Spray Characteristics in CI Engines Fuelled with Vegetable Oils and Its Derivatives

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Key Words: Viscosity, Empirical correlations, Vegetable oil and its blend, Biodiesel and its blends, Compression ignition engine

Abstract

In this article, spray characteristics in CI engines fuelled with vegetable oils and its derivatives will be reviewed. Of edible vegetable oils, soybean oil and rapeseed oil were mainly investigated. Of inedible vegetable oils, jatropha oil and used frying oil were main concern on the research on the spray characteristics in CI engine. Spray angle and spray penetration were mainly examined among the macroscopic spray characteristics and Sauter mean diameter was only investigated among the microscopic spray characteristics. There exist six different definitions of spray angle which should be examined. Neat vegetable oil and biodiesel fuels show smaller spray angle than diesel fuel. Biodiesel fuel and vegetable oils and its blend have a longer spray penetration than diesel fuel. However, biodiesel blends with diesel shows the similar spray penetration with diesel fuel. SMDs in the biodiesel spray, vegetable oils and its blends spray are higher than that in the diesel spray.

1. Introduction

Due to the limited fossil fuels, the development of alternative fuels is required. Due to the global climate change, CO_2 emission reduction is required through the use of compression ignition (CI) engine in internal combustion engines. Therefore, the application of vegetable oils, biodiesel, DME and Fischer-Tropsch diesel in CI engine can be a solution for the above two problems simultaneously[(1,2)].

Of four alternative fuels for CI engines, vegetable oils can be grouped as edible and inedible oils. The edible vegetable oil in use at present is soybean, sunflower, rapeseed (canola), coconut and palm oils. The use of edible vegetable oils for making biodiesel has the disadvantage of high feedstock cost. The development of inedible vegetable oil for the production of biodiesel is getting a renewed attention because of concerns for long-term food and energy securities. The inedible vegetable oil used as feedstock for biodiesel production includes jatropha, karanja, mahua, linseed, rubber seed, cottonseed, and neem oils etc.[(3-5)].

The first review on the combustion of fat and vegetable oil derived fuels in CI engines was reported by Graboski and McCormick in 1998[(6)]. As well as neat biodiesel and biodiesel blends, the prospects and opportunity of introducing neat vegetable oil and vegetable oil blends are reviewed by Babu and Devaradjane[(7)]. They suggested that a blend of 25% diesel fuel and 75% vegetable oil offers better engine performance and lower emissions and carbon deposit buildups. Even though Ramadhas *et al.*[(8)] presented a review paper entitled on "use of vegetable oils as IC engine fuels-a review", a graphical comparison of engine performance and emission for five different vegetable oils and their methyl esters in comparison to fossil

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diesel came from only one paper reported by Altin *et al.*(9).

In the review of biofuels applications as fuels for internal combustion engines, Agarwal(10) focuses on performance and emission of biodiesel in CI engines, combustion analysis, wear performance on long-term engine usage, and economic feasibility. They suggested that the main resources for biodiesel production can be inedible oils obtained from plant species such as jatropha, karanja, nagchampa and rubber seed oils.

A literature review of the application of biodiesel for CI engines between 1900 and 2005 was recently reported by Shahid and Jamal(11). In this article, the typical edible vegetable oils for the production of biodiesel such as sunflower, soybean, rapeseed, palm, cotton seed and peanut oils are considered. Lapuerta *et al.*(12) reported the review about the effect of biodiesel fuels on diesel engine emissions. In the engine performance, they found that the highest consensus lies in an increase in fuel consumption in approximate proportion to the loss of heating value. In the emission characteristics, the highest consensus was found in the sharp reduction in particulates emission. A literature review work on biodiesel production, combustion, performance and emissions was conducted by Basha *et al.*(13). They observed that biodiesel has similar combustion characteristics as fossil diesel and blends of biodiesel with fossil diesel were found shorter ignition delay, higher ignition temperature, higher ignition pressure and peak heat release. The emissions of HC and NOx from the engine were found to be more and higher on the all of the fuel blends as compared to fossil diesel.

Recently, Hossain and Davies(14) reported a technical review and life-cycle analysis of vegetable oils as alternative fuels for CI engines. This review showed that a number of neat vegetable oils can be used satisfactorily in CI engines by preheating the oil and/or modifying the engine parameters and the maintenance schedule without through transesterification process. In addition, they emphasized that the life-cycle output-to-input energy ratio of neat vegetable oils was around 6 times and 2-6 times higher than fossil diesel and biodiesel, respectively. Moreover, they found that neat vegetable oils have the highest potential of reducing life-cycle green house gas emissions as compared to biodiesel and fossil diesel. Several recent books discussed vegetable oils and biodiesel in whole or in part, which include Saka(15), Demirbas(16), Soetaert and Vandeamme(17) and No(18).

There exist so many articles related to the review on production of biodiesels from edible and inedible vegetable oils, performance and exhaust emissions of CI engine fuelled with vegetable oil and its derivatives as discussed in the above. However, spray characteristics was not considered in those reviews. In this article, therefore, spray characteristics in CI engines fuelled with vegetable oils and its derivatives will be reviewed.

2. Spray angle

The research on the spray angle in the application of vegetable oils and its derivative to CI engines can be grouped as follows.

2.1 Neat SO and its blend

According to Ryan and Bagby(19), heating the vegetable oils such as peanut, sunflower, cottonseed and soybean oils to reduce their viscosity from 40 to 4 cSt resulted in decrease in spray angle. The vegetable oils show characteristics that are the opposite to those expected in most other fossil fuels. Experiences with diesel fuel indicated that spray angle decreases with increase in fuel viscosity(20). They concluded that the chemical changes that occur during the injection process could account for the unexpected spray characteristics of the vegetable oils.

2.2 Neat SO biodiesel and its blend

Four studies on the spray angle in the application of neat soybean oil(SO) biodiesel and its blend to CI engines can be found in the literature.

In the behaviour of diesel and biodiesel spray generated by a mini-sac nozzle, with a symmetrical distribution of the five holes around the injector axis, higher values for the diesel spray cone angles than biodiesel ones with the cylindrical holes nozzle at back pressure of 3 MPa and at least at 50 MPa and 100 MPa injection pressure were observed(21). In addition, slightly higher differences were detected for the cases of 1 MP and 5 MPa back pressures. However, there was no big difference between diesel and biodiesel spray angles with the conical converging holes nozzle at back pressure of 5 MPa. In this case, the effect of ambient pressure on the spray angle of diesel and biodiesel was not clearly explained.

According to the calculation of spray angle by introducing the one of theoretical correlation for spray angle, Faria *et al.*(22) reported that there were no big differences for all the diesel/biodiesel mixtures from 2% to 20% and for two operating conditions. In addition, the difference in predicted spray angle for two biodiesels with widely different viscosity could not be seen. This may be due to the selection of too simple theoretical correlation which is considering the air density/liquid density only even though there are many different theoretical and empirical correlations developed for the spray angle in plain-orifice atomizer(23).

Based on the modelling results for soybean oil methyl ester and other two biodiesels by using the modified KIVA 3V code that could be applied to biodiesel fuel, Yuan *et al.*(24) found that the biodiesel fuels showed smaller spray angles than diesel fuel, and suggested that the decreased spray angle was one of the main reasons for the increased NOx emissions from biodiesel combustion. One possible explanation for the effect of spray angle on NOx emissions is that the decreased spray angle of biodiesel increases the spray penetration which consequently increased the degree of widespread combustion in the chamber thus also increasing NOx emissions. (spray angle - spray penetration - NOx) However, the definition of spray angle in their calculation was not clearly mentioned.

In the prediction of spray angles for neat SO biodiesel from the different type of nozzle orifice by using the two-fluid model FIRE code, Park *et al.*(25) found that even though in the nozzle orifice with tapered inlet shape, the cavitation with the increase of injection pressure didn't affect the spray angle too much, the nozzle orifice with sharp edged inlet, the spray angle abruptly increased in the region of cavitating flow and then suddenly decreased at the hydraulic flup region.(nozzle shape – injection pressure - cavitation)

According to Alloca *et al.*(26), spray angle of neat SO biodiesel at injection pressure of 50 MPa was 9% narrower than that of diesel. In this study, spray angle was defined as the angle between the tangents to the spray edges in the region up to the axial distance of 10 mm from the nozzle.

It is clear from the above studies that the spray angle in the biodiesel spray will be affected by nozzle orifice shape, injection pressure and back pressure.

2.3 Neat RO and its blend

Yoshimoto(27) confirmed that spray angle for the equal proportions of rapeseed oil and diesel (50/50%) shows the quite similar to diesel spray. Compared with diesel fuel, spray angle for neat rapeseed oil is very small. It should be pointed out that the spray angle in this study was determined from the photos at the distance 200~250 do (do: nozzle orifice diameter) downstream the nozzle. The angle of a diesel spray is normally defined as the angle formed by two straight lines drawn from the discharge orifice to the outer periphery of the spray at a distance 60 do downstream of the nozzle(20,23). For the emulsified fuel, spray angle decreased with the increase in water content due to the increase kinematic viscosity regardless of nozzle opening pressure.

2.4 Neat RO biodiesel and its blend

In the spray generated by a commercial high-pressure common-rail injection system when fed with diesel fuel, a blend of diesel fuel and rapeseed oil (RO) biodiesel (67/37%) and neat RO biodiesel, Grimaldi and Postrioti(28) defined the near and far spray angles due to the non-axisymmetrical structure of spray. Near spray angle was defined as the angle that includes the spray structure from the nozzle tip up to

1/3 of penetration. Far spray angle was an angle which includes the spray up to the entire spray penetration length. They found that near spray angle showed a globally monotonously decreasing trend in time at lower injection pressures, while minimum was evident for higher injection pressures. They analyzed that this behaviour was due to the onset of large vorticose structure in the spray. In addition, they concluded that neat RO biodiesel was generally characterized by lower spray angles.

On the other hand, Li *et al.*(29) introduced the different concept of two spray angles, i.e. near-field angle and far-field angle instead of near and far spray angles defined by Grimaldi and Postroti(28). The near-field angle was defined as the angle between the tangents to the spray envelope in the region between 10 mm and 20 mm extending from the nozzle tip. Similarly, the far-field angle was computed in the region from 20 mm to further downstream of the spray. Their result show that neat RO biodiesel had smaller spray angle and the spray angles of them were only about half of that of diesel due to its higher viscosity, surface tension and boiling point. In addition, they found that spray angle increased with the increase of the nozzle orifice diameter.

Even though quantitative results were not included in the study of effect of biodiesel on emissions of a bus diesel engine, Kegl(30) found that diesel and RO biodiesel lead to different injection characteristics and consequently to different fuel spray. The spray comparison for diesel and biodiesel at peak torque condition showed that spray angle of RO biodiesel was narrower than that of diesel.

In the measurement of spray development using the high-speed digital camera for diesel and neat RO biodiesel fuel at 500 rpm, the differences in physical properties of fuels results in a higher injection pressure and narrower spray angle of biodiesel. However, simulations by FIRE v8.4 in bus engine MAN D2566 showed that spray angle appears to be almost the same for diesel and neat RO biodiesel spray(31).

Recently, Desantes *et al.*(32,33) defined the spray angle as the cone angle formed by the spray considering a 60% penetration where they compare the influence of using biodiesels with conventional injection systems. Three different fuels introduced in their study were: one was commercial diesel with 5.75% of RO methyl ester (B5), another was 30% mixture of the same vegetable oil and standard diesel fuel (B30) and the last one was a neat RO biodiesel (B100). For the injection pressures such as 50 and 120 MPa(32) and 160 MPa(33), spray angles for B5 and B30 were similar, but spray angle for B100 was narrower than that for other two fuels.

According to the their definition of spray angle as the angle between the tangents to the spray edges in the region up to the axial distance of 10 mm from the nozzle, Alloca *et al.*(26) reported the narrower spray angle of neat RO biodiesel than that of diesel and neat SO biodiesel.

2.5 Other VO and its blends

For the application of rubber seed oil(RSO), one of typical inedible vegetable oils, as a diesel fuel substitute/extender for diesel engine, the variation of spray angle with liquid viscosity was measured by Perera and Dunn (34). It can be seen from this study that spray angle decreases as the viscosity of liquid fuel increases. It should be noted that only half of the value of spray angle of diesel fuel was obtained for RSO in this work due to the high viscosity of RSO.

2.6 Other VO biodiesel and its blends

The research on the spray angle for used cooking oil derived biodiesel blends with dimethyl ether (DME) was carried out by Kim *et al.*(35). There was no appreciable difference in spray angle between diesel and DME blended biodiesel. However, it should be pointed out that droplet evaporation occurred at 18 ms after start of injection (SOI) for DME blended biodiesel, which was not observed for diesel fuel.

Spray characteristics of waste cooking oil derived biodiesel in a single-cylinder, DI CI engine with 4-hole nozzle and Bosch type injection system was investigated by Senda *et al.*(36). In this work, they newly suggested the definition of two angles: i.e. spray cone angle and spray angle. Spray cone angle was defined as the angle formed by two straight lines drawn from the discharge orifice to the outer periphery of the spray at a distance L/3 (L: spray penetration) downstream of nozzle as follows.

$$\tan(\theta_{1/3}/2) = (W/2)/(L/3) \qquad (1)$$

$$\tan(\theta_{max}/2) = [(W_{max}/2)/L'] \qquad (2)$$

where $\theta_{1/3}$ is the spray cone angle, θ_{max} is the spray angle, W is the spray width in radial direction, W_{max} is the maximum spray width in radial direction, L is the spray penetration and L' is the axial distance at W_{max}. Spray angle was defined at a distance with the maximum dispersion width in radial direction downstream of nozzle. They emphasized that spray cone angle is related to the atomization process near the nozzle exit, while spray angle is related to the large scale vortex structure at the spray peripheral region. They found that both spray cone angle and spray angle for neat biodiesel is narrower than those for B20 and diesel fuel in the quasi-steady state.

It is clear that Senda *et al.*(36) had slightly modified the definition of near spray angle and far spray angle by Grimaldi and Postrioti(28). Spray cone angle of Senda *et al.*(36) is exactly same with the near spray angle of Grimaldi and Postiroti(28). However, even though spray angle is introduced instead of far spray angle, θ_{max} was measured at the position of W_{max} instead of entire tip penetration length in far spray angle.

To evaluate the effect of physic-chemical properties of diesel/biodiesel mixture in a diesel engine equipped with a common rail direct injection system, Faria *et al.*(22) introduced the several blends of soybean oil derived biodiesel and two different castor oil biodiesels and diesel fuel. They found that at low and moderate operating conditions, there was no difference between several castor oil biodiesel blends and diesel fuel. However, one of their conclusions reveals that the original vegetable oil for the production of biodiesel affects the spray characteristics and quality of atomization. The effects were more pronounced in samples of biodiesel from castor oil than for samples of biodiesel from soybean oil.

In the experimental study of spray characteristics of biodiesel based on three inedible vegetable oils, Gao *et al.*(37) defined the spray cone angle as the maximum angle which forms the angle between the bottom edge of the triangle and the nozzle during the process of spraying. This is the same concept with the spray angle defined at the maximum spray width in radial direction by Senda *et al.*(36). They concluded that spray cone angle decreased as the biodiesel content in the blend increased. In addition, they mentioned that increase in injection pressure causes the spray angle to widen. It should be noted that they did not used the definition of two spray angles used in Li *et al.*(29) even though they are exactly same research group.

Recently, Li *et al.*(38) introduced the definition of spray angle suggested by Delacourt *et al.*(39) in the measurement of spray angle produced by jatropha oil biodiesel and palm oil biodiesel.

2.7 Unknown biodiesel

Bang *et al.*(40) carried out the research on the spray characteristics of biodiesel blends with DME. Remarkable effect of ambient pressure on spray angle was observed. The spray angle widened considerably with increase in ambient pressures. However, the influence of mixing ration on spray angle was not clearly illustrated and the effect of injection pressure on spray angle was not included.

Mao *et al.*(41) found from numerical simulation of spray characteristics of biodiesel that spray angle of biodiesel was smaller for about 3 degree than that of diesel fuel. They suggested for the reason that biodiesel was more difficult to break up due to its higher viscosity than diesel. In addition to the original vegetable oil for biodiesel, they also did not explain the name of CFD code.

3. Spray penetration

The research works on the penetration of spray produced from neat vegetable oil and its blend, neat vegetable oil biodiesel and its blend can be divided by two area; i.e. vapour phase penetration and liquid phase penetration(42,43). However, spray penetration will be used as the synonym with the vapour phase penetration.

3.1 Neat SO and its blend

In general, an increase in fuel viscosity typically results in an increase in spray penetration(20). However, Ryan and Bagby(19) found that reduction of viscosity for neat soybean oil(SO) by heating resulted in increases in the spray penetration. They suggested that the chemical changes that occur during the injection process could account for the opposite spray characteristics of several vegetable oils including neat SO.

3.2 Neat SO biodiesel and its blend

In the case of cylindrical holes nozzle among the work reported by Postrioti *et al.*(21), spray penetration for SO biodiesel showed slightly longer one than that for diesel at only injection pressure of 5 MPa with the back pressure of 3 MPa due to longer break-up times of spray. They suggested that the shorter break-up times for the diesel spray could be due to the more intense cavitation inside the nozzle hole with respect to biodiesel beyond the different properties such as density and viscosity of two fuels. For all the injection and back pressure conditions, the use of the conical converging holes nozzle leads to clearly higher spray penetration for diesel in comparison to SO biodiesel. It is clear from this result that spray penetration between diesel and biodiesel could be widely different with the nozzle shape.

Park *et al.*(44) measured and calculated spray penetration of neat SO biodiesel. The experimental results were compared with the numerical results obtained from KIVA-3V code. The spray penetration of diesel and biodiesel showed the similar tendency with the increase of time after start of injection. The calculated results for biodiesel fuel were good agreement with the experimental results at lower ambient pressure, whereas there were some differences between numerical and experimental results at a higher ambient pressure. The effect of ambient pressure and injection pressure on spray penetration of SO biodiesel was not clear due to the results reported at the only two ambient pressures and injection pressures. In their continued work(45), the effect of injection pressure, ambient gas temperature, fuel temperature on spray penetration for neat SO biodiesel was studied. They found that the increase of fuel temperature slightly affects the spray penetration. This may be due to the small difference of fuel temperature from 300 K to 360 K. The increase of ambient gas temperature resulted in a increase in spray penetration. The spray penetration was increased with the increase of injection pressure. The numerical results for spray penetration consistently underestimated the experimental results at most of experimental conditions. In this study, the data obtained for diesel for comparison was not reported.

However, for two vegetable oil biodiesel(rice bran oil and soybean oil), the biodiesel blended with diesel fuel (B20 and B40) shows the similar spray penetration with that of conventional diesel fuel(46). This means that the biodiesel content in the blended fuel has little effects on spray penetration. This tendency also appeared on the spray penetration of SO biodiesel and SO biodiesel blended with 20% of ethanol(47).

Faria *et al.*(22) had measured and estimated spray penetration of SO biodiesel and diesel blends. It is very interesting to use one empirical correlations suggested by Sitkei for low load condition and another one theoretical correlations suggested by Dent at moderate load conditions(20,42). As biodiesel content in the blends increases, spray penetration is decreased at low and moderate load conditions for SO biodiesel blends.

The effects of the physic-chemical properties of the most promising alternative renewable diesel fuels such as RO biodiesel, SO biodiesel and GTL (Gas to Liquid) on performance and pollutant emissions in non-evaporating and evaporating conditions for diesel engines were recently studied by Allocca *et al.*(26) Four fuels (diesel, RO biodiesel 50% blend, SO biodiesel 50% blend and GTL 50% blend) had been injected by a second-generation Bosch common rail system and double injection (pilot + main) had been implemented. They found in non-evaporating condition that spray penetration of RO biodiesel blend was longer than that of SO biodiesel blend and both spray penetrations were shorter than those of diesel and GTL. However, there was no report about the comparison of liquid phase penetration for four fuels in evaporating condition. They only compared the spray tip penetration between diesel and GTL in evaporating and non-evaporating conditions.

3.3 Neat RO and its blend

According to Yoshimoto(27), spray penetration for neat rapeseed oil (RO) increases gradually, and at 0.5 ms after start of injection, there is a 29% difference between neat RO and the equal proportion of RO-diesel blend. The equal proportion of RO-diesel blend and its water emulsified fuel show quite similar spray penetration initially, while at 0.2 ms after start of injection spray penetration with the emulsion tends to increase slightly.

3.4 Neat RO biodiesel and its blend

In the study of a commercial high pressure, common rail injection system for automotive DI diesel engines fuelled with standard diesel, a blend of RO biodiesel and diesel fuel (33/67%) and neat RO biodiesel, Grimaldi and Postrioti(28) found that higher biodiesel content in a blend of diesel and biodiesel determines higher break-up times and in general higher spray penetrations. This result is different with the result obtained for SO biodiesel blends by Lee *et al.*(46) In addition, they suggested that the dependence of spray penetration on fuel properties is more complex than that stated by classical and empirical correlations.

Spray penetration of three different biodiesels and diesel fuel in diesel engines equipped with common rail direct injection system for nitrogen back pressure of 1.2 and 5.0 MPa and injection pressure of 120 MPa are reported by Senatore *et al.*(48). Three biodiesels introduced in this work include neat rapeseed oil derived biodiesel (A), blend of rapeseed oil biodiesel and soybean oil biodiesel (B; 60/40%) and mixture of rapeseed oil biodiesel/used frying oil biodiesel (C; 75/25%). At ambient pressure of 1.2 MPa, spray penetration of diesel fuel and three biodiesels did not show significant differences overlapping in the investigated time range. However, at ambient pressure of 5.0 MPa, spay penetration curve of diesel fuel showed remarkably lower vales that those of three biodiesels. It is clear from this study that at higher ambient pressure, spray penetration increases with the increase of rapeseed oil biodiesel content in the blend. This result is coincident with the result obtained by Grimaldi and Postrioti(28)

According to Li *et al.*(29), neat RO biodiesel had larger spray penetration than that of diesel due to mainly its higher density. In the measurement of spray development using the high-speed digital camera for diesel and neat RO biodiesel fuel at 500 rpm, neat RO biodiesel spray showed about 5% longer spray penetration than diesel at the end of injection. In the simulation by FIRE v8.4 in bus engine MAN D2566, slightly longer penetration in the case of neat RO biodiesel fuel can be confirmed(31).

According to Kegl(30) rapeseed oil biodiesel spray formed a narrower and longer spray penetration in comparison to diesel at most tested operating conditions. Some of the most important reasons for that were low fuel vaporization, worse atomization, and higher injection pressure of neat biodiesel. He analyzed that worse atomization came from the higher surface tension and viscosity of rapeseed oil biodiesel. This leads to higher spray penetration and to higher SMD of biodiesel spray.

For commercial diesel (B5), B30 and neat RO biodiesel (B100), all fuels showed very close spray penetration, but neat RO biodiesel had higher penetration(32). Higher inertial mass due to higher density and bigger droplets lead to such result that the neat RO biodiesel penetrates more than a regular diesel. Their results indicated that spray penetration for three fuels was increase with the increase of injection pressure from 50 MPa to 120 MPa.

A study was performed by Pastor *et al.*(49) to analyze the evolution of liquid phase penetration of evaporating sprays under engine-like conditions with neat RO biodiesel and blends with 5 and 30% mass rate of RO biodiesel with diesel fuel. Increase in biodiesel content in the blended diesel fuel with RO biodiesel leaded to an increase of liquid phase penetration for all of the injection pressure from 30 MPa to 160 MPa. Increase in injection pressure caused the liquid phase penetration to slightly increase. The small influence of injection pressure on liquid phase penetration is similar to other results obtained from diesel fuel on multi-hole nozzles. Increase in injection pressure also shortens the time required to reach the quasi-steady liquid spray penetration period.

3.5 Other VO and its blends

The effect of viscosity and surface tension on spray penetration was studied by Perera and Dunn(34) in order to identify the differences between inedible vegetable oil, rubber seed oil(RSO) and diesel oil. They found that the surface tension of liquid fuels has no any noticeable effect on spray penetration curves. However, it was clear that spray penetration increases with the increase in viscosity of liquid fuel. Therefore, RSO had a higher penetration than diesel oil. This result reveals that high viscosity oils such as RSO produce sprays with small spray angle which tend to penetrate further when compared to diesel oil sprays.

3.6 Other VO biodiesel and its blends

Effect of biodiesel content in the blends and injection pressure on spray penetration for rice bran oil biodiesel was evaluated by Lee *et al.*(46). Their result indicated that biodiesel content in the blends has little effect on spray penetration. This may be due to the selection of two blends with small difference, B20 and B40. For diesel and B20 of rice bran oil biodiesel blend, they confirmed that spray penetration was increased with increase in injection pressure.

Spray penetration for the blend of used cooking oil derived biodiesel and dimethyl ether (DME) was investigated by Kim *et al.*(35). They found that spray penetration of DME blended biodiesel showed nearly the same value compared to diesel fuel as time progressed to 12 ms. This means that DME blending in biodiesel has appreciable effect on spray penetration because spray penetration of most biodiesel is longer than that of diesel.

Yamane *et al.*(50) investigated the effect of physical properties of used cooking oil derived biodiesels on spray penetration. They found that spray penetration for two biodiesels with different constituents is shorter than that of diesel fuel at injection pressure of 130 MPa. They suggested that this short spray penetration is due to the higher kinematic viscosities of biodiesels (2.2~3.3 times higher than diesel) at lower fuel temperature.

In a single-cylinder, DI diesel engine with toroidal type combustion chamber, 4-hole nozzle and Bosch type injection system, two waste cooking oil derived biodiesels were tested by Senda *et al.*(36). They found that spray penetration of neat biodiesel was slightly longer than other fuels such as B20 and diesel fuel due to the distillation properties. This longer penetration affected to the smaller spray angle of neat biodiesel. Even though the kinematic viscosity of biodiesel was two times higher than diesel (55 mm^2/s for biodiesel and 2.5 mm^2/s for diesel), the longer spray penetration than diesel is the opposite result of Yamane *et al.*(50).

Influence of biodiesel content on spray penetration for two kinds of castor oil biodiesels at low and moderate load conditions was investigated by Faria *et al.*(22). The experimental results show a tendency of reduced spray penetration as biodiesel content increases. For castor oil biodiesels at B20, there is a reduction of at maximum 5% in the percentage penetration in relation to pure diesel. Comparing castor oil biodiesel (B100) to pure diesel, there is a penetration reduction of around 28% for castor biodiesels. These results are the opposite of those obtained from most other biodiesel blends and researchers.

To reformulate the physical properties of biodiesel, Senda *et al.*(51) introduced the lower boiling point fuel into the waste cooking oil derived biodiesel. In the study of spray characteristics, spray penetration was decreased with the increase of lower boiling point fuel content in the later part of injection. It should be pointed out that they reported the data for liquid phase penetration which was defined as the area of 3% or less of the maximum intensity in each images. As the lower boiling point fuel content increased, liquid phase penetration decreased because early evaporation was promoted in case of the mixed fuel spray.

Effect of biodiesel content on spray penetration for jatropha, palm and used frying oils was also investigated experimentally and numerically by Gao *et al.*(37). It should be noted that they classified palm oil as inedible oil. They found that spray penetration increased with increasing biodiesel blending ratio of biodiesel in the fuel such as B5, B10, B20, B50 and B100. The differences in spray penetration between diesel and three biodiesels at blend ratios of B5, B10 and B20 remained within 6%. It was also found that the differences in spray penetration between diesel and different biodiesel blends were small during the first 0.6~0.8 ms after start of injection. After 0.8 ms, differences in spray penetration increased with increase in the biodiesel blending ratios. The calculated spray penetrations by using Star-CD CFD code were in good agreement with the experimental data.

3.7 Unknown biodiesel

There are some works which the original vegetable oil or waste material for production of biodiesel is not clearly illustrated in the paper. Higgins *et al.*(52) had investigated the effect of nine different alternative fuels including neat biodiesel for diesel engine on liquid-phase penetration in direct injection sprays and suggested a correlation for the stationary liquid-phase penetration length depending on the fuel/ambient density ratio and the specific energy ratio. The specific energy ratio was defined by the heat required to vaporize the liquid (sensible plus latent) divided by the heat available from the in-cylinder gases entrained into the spray. Their correlation predicted well the data related to most of the fuels tested in their study. However, their correlation was less accurate with neat biodiesel. In addition, the original vegetable oil used for the production of biodiesel tested in their experiment was not clearly mentioned and they assumed the following mass-fraction distribution of acid methyl esters: 5% stearic, 25% oleic, 52% linoleic, 6% linolenic, and 12% n-hexadecanoic. They believed that the large deviation between the correlation and the experimental results for neat biodiesel is due to first incorrect proportions of the constituent molecules in the assumed composition and secondly the interphase transport at the droplet surface instead of mixing-limited vaporization for other fuels.

Comparison of spray penetration between diesel and biodiesel sprays in the early stage of injection was conducted by Jimenez *et al.*(53). In this study, spray penetration increased linearly as time progressed to 600 μs and there was no appreciable difference between two fuels. However, spray penetration increased with increase in ambient temperature due to the decrease in air density. The empirical correlation for the calculation of spray penetration in the early stage of injection was newly suggested as follows.

$$S = 0.6\times10^{-3}\ U_o t^{0.9}(\rho_G/\rho_L)^{-0.163} \quad (3)$$

where S is the spray penetration in mm, U_o is the mean velocity of jet in m/s, t is the time after SOI in μs, and ρ_G and ρ_L are the air and fuel density in kg/m^3, respectively. This empirical correlation is different with other existing correlations reported in the literature(42) and verification of it is required.

Spray penetration for biodiesel blends with DME was investigated by Bang *et al.*(40). No significant effect of injection pressure on spray penetration was observed due to the small difference of injection pressure between 50 MPa and 60 MPa at the high ambient pressure of 4 MPa. In addition, mixing ratio of DME has no appreciable effect on spray penetration, particularly at the high ambient pressure of 4 MPa, while it is not true at the low ambient pressure of 1 MPa. It was observed that spray penetration of DME blended biodiesel decreased with increase in ambient pressure. According to the numerical simulation by CFD code, spray penetration of biodiesel and diesel were nearly the same up to 1.2 ms after start of injection, while the former is longer than the later as time progressed to 3.0 ms(41).

It is clear from the above that as biodiesel content increases, spray penetration is increased for rapeseed oil biodiesel(28), jatropha, palm and used frying oil biodiesels(27). However, it has minor effect for soybean oil biodiesel(22,46) and spray penetration is decreased for castor oil biodiesel(22).

The existing correlations for estimating viscosity of vegetable oil and its derivatives are reviewed and classified. The predictive methods discussed in the previous section are by no means a complete list of available methods. They are all predictive, but limited in the types of compounds to which it can be applied and also limited to temperatures of the components comprising the mixture. The study for the verification of applicability of predictive correlations discussed here to non-edible vegetable oil and its derivatives is required.

4. Sauter mean diameter

The droplet size distribution is frequently characterized by its Sauter mean diameter. In turn, the SMD is influenced by the properties of the atomized and atomizing fluids and by the nozzle design and operating conditions.

4.1 Neat SO biodiesel and its blend

It was not possible to find the work related to the SMD of neat SO and its blends. There exist several works about the SMD of neat SO biodiesels and its blends

In the study of atomization characteristics for the blend of SO biodiesel and diesel in a common rail direct injection engine, mean droplet size distribution with the time after start of injection was measured by Lee *et al.*(46). Sauter mean diameter (SMD) of B20 and B40 of SO biodiesel is larger than that of the diesel fuel. At room temperature and at 0.5 ms after start of injection, SMD from the blends of biodiesel and diesel was, particularly, about twice than that for diesel fuel. However, this biggest difference was decreased as time progressed to 4 ms.

According to the work of Postrioti *et al.*(21), only moderate differences were observed between diesel and SO biodiesel fuel sprays produced from cylindrical and conical holes nozzles in terms of SMD.

In the study on the fuel injection and atomization characteristics of SO biodiesel, Park *et al.*(44) found that SMD of SO biodiesel decreased along the axial distance of spray and showed slightly larger than that of diesel fuel. In addition, the predicted local and overall SMD distribution obtained by KIVA-3 code for both diesel and biodiesel were in good agreement with the experimental SMD distribution. In the continuing work by same authors(45), the effect of fuel temperature on SMD of SO biodiesel was investigated. As the fuel temperature increased, they found that the detected local drop size of SO biodiesel at the spray axis also increased, because the small drop in the detecting volume were more easily evaporated, while the larger drop remain.

4.2 Neat RO biodiesel and its blend

It was not possible to find the study which is relevant to the SMD of neat RO and its blends. According to Pogorevc *et al.*(31), diesel and RO biodiesel fuel spray simulations by FIRE v8.4 in bus engine MAN D2566 showed that biodiesel droplets are around 20% bigger than diesel droplets, and therefore, their evaporation process is longer. Accordingly undesired fuel-rich mixture areas can occur.

4.3 Other VO and its blends

The droplet size distribution of rubber seed oil (RSO), one of typical inedible vegetable oil, was measured from the distance of 7.5 cm downstream from the nozzle tip by Perera and Dunn(34). Sauter mean diameter (SMD) of liquid fuel sprays such as diesel oil, RSO biodiesel, blends of RSO50/D50, and neat RSO were determined by using Malvern particle size analyzer. It was clear from this study that there is an increase in SMD with increase in liquid viscosity and RSO has a SMD of more than three times than that of diesel oil.

4.4 Other VO biodiesel and its blends

For the blend of rice bran oil biodiesel and diesel in a common rail engine, Lee *et al.*(46) reported the SMD according to the variation of time after start of injection up to 4 ms. All the trend is much similar for the data from the blend of SO biodiesel and diesel. However, the SMD difference in case of rice bran oil biodiesel blends was bigger than that of SO biodiesel blend.

Spray characteristics of a blend of biodiesel from used cooking oil with DME were investigated by Kim *et al.*(35) with the variation of injection pressure and ambient pressure. The analysis of fuel type effect on SMD revealed that SMD of used cooking oil biodiesel was bigger than diesel, while DME 50 blended biodiesel showed the smaller than diesel. The SMD of neat DME showed the smallest of the four fuels tested in this study. Increase of injection pressure up to 4 MPa for DME 50 blended biodiesel leaded to the decrease of SMD, while SMD increased for over injection pressure of 4 MPa. They found that optimum ambient pressure of minimum SMD for DME 50 blended biodiesel; for example, SMD showed its minimum value at ambient pressure of 0.5 MPa for injection pressure of 2.0 MPa, and at ambient pressure of 0.2 MPa for injection pressure of 4.0 MPa, respectively.

4.5 Unknown biodiesel

It can be found from the numerical simulation work of Mao *et al.*(41) that the SMD of both biodiesel and diesel decreased very rapidly up to 0.6 ms after SOI and they had nearly the same drop size. Even though the different SMD for two fuels were obtained after 0.6 ms, maximum difference between two fuels was 1.3%. This tendency of SMD variation with time after SOI is very similar with the works by Park *et al.*(44,45) and Lee *et al.*(46).

5. Results and discussion

The researches on the spray characteristics of vegetable oils and its derivatives were limited to the mainly edible vegetable oil, namely soybean and rapeseed oil. Moreover, the macroscopic spray characteristics which are mainly investigated up to now are spray angle and spray penetration. The microscopic spray characteristics mainly studied up to now is only Sauter mean diameter.

It is clear from the above that compared with diesel fuel, spray angle of neat vegetable oil is very small. Spray angle of vegetable oils and its blend decreases with increase in fuel temperature and with decrease in fuel viscosity. The effect of vegetable contents in the blends on spray angle is negligible. The influence of ambient pressure, ambient temperature, injection pressure and orifice diameter on spray angle for vegetable oils and its blends should be examined. It can be found from the above that due to the non-axisymmetrical structure of vegetable oils and its derivative spray, there are six different definitions of spray angle, i.e. by Grimaldi and Postrioti(28), Senda *et al.*(36), Li *et al.*(29), Gao *et al.*(37), Delacourt *et al.*(39) and Desantes *et al.*(32,33). A correlation was suggested for the prediction of stationary liquid-phase penetration in direct injection sprays. Biodiesel fuels showed smaller spray angle than diesel fuel. Increase in orifice diameter and ambient pressure produces a wider spray angle of neat biodiesel and its blends. In addition, spray angle decreases with increase in injection pressure and biodiesel contents in the blend. Nozzle shape has no appreciable effect on spray angle of neat biodiesels.

Vegetable oils and its blend have a longer spray penetration than diesel fuel. An increase in fuel temperature or a decrease in fuel viscosity causes the spray to a decrease in spray penetration of vegetable oils and its blend. Biodiesels has a higher spray penetration than diesel fuel and biodiesel blended with diesel shows the similar spray penetration with diesel fuel. Spray penetration of biodiesels and its blends increases with increase in ambient temperature, injection pressure and biodiesel contents in the blends.

Vegetable oils and its blends have larger SMD than diesel fuel. An increase in fuel temperature or a decrease in fuel viscosity produces a smaller SMD in vegetable oils and its blends. The effect of ambient pressure, ambient temperature, injection pressure, orifice diameter, nozzle shape and vegetable oil contents in the blends on SMD should be examined. SMD in the biodiesel spray is higher than that in the diesel spray. In the case of biodiesel, an increase in fuel temperature leads to an increase in SMD. The studies on the relation between ambient pressure and temperature, injection pressure, orifice diameter, nozzle shape and biodiesel contents in the blends are required.

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