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Full Length Article

Investigation of the macroscopic characteristics of Hydrotreated Vegetable Oil (HVO) spray using CFD method

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ABSTRACT

The main macroscopic characteristics of Hydrotreated Vegetable Oil (HVO) spray in both injection and post-injection periods are investigated via computational fluid dynamics (CFD) in this research. A 2D CFD work employing the Wave breakup model and the KHRT breakup model are validated by the experimental data from a Constant Volume Vessel (CVV). Spray tip penetration and cone angle are obtained by the CFD model under various conditions, where the rail pressure, fuel temperature, ambient pressure and ambient temperature are independently varying. Results demonstrate that the Wave model has overall higher precision in predicting the spray tip penetration and the average cone angle than the KHRT model. By the End of Injection (EOI), spray tip penetration is significantly increased by increasing rail pressure and decreasing ambient pressure. While the average cone angle is larger at high ambient pressure but not sensitive to rail pressure at the cold ambient condition. The average cone angle during injection can be enlarged by high ambient temperature, especially when the rail pressure is also high. Nevertheless, spray tip penetration can only be slightly promoted by high ambient temperature. Fuel temperature has no comparable impact on spray tip penetration and cone angle during injection. In the post-injection period (after the EOI), ambient temperature becomes dominant and spray tip penetration can be reduced by either ambient temperature or fuel temperature. An empirical model is also correlated via Design of Experiments (DoE) and has high precision in predicting spray tip penetration after the breakup time.

1. Introduction

Biodiesel produced by transesterification usually refers to fatty acid methyl esters (FAME). The unsaturated compositions of FAME have an adverse influence on the oxidation stability leading to the limitation on their percentage blending with standard diesel fuel [1]. As a second-generation biodiesel, Hydrotreated Vegetable Oil (HVO) is the mixture of n- and i-paraffin, which are the products of hydrogenation. Compared with biodiesels, HVO has high cetane number and high energy density, and excludes aromatics, naphthene, sulphur and oxygenates, which enables high oxidation stability and high percentage of blending with standard diesel fuel [1,2]. As a result, it is beneficial in improving engine output and reducing emissions. Furthermore, unlike biodiesels, HVO has good storage stability and excellent cold starting without suffering from deposition and low engine output, and thus makes it a superior alternative fuel [3,4].

Previously reported research on HVO mainly focus on its performance in engines or vehicles [5]. For example, Millo et al. [1] studied the emissions of HVO and some other biofuels in a diesel engine and found reduced CO and unburnt hydrocarbons (UHC) but comparable NO_x emissions with standard diesel fuel. Sugiyama et al. [6] did similar research on HVO in an inline 4 cylinder diesel engine at a fixed speed and varying torque and found soot can also be reduced apart from CO and UHC, but NO_x emissions sometimes were higher than standard diesel fuel. Lehto et al. [7] studied HVO in a single-cylinder engine with 30% exhaust gas recirculation (EGR) and demonstrated HVO generated less smoke and can adapt to higher EGR conditions than standard diesel fuel. Singh et al. [8] employed a heavy-duty diesel engine to study the emissions and fuel consumption of HVO. It was reported that the particulate matter (PM), carbon monoxide (CO), unburnt hydrocarbon (UHC) and brake specific fuel consumption (BSFC) were all lower than those of diesel fuel. However, most researches of HVO were about its

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engine performance, but its spray characteristics were rarely mentioned.

The spray is an important process for liquid fuels, as it influences the performance of in-cylinder combustion and thus determines the formation of pollutants. A series of studies of various fuels were conducted on the spray characteristics. Chen et al. [9] compared the spray properties of biodiesel and its blend with standard diesel and found biodiesel experienced longer penetration and larger size of droplets. Nevertheless, this study was done at room temperature and room pressure, which is far from the condition in the diesel engine. Mohan et al. [10] demonstrated that spray penetration would reduce with the increase of ambient pressure, while Gao et al. [11] found it increases almost linearly with increasing injection pressure at the initial breakup stage. However, these studies did not consider the effect of ambient temperature. In contrast, several researchers [12–14] investigated various fuels spray at a different ambient temperature and all reported reduced penetration at high ambient temperature. On one hand, the ambient pressures in these studies were all not set to constant when increasing the ambient temperature, so the reduced penetration cannot be certainly attributed to increasing ambient temperature. On the other hand, the previously reported works were all about esterified biofuels or alcohol substances but not HVO. Hulkkonen et al. [15] and Sugiyama et al. [6] compared the spray properties of HVO and standard diesel fuel at the same conditions but found no significant difference between them in terms of spray tip penetration and cone angle. In contrast, Thomas et al. [16] investigated the spray characteristics of some biofuels containing HVO at constant ambient temperature and pressure and reported HVO produced the shortest spray tip penetration and the largest overall cone angle. However, the influences of injection pressure, fuel temperature, ambient pressure and ambient temperature were not considered in the work.

Numerical studies were also conducted on liquid fuel spray by Computational Fluid Dynamics (CFD) simulation. The Wave breakup model [17] and the KHRT breakup model [18] were two widely used breakup models for spray in the CFD simulation, and the results of the models showed a good agreement with experimental data when predicting spray characteristics of various fuels in previous researches [19–22]. However, none of these researches had comprehensively considered and investigated all the effects of injection pressure, fuel temperature, ambient temperature and ambient pressure, and HVO was also not studied in these numerical works. Gong et al. [23] built CFD models for HVO spray via the large eddy simulation (LES) and RANS respectively. The models were run at both non-evaporating and evaporating conditions and their results on liquid and vapour penetrations as well as the Sauter Mean Diameter (SMD) agree with experimental data well. However, only the impact of ambient temperature was analysed in the models. The differences in droplet size and spray tip penetration between HVO and standard diesel fuel were found negligible at room temperature but became slightly larger at high temperature. Moreover, most studies did not analyse the spray characteristics after the end of injection (EOI), which is also important to evaluate fuel spray at long ignition delay conditions, e.g., at the cold start conditions. Moreover, no quantitate correlation between spray and experimental variables were previously obtained and reported by the researchers.

Several empirical models were thus developed [14,24,25]. For example, Hiroyasu and Arai [25] divided the spray process into two periods by the breakup time. Results indicate fuel does not break up yet before the breakup time and thus fuel properties dominate the spray tip penetration during this period. After breakup time (usually at about 0.03–0.1 ms), the ambient conditions are dominant and the injection conditions (e.g. fuel injection pressure and fuel properties) become not comparable. Accordingly, they proposed a spray tip penetration model consisting of two equations to predict penetration before and after breakup time, as shown in Eqs. (9) and (10), which has been well-adopted in studies of many different biofuels. Nevertheless, the model was only validated at relatively low fuel pressure and low ambient pressure. Based on Hiroyasu and Arai's principles, a detailed model named Naber and Siebers model [24] was formulated to include more parameters, but its results were proved insignificant to the spray penetration. In contrast, Bohl et al. [16] announced that fuel density should be considered and thus modified the Hiroyasu and Arai model to obtain better prediction on spray tip penetration under high fuel injection pressure conditions. However, all the models above did not analyse the significance of each parameter.

Design of Experiments (DoE) is an experimental method including various approaches for the design of experiments and analysing results based on mathematical statistics [26]. DoE method is popular in many research fields, which not only can effectively reduce the number of experiments but also correlate experimental variables to results with the analysis of the significance of each independent variable. Chen et al. [27] employed the Mixture Design Method (MDM) of DoE to formulate fuels and analyse the particulate matter emissions via a GDI engine. However, the MDM is particularly for the design of compositions of mixtures but cannot be used in other fields involving independent variables. DoE was also introduced in the authors' previous work [28] where a semi-empirical model on the Sauter Mean Diameter (SMD) of spray by another approach named Response Surface Method (RSM). However, macroscopic characteristics of spray were not analysed in this work.

In summary, as a newly developed alternative fuel for diesel engines, the spray characteristics of HVO have not been thoroughly studied, especially those at post-injection period are rarely analysed. Meanwhile, most researches conducted on fuel spray did not cover all the impacts of fuel temperature, injection pressure, ambient temperature and ambient pressure, and did not independently control the ambient pressure and ambient temperature, which brings in difficulties to understand the effect of ambient conditions. Moreover, previous models on spray penetration did not include enough variables such as fuel temperature and excluded the analysis on the significance of each variable. In addition, the DoE method showed advantages in designing conditions of experiments and formulating models with the analysis of variables. Accordingly, the influences of fuel conditions (fuel temperature and injection pressure) and ambient conditions (ambient pressure and ambient temperature) on the main macroscopic characteristics of HVO spray would be investigated via CFD simulation, which is validated by experimental data in a CVV. Furthermore, a new empirical model of spray tip penetration will be developed by fully analysing the significance of each factor by the RSM of the DoE method.

2. Description of experiment processes

2.1. Test Rig

As shown in Fig. 1, the test rig contains a common rail fuel delivery system, optical diagnostic devices and a constant volume vessel (CVV). The common rail enables as high as 1800 bar fuel pressure for injection. The CVV was designed to withstand internal air pressure and temperature at up to 100 bar and 1000 K respectively. A 4.5 kW heater is around the wall of the vessel and heats the internal air temperature to about 700 K, which is measured by a type K thermocouple. A high-pressure nitrogen bottle provides up to 70 bar internal air pressure for the CVV. Four fused silica glass windows with 90 mm viewing size and 70 mm thickness are equally located on the wall for optical diagnostics. A LAUDA Integral XT 150 thermostat is connected to the CVV to prevent the temperature around windows exceeding 150 °C. A single-hole solenoid injector with 0.16 mm orifice diameter is selected according to the specification of a Cummins ISB 4.5 diesel engine and installed at the top of the CVV. The injector is triggered by a TTL signal via a National Instrument data acquisition card PCI-6071E by a LabVIEW program. The main parameters of the CVV are shown in Table 1.

The spray is observed through a window by a high-speed PHANTOM