Spray Characteristics of Hydrotreated Biodiesel Blended Fuels

Duckhan Kim[†], Sehun Oh[*], Seonghwan Kim[*] and Soo-Young No[**]

Key Words: BD, HBD, SMD, Spray angle, Spray tip penetration

Abstract

Hydrotreated biodiesel (HBD) would be one of the promising alternative fuels instead of current biodiesel. In this study, spray characteristics in terms of spray penetration and spray angle were conducted experimentally including calculated SMDs as well. The ambient pressures of 1, 3, and 5 MPa and injection pressures of 30, 80, and 130 MPa were introduced and the fuels employed were petro-diesel, and 2, 10, 20, 30, and 50% for hydrotreated biodiesel, respectively. The result of this study found that the more HBD blended diesels have the slightly shorter spray tip penetration lengths especially on the lowest injection pressure and at the highest ambient pressure, but have the larger spray angles and SMDs than petro-diesel. Consequently, this study found that HBD has a little bit merits and demerits of macro- and micro- spray patterns compared to petro-diesel.

1. Introduction

Hydrotreated biodiesel is already a well-known advanced biodiesel, especially in Europe. HVO (Hydrotreated Vegetable Oil; one of another name of HBD made by Neste Oil) has been already selling in Europe during many years. HBD has better properties than BD as one of the alternative diesel fuels. The reason is that HBD has better cold flow properties such as lower CFPP (Cold Filter Plugging Point) and PP (Pour Point) than biodiesel and/or petro-diesel. The merits of HBD are not only similar chemical structures with petro-diesel but also better cold flow properties. On the contrary, demerit of HBD is not found yet for CI engines. The better cold flow properties, lower density, and sulfur free are typical better properties of HBD than BD and petro-diesel.

There are many kinds of previous studies and literatures comparing biodiesels with petro-diesel. Wang studied the effects of spray characteristics between biodiesel and diesel at the ultra-high injection pressure[(1)]. No investigated the effects of various vegetable oil derived biodiesels for spray characteristics in CI engines[(2)]. Ing performed spray characteristics of palm biofuel blends[(3)]. Mancaruso analyzed the first and second generation biodiesels spray characteristics in a diesel engine[(4)], and so on.

However, it is rare that literatures compared HBD and petro-diesel, especially various blending ratios of HBDs in petro-diesel. Hulkkonen reported that spray characteristics between HVO and crude oil based EN (European Fuel Standards) 590 diesel[(5)]. Sugiyama studied that comparison of HVO and petro-diesel spray characteristics using spray analyzer[(6)]. Gong analyzed that a computational investigation of HVO sprays using simulation models[(7)].

These previous studies did not compare various mixtures of them, but investigated only between hydrotreated biodiesel and petro-diesel. Therefore, the aim of this study is to widen current knowledge

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[*]Energy R&D Center, SK Innovation
[**]Dept. of Biosystems Engineering, Chungbuk National University
[†]책임저자, 회원, Energy R&D Center, SK Innovation
E-mail : dhkwin@sk.com
TEL : (042)609-8891 FAX: (042)609-8502

of HBD, especially about the macro- and micro- spray characteristics such as spray tip penetration, spray angle, and calculated SMD, as comparing with petro-diesel as using various ratios of mixtures. As mentioned previously, HBD has many merits such as better cold flow properties, lower density, and higher cetane value than BD. Thus, HBD regarded as one of promising alternative biofuels instead of biodiesel.

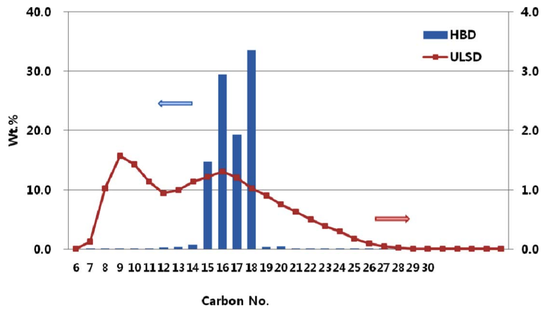

Fig. 1 Distribution of n-paraffin as carbon number of HBD and petro-diesel

2. Experimental Methods

2.1 Fuel Preparations

In this study, 6 different types of fuel were tested: petro-diesel, and 2, 10, 20, 30, and 50% of HBD blended mixtures, respectively. Petro-diesel was prepared as a typical petro-derived ultra-low sulfur diesel (ULSD), of which sulfur content is under 10 ppm. The 6 samples were prepared to compare petro-diesel with HBD blended mixtures. Especially, 2% of HBD blended diesel fuel was included because of selling 2% biodiesel blended fuel in Korea. The properties of blending stocks of these samples are shown in Table 1.

The petro-diesel is current commercial diesel fuel and contains 2% of biodiesel (FAME). The FAME consists of 80% of PME (Palm-based Methyl Ester) and 20% of Used Cooking Oil derived FAME, which is typical blending ratio of commercial biodiesel selling in Korea. All test fuels were treated with 1,000 ppm of WAFI (Wax Anti-settling Flow Improver, Clariant, Germany).

HBD has only carbon chain in contrast with BD, which has oxygen molecular. Moreover, HBD consists of C15-C18, which is midst of the entire petro-diesel carbon chain. Normally, petro-diesel consists of C6 - C30 as shown in Fig. 1.

The spray tip penetration is defined that the distance is from nozzle tip to the front end of sprayed fuel[1,8]. In this study, the spray angle was measured based on the radial distance at the axial location of 2/3 from nozzle tip to the front end of sprayed fuel[1,8] as shown in Fig. 2.

2.2 Experimental conditions and setup

In order to compare the differences on the real conditions of field, solenoid type 6 holes injector was used with 30, 80, and 130 MPa of 3-step injection

Table 1 The properties of 6 test fuels

	Petro-diesel	HBD 2	HBD 10	HBD 20	HBD 30	HBD 50
Density (kg/m^3@15°C)	824	823	819	815	811	803
Surface Tension (nm/m)	27.36	27.30	27.25	27.14	27.23	27.48
Kinematic Viscosity (mm^2/s@40°C)	2.46	2.47	2.53	2.59	2.67	2.82
Dynamic Viscosity (kg/m·s)	2.03	2.03	2.07	2.11	2.17	2.26
Flash Point (°C)	52	52	54	54	56	63
Cetane Index	53.5	55.2	57.8	61.3	64.4	72.3
CFPP (°C)	- 17	- 17	- 15	- 10	- 4	4
Pour Point (°C)	- 30	- 27.5	- 15.0	- 10.0	- 2.5	5.0
Caloric Value (cal/ml)	9,068	9,069	9,041	9,009	9,001	8,916
Sulfur (wt.ppm)	4	4	4	4	4	4

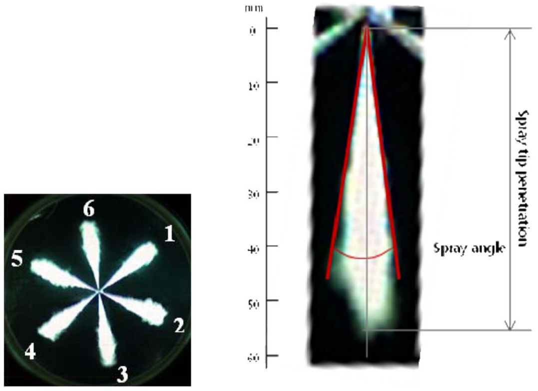

Fig. 2 The fundamental spray characteristic, spray tip penetration and spray angle

Table 2 Experimental conditions

Nozzle	Bosch, orifice: ø 0.120 mm × 6 hole × 156°, VCO type
Injection Pressure	30 MPa, 80 MPa, 130 MPa
Injection Duration	1.0 ms
Ambient Gas Pressure	1 MPa, 3 MPa, 5 MPa
Ambient Gas Temperature	20 ± 1°C
Fuel Temperature	40°C

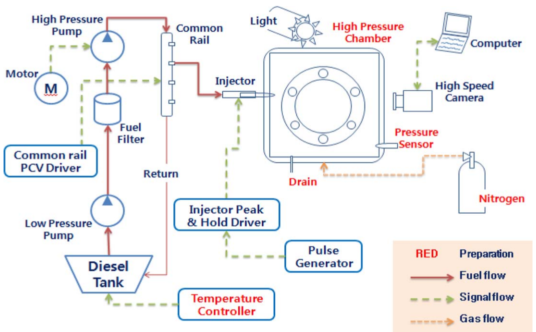

Fig. 3 Schematic diagram of the experimental setup for spray test

pressures, which are the conditions of minimum, medium, and maximum load. Orifice diameter of VCO type is 0.120 mm. The measurement of spray tip penetrations and spray angles were implied at the #6 hole only. The experimental conditions are presented in Table 2.

Fig. 3 shows the configuration of integrated spray test rig with injection system, camera, controllers, and data logging systems. Constant volume of injection was controlled high pressure Bosch pump with common rail PCV driver (Zenobalti ZPD-1000), and the injector was activated by the single cylinder engine controller (Zenobalti ZB-8100) and injector peak & hold driver (Zenobalti ZID-1000S).

The cylinder type of high pressure chamber is 300 mm diameter and 330 mm lengths, add set up two 250 W metal halide lights for light source. Nitrogen was filled up the chamber for the ambient gas. The chamber has three round quartz windows (ø 110 mm). Two windows are for illumination of light sources, and one is for visualization of injection by camera. The internal space of chamber is 137 mm length of a regular hexahedron structure. The chamber was designed for 9 MPa of maximum pressure. High speed color digital camera (Phantom V5.2, 256 × 256 resolution, 10,000 fps) was used.

3. Results and Discussion

3.1 Spray tip penetrations

In this study, spray tip penetrations were measured and analyzed between 0.0 ms and 3.0 ms after start of injection. Pictures were taken at every 0.1 ms of time frames. In case of 30 MPa of injection pressure regardless of ambient pressure, 0.1 ms of injection delay was observed as one frame delay. This is similar phenomena with earlier studies by Hulkkonen.[2] Spray tip penetration were measured with the same scale of ruler.

Spray tip penetrations were mostly affected by the injection pressure and ambient pressure. Thus, there were little significant differences of spray tip penetrations among test fuels. Especially the most discrepancies of spray tip penetrations among fuels were shown at the 30 MPa of injection pressure regardless of ambient pressures. All fuels had smallest discrepancies of spray tip penetrations at the 80 MPa of injection pressure and 5 MPa of ambient pressure.

These results explained that HBD has similar spray patterns with petro-diesel, because chemical structure of HBD is very similar with that of petro-diesel. However, some test results of HBD at the certain conditions showed moderately different patterns to petro-diesel, due to moderately different density, viscosity, and surface tension from each other.

3.1.1 Effects of mixture on spray tip penetration for different injection pressure and ambient pressure

At the same time frame after injection, moderately shorter penetration lengths were observed to the more HBD blended fuels than petro-diesel, but the discrepancies are not too much. However, more significant differences were shown at the higher (5 MPa) ambient pressure and the lower (30 MPa) injection pressure than other conditions. HBD 50% blended fuel showed 10% of penetration length reduction at this condition compared to petro-diesel, as shown in Fig. 4.

It can be explained that lower density of HBD made shorter spray tip penetration than petro-diesel. Therefore, the more blended HBD fuels showed the less length of spray tip penetration at higher ambient pressure condition. The typical density of HBD is 776-778 kg/m^3@15°C, while that of petro-diesel is 824-825 kg/m^3@15°C. Thus, density is the main factor of this discrepancy in this test.

3.1.2 Effects of injection pressure on spray tip penetration for different mixture

Spray tip penetrations were longer when injection

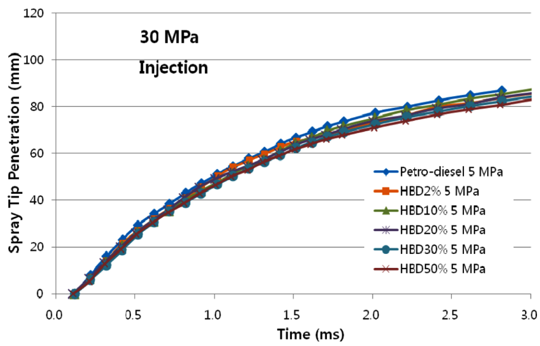

Fig. 4 Effects of mixture on spray tip penetration for injection pressure of 30 MPa and ambient pressure of 5 MPa

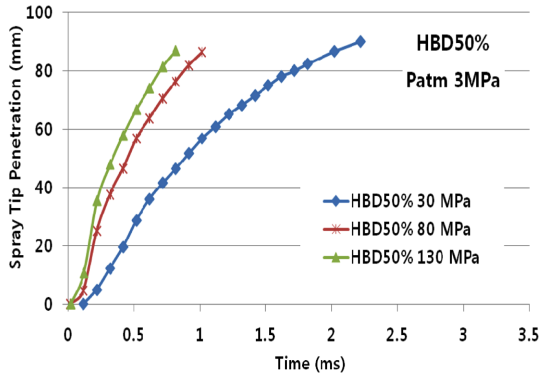

Fig. 5 Effects of injection pressure on spray tip penetration for ambient pressure of 3 MPa and HBD 50%

pressures were higher, regardless of fuels at the same time frame. 30 MPa of injection pressure of HBD 50% blended fuel at the 3 MPa ambient pressure was shown 65% of penetration length reduction than 130 MPa of injection pressure condition, as shown in Fig. 5. The differences among fuels were negligible.

3.1.3 Effects of ambient pressure on spray tip penetration for different mixture

Spray tip penetrations were shorter when ambient gas pressures were higher. This is due to the fact that the higher the ambient pressure, the harder the fuel droplets can diffuse into the gas ambient, which consequently results in shorter penetration length[9]. Another explanation seems more reasonable. The droplets at the front of the spray were decelerated due to the

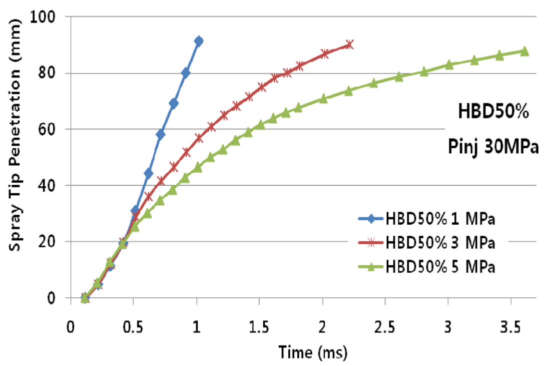

Fig. 6 Effects of ambient pressure on spray tip penetration for injection pressure of 30 MPa and HBD 50%

momentum exchange with the higher ambient pressure of surrounding air in the chamber[10]. Thus, spray tip penetration length were shorter than lower ambient pressure condition.

5 MPa ambient pressure of HBD 50% blended fuel at the 30 MPa of injection pressure was shown 44 % of penetration length reduction than 1 MPa condition, as shown in Fig. 6.

Consequently, this study shows that HBD has very similar pattern of spray characteristics. Therefore, HBD can be blended into petro-diesel limitlessly, which is the significant point of this study.

3.2 Spray angles

It was difficult to measure spray angles because of low resolution. Thus, spray angles were measured after 0.2 ms of injection. Be taken altogether, in spite of some deviations by ambient pressures, spray angles have the pattern of converging a consistent value.

3.2.1 Effects of mixture on spray angle for different injection pressure and ambient pressure

Relatively larger spray angles were observed to the more HBD blended diesel than petro-diesel at the same time frame after injection. HBD 50% blended fuel was shown 15% of spray angle increase at the 1.0 ms of time after start of injection compared to petro-diesel, as shown in Fig. 7.

It can also be explained as similar patterns with spray tip penetration result, as mentioned above. The lower density made the larger spray angle. And the

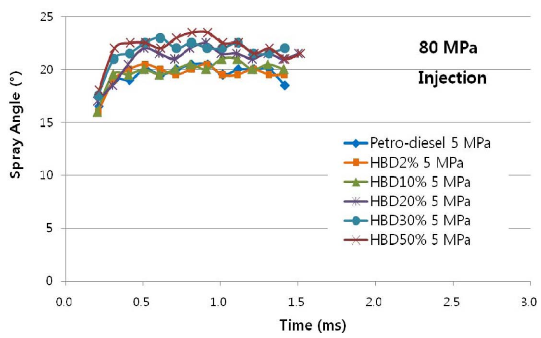

Fig. 7 Effects of mixture on spray angle

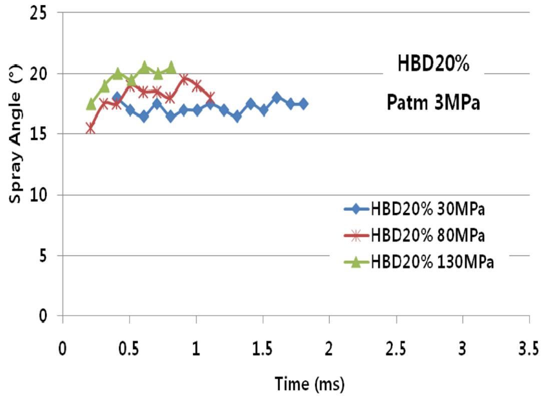

Fig. 8 Effects of injection pressure on spray angle

density of HBD is lower than that of petro-diesel. Thus, the more HBD blended fuel shows the larger spray angle.

3.2.2 Effects of injection pressure on spray angle for different mixture

In a relative sense, the larger spray angles were shown at the higher injection pressures, as shown in Fig. 8. The 130 MPa of injection pressure of HBD 20% blended fuel was shown 15% increase of spray angle than 30 MPa at the 3 MPa of ambient pressure condition.

3.2.3 Effects of ambient pressure on spray angle for different mixture

In case of 1 MPa ambient pressure, it was difficult to measure spray angles precisely because of a few detecting points, but their trends of angles can be

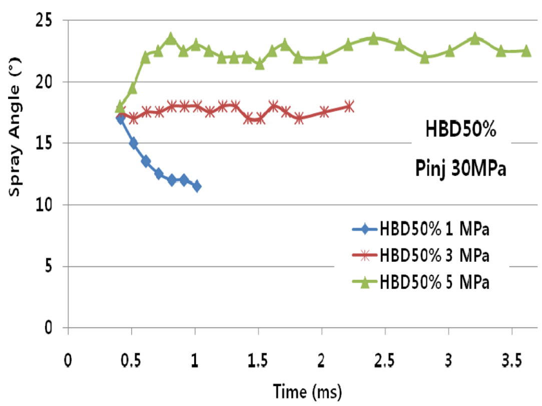

Fig. 9 Effects of ambient pressure on spray angle

interpreted. The 1 MPa of ambient pressure of HBD 50% blended fuel at the 30 MPa of injection pressure was shown 50% reduction of spray angle, as shown in Fig. 9.

3.3 Mathematical Correlations for Sauter Mean Diameter

SMD correlations among surface tensions, densities and viscosities of petro-diesel and HBD blended diesels were calculated by means of two typical numerical equations[11].

Equation (1) is the regression model developed for the experimental data acquired using Malvern Particle Size Analyzer[12].

$$SMD = 0.002103\ \mu + 0.000330\ \sigma \qquad (1)$$

Where μ is the dynamic viscosity (Pa.s) and ó is the surface tension.

In this calculation, the results on SMD can be seen in Fig. 10 that viscosity has more positive effects than surface tension. Therefore, the more HBD blended fuels were shown the slightly larger SMDs than petro-diesel, because of larger viscosity of HBD than that of petro-diesel, and also, surface tension has relatively lower correlation than viscosity.

Equation (2) is empirical equation developed for pintle type plain-orifice atomizer suggested by Elkotb[13].

$$SMD = 6156\ \nu^{0.385}\ (\sigma \rho_L)^{0.737}\ \rho_G^{0.06}\ \Delta p^{-0.54}\ \mu m \quad (2)$$

Where ν is the kinematic viscosity (mm^2/s), σ is the surface tension, ρ_G is air density and ρ_L is fuel density, and Δp is the pressure drop across fuel nozzle.

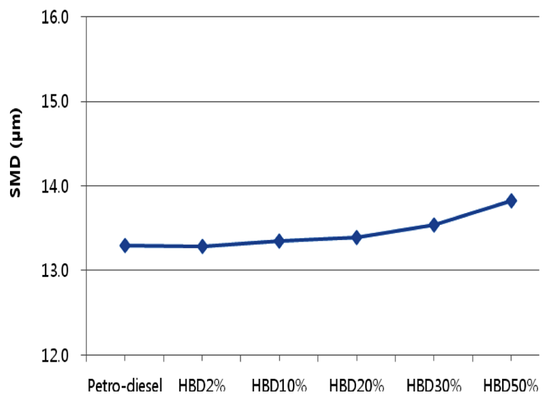

Fig. 10 SMD correlations of petro-diesel and HBD blended diesel by using regression model equation

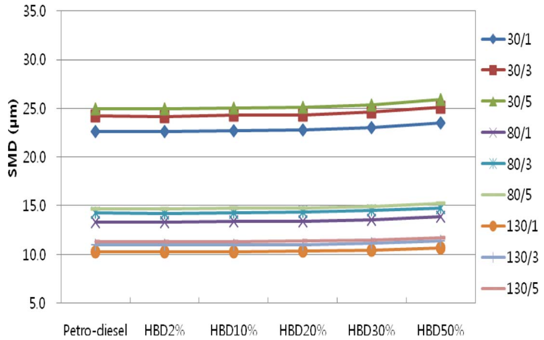

Fig. 11 SMD correlations of petro-diesel and HBD by using Elkotb equation

In this calculation, it can be additionally explained that the lower injection pressure and the higher ambient pressure more influenced to make the larger SMD than HBD blending ratios, as shown in Fig. 11.

At this result, the more HBD blended fuel shows the larger SMD, due to higher viscosity of HBD than that of petro-diesel. It also shows typical trends that the higher viscosity makes the larger SMD.

4. Conclusions

The more HBD blended diesel had the slightly shorter spray tip penetration than petro-diesel at the same time frame after injection. The more HBD has the larger spray angles than petro-diesel with the similar patterns among various HBD blending ratios. Injection delay was affected not the fuel differences but the injection pressures. The more HBD blended fuels were shown the slightly larger SMDs than petro-diesel, because of larger viscosity of HBD than that of petro-diesel. It can be explained that the lower injection pressures and the higher ambient pressures have the larger SMDs. Consequently, this study has found that HBD has a little bit merits and demerits of macro- and micro- spray patterns compared to petro-diesel.

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