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A Review on Spray Characteristics of Biobutanol and Its Blended Fuels in IC engines

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Abstract

This review will be concentrated on the spray characteristics of biobutanol and its blends fuels in internal combustion engines including compression ignition, spark ignition and gas turbine engines. Butanol can be produced by fermentation from sucrose-containing feedstocks, starchy materials and lignocellulosic biomass. Among four isomers of butanol, n-butanol and iso-butanol has been used in CI and SI engines. This is due to higher octane rating and lower water solubility of both butanol compared with other isomers. The researches on the spray characteristics of neat butanol can be classified into the application to CI and SI engines, particularly GDI engine. Two empirical correlations for the prediction of spray angle for butanol as a function of Reynolds number was newly suggested. However, the applicability for the suggested empirical correlation is not yet proved. The butanol blended fuels used for the investigation of spray characteristics includes butanol-biodiesel blend, butanol-gasoline blend, butano-jet A blend and butanol-other fuel blends. Three blends such as butanol/ethanol, butanol/heptane and butanol/heavy fuel oil blends are included in butanol-other fuel blends. Even though combustion and emission characteristics of butanol/diesel fuel blend in CI engines were broadly investigated, study on spray characteristics of butanol/diesel fuel blend could not be found in the literature. In addition, the more study on the spray characteristics of butanol /gasoline blend is required.

Key Words: Spray characteristics, butanol, butanol blended fuel, CI engine. GDI engine, gas turbine

1. Introduction

Among alcohol family, the only three alcohols such methanol, ethanol and butanol are competitive alternative fuels due to their physico-chemical properties. Ethanol and butanol are considered to possess the potential to alternative fuels for internal combustion (IC) engines, based on grounds of production rate, ease of use, sustainability, and particulate matter reduction capability(1). Particularly, it is known that butanol is a more compatible alcohol fuel than ethanol for use with current vehicle and engine technologies, as well as with existing supply and distribution infrastructure(2). Butanol has received increasing attention in recent years after being identified as a feasible alternative for spark ignition (SI) and compression ignition (CI) engines.

Advances in diesel-alcohol blends and their effects on the combustion, performance and emissions of diesel engines were reviewed by Kumar et al.(3). They found that blending of alcohols, along with some cetane number improver, to diesel fuels can reduce exhaust emissions without adverse impacts on the performance of diesel engines. They concluded that butanol (butyl alcohol) is a better alternative for diesel fuel due to its superior fuel properties and miscibility with diesel fuel than those of methanol and ethanol. A comprehensive review on exhaust emissions with ethanol or n-butanol diesel fuel blends during transient operation was reported by Giak-

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oumis *et al.*(1). They found that a decreasing trend in PM and CO emissions, and an increasing trend in HC emission with increase in alcohol percentage were shown in diesel engine fueled with ethanol or n-butanol/diesel fuel blends during transient conditions. However, the trend for NOx emissions was not clear with both increase and decreases being reported according to the specific alcohol content. In addition, n-butanol or iso-butanol has been also used as a surfactant/cosolvent to improve the stability of ethanol-gasoline and methanol-gasoline blends.

In the review of alternative fuels for transportation vehicles, Salvi *et al.*(4) briefly discuss the butanol production only. Extensive literature review on the progress in the production and application of n-butanol as a biofuel was conducted by Jin *et al.*(5). In addition to the improvement in butanol production, studies of basic combustion of butanol as a substitute for gasoline in SI engines, and supplement for diesel fuel in CI engines were addressed. It is important to note that they emphasized the possibility of application of n-butanol to CI engines with advanced combustion technologies, i.e. homogeneous charge compression ignition (HCCI) or low temperature combustion (LTC).

1-butanol, also known as n-butanol, can be produced from fossil fuel as petro-butanol and from biomass as biobutanol, but biobutanol and petro-butanol have the same chemical properties. As same as ethanol(6), biobutanol can be produced by alcoholic fermentation from agricultural feedstocks such as corn, wheat, sugar beet, sorghum, cassava and sugarcane(5). Alternatively, in order to increase the production scale and avoid the use of food crops, a bacterial fermentation process for the production of biobutanol from lignocellulise is also developed as shown in Fig. 1.(1, 7)

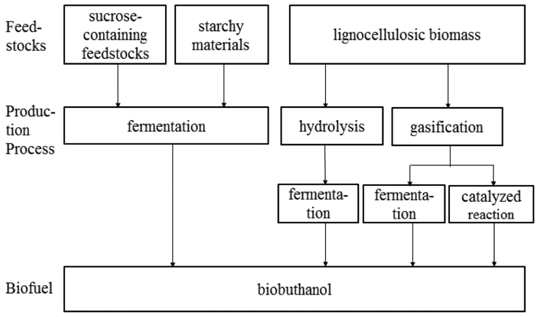

Fig. 1 Feedstocks and production process of biobuthanol.

As a four carbon alcohol compound (C4H9OH), butanol exists as four different chemical isomers based on the location of the hydroxyl (OH) group and carbon chain structure(8). As can be seen in Table 1, anti-knock index (AKI) as octane rating of 1-butanol and iso-butanol are very high and water solubility values of them are relatively low. These advantages of both butanol compared with other butanol isomers are likely the reason for them being considered one of the most promising alternative fuels in SI and CI engines. Isobutanol has been also used as a surfactant/cosolvent to improve the stability of methanol-gasoline ad ethanol-gasoline blends(9).

The primary objective of this review is to provide an update on the spray characteristics of biobutanol and its blended fuels in IC engines. In addition, the field of researches on the spray characteristics of biobutanol which is required in the future will be suggested.

Table 1 Comparison of properties for butanol isomers(3, 5, 8)

Property	1-butanol	1-butanol	1-butanol	Iso-butanol
Density (kg/m^3)	810	806	789	802
AKI	87	66.5	97	103.5 (98*)
Water solubility (g/100 mL)	7.7	12.5	miscible	8.5
Flash point (°C)	35	24	11	28
Boling point(°C)	118	99	82	108

AKI(anti-knock index)=(MON+RON)/2
*value from (8)

2. Spray Characteristics of Neat Butanol

The researches on the spray characteristics of neat butanol can be classified into the application to CI and SI engines, particularly GDI engine as follows. The discussion will be followed by spray characteristics of neat butanol in CI engines and SI engines in order.

2.1 CI engines

Spray penetration in CI engine conditions is the penetration of the mixture of vapor and liquid. For non-evaporating sprays, the vapor part and the liquid part of penetration are equal, while the liquid part of the penetration is limited by the lifetime of the droplet. Therefore, spray penetration in the evaporating fuel jets can be divided into vapor-phase penetration and liquid phase penetration(10). Liquid phase penetration of neat n-butanol spray was measured by Liu *et al.*(11) on a constant volume chamber at ambient temperature of 1000 K and three different oxygen concentrations of 21, 16, and 10.5%, respectively. To simulate the EGR with the oxygen concentration, they assumed no EGR for 21%, medium EGR for 15% and heavy EGR for 10.5%, respectively. Liquid phase penetration was increased with decrease in ambient oxygen concentration. This is because it takes longer time for the fuel to auto-ignite with less oxygen present, thus allowing spray to penetrate further into the combustion chamber. In their continued work(12), the data obtained in the previous study had compared with those of soybean biodiesel. In addition, various ambient temperature ranged from 700 K to 1000 K were tested to mimic the diesel in-cylinder environment covering both conventional and low temperature combustion conditions. They found that the overall liquid phase penetration decreased with the increase of ambient temperature due to the fast evaporation rate. They also concluded that the transient liquid phase penetration of n-butanol was less affected by the downstream flame and was shorter than that of soybean biodiesel under similar conditions. Their works further continued to compare the spray and combustion characteristics of neat acetone-butanol-ethanol (ABE 100), n-butanol (Bu100), and diesel in a constant volume chamber(13). In this study, ABE 100 revealed relatively shorter liquid phase penetration than that of Bu100 at the lower ambient temperature of 800 K, but at higher ambient temperatures of 1000 K and 1200 K, the difference in liquid phase penetration between ABE 100 and Bu100 was nearly negligible. The liquid phase penetration of diesel fuel showed the longest one at every ambient temperature and ambient oxygen concentration. They argued that the low boiling point, high vapor pressure, and low viscosity of both acetone and ethanol in ABE enhanced the spray breakup early for ABE 100 relative to Bu100 under low ambient temperature. They concluded that although ambient temperature affect significantly to the liquid phase penetration, the ambient oxygen concentration shows slight effect on it.

Reddemann *et al.*(14) had measured the liquid and vapor phase penetrations for five different fuels including butanol and ethanol within optically accessible pressurized chamber. The ambient conditions had been set to temperatures of 600 K, 700 K and 800 K and ambient pressure of 5 MPa for all experiments. They found that initial liquid phase penetration (from 0.3 to 0.55 ms after SOI) for butanol is nearly similar with that of ethanol, but two liquid phase penetrations in the latter stage (from 0.6 to 1.4 ms after SOI) shows the difference, particularly in the higher ambient temperature. However, vapor phase penetration remains largely unaffected by fuel properties and ambient temperature. In their continued study(15), the effect of fuel properties on liquid phase penetration, droplet size and velocity distribution of spray for the same five fuels with the previous study was investigated. They found that butanol has the bigger SMD than that of ethanol because of its high surface tension, which is the most relevant parameter for the initial droplet diameter. However, lower enthalpy of vaporization, i.e. higher evaporation rate of n-butanol that that of ethanol resulted in a comparatively shorter liquid phase penetration.

In the study of the influence of fuel properties on primary jet breakup for a piezo injector with midi-sac hole nozzle in a state-of-the-art diesel injection system, n-butanol was included among eleven different fuels and six different injection pressures selected to cover a wide range of Reynolds numbers and gaseous Weber numbers(16). An empirical correlation for the prediction of spray angle as a function of Reynolds numbers was newly suggested in this study as follows.

$$\theta = \mathrm{G} \log [\mathrm{Re}/2300]$$
$$\text{for } 10^3 < \mathrm{Re} < 10^5,\ 10^2 < \mathrm{We} < 10^3 \qquad (1)$$

where θ is spray angle, G is the nozzle geometry factor (=4.3°), and Re is Reynolds number based on outlet velocity of the liquid jet from the nozzle in the stationary regime. It is interesting to note that the measurement position for spray angle was defined depending on the ratio between spray penetration and vertical picture width which is arbitrary fixed.

In their continued study(17), sixteen fuels including 1-butanol and three different ambient densities were introduced to analyze the macroscopic spray characteristics such as penetration, spray angle and spray volume by using the high speed camera. They found that the liquid density is the main affecting fuel property for the spray penetration. They newly suggested the following empirical correlation for the prediction of spray angle.

$$\theta = C\, Re^{m}\, \rho^{*n}$$
$$\text{for } 10^3 < \mathrm{Re} < 10^5 \text{ and } 10^{-3} < \rho^* < 0.7 \times 10^{-1} \qquad (2)$$

where θ is spray angle, C = 22.7817, m = 0.0568, and n = 0.1940, Re is Reynolds number same as the previous work(16), and ρ^* is the density ratio (ambient density/ liquid density). At first, this correlation is different with one in previous work by the same author. It should be noted that spray angle was determined at an axial distance of 200 d_o from the nozzle, which is widely different from their previous work(16) and the other literatures(18). Here d_o designates the nozzle orifice diameter. It is well known in the work by Heywood(19) that the most significant variables for spray angle are gas/liquid density ratio and nozzle geometry. However, it should be noted that the Reynolds number is newly introduced as one of main parameters in this study.

In the study related to atomization characteristics of microscale liquid jet for a better understanding of primary breakup, Reddemann *et al.*(20) developed a new simple double-imaging transmitted light microscopy technique enabling a basic investigation of primary breakup of a microscale liquid jet. This method was applied to an optically dense spray of 1-butanol emerging from a 109 μm diesel nozzle at various injection pressures under atmospheric conditions. They found that the microscopy technique is the appropriate tool for the investigation of selected droplets inside the droplet cloud at the spray edge.

To summarize, the effects of ambient temperature and fuel properties on liquid and vapor phase penetration, droplet size and velocity distribution of spray in CI engine for neat butanol were investigated. For spray angle, two empirical correlations were suggested.

2.2 SI engines

It was not possible to find out the study on the spray characteristics of neat butanol in PFI SI engine. However, there are many studies on the application of neat butanol to GDI engines, which is newly designed spark ignition engine. An understanding of spray and atomization characteristics of butanol is critical to optimizing the GDI injector in practical engine.

Zhang *et al.*(21) conducted the spray visualization and particle size measurement under two different injection pressures (7.0 and 10.2 MPa) to address the spray characteristics of neat butanol, ethanol and iso-octane for spray used in GDI engines. In their study, spray structure and spray angle were analyzed, and the SMD, DV(50) and DV(90) were reported. Of three fuels, butanol showed the smallest spray angle values at low injection pressure, and there was no difference between low and high injection pressure. It should be noted that the increase of injection pressure in initial and development phases of the spray did not reduce the SMD for butanol and ethanol. However, two injection pressures are not enough to discuss the tendency for the influence of injection pressure on SMD.

The effect of fuel type on spray development from a GDI multi-hole injector operating under realistic engine conditions of temperatures and load was investigated by Serras-Pereira *et al.*(22). The fuels considered in their study were ethanol, butanol, iso-octane and gasoline. Apart from the works related to macroscopic spray characteristics, projected spray areas were calculated from the images acquired through the piston crown. They found that the growth rates of spray areas were lower for alcohol fuels than for both iso-octane and gasoline, showing peak values of spray area at the end of injection 20% lower for butanol. In addition, peak values of spray area were highest for ethanol, with gasoline, butanol and iso-octane following.

The operation of GDI engines with relatively high injection pressure in order to provide efficient fuel atomization and mixture formation leads to spray impingement onto wall such as piston crown and liner. This results in a deteriorate effect on the exhaust emission, particularly HC and PM. The researches related to minimize liquid fuel impingement onto the cylinder walls and take into consideration various type of biofuels are, therefore, required. In their continued works(23, 24), the analysis of wall impinging sprays of butanol, ethanol, gasoline, iso-octane and E10 in a GDI engine was conducted. Adopting split injections to break up the high spray momentum of a single injection was found to be a successful way for decreasing the spray tip penetration and thus reducing impingement onto the engine's liner. They found that the difference in timing of peak heat flux between the different fuels was a measure of the differences in rates of spray tip penetration as a result of different physical properties of fuels considered. In their latter work, they found that the general spray behavior was different for the alcohols to that of hydrocarbons, with butanol exhibiting effects related to poor atomization and slow evaporation. The basic phenomena and physical mechanisms of droplet/wall interaction can be found in the extensive review reported by Moreira *et al.*(25)

The atomization and evaporation of several biofuels at different ambient conditions were investigated by Knorsch *et al.*(26) For moderate ambient conditions such as 0.56 MPa/473 K, isooctane, gasoline, ethanol and three component biofuel mixture (35% n-hexane with low boiling point, 45% isooctane with middle boiling point and 20% n-decane with high boiling point) showed the similar evaporation rates by similar droplet sizes, in spite of large difference in boiling point, vapor pressure and evaporation enthalpy of the single component fuel. However, n-butanol as a higher viscosity with the highest boiling point of the fuels (see Table 2) considered and a relatively high evaporation enthalpy shows the largest droplet mean diameter, followed by other three component biofuel mixture (10% n-hexane, 75% ethanol, and 15% n-butanol). Even though this mixture contains only 15% by volume of n-butanol spray behavior of this mixture was much more similar to n-butanol, rather than to ethanol which is 75% by volume. They concluded from this point of view that the high boiling point components plays important role in the spray behavior and atomization.

In their continued investigation(27), the ambient conditions at low, moderate and high ambient pressures and temperatures (0.04, 0.56 and 0.80 MPa, and 293, 373, 473, 673 K) were introduced. They found that the fuels with the highest heat of vaporization values such ethanol and n-butanol revealed the longer spray penetration than that of other four fuels considered. For low and moderate ambient pressures and temperatures, high boiling point components such as n-butanol (see Table 2) showed a strong effect on the droplet size distribution. They concluded that the heat of vaporization is a dominant physico-chemical property for the droplet evaporation rate.

Aleiferis and van Romude(28) studied the effects of fuel properties, temperature and pressure conditions on the extent of spray formation from a six-hole injector with gasoline, iso-octane, n-pentane, ethanol and n-butanol. Those fuels were tested at injector body temperature of 293, 323, 363 and 393 K for ambient pressures of 0.05 and 0.1 MPa. Both high speed imaging and droplet sizing techniques were

Table 2 Physico-chemical properties of alternative and conventional fuels(5, 28)

Propertiy	Diesel	Gas-oline	Iso-octane	Etha-nol	Metha-nol	n-buthanol
Density (kg/m^3 at 20°C)	820-860	720-780	692	790	796	808-809
Kinematic viscosity (mm^2/s at 40°C)	1.9-4.1	0.4-0.8	-	1.08	0.5p	2.63 (3.71^b)
Surface tension (mN/m at 20°C)	-	25.8	14.7	22.4	-	25.4
Cetane number	40-55	0-10	-	8	3	25
AKI	~25	90	100	9.8	-	87
Flash point (°C)	65-88	-45 ~ -38	-	8	12	35
Boiling point (°C)	180-370	25-215	99.8	78.4	64.5	117.7
Latent heat (kJ/kg at 25°C)	270	364-500	305	904	1109	582
LHV (HJ/kg)	42.5	42.7-44.0	45.0	26.8	19.9	33.1
Autoignition temp (°C)	~200	~300	-	434	47	385

a: at 20°C, b:calculated from Table 1 in (28)
AKI: Anti-Knock Index

applied for the measurement of spray penetration, spray angle, droplet sizes and velocities. Although the macroscopic spray structure of n-butanol was similar to iso-octane's one over the range of test conditions, n-butanol showed less well atomized than iso-octane up to 363 K, which is likely due to higher viscosity and surface tension effects as shown in Table 2. This is in good agreement with the results obtained by Serras-Pereira *et al.*(24). At 0.5 MPa gas pressure, there was an increase in spray penetration by ~120% for most fuels. Increase in injector temperature showed an small effect on spray penetration for a given ambient pressure without any spray collapse, which were typically ~10% longer at 363 K, 0.1 MPa. Even though both ethanol and gasoline sprays revealed a clear reduction in spray angle with an increase in injector temperature, n-butanol showed very small changes in spray angle. It should be noted that the measurement of droplet size and velocities was not performed for n-butanol in this study.

The effect of fuel properties and injection pressure on spray propagation and near-nozzle velocities of GDI hollow -cone sprays for ethanol, n-butanol, and 1-decanol, including three alkanes and one alcohol with cyclic structure was investigated by Mathieu *et al.*(29). It was clear from this study that spray tip penetration for 1-butanol was shorter than that for ethanol due to the higher viscosity as can be seen in Table 2. It is notable from Table 2 that butanol is more hydrocarbon-like in its properties.

An experimental imaging study into the influences of fuel properties, temperatures and pressure condition on the extent of cavitation, flash-boiling and, subsequently spray formation was conducted by Aleiferis *et al.*(30). To avoid the exact complexity of the multi-hole GDI injectors, two optical nozzles with the diameter of 0.5 mm and 0.2 mm, respectively were designed for simultaneous images of both the nozzle flow and the resulting spray. Five fuels including butanol and ethanol were tested at 293, 323 and 363 K injector body temperatures for ambient pressures of 0.05 MPa and 0.1 MPa. They found that the cavitation films appeared thinner with two alcohols, particularly butanol, in comparison to the hydrocarbons. Two alcohols were placed in the second wind induced regime and cross into atomization regime only when at quite higher temperatures than 353 K. An increase in fuel temperature of butanol from 293 to 323 K resulted in the slight difference to the in-nozzle cavitation or the spray formation.

To summarize, the effect of injection pressure, fuel properties, ambient pressure and temperature on the macroscopic and microscopic spray characteristics as well as evaporation and cavitation of neat butanol in GDI spray were extensively studied.

3. Spray Characteristics of Butanol Blended Fuels

Even though combustion and emission characteristics of butanol/diesel fuel blend in CI engines or LTC were mainly investigated(31-37), study on spray characteristics of butanol/diesel fuel blend could not be found in the literature. There are so many studies on combustion and emission characteristics of butanol/gasoline blends in SI engines(38-43). However, the research on the spray characteristics of butanol/gasoline blends is limited. Therefore, in this review, the spray characteristics of butanol-biodiesel-diesel blends will be discussed at first and then the spray characteristics will be followed for butanol-gasoline blends, butanol-jet A blends and butanol-other fuel blends. As B has traditionally been used for the abbreviation of biodiesel in the expression of biodiesel blends, Bu in the expression of butanol blends will be used for the abbreviation for butanol or biobutanol in this study.

3.1 butanol-biodiesel-diesel blend

It is known that the solubility of diesel-biodiesel-butanol is higher than the solubility of diesel-biodiesel-ethanol at temperatures of 283-303 K(44). In addition, as an alternative fuel in diesel engines, the blend of 85% diesel, 10% biodiesel and 5% butanol is recommended because it provided a stable mixture and acceptable fuel properties.

In the investigation of spray and combustion characteristics of a ternary blend of butanol-biodiesel-diesel under diesel engine-relevant conditions by Liu *et al.*(45,46), the liquid phase penetration of the butanol-biodiesel-diesel blends is decreased with the increase in the ambient temperature (800, 900, 1000 and 1200 K) and the butanol contents (0, 5 and 10%). Even though the dispersion angle instead of spray angle was defined by taking the arctangent of half maximum radial spray width divided by axial location of the spray width, the data for dispersion angle cannot be found in both papers.

Since the volatilities and boiling points of butanol and diesel/biodiesel are significantly different, micro-explosion can be expected in the atomization of blend spray. A numerical model of micro-explosion in multi-component bio-fuel droplets was proposed by Shen *et al.*(47). In their study, they found that no micro-explosion is observed for butanol-diesel blends with butanol composition varying from 20% to 80%. This is because the difference in volatility and boiling point between butanol and diesel may not be significant enough to support homogeneous nucleation. However, micro-explosion in butanol-biodiesel blends was observed because biodiesel had a higher boiling point that diesel.

3.2 Butanol-gasoline blends

There is only one reference as to the spray characteristics of butanol/gasoline blends in SI engine, particularly GDI engine. In parallel to the combustion and emission characteristics, effect of injection pressure and blending ration on SMD, one of microscopic spray characteristics, of butanol/gasoline blends in GDI engine with six hole injector was investigated by Ko(48). In order to measure the SMD for the different blends of Bu0, Bu20, Bu40, Bu60, Bu80, Bu100, phase doppler particle analyzer (PDPA) system with the light source of Ar-ion laser was introduced. They found that SMD of butanol/gasoline blends was decreased with increase in injection pressure and was increased with increase in butanol percentage in the blends.

3.3 Butanol-Jet A blends

The effect of butanol/Jet A blends (Bu25, Bu50, and Bu75) on the performance and emission characteristics of a gas turbine engine was investigated by Mendez *et al.*(49), They concluded that the blends of butanol with Jet A are promising alternative fuels with performance similar to that of Jet-A, but with less CO and NOx emissions. However, they couldn't find the any tendency in the reduction of CO and NOx with increase in the blending ratio of butanol with Jet A.

Nine potential bioderived fuels including n-butanol were tested by Chuck and Donelly(50) for their compatibility with Jet A-a aviation kerosene. The key fuel properties such as kinematic viscosity, cloud point, distillation, lower calorific value, flash point, and density of the biofuels and their blends with JetA-1 were assessed. They found that the viscosity of n-butanol even at low blend levels was too great to be compatible with Jet A-1. In addition, the cloud point and flash point of n-butanol blends were out of specification.

3.4 Butanol/other fuel blends

As one of n-butanol/other fuel blends, electrosprays of butanol/ethanol and butanol/heptane blends including ethanol/heptane blends with the same electric conductivity and surface tension were experimentally investigated by Agathou and Kyritsis(51). They summarized that even though sprays of butanol-containing blends were amenable to electrostatic manipulation, the monodispersion was practically non-acheivable for the range of droplet sizes, velocities and nozzle configurations that should pertain to automotive application. They also found that electrical conductivity and surface tension do not determine fully the spray behaviour.

Spray characteristics of n-butanol/ heavy fuel oil (HFO) blends were numerically investigated by Nowruzi *et al.*(52) under injection pressures of 60 and 100 MPa in marine CI engine. An Eulerian-Lagrangian multiphase scheme in OpenFOAM CFD toolbox was used to simulate blends of HFO and 0%, 10%, 15%, and 20% by volume of n-buanol. They found that the effects of n-butanol addition to neat HFO on spray penetration were negligible for both injection pressures. The average velocity of spray for n-butanol/HFO blends was increased that that of neat HFO, particularly more evident at injection pressure of 60 MPa. In addition, the average of particle diameter for all n-butanol/HFO blends except Bu20 at 60 MPa was decreased.

To summarize, the studies on the spray characteristics of butanol-biodiesel-diesel blends in diesel engine, butanol-gasoline blends in GDI engine, and butanol-Jet A blends in gas turbine engine were conducted.

4. Discussions and Summary

The researches on the spray characteristics of neat butanol are mainly conducted in CI and GDI engines. For neat butanol, the effects of ambient temperature and fuel properties on liquid and vapor phase penetration, droplet size and velocity distribution of spray in CI engine condition were investigated. For spray angle, two empirical correlations were suggested. Two empirical correlations for the prediction of spray angle for butanol as a function of Reynolds number was newly suggested. However, the test of applicability for the suggested empirical correlation is required.

The literature concerning the spray characteristics of neat butanol is limited to GDI engines. Most works were conducted to compare the spray characteristics of butanol with those of ethanol, iso-octane or gasoline in GDI engine.

The effect of injection pressure, fuel properties, ambient pressure and temperature on the macroscopic and microscopic spray characteristics as well as evaporation and cavitation of neat butanol in GDI spray were extensively studied.

The butanol blended fuels used for the investigation of spray characteristics includes butanol-biodiesel blend, butanol-gasoline blend, butanol-jet A blend and butanol-other fuel blends. Butanol/other fuel blends include butanol/ethanol, butanol/heptane and butanol/heavy fuel oil blends. Even though the investigation on combustion and emission characteristics of butanol/diesel fuel blend in CI engines were widely conducted, study on spray characteristics of butanol/diesel fuel blend could not be found in the literature. There are so many studies on combustion and emission characteristics of butanol/gasoline blends in SI engines. However, the only one research on the spray characteristics of butanol/gasoline blends is found in the literature. The more study concerning the spray characteristics of butanol/gasoline blend is required.

The blends of butanol with Jet-A are promising alternative fuels with performance similar to that of Jet-A, but with less CO and NOx emissions for gas turbine engine.

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