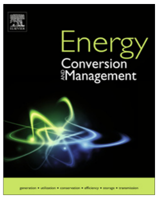
Energy Conversion and Management 134 (2017) 47–58

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman



Numerical study on fuel physical effects on the split injection processes on a common rail injection system

Dong Han *, Ke Li, Yaozong Duan, He Lin, Zhen Huang

Key Laboratory of Power Machinery and Engineering, Ministry of Education, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 7 September 2016
Received in revised form 12 November 2016
Accepted 10 December 2016
Available online xxxx

Keywords:
Split injection
Common rail
Fuel
Density
Viscosity
Bulk modulus of compressibility

ABSTRACT

As biodiesel can be used as an alternative fuel for diesel engines, the changed fuel physical properties are found to have influences on the injection characteristics. In this study, a one-dimensional hydraulic model was established to identify the isolated effect of fuel density, viscosity and bulk modulus of compressibility, on the injection mass and pressure propagation waves of a split injection strategy on a common rail injection system. The numerical simulation results indicated that fuel density and bulk modulus of compressibility have more prominent influences on the fuel injection mass and pressure fluctuation characteristics at the injector inlet during the main injection event, while fuel viscosity effects are modest. In addition, injection dwell time between the pilot and main injection is also a crucial parameter affecting the injection characteristics of the main injection event, because the lengths of the injection dwell time influence the initial pressures at the start of the main injection stage and the mean pressures of the main injection stage. The change in these pressures finally affects the injection mass in the main injection event. Therefore, specific effects of fuel physical properties on the main injection process are subject to the injection dwell time, i.e. the specific split injection strategy.

1. Introduction

Common rail injection systems are widely used in modern diesel engines due to such advantages as ultra-high injection pressure, flexible and precise injection control and improved consistence of fuel injection quantity in each cylinder. Split injection strategies [1–4], aiming to form ideal injection rate profiles for simultaneous reduction in the combustion noise and engine-out emissions, could be easily achieved and modulated by the common rail injection systems. In the split injection strategies, a small amount of fuel is first injected into the cylinder to generate the partially premixed mixture. This partially premixed mixture could form a quasi-reactive in-cylinder environment, thus shortening the ignition delay time of the fuel injected in the main injection stage and reducing the maximum pressure rise rate. This could produce a mild heat release process and reduce NOx emissions. The main injection stage usually features short injection duration but high injection rate, so this fast injection could limit the main combustion process within an optimized crank angle window, contributing to engine power elevation and fuel consumption minimization.

The proportion of fuel mass injected in the pilot and main injection stages is crucial in the design of the split injection strategies, as it determines the boundary conditions of the fuel spray development [5,6], the fuel/air mixture stratification [7], as well as the subsequent heat release process [8,9]. As found in previous studies, the second injection event in a split injection strategy leads to slower penetration at the early stage due to droplet collision, but then produces higher penetration as the spray proceeds [6]. In addition, the ignition delay of the second-stage fuel injection is determined by the time of its fuel vapor interacts the radicals released from the first-stage fuel injection [8]. Therefore, extensive research has been conducted on investigating the fuel mass injected [10,11] and the fuel pressure wave propagation phenomena [12,13] in the split injection strategies, as the injection timing and duration of individual injection stage vary. The results showed that the injection-induced pressure oscillations as well as the length of dwell time between consecutive injection events have prominent effects on the injected quantity of the latter injection event.

The fuel physical property is another important factor that influences the fuel injection characteristics [14–16]. Since biodiesel was proven to be a suitable alternative fuel to the petroleum diesel in vehicle engines [17–20], researchers have tried to investigate the injection characteristics of biodiesel and observable differences

---

* Corresponding author.
E-mail address: aureolous@gmail.com (D. Han).

http://dx.doi.org/10.1016/j.enconman.2016.12.026
0196-8904/

Nomenclature

CAD	Crank Angle Degree	SOMI	Start of Main Injection
IDT	Injection Dwell Time	EOMI	End of Main Injection
IP	Injection Pressure	PIQ	Pilot Injection Quantity
MET	Main Energizing Time	MIQ	Main Injection Quantity
PET	Pilot Energizing Time	TIQ	Total Injection Quantity

between diesel and biodiesel have been found in the split injection processes. Han et al. [21] experimentally studied the two-stage injection processes of three biodiesel surrogate fuels (methyl laurate, methyl oleate and ethyl oleate) on a high pressure common rail injection system, and it was found that the fuel properties cause modest changes in the main injection mass as well as the pressure fluctuation after the end of injection. Payri et al. [22] and Salvador et al. [23] developed a one-dimensional model to investigate the dynamic feature of diesel and biodiesel in a main plus post injection strategy. They found that the post injection mass of biodiesel was less than diesel and the pressure wave propagation at the injector inlet was considerably changed. This injection difference between diesel and biodiesel was more noticeable at low injection pressures. Similarly, Boudy and Seers reported that the fuel property changes remarkably influence the post injection event due to the change in the friction coefficient and pressure wave fluctuation in a given triple injection strategy. They found that the mass injected in the post shot is reduced with increased bulk modulus or decreased density [24]. Plamondon and Seers [25] proposed a mathematical model for an indirect-acting piezo-actuated common-rail injector and used it to evaluate the double injection characteristics of different fuels. The damping coefficient on the needle-valve was adjusted based on the fuel properties, and they found that the use of pressure dependent bulk modulus was crucial in generating satisfactory predictions of the mass flow rate.

The aforementioned research has proved that the fuel physical properties have influences on the injection mass and pressure propagation characteristics of the split injection strategies. However, little research was able to isolate the individual effect of each physical property, i.e. fuel density, viscosity and bulk modulus of compressibility on the split injection characteristics. In this study, the isolated effect of each individual physical property on the injection mass and pressure propagation features in the pilot plus main injection strategies is identified, with the dwell time between these two consecutive shots varied.

2. Model development and validation

The fuel injection simulations were carried out using AVL HYDSIM, a one-dimensional tool used for the transient behavior simulation of hydraulic systems, e.g. fuel injection systems. Fig. 1 and Table 1 schematically describe this one-dimensional model, in which the hydraulic, mechanical and electronic elements in the fuel injection system were modularized, according to their specific features, to volume, line, valve or annular gap leakage modules [26]. The pressure control chamber, fuel return chamber and common rail pipe can be considered as the volume module, in which the pressure change is caused by the volume change and the change of fuel flow rate at the inlets and outlets. The fuel duct in the injector and the high pressure fuel pipe are considered as the line module. The geometry parameters in the model were selected based on the test injection systems used in the authors' previous work [27], and some parameters are listed in Table 1.

This one-dimensional model is first validated against the measured volumetric injection rates of diesel fuel from Han et al. [21], under the single injection strategies with injection pressures (45 MPa, 60 MPa, 80 MPa and 100 MPa) and injection durations (0.5 ms, 1.0 ms and 2.0 ms) changed. The test facility for fuel injection rate measurement is a mono injection qualifier, by which the injection rate and quantity is calculated based on the piston displacement located in a closed chamber. The fuel quantity measurement range and relative measurement accuracy of the mono injection qualifier is 0–600 mm^3 and 0.1%, respectively [21]. As shown in Fig. 2, given the injection pressure, changed energizing time affects the shape of the injection rate profile. In addition, given the energizing time, the increased injection pressure significantly increases the injection rate. The calculated injection rate results satisfactorily agree with the experimental measurements, capturing the shapes of the injection rate profiles as well as the start and end moments of injection events.

To further examine the validity of this model over a broad range of fuels and injection strategies, the injection rate profiles and pressure waves at the injector inlet predicted by this model were compared against the measured data for different fuels and different injection strategies, as shown in Figs. 3 and 4. From Fig. 3, it is seen that except for the injection rate profiles, this model also satisfactorily reproduces the measured pressure traces at the injector inlet of different fuels in a single injection strategy. Similarly, this model could also well capture the characteristics of cycle volumetric injection rate and pressure wave propagation of different test fuels under a split injection strategy, as shown in Fig. 4. The well agreement between the simulation and experimental results proves the validity and applicability of this model for the injection prediction of various fuels and injection strategies.

3. Results and discussion

3.1. Effect of fuel density

Based on this one-dimensional hydraulic model, the isolated effect of each individual physical property, i.e. density, viscosity and bulk modulus of compressibility on the split injection processes is analyzed using the control variable method. The range of each physical property, covering the properties of diesel and different biodiesel fuels [16], is listed in Table 2, and the dwell time between two consecutive injections is held at 5.0 ms.

The effects of fuel density on the pressure propagation characteristics at the injector inlet in a split injection process are shown in Fig. 5. The density effect on the magnitude of the pressure wave during the pilot injection stage is negligible, but increased density slightly retards the pressure drop process after the pilot injection period. More obvious influences of fuel density on the magnitude and frequency of the pressure wave are observed during and after the main injection stage. Increased fuel density leads to an increased pressure drop at the main injection stage, followed by an increased pressure rise. This is because the fuel density is related to the inertia resistance, thus higher fuel density slows