to simulate the environment of the spray-wall impingement process, and the wall film ratio

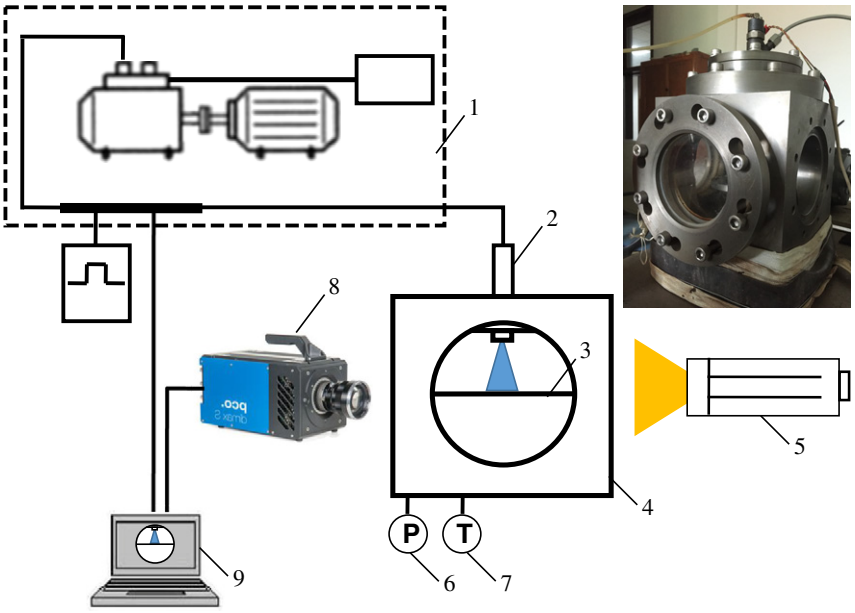

Fig. 1. Visualization system for spray-wall impingement (1 - common-rail system, 2 - nozzle, 3 - impingement disk, 4 - volume constant vessel, 5 - light source, 6 - pressure sensor, 7 - temperature sensor, 8 - ICCD camera, 9 - data acquisition system).