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Experimental Investigation on Fuel Injection and Spray Characteristics of Commercial Diesel and Hydrotreated Vegetable Oil (HVO) with Different Injection Pressure Using High Pressure Fuel Injection System

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Abstract

Hydrotreated vegetable oil (HVO) is one of promising advance alternative biofuels to use instead of diesel fuel. HVO has many the beneficial fuel properties such as low sulfur, low aromatics, high cetane number, high heating value, similarity of density and viscosity with diesel. The objectives of this paper is to investigate the effects of HVO physical and chemical properties on fuel injection characteristics, spray characteristics and air entrainment. The fuel injection characteristics were investigated under Zeuch method. The fuel spray characteristics were investigated under non-vaporizing conditions using shadowgraph technique and air entrainment analysis. The fuel injection and spray results of diesel and HVO were evaluated with a single-hole solenoid injector with orifice diameter 0.2 mm, and various injection pressure 40 MPa to 140 MPa. The results shows that fuel injection rate profile, measured injection rate and injection quantity of diesel have similar results compare to HVO. The spray tip penetration and spray angle of diesel show similar results as HVO. Local equivalence ratio and the mass of air entrained of diesel and HVO show similar results. In addition, effects of high pressure fuel injection show significantly increasing fuel injection rate profile, measured injection rate, injection quantity, and the mass of air entrained but decreasing local equivalence ratio. These results relate strongly to combustion process and emissions in diesel engines due to differences of fuel properties.

Keywords: hydrotreated vegetable oil (HVO), fuel injection and spray characteristics, Zeuch method, shadowgraph technique, air entrainment analysis.

1. Introduction

Hydrotreated vegetable oil (HVO) is a second generation of biofuels which can be produced from many kinds of vegetable oil by using hydrotreating process (remove oxygen contain without removing carbon contain) [1]. HVO has many advantages to use instead of conventional diesel fuel for compression ignition (CI) engines in term of variety of bio feedstock, low aromatic, low sulfur, high cetane number and heating value, similarity of viscosity and density with diesel [1-9]. However, there are some disadvantages that may limit to use HVO from previous study such as poor low-temperature properties, as displayed by cloud point, pour point and cold filter plugging point (CFPP) [1,2]. Therefore, an improvement process as isomerization process is may be use to solve that problem then HVO would be iso-HVO. Since iso-HVO still have some disadvantage as too high cetane number and low lubricity, this work has concerned and would not be recommended to blend HVO over 50% [2]. Since HVO has been attracted many researcher for adopting it into CI engines so that many researches have done an investigation effects of fuel properties of HVO and HVO blended with diesel on engine performance and emissions [3-11]. Previous study on effects of HVO on engine performance show that HVO and HVO blend show decreasing fuel consumption [3-7], increasing brake fuel conversion efficiency [8], with brake specific fuel consumption also can decrease with optimizing start of injection for specific engine calibration [9]. Furthermore, the use HVO combined with various exhaust gas recirculation (EGR) system still show significant lower fuel consumption [6,7,9]. Previous research on combustion characteristics in CI engine show that HVO and HVO blend can significantly reduce the ignition delay because HVO show beneficial fuel properties such as high cetane number and lower distillation temperature as high ignition quality. Also, combustion duration can reduce because HVO can reduce time for mixture formation as more fuel vaporize and air-fuel interaction inside combustion chamber very well during combustion phase. Furthermore, HVO and HVO blend provide higher combustion pressure, heat release rate, and combustion efficiency compare to diesel [6-9] because fuel and air are very well mixed that lead to better ignition quality.

Previous study on effects of HVO properties on emissions conclude that the employment of HVO can be relevant reduced exhaust gas emissions such as hydrocarbon (HC), carbon monoxide (CO), nitrogen oxide (NO_x) and particulate matter (PM), especially decreasing in HC and CO emissions which are derived from incomplete combustion even through it combined with EGR [3-5,7-9]. Furthermore, researcher conclude that not only HC and CO decrease but also NO_x, particulate matter (PM) decrease [3-5,9], while some research conclude that PM was depended on combustion mode [7].

A few work has done HVO on fuel injection and macroscopic fuel spray characteristics. Pop-Paul et al. [10]. investigated effects of diesel, HVO and HVO blended with diesel on fuel injection characteristics under Zeuch method and concluded that injection delay was shorter with increasing HVO fraction that cause by fuel viscosity. Injection duration, injection quantity, and injection rate of diesel show similar results as HVO and HVO blend. Furthermore, discharge coefficient increase with increasing HVO fraction due to lower density and viscosity that make lower friction loss. Sugiyama et al. [6]. investigated effects of HVO properties on spray characteristics and concluded that spray penetration and spray angle of diesel show same results as HVO. This shows good agreement with the results of Hullkkonen et al. [11]. concluded that no significant difference in spray tip penetration were found between diesel and HVO with increasing injection pressure. However, spray angle of diesel shows slightly narrower than HVO with increasing injection pressure. Chen et al. [12]. investigated effects of HVO on macroscopic fuel spray using common-rail high-pressure fuel injection system and reported that spray tip penetration and spray angle of diesel have longer and narrower than HVO for all injection pressure due to its higher density. Furthermore, spray tip penetration of diesel and HVO increase with increasing injection pressure, while spray cone angle is no significant with increasing injection pressure. F. Millo et al. [9]. investigated effects of HVO blend on fuel injection system using Zeuch method and concluded that diesel show similar spray tip penetration but spray cone angle show wider than HVO blend.

From previous studies, effects of HVO properties have shown superior advantages for adapting it into CI engine as increasing engine performance, decreasing regulated and unregulated emissions. Furthermore, since its properties are similar with diesel, it also shows quite similar fuel injection and spray characteristics. However, to better understand effects of HVO advance properties on combustion, engine performance and emissions characteristics. It is required fuel characteristics which are fuel injection characteristics, fuel spray characteristics [13]. The injection and fuel spray characteristics. All the most injection characteristics such as injection delay, injection duration, injection quantity, injection rate profile and injection pressure, and spray characteristics such as spray tip penetration, spray angle, local equivalence ratio and air entrainment determine input energy, heat release, mixture formation, combustion pressure and temperature, combustion efficiency which relate strongly to engine performance and emissions.

The objectives of this paper are to investigate effects HVO physical and chemical properties on fuel injection characteristics, fuel spray characteristics, and fuel-air mixing process in various injection pressure to clearly understand the effects of injection pressure on fuel injection and spray characteristics.

2. Materials and Methods

2.1 Zeuch method for measuring injection rate

Measuring injection rate using Zeuch method [14]. Tested fuel is filled into a constant Zeuch chamber at the certain pressure then injected test fuel into the chamber. The chamber pressure rise (ΔP) proportional to injected fuel. Then pressure transducer detects the pressure rise from injected fuel. Fuel bulk modulus is fuel resistance as compressibility of liquid fuel which can be calculated from the change of volume chamber (ΔV) and pressure rise as shown in Eq. (1).

$$K = V_o \frac{\Delta P}{\Delta V} \tag{1}$$

Where K is fuel bulk modulus, V_o is Zeuch chamber volume. Using of fuel bulk modulus and pressure rise from injected fuel, then the measured injection rate can be determined by Eq. (2) [14].

$$\dot{m}_{measured} = \frac{dm}{dt} = \rho \frac{V_o}{K} \frac{dP}{dt} \tag{2}$$

The theoretical mass flow rate defined as theoretical mass flow rate of injected fuel, is derived from a combination of the continuity equation and Bernoulli's equation, assuming that the inlet velocity is negligible which can be determined from Eq. (3) [15].

$$\dot{m}_{th} = n_{orifice} \cdot S \sqrt{2 \Delta P \cdot \rho_f} \tag{3}$$

Where $n_{orifice}$ is the number of orifices on the nozzle, S is the outlet geometric cross-section area of the orifice, ΔP is the pressure difference of injection pressure and back pressure, ρ_f is fuel density.

Fig. 1 shows the definition typical fuel injection process, injection rate profile calculated by using Eq. (2). Start of energizing signal (SOE) to start of fuel injection (SOI) is defined as injection delay. Injection duration is defined as a period from SOI to end of fuel injection (EOI). Injection quantity defined as a total amount of fuel injected is calculated by integration under injection rate curve area from SOI to EOI.

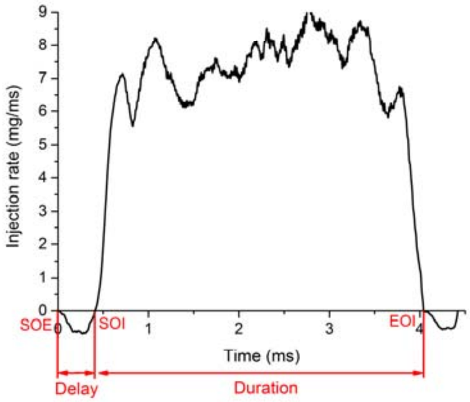

Fig. 1 Definition typical injection process

2.2 Fuel spray images analysis

The definition of fuel spray injection is presented in Fig. 2. Spray tip penetration (S) defined as the distance from injector tip to spray tip in the axial direction. Spray angle (θ) defined as the maximum angle of each side spray at ($S/2$) from the tip of injector. The sequence spray images were analyzed by image processing using MATLAB program. Spray tip penetration and spray angle data from image processing are used to determine air entrainment and local equivalence ratio.

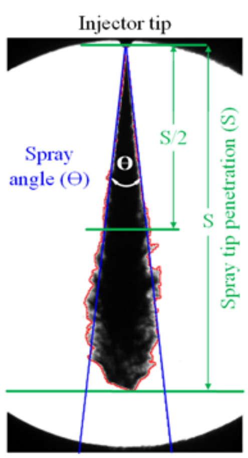

Fig. 2 Definition of fuel spray injection

2.3 Air entrainment analysis

The mass of air entrained (m_a) is presented as a function of spray angle, spray tip penetration, and ambient density can be calculated by Eq. (4) [16].

$$m_a = (\pi/3)(\tan(\theta/2))^2 S^3 \rho_a \tag{4}$$

The mass of air entrained defined as air entrained to fuel spray. For actual combustion in CI engine, it is defined as mixture formation of fuel spray inside the combustion chamber. There are many factors affecting to air entrainment such as spray tip penetration, spray angle, and ambient conditions.

2.4 Local equivalence ratio

For actual combustion in CI engine, the equivalence ratio defined as the operating combustion mode, and is a measure of air-fuel mixture relative to stoichiometric conditions. For this experiment, equivalence ratio is affected by fuel and ambient density, fuel spray, and orifice diameter.

The local equivalence ratio defined as a function of fuel density (ρ_f , kg/m^3), ambient density (ρ_a , kg/m^3), spray tip penetration (m), spray angle (rad) and orifice diameter (D_o , m), as shown in Eq. (5) [16].

$$\phi = \sqrt{\frac{\rho_f}{\rho_a}} \frac{D_o}{2S\tan(\theta/2)} \tag{5}$$

3. Experimental setup and condition

This investigation included two experiment: fuel injection experiment using Zeuch method and fuel spray experiment using shadowgraph technique as shown in Fig. 4 and Fig. 5, respectively.

3.1 Fuel injection and spray experiment

Fig. 4 shows the schematic diagram of the fuel injection experiment. A single-hole solenoid injector with orifice diameter 0.2 mm was installed at the top of 40 cm^3 Zeuch chamber capacities to clearly determine pressure signal for measuring injection rate [14]. Hand pump was used to generate back pressure by filling test fuel into the chamber via the intake valve at a certain pressure. Two pressure transducer were used in this investigation. First, a static pressure transducer was used to measure back pressure. Second, a piezoelectric pressure transducer (Kistler 6053CC60) and charge amplifier (Kistler 5011) were used to measure pressure rise from injected fuel. The pressure increase of fuel injected was recorded by oscilloscope (RICOL DS1052E) with sampling rate 2x10^8 S/s

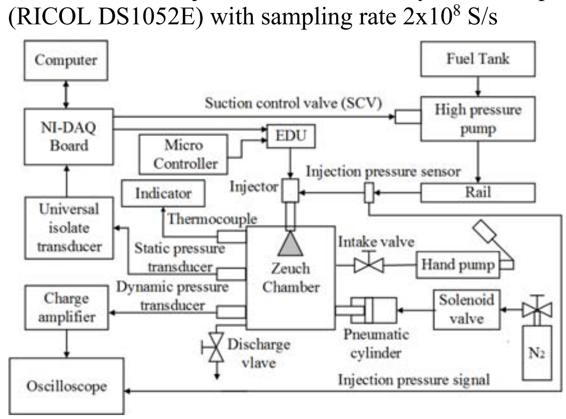

Fig. 4 Fuel injection experiment

Fig. 5 shows the schematic diagram of fuel spray experiment. A single-hole solenoid injector with orifice diameter 0.2 mm was installed at the top of constant volume combustion chamber (CVCC) to inject tested fuel. Nitrogen (N_2) gas was used to simulate ambient density conditions as back pressure via the intake valve. A static pressure transducer was used to measure back pressure. In addition, Shadowgraph technique was setup to visualize fuel spray and capture high speed video spray by using high speed video camera (Photron: FASTEAM MINI UX100) with frame rate of 10,000 frame per picture.

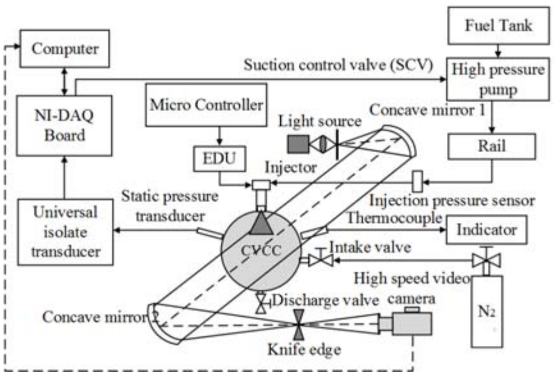

Fig. 5 Fuel spray experiment

3.1 Experimental condition

Two experiments were conducted with a second generation common-rail fuel system in order to generate high fuel injection pressure 40 to 140 MPa, a single-hole solenoid injector with orifice diameter 0.2 mm, energizing time 2.5 ms, 2.5 MPa back pressure (28 kg/m^3 ambient density) that refer to CI condition at the end of compression stroke. Fuel injection and spray experiment were performed under ambient temperature 300 ± 2 K and non-vaporizing conditions as shown in Table. 1.

Table. 1 Experimental condition for fuel injection and spray measurement

Parameters	Conditions
Test fuels	Commercial diesel, HVO
Orifice diameter	Single hole 0.2 mm
Energizing time	2.5 ms
Back pressure	2.5 MPa
Injection pressure	40-140 MPa
Ambient temperature	300 ± 2 K
Repeat	10 times / condition

3.3 Test fuels

In this study, two different fuels were hydrotreated vegetable oil (HVO) and commercial diesel. Fuel viscosity, density, and surface tension of diesel have higher 22.72%, 5.91%, and 11.26%, but air-fuel ratio and heating value have lower 2.56% and 2.13%. The fuel properties of test fuels were comparatively shown in Table. 2.

Table. 2 Fuel properties

Properties	Standard	Commercial diesel	HVO
C (%wt)	ASTM D5291	85.73	84.24
H (%wt)		13.22	15.05
O (%wt)		-	-
Chemical formula	-	$C_{14.11}H_{26.23}$	$C_{14.03}H_{29.86}$
$(A/F)_{st}$	-	14.48	14.86
Kinematic viscosity @40°C (cSt)	ASTM D445	3.24	2.64
Density @30°C (kg/m^3)	ASTM D4052	824	778
Surface tension (mN/m)	ASTM D1590	26.98	24.25
Q_{LHV} (MJ/kg)	ASTM D240	45.86	46.86

4. Results and Discussions

The effects of physical and chemical properties of commercial diesel and hydrotreated vegetable oil (HVO) on fuel injection characteristics are discussed such as injection rate profile, measured injection rate, injection quantity. The effects on spray characteristics such as spray tip penetration, spray angle, the mass of air entrained, and local equivalence ration also are discussed in this study. Both fuel injection and spray characteristics were investigated using high fuel injection system.

4.1 The comparison of the injection rate profile between diesel and HVO for different injection pressure

Fig. 6(a) and Fig. 6(b) show effects of different fuel properties and injection pressure between diesel and HVO on injection rate profile. The injection rate profile is presented as a function of fuel density, fuel bulk modulus, Zeuch chamber capacity, and the pressure increase of fuel injected which is calculated from Eq. (2). The injection rate profile shows the negative value from SOE to SOI because movement of needle lift cause changing volume of the system then chamber pressure decrease. Diesel and HVO show an increase in the injection rate profile with increasing injection pressure because increased injection pressure enhances flow capacity. The injection delay injection duration were decreased with increasing injection pressure because the increased injection pressure provides higher lift force to make opening the needle lift rapidly [17]. Therefore, the employment of an increase in injection pressure is improvement of injection rate patterns such as sufficiently increase injection rate profile, measured injection rate, and injection quantity, but decrease injection delay and injection duration.

Effects of diesel and HVO on injection rate were comparatively evaluated as a representative shown in Fig. 6(c). It can be seen that injection rate profile of diesel show the same trends as HVO. This means that there is no significant effect of fuel density on injection rate profile for same injection pressure because the mass flow rate is a function of the square root fuel density [15] then as diesel density has higher 5.91% compare to HVO, lead to increasing 2.91% in injection rate. However, clearly decrease of injection delay and injection duration were found between diesel and HVO when injection pressure increase. HVO has shown shorter injection delay and injection duration due to its lower 22.73% viscosity that lead to lower resistance force to needle lift [19].

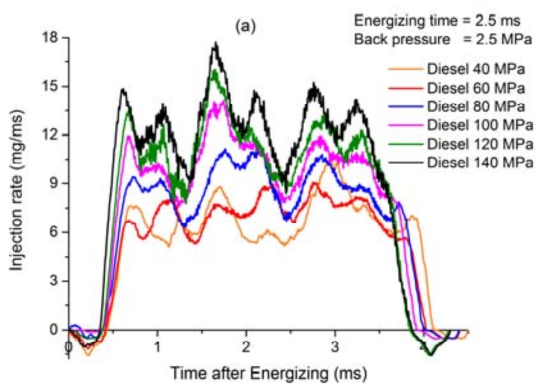

Fig. 6(a) Injection rate profile of diesel and various injection pressure

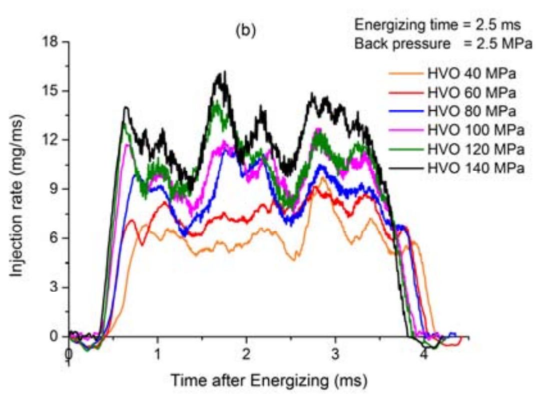

Fig. 6(b) Injection rate profile of HVO and various injection pressure

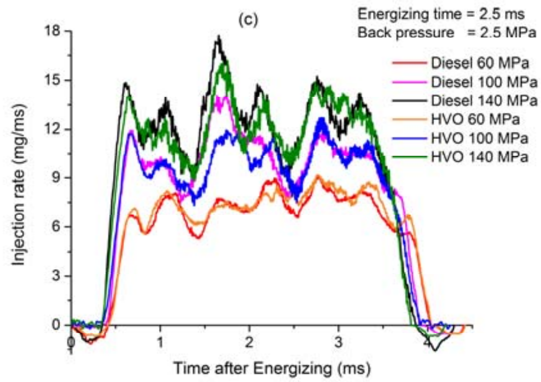

Fig. 6(c) Injection rate profile of diesel and HVO and injection pressure of 60, 100 and 140 MPa

4.2 The comparison of the measured injection rate between diesel and HVO for different injection pressure

Fig. 7 shows comparison of measured injection rate as actual injection rate between diesel and HVO for different injection pressure. Since theoretical injection rate of diesel show higher than those of HVO due to its higher 5.91% density, the measured injection rate also show the same trends as theoretical as well. The measured injection rate of diesel show higher by 13.25%, 5.42%, 2.02%, 1.68%, 4.86%, 5.36%, respectively compare to HVO because of slightly effect of diesel mass flow rate as injection rate profile results. Therefore, the main advantage of the increased injection pressure is to increase of measured injection rate and injection quantity because the higher injection pressure make larger pressure difference in Eq. (3) then it has increased theoretical mass flow rate so the measured injection rate also increase.

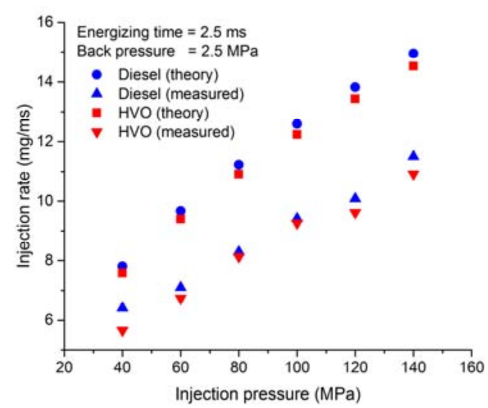

Fig.7 Measured injection rate and various injection pressure

4.3 The comparison of injection quantity between diesel and HVO for different injection pressure

Fig. 8 shows the comparison of injection quantity between diesel and HVO for different injection pressure. Injection quantity is calculated from the integration under injection rate curve area as shown in

Fig. 1. The total amount of fuel injected as injection quantity show the same trends as the measured injection rate as well. Injection quantity of diesel show higher by 13.17%, 5.45%, 2.52%, 3.83%, 8.51%, 6.66%, respectively compare to HVO because diesel has higher injection rate profile so that the injection rate curve area has increased then lead to increasing injection quantity that supply to combustion chamber. The increased amount of fuel provides increase of an input energy as heat input in combustion process for CI engines [18].

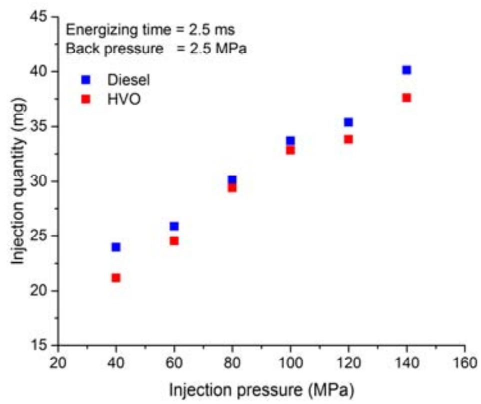

Fig. 8 Injection quantity and various injection pressure

4.4 The comparison of air entrainment between diesel and HVO for different injection pressure

Fig. 9(a) and Fig. 9(b) show comparison of air entrainment by time after energizing between diesel and HVO. Air entrainment is presented as a function of spray angle, spray tip penetration and ambient density as shown in Eq. (4). The mass of air entrained increase with increasing injection pressure. The increased injection pressure cause higher the air entrained because the wider of spray angle [16]. These mean the air can entrained to fuel spray greatly with increasing injection pressure.

Effects of diesel and HVO on mass of air entrained were comparatively evaluated as a representative shown in Fig. 9(c). It can be seen that diesel air entrainment shows the similar results as HVO for all injection pressure because similar spray tip penetration and spray angle results even through viscosity and surface tension of diesel were higher by 22.72%, 5.91%, and 11.26%, respectively compare to HVO.

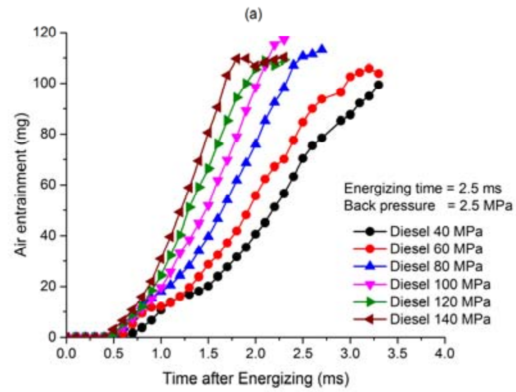

Fig. 9(a) Air entrainment of diesel and various injection pressure

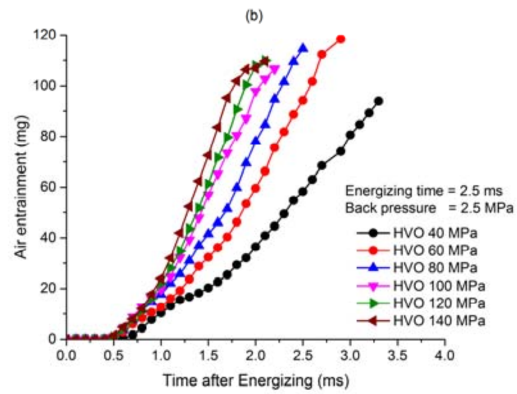

Fig. 9(b) Air entrainment of HVO and various injection pressure

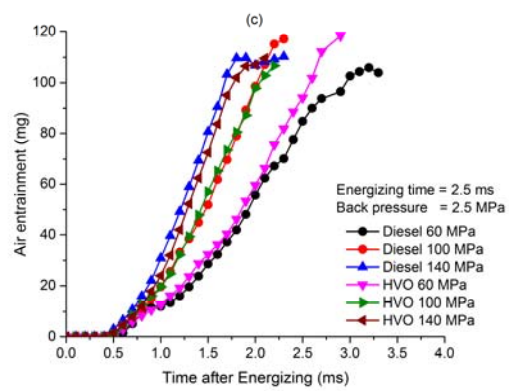

Fig. 9(c) Air entrainment of diesel and HVO and injection pressure of 60, 100 and 140 MPa

4.5 The comparison of the local equivalence ratio between diesel and HVO for different injection pressure

Fig. 10(a) and Fig. 10(b) show local equivalence ratio by time after energizing of diesel and HVO. Local equivalence ratio is presented as a function of fuel and gas density, spray tip penetration, and spray angle which is calculated from Eq. (5). Local equivalence ratio is higher initially at nearby 0.4 ms because SOE and SOI are observed around 0 ms to 0.4

ms as shown in Fig 6. Diesel has slower increase of equivalence ratio compare to HVO for all an injection pressure due to its higher viscosity that make its slower opening the needle lift [19]. With diesel show slightly lower equivalence ratio compare to HVO due to its lower stoichiometric air- fuel ratio [16].

Effect of diesel and HVO on local equivalence ratio as a representative were shown in Fig. 10(c). Local equivalence ratio results of diesel show the same trends as HVO because the spray results as spray angle and spray tip penetration of diesel and HVO were similar. This can concluded that HVO properties have not affected to spray angle, spray tip penetration as previous research [11,12] so that local equivalence ratio were similar results. Therefore, as the spray tip penetration and spray angle between diesel and HVO show similar trends so that local equivalence ratio and air entrainment also show similar results as well. This can concluded that local equivalence ratio decrease corresponded with increasing the mass of air entrained.

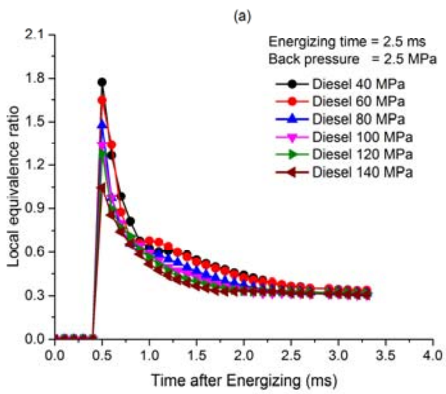

Fig. 10(a) Local equivalence ratio of diesel and various injection pressure

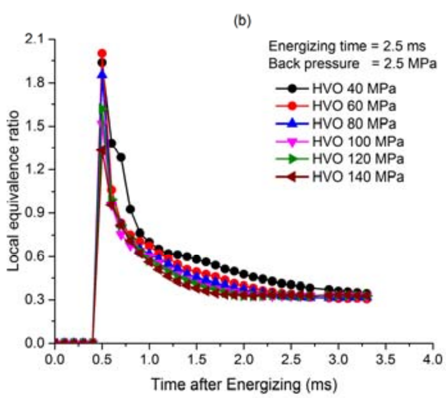

Fig. 10(b) Local equivalence ratio of HVO and various injection pressure

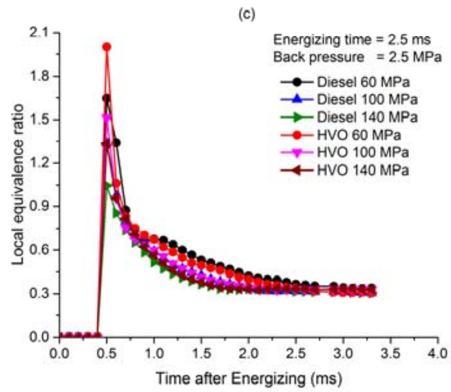

Fig. 10(c) Local equivalence ratio of diesel and HVO and injection pressure of 60, 100 and 140 MPa

5. Conclusions

The effects of diesel and hydrotreated vegetable oil (HVO) on fuel injection and spray characteristics with various injection pressure were investigated using Zeuch method, shadowgraph technique and air entrainment analysis. The injection rate profile, measured injection rate, injection quantity, the mass of air entrained, and local equivalence ratio were summarized as follows:

Fuel Injection characteristics

No significant differences of fuel injection rate profile and measured injection rate were found between diesel and HVO even through increasing fuel injection pressure.

Significant differences of injection delay and injection duration were found between diesel and HVO. The differences cause by lower viscosity of HVO. Also injection quantity of diesel has higher than HVO due to its lower density.

In addition, significant improvement of injection rate profile such as decreasing injection delay and injection duration, but increasing actual injection rate and injection quantity with increasing injection pressure.

Spray characteristics

No significant differences of the mass of air entrained and local equivalence ratio between diesel and HVO were found due to its same spray tip penetration and spray angle.

6. Acknowledgement

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