

A Review on Spray Characteristics of Bioethanol and Its Blended Fuels in CI Engines

Soo-Young No[†]

Key words: Bioethanol, Ethanol-diesel, Ethanol-biodiesel, Spray characteristics, Compression ignition engines

Abstract

This review will be concentrated on the spray characteristics of bioethanol and its derived fuels such as ethanol-diesel, ethanol-biodiesel in compression ignition (CI) engines. The difficulty in meeting the severe limitations on NO_x and PM emissions in CI engines has brought about many methods for the application of ethanol because ethanol diffusion flames in engine produce virtually no soot. The most popular method for the application of ethanol as a fuel in CI engines is the blending of ethanol with diesel. The physical properties of ethanol and its derivatives related to spray characteristics such as viscosity, density and surface tension are discussed. Viscosity and density of e-diesel and e-biodiesel generally are decreased with increase in ethanol content and temperature. More than 22% and 30% of ethanol addition would not satisfied the requirement of viscosity and density in EN 590, respectively. Investigation of neat ethanol sprays in CI engines was conducted by very few researchers. The effect of ambient temperature on liquid phase penetration is a controversial topic due to the opposite result between two studies. More researches are required for the spray characteristics of neat ethanol in CI engines. The ethanol blended fuels in CI engines can be classified into ethanol-diesel blend (e-diesel) and ethanol-biodiesel (e-biodiesel) blend. Even though dodecanol and n-butanol are rarely used, the addition of biodiesel as blend stabilizer is the prevailing method because it has the advantage of increasing the biofuel concentration in diesel fuel. Spray penetration and SMD of e-diesel and e-biodiesel decrease with increase in ethanol concentration, and in ambient pressure. However, spray angle is increased with increase in the ethanol percentage in e-diesel. As the ambient pressure increases, liquid phase penetration was decreased, but spray angle was increased in e-diesel. The increase in ambient temperature showed the slight effect on liquid phase penetration, but spray angle was decreased. A numerical study of micro-explosion concluded that the optimum composition of e-diesel binary mixture for micro-explosion was approximately E50D50, while that of e-biodiesel binary mixture was E30B70 due to the lower volatility of biodiesel. Adding less volatile biodiesel into the ternary mixture of ethanol-biodiesel-diesel can remarkably enhance micro-explosion. Addition of ethanol up to 20% in e-biodiesel showed no effect on spray penetration. However, increase of nozzle orifice diameter results in increase of spray penetration. The more study on liquid phase penetration and SMD in e-diesel and e-biodiesel is required.

1. Introduction

The addition of oxygenates such as ester, ether and alcohol with diesel fuel was found to have significant

effects on the fuel properties, in turn, spray, combustion and emission characteristics of diesel fuel in compression ignition (CI) engines. The ester or biodiesel from renewable sources has widely been discussed as an alternative fuel of petroleum based diesel⁽¹⁻⁴⁾. In addition, ethanol or bioethanol has received considerable attention over the last years because it is one of renewable, sustainable and alternative liquid fuel and fuel extender in spark ignition (SI) and CI engines. It is well known that burning of ethanol in

(Received: 24 Sep 2014, Received in revised form: 18 Dec 2014, Accepted: 19 Dec 2014)

[†]Dept. of Biosystems Engineering, Chungbuk National University, Cheongju 361-763, Korea
E-mail : sooyoung@chungbuk.ac.kr
TEL : (043)261-2583 FAX : (043)271-4413

SI engines reduces emissions of CO and HC, whereas there are some inconsistencies in NO_x emissions⁽⁵⁾.

Due to its inherent limitation, the 1st generation bioethanol produced from food crops will be replaced with the 2nd generation bioethanol obtained from lignocellulosic feedstocks in the near future⁽⁶⁻⁷⁾. The feedstocks for producing bioethanol can be divided into three major groups: (1) sucrose-containing feedstocks such as sugarcane, sugar beet, sweet sorghum and fruits, (2) starchy materials such as corn, milo, wheat, rice, potatoes, cassava, sweet potatoes and barley, and (3) lignocellulosic biomass such as woodchips, sawdust, straw, grasses, forest waste, agricultural residues, etc. Both the sucrose-containing feedstocks and starchy materials can be converted to bioethanol by fermentation. Lignocellulosic biomass can be converted to bioethanol by two different pathways: (1) as a biochemical processes, hydrolysis and subsequent fermentation, (2) as a thermochemical processes, gasification followed either fermentation, or by a catalyzed reaction. The ethanol produced from lignocellulosic biomass is called cellulosic ethanol or cellanol⁽⁸⁾. The feedstocks and production processes of bioethanol is depicted in Fig. 1. Hydrolysis of cellulose in the lignocellulosic biomass to produce sugars, and fermentation of the sugars to ethanol are reviewed extensively by Sun and Cheng⁽⁹⁾. The biochemical and thermochemical processes of bioethanol production were reviewed by Balat and Balat⁽¹⁰⁾. A techno-economic comparison of two different process alternatives, i.e. enzymatic hydrolysis and fermentation and the gasification and fermentation

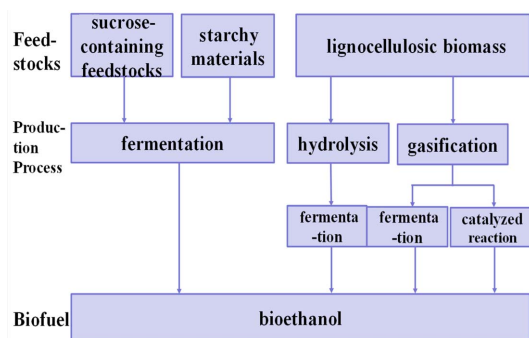


Fig. 1 Feedstocks and production process of bioethanol

process for the production of bioethanol for fuel from lignocellulosic feedstock were conducted by Piccolo and Bezzo⁽¹¹⁾. Bioconversion of water hyacinth into ethanol using two-sequential step of hydrolysis and fermentation was reviewed by Ganguly *et al.*⁽¹²⁾

In the life cycle implications of a wide range of fuels and propulsion systems, MacLean and Lave⁽¹³⁾ concluded that ethanol could become the dominant fuel if energy independence, sustainability, or very low carbon dioxide emissions become important-or if petroleum prices double. Recently, Boggavarapu and Raviskrishna⁽¹⁴⁾ reviewed the atomization and sprays of biofuels for IC engines application. However, ethanol spray in SI engines were briefly discussed, although sprays of biodiesel, straight vegetable oil, DME for CI engines were reviewed in a detailed manner. A comprehensive literature review of bioethanol production and costs, engine performance and emissions etc was recently reported by Sadeghin-zhad *et al.*⁽¹⁵⁾ However, spray characteristics for bioethanol application to IC engine and engine performance and emission characteristics in advanced IC engines were not included in their review.

Lapuerta *et al.*⁽¹⁶⁾ investigated the conditions in which diesel-bioethanol blends are stable. Their results show that the presence of water in the blends, low temperature and high ethanol contents result in the phase separation. To prevent the phase separation, two different ways are generally employed: the addition of emulsifier (surfactant) which acts to suspend small droplets of ethanol within the diesel fuel or the addition of co-solvents that acts as a bridging agent to produce a homogeneous blend⁽¹⁷⁾. Many investigators have used the term “e-diesel” to define the mixture of ethanol and diesel. The ethanol blended with diesel fuel will be called here as e-diesel and the ethanol blended with biodiesel e-biodiesel. Because of the chemical structure of bioethanol does not differ from that of the common ethanol, they will be interchangeably used here.

It is required to summarize the investigation of the atomization and spray characteristics of ethanol blended fuels because these parameters have a significant effect on the combustion process. The purpose

of this review is to discuss the spray and atomization characteristics of bioethanol and its blends when they have been applied to CI engines. The bioethanol blends include ethanol-diesel, ethanol-biodiesel and ethanol-biodiesel-diesel in this study.

2. Properties of Ethanol and Its Blended Fuel

It is well known that macro- and micro-spray characteristics are influenced by fuel properties such as density, viscosity, and surface tension⁽¹⁸⁻²¹⁾. Therefore, the fuel properties of neat ethanol, ethanol blended diesel related only to spray characteristics will be briefly discussed.

2.1 Neat ethanol

The effect of temperature on density, viscosity, surface tension of neat ethanol in addition to several thermodynamic properties was reported by Spiekermann *et al.*⁽²²⁾ They found that the density of neat ethanol is linearly decreased with increase in temperature, but abruptly decreased after 500 K. In addition, the viscosity and surface tension of neat ethanol are exponentially decreased with the increase of temperature.

2.2 E-diesel and e-biodiesel blends

Ethanol can be used as a fuel in CI engines by many techniques and application. Those include blends, fumigation, dual fuel injection etc. The most used method will be ethanol blends. Blending of ethanol to diesel fuel has affected certain important physico-chemical properties such as lower heating value, cetane number, viscosity, stability and lubricity etc. The properties and specifications of ethanol blended with diesel fuel were broadly discussed by Hansen *et al.*⁽¹⁷⁾ and Kumar *et al.*⁽²³⁾ recently.

Viscosity: The kinematic viscosity of five ethanol-diesel blended fuels (E5, E10, E15, E20 and E25) as well as petro-diesel (E0) was reported by Li *et al.*⁽²⁴⁾ They found that the addition of ethanol to diesel lowers the viscosity of blended fuel. However, up to ethanol content of 20%, the kinematic viscosity of e-

diesel fulfill the minimum requirements for diesel fuel. The effect of ethanol addition and temperature on the dynamic viscosity of ethanol-diesel blend fuel was investigated by Chen *et al.*⁽²⁵⁾ The experimental results for E0, E10, E20 and E30 showed that an increase in ethanol fraction and temperature resulted in the decrease of viscosity of the blends. The kinematic viscosity of the e-diesel blends for 0 to 90% in volume was measured at 40°C by Lapuerta *et al.*⁽²⁶⁾ With regard to the diesel quality norm EN 590, blends with more than 22% (v/v) ethanol would not satisfied the requirement of viscosities above 2 cSt. Those results are in accordance with the previous work⁽²⁴⁾. In addition, they had tried to estimate the kinematic viscosity of liquid mixture by introducing the correlation suggested by Grunberg-Nissan⁽²⁷⁾, but failed to obtain the reasonable result.

Torres-Jimenez *et al.*⁽²⁸⁾ was measured the kinematic viscosity of e-diesel with from 5% to 15% ethanol according to ISO 3104 at 40°C. They argued that due to the linear decrease of kinematic viscosity of e-diesel by ethanol addition, atomization of e-diesel will not be deteriorated. It is known that the addition of ethanol to diesel fuel from 0% to 50% linearly decreases kinematic viscosity of e-diesel with 10% of biodiesel as an emulsifier. An increase in fuel temperature resulted in decrease in kinematic viscosity⁽²⁹⁾. Fuels with lower viscosity and surface tension can help in better atomization and lead to lower droplet diameter⁽³⁰⁾. The disadvantages associated with ethanol properties are lower volatility and energy density, miscibility with water, and a tendency towards pre-ignition⁽³¹⁾.

The effect of temperature on the dynamic viscosity for e-biodiesel (B80E20) was investigated by Kim *et al.*⁽³²⁾ Their experimental results showed that the dynamic viscosity of B80E20 and neat biodiesel was decreased exponentially with increase in temperature. The variation of viscosity for e-biodiesel with the increase of ethanol percentage was measured by Lee *et al.*⁽³³⁾ They found that the viscosity of e-biodiesel is decreased exponentially with increase in ethanol percentage and B80E20 has the equivalent viscosity to ULSD, which is the reason that B80E20

was selected for engine testing.

Density: Torres-Jimenez *et al.*⁽²⁸⁾ found in the e-diesel from 0 to 15% of ethanol that density of e-diesel was decreased with increase in bioethanol content. However, density values for all samples tested are within the standard range (limit of EN 590 Min / Max = 820 / 845 kg/m³ at the reference temperature of 288 K. This means that there will be no problems related to atomization of e-diesel. The measurement results by Park *et al.*⁽²⁹⁾ showed that the density of e-diesel with 10% of biodiesel (soybean oil methyl ester) as emulsifier generally decreased with the increase in bioethanol content from 0 to 50%. However, density values for more than 30% of bioethanol content are not within the standard range of EN 590. In addition, an increase in fuel temperature resulted in decreased in density.

According to the study on the fuel properties of the blends at different ratios of diesel, biodiesel and ethanol⁽³⁴⁾, the density of the blends decreased with an increase in the percentage of ethanol from 5 to 15% in the blends. However, as the biodiesel percentage from 5 to 15% was increased, the density of the blends increased. It is generally recognized that higher density leads to the high viscosity, resulting in the poor atomization of fuel.

The effect of temperature on density for e-biodiesel (B80E20) was investigated by Kim *et al.*⁽³²⁾ According to the increase of temperature, density of e-biodiesel and neat biodiesel was decreased linearly. This linear decrease of density for e-biodiesel with the increase of ethanol percentage was also found by Lee *et al.*⁽³³⁾ They also found that B80E20 has slightly higher density than ULSD, which would have no effect on engine performance.

Surface tension: It is well known that surface tension as well as density and viscosity of fuel affects the spray and atomization characteristics of fuel droplets⁽³⁵⁾. Only two studies in the literature were found in relation to surface tension of e-diesel. The exponential decrease of the surface tension from E0 to E25 in e-diesel was found by Li *et al.*⁽²⁴⁾ The surface tension of e-diesel exponentially decreased with increase in bioethanol content up to 20% of bioetha-

anol, and thereafter addition of bioethanol didn't affect the surface tension of e-diesel⁽²⁹⁾. It should be pointed out that the exact value of surface tension for the same e-diesel was widely different from two studies, due to different surface tension of diesel tested in the experiment, respectively.

3. Spray Characteristics of Neat Ethanol

Effects of ambient gas density and ambient gas temperature variations on spray penetration and spray angle of neat ethanol sprays in common-rail diesel engine-like conditions were investigated by Spiekermann *et al.*^(22,36) Raman scattering technique was used for the investigation of the reference experiment and an optically simultaneous Mie scattering and shadowgraphy technique was employed for the five spray vessel experiments. It should be noted that spray penetration and spray angle is divided into liquid phase and vapor phase, respectively. They found that based on a quantitative comparison for liquid and vapor penetration length versus time after start of injection, both techniques showed similar results. Even though Raman scattering technique revealed a similar spray angle with the Mie images for the liquid phase, Raman scattering technique yielded more wider spray angle than the shadowgraphy images.

For ambient gas densities of 5.4, 13.4 and 21.4 kg/m³ at constant gas temperature of 800 K, the increase in ambient gas density resulted in the shorter both liquid phase and vapor phase penetrations. For ambient gas temperatures of 500, 700 and 800 K at constant ambient gas density of 21.4 kg/m³, a higher ambient gas temperatures led to a shorter liquid phase penetration and a nearly similar vapor phase penetration.

For a constant ambient gas temperature, a higher ambient gas density results in an increased spray angle of both phases. For a constant ambient gas density, a higher ambient gas temperatures leads to a slightly increased liquid phase spray angle and no influence on vapor phase spray angle. It should be noted that in these studies spray angle is defined as

the angle between the tangents and the spray envelope at a distance $100 d_0$ downstream of the nozzle, not normally $60 d_0$ (d_0 = nozzle orifice diameter) for diesel spray⁽¹⁸⁾.

In these studies, the comparison of experiments and CFD simulation for a variation of the spray vessel conditions was also undertaken. The CFD code used in this study was AC-Flux, formerly known as GMTEC. It should be noted that this code is a flow solver based on finite volume methods, not popular finite difference method. All simulation results yield a good agreement for liquid phase and vapor phase spray penetration.

The liquid and vapor penetration of five different fuels including neat ethanol from common rail diesel injector were analyzed by Reddemann *et al.*⁽³⁷⁾ using Mie scattering and shadowgraphy methods in high pressure constant volume chamber. Liquid penetration of ethanol increased with increase in ambient temperature. In addition, ethanol showed an increase of the cavitation number for fuel temperature above 400 K. Taking only the physical properties into account, ethanol should have a shorter liquid penetration than butanol and dodecane because of its high Weber number, but ethanol showed a longer liquid penetration length due to its high heat of vaporization. The vapor penetration remained largely unaffected by the variation of the fuel properties.

It is clear from the above that more researches are required for the neat ethanol spray on diesel engine and the effect of ambient temperature on liquid phase penetration is a controversial topic due to the opposite result between two research groups.

4. Spray Characteristics of Ethanol Blended Fuels

The difficulty in meeting the stringent limitations on NO_x and PM emissions in CI engines has stimulated many techniques and application in CI engines fuelled with ethanol because ethanol diffusion flames produce virtually no soot⁽³⁸⁾. The most popular technique by which ethanol can be used in CI engine is

the in the form of blends. The ethanol blended fuels in CI engines can be classified into ethanol-diesel blend and ethanol-biodiesel blend. Because most studies introduced biodiesel as a co-solvent in the ethanol-diesel blend, ethanol-diesel blend is treated as the binary mixtures of ethanol and diesel in this study, not ternary mixtures of ethanol-biodiesel-diesel in the study done by Lee *et al.*⁽³⁹⁾

4.1 Ethanol-diesel blend

As pointed out in the above, the addition of ethanol to diesel requires a co-solvent or emulsifier to improve the miscibility of them. Typical co-solvents introduced in the studies up to now are biodiesel. A mixture of petro-diesel, biodiesel and bioethanol are termed as “Diesterol” by Rahimi *et al.*⁽⁴⁰⁾ as “EB-diesel” by Fernando and Hanna⁽⁴¹⁾, as “BE-diesel” by Gonca⁽⁴²⁾, or as “e-b-Diesel blends” by Lapuerta *et al.*⁽⁴³⁾ Regardless of co-solvents type, the blended fuel of diesel and ethanol was designated as “diesehol” by Liu *et al.*⁽⁴⁴⁾, as “diesohol” by Kwanchareon *et al.*⁽³⁴⁾ and Shahir *et al.*⁽⁴⁵⁾, as “E-diesel” or “e-diesel blends” by Pantar and Corkwell⁽⁴⁶⁾, Kumar *et al.*⁽²³⁾ and Lapuerta *et al.*⁽⁴³⁾ Although 1-dodecanol⁽⁴⁷⁻⁵⁰⁾ and n-butanol⁽⁵¹⁾ are adopted in the ethanol-diesel blend as emulsifier in many studies on the performance and emissions of diesel engine fuelled with ethanol-diesel blends, the discussion for these works will be excluded in this review because spray characteristics of e-diesel was not included in these studies. It is usually blended with conventional diesel denoted as DEXX that XX will be ethanol percentage in volume of ethanol in diesel.

To investigate the macroscopic spray characteristics of ethanol, diesel and their blends (DE10, DE20 and DE30), Chen *et al.*⁽⁵²⁾ conducted the experiments in a constant volume chamber with schlieren photography technique using high speed camera. They found that spray penetration of ethanol and ethanol-diesel blend were slightly shorter than the diesel's one. The spray angle of ethanol was slightly larger than that of diesel. Numerical simulation was also carried out by KIVA-3V. Based on the comparison of breakup models such as TAB and Wave-KH models, they found

that the Wave-KH model is more suitable for the spray simulation of ethanol and ethanol-diesel blend. They also found that spray penetration and spray angle of ethanol and ethanol-diesel blend obtained by numerical simulation shows the same trend with the experimental results. Unfortunately, the effect of ethanol percentage in the blend on spray characteristics as well as the definition of spray penetration and spray angle was not clearly described in this study.

The macroscopic spray characteristics of ethanol-diesel blends in a common-rail direct injection system with a single hole injector was investigated by Park *et al.*⁽⁵³⁾ The spray images for the different blends of DE0, DE10, DE20 and DE30 with 5% of biodiesel as emulsifier were obtained by high speed camera at the injection pressures of 60 and 120 MPa, ambient pressures of 2 and 3 MPa, and fuel temperatures of 290, 330 and 370 K, respectively. There was slight effect of ethanol blending percentage on spray penetration and spray angle, whereas the droplet size of the different blended fuels decreased with increase in the ethanol blending proportions. For E0, an increase in the fuel temperature resulted in an increase in spray penetration and in slight effect on spray angle. In the case of E30, the increased fuel temperature has little effect on spray penetration and spray angle.

The spray tip penetration and spray angle for two ethanol-diesel blends (DE10, DE20) in CI engine-like condition with seven hole injector were compared with those of ultra low sulfur diesel (ULSD: DE0) at the injection pressure of 70 MPa and the ambient pressure of 3 MPa by Park *et al.*⁽⁵⁴⁾ Unlike the addition of 5% biodiesel as a co-solvent in their previous study (Park *et al.*⁽⁵³⁾), 10% of biodiesel was added in the blends in this study. Even though three test fuels showed the similar spray penetration during the initial injection period, DE0 had the longest spray penetration among the three fuels after the end of injection. They found that the increase of ethanol blending ratio resulted in the decrease of spray penetration due to the decrease of fuel density. This seems to be due to different concentration of biodiesel in e-diesel between two studies. Spray angle was increased with increase in the ethanol concentration and ULSD

showed the smallest spray angle due to highest fuel density among the fuel tested. It is clear from the review by No⁽⁵⁵⁾ and the book by Lefevbre⁽¹⁸⁾ that spray angle increases with increasing gas/liquid density ratio (ρ_g/ρ_l) in the theoretical and empirical correlations for spray angle in plain-orifice atomizer. However, in this study, only two ethanol blending ratios were not enough to discuss the effect of blending ratio on macroscopic spray characteristics because ULSD didn't mixed with biodiesel.

The effects of engine load and blending proportion of ethanol in diesel on spray characteristics from solenoid-type injector with seven nozzle holes in high-pressure chamber was investigated by Jeong *et al.*⁽⁵⁶⁾ using high-speed camera. The experiments were performed by introducing three fuels, i.e. DE0 (ULSD), DE10 and DE20, engine loads of 30, 60 and 90%, injection pressure of 70MPa and ambient pressure of 30 MPa, respectively. It should be noted that 10% volume of biodiesel (soybean oil methyl ester) was add to prevent phase separation. Increase of engine load at the peak injection rate region had slight influence on the spray penetration, and the spray angle showed the maximum value at 60% engine load. In addition, as the ethanol blending proportion at each engine load was increased, spray penetration was decreased and spray angle was increased. As same case with Park *et al.*⁽⁵⁴⁾, the discussion on the effect of blending ratio on macroscopic spray characteristics is not suitable because DE0 didn't mixed with biodiesel. In addition, the data and experimental results for the same ethanol blended fuels and engine load conditions in this study were included in the work of Park *et al.*⁽²⁹⁾ which is recently published.

Recently the work using dodecanol as a co-solvent was reported by Cardenas *et al.*⁽⁴⁷⁾ In this study, only liquid phase penetration and spray angle were investigated by high speed image method for 29.4% ethanol-68.6% diesel fuel blend with 2% 1-dodecanol to improve miscibility. This work was aimed to find out the proper fuel blends having low cetane number and high volatility such as ethanol-diesel blend, gasoline-diesel blend for the application of HCCI engines. In

addition, diesel fuel was employed for the comparison. It should be pointed out that spray cone angle was measured at the 75% of the liquid phase penetration. In this study, the fuel temperature was controlled and kept at 298 K because the mixture separation into two phases was detected at 290 K. They found that for all ambient conditions and injection pressures, diesel fuel showed the highest liquid phase penetration for the same injection time. The ethanol-diesel blend presented higher liquid phase penetration than the gasoline-diesel blend when either the ambient or the injection pressure was increased. As the ambient pressure increase, liquid phase penetration was decreased, but spray angle was increased for all fuels. The variation of ambient temperature showed the slight effect on liquid phase penetration, but the spray angle was decreased with the increase in ambient temperature for three fuels. It should be pointed out that in their study, there was no clear description about the technique for the discrimination between vapor and liquid phase in the spray.

A numerical study of micro-explosion in ternary mixtures of ethanol (30%)-biodiesel (20%)-diesel (50%) as well as in binary mixtures of the ethanol-diesel and ethanol-biodiesel was conducted in diesel engine operation conditions by Lee *et al.*⁽³⁹⁾ using a modified KIVA-3V Release 2 code. It should be noted that tetradecane was used to describe diesel fuel in this study. It was reported that micro-explosion significantly enhanced by introducing biodiesel into the fuel blends of ethanol and diesel, particularly at high ambient pressure. In addition, the variation of ambient temperature had nearly no effects on inducing micro-explosion. In the simulation results, the secondary atomization of bio-fuel and diesel blends can be achieved by micro-explosion under typical diesel engine operation conditions. They concluded that this secondary atomization and spray dispersion from micro-explosion can improve engine performance. The optimum composition of ethanol-diesel binary mixture for micro-explosion was approximately E50D50, while that of ethanol-biodiesel binary mixture was E30B70 due to the lower volatility of biodiesel. Adding less volatile biodiesel into

the ternary mixture of ethanol-biodiesel-diesel can remarkably enhance micro-explosion.

In their continued work⁽⁵⁷⁾, a numerical study with the same code with the previous study⁽³⁹⁾ was conducted to examine the effects of ambient pressure, ambient temperature and composition of the mixture on the onset of micro-explosion. The different breakup model with the previous study⁽³⁹⁾, called the minimal surface energy (MSE) approach was used for the same binary and ternary mixtures of fuel. They found that there exists an optimal droplet size for the onset of micro-explosion. In case of a binary droplet composed of 50% ethanol and 50% tetradecane at typical engine condition, the optimum initial radius of approximately 25 μm for the onset of micro-explosion was found. The effect of ambient temperature on the occurrence of micro-explosion for ethanol-diesel blends was less significant. Micro-explosion for ethanol-diesel blend is more likely to take place under lower ambient pressure condition with the increase in ambient pressure.

4.2 Ethanol-biodiesel blend In the study reported by Lee *et al.*⁽³³⁾ ethanol-biodiesel blends are denoted as “e-biodiesel” and BXXEYY corresponding to the blending ratios, for example, B80E20 represents 80% v/v biodiesel and 20% v/v ethanol. This review will follow this expression for ethanol-biodiesel blend.

The experimental and numerical analysis of the spray characteristics in terms of spray penetration and SMD of biodiesel, biodiesel-ethanol blend (B80E20) and DME in common rail injection system was performed by Kim *et al.*⁽³²⁾ PDPA system was employed for the experimental work and the results were compared with the numerical study by KIVA code. It is clear from this study that the addition of ethanol up to 20% has no effect on spray shape, spray penetration and overall SMD of biodiesel spray. They found that the calculated results using hybrid model combined with primary and secondary breakup showed good agreement with the experimental results in the spray development process. In this study, the experimental data of diesel fuel for comparison was not included.

In their continued study⁽⁵⁸⁾, injection performance

and SMD of B80E20 were compared with those of diesel and biodiesel sprays. They found that local and overall SMD of ethanol blended biodiesel was much smaller than that of biodiesel at the same injection pressure of 80 MPa. However, in the downstream from nozzle tip, local SMD of ethanol blended biodiesel spray was much bigger than that of diesel spray. This result is in contrast to the previous study⁽³²⁾ performed in the same research group. This is likely to be due to the difference of injection pressure between 80 MPa in this study and 60 MPa in the previous study.

The spray penetration and angle, spray centroid, droplet size and velocity of biodiesel-bioethanol blends (B100E0, B90E10, B80E20, and B70E30) were investigated by Park *et al.*⁽⁵⁹⁾ with the variation of injection and ambient pressures, ambient temperature. It should be noted that in this study, spray angle was defined as the angle formed between the nozzle tip and two lines that delineate the maximum outer region of the spray. The blended fuel showed very similar spray penetration with biodiesel spray, although spray angle of blended fuel was larger than that of biodiesel spray. Spray penetration of blended fuel decreased with the increase in ambient temperature due to the low boiling temperature and high volatility of ethanol, which in turn promoted the fuel evaporation of the blended fuel. With the increase of bioethanol content in the e-biodiesel, the droplet size of blended fuel decreased and the ratio of smaller size droplets increased. They also found that the theoretical and empirical correlations developed for the prediction of spray penetration of diesel fuel can be applied to the biodiesel and biodiesel-bioethanol blended fuel. It should be pointed out that the experimental results of Park *et al.*⁽⁵⁸⁾ and the contents of Kim *et al.*⁽³²⁾ are the merely the part of the experimental results of Park *et al.*⁽⁵⁹⁾

Effect of e-biodiesel mixture ratio on fuel properties and spray characteristics was recently investigated by Lee *et al.*⁽³³⁾ Spray characteristics in terms of spray penetration and spray area were investigated with a single hole injector by schlieren photography. B100, B80E20 and B60E40 as fuels, ambient pres-

ures of 0.1 and 0.4 MPa, and orifice diameters of 80 μm and 150 μm were selected for the experiment. They concluded that spray penetration of e-biodiesel decreases with increase in ethanol addition, and in ambient pressure. In addition, experimental results of two orifice diameters reveal that the increase of nozzle orifice diameter results in the increase of spray penetration. It should be pointed out that more research is required because of limited parameter for ambient pressure and orifice diameter. In addition, data for spray angle and SMD of e-diesel spray was not reported in this study.

It is clear from several studies^(32,33,58) that the increase of ethanol more than 20% in e-biodiesel results in the decrease of spray penetration, although the addition of ethanol up to 20% shows no effect on spray penetration

A numerical simulation of micro-explosion in binary mixtures of e-biodiesel was conducted by Lee *et al.*⁽³⁹⁾ using KIVA 3V code. The optimum composition of binary mixture of ethanol-biodiesel for micro-explosion was approximately B70E30 due to the lower volatility of biodiesel.

5. Discussion and Summary

The most popular method for the application of ethanol as a fuel in CI engines is the blending of ethanol with diesel.

An increase in ethanol percentage and temperature resulted in the decrease of viscosity and density of e-diesel blends. More than 22% and 30% of ethanol addition would not satisfied the requirement of viscosity and density in EN 590, respectively. The surface tension of e-diesel exponentially decreased with increase in bioethanol content up to 25% of bioethanol. However, the study of the influence of temperature on surface tension could not be found.

Investigation of neat ethanol sprays in CI engines was conducted by very few researchers. The effect of ambient temperature on liquid phase penetration is a controversial topic due to the opposite result between two studies. More researches are required for the

spray characteristics of neat ethanol in CI engines.

The ethanol blended fuel in CI engines can be classified into ethanol-diesel blend and ethanol-biodiesel blend. The addition of biodiesel as blend stabilizer is the prevailing method because it has the advantage of increasing the biofuel concentration in diesel fuel.

Increase of ethanol concentration in e-diesel and e-biodiesel generally resulted in the decrease of spray penetration and SMD. However, spray angle is increased with increase in the ethanol percentage in e-diesel.

As the ambient pressure increases, liquid phase penetration was decreased, but spray angle was increased in e-diesel. The increase in ambient temperature showed the slight effect on liquid phase penetration, but spray angle was decreased.

Addition of ethanol up to 20% in biodiesel-ethanol blend showed no effect on spray penetration. However, increase of nozzle orifice diameter results in increase of spray penetration.

The more study on liquid phase penetration and SMD in e-diesel and e-biodiesel is required.

Acknowledgements

This work was supported by Chungbuk National University Research Grant in 2013.

The author wishes to deeply thank many persons who had supplied their papers for this review. They include Prof. G. Nagarajan, Institute for Energy Studies, Anna University, Chennai, India, Prof. R.V. Ravikrishna, Dept. of Mechanical Eng. Indian Institute of Science, Bangalore, India, Dr. Graham Pitcher, LOTUS Engineering, Norfolk, UK.

Abbreviations

CFD : computational fluid dynamics
 CI : compression ignition
 DISI : direct injection spark ignition
 DME : dimethyl ether
 E85 : mixture of 85% ethanol and 15% gasoline
 GDI : gasoline direct injection

HCCI : homogeneous charge compression ignition
 IC : internal combustion
 LIEF : laser induced exciplex fluorescence
 PDA : phase Doppler Anemometry
 PDPA : phase Doppler particle analyser (anemometry)
 PFI : port fuel injection
 PLIF : planar laser-induced fluorescence
 PM : particulate matter
 SIDI : spark ignition direct injection
 SMD : Sauter mean diameter
 SOI : start of injection
 ULSD : ultra low sulfur diesel

References

- (1) G. Knothe, *The biodiesel handbook*, AOCS press, 2005.
- (2) A. Demirbas, *Biofuels*, Springer, 2009.
- (3) S. Y. No, How vegetable oils and their derivatives affect spray characteristics in CI engines-A review, *Atomization and Sprays*, Vol. 21, No. 1, 2011, pp. 87-105.
- (4) S. Y. No, Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: A review, *Renewable & Sustainable Energy Reviews*, Vol. 15, 2011, pp. 131-149.
- (5) B. M. Masum, H. H. Masjuki, M. A. Kalam, I. M. R. Fattah, S.M. Palash, M.J. Abedin, Effect of ethanol-gasoline blend on NOx emission in SI engine, *Renewable & Sustainable Energy Reviews*, Vol. 24, 2013, pp. 209-222.
- (6) R. E. H. Sims, W. Mabee, J. N. Saddler, M. Taylor, An overview of second generation biofuel technologies, *Bioresource Technology*, Vol. 101, 2010, pp. 1570-1580.
- (7) B. F. Sarrouh, R. R. Philippini, S. S. da Silva, Lignocellulosic Bioethanol Production: Perspectives and Challenges, *International Review of Chemical Engineering*, Vol. 1, No. 6, 2009, pp. 614-622.
- (8) B. M. M. Bomani, D. L. Bulzan, D. I. Centeno-Gomez, R. C. Hendricks, "Biofuels as an Alternative Energy Source for Aviation A Survey" NASA/TM 2009-215587, NASA Glenn Research Center, 2009.
- (9) Y. Sun and J. Cheng, Hydrolysis of lignocellulosic materials for ethanol production: a review, *Bioresource Technology*, Vol. 83, 2002, pp.1-11.
- (10) M. Balat, M. and H. Balat, Recent trends in global pro-

- duction and utilization of bio-ethanol fuel, *Applied Energy*, Vol. 86, No. 11, pp. 2273-2282.
- (11) C. Piccolo and F. Bezzo, A techno-economic comparison between two technologies for bioethanol production from lignocelluloses, *Biomass and Bioenergy*, Vol. 33, 2009, pp. 478-491.
 - (12) A. Ganguly, P. K. Chatterjee, A. Dey, Studies on ethanol production from water hyacinth-A review, *Renewable & Sustainable Energy Reviews*, Vol. 16, 2012, pp. 966-972.
 - (13) H. L. MacLean, L. B. Lave, Evaluating automobile fuel/propulsion system technologies, *Progress in Energy and Combustion Science*, Vol. 29, 2003, pp. 1-69.
 - (14) P. Bogavarapu and R.V. Ravikrishna, A Review on Atomization and Sprays of Biofuels for IC Engine Applications, *International Journal of Spray and Combustion Dynamics*, Vol. 5, No. 2, 2013, pp. 85-121.
 - (15) E. Sadeghinezhad, S. N. Kazi, F. Sadeghinezhad, A. Badarudin, M. Mehrali, R. Sadri, M. R. Safaeri, A comprehensive literature review of bio-fuel performance in internal combustion engine and relevant costs involvement, *Renewable & Sustainable Energy Reviews*, Vol. 30, 2014, 29-44.
 - (16) M. Lapuerta, O. Armas, R. Garcia-Contreras, Stability of diesel-bioethanol blends for use in diesel engines, *Fuel*, Vol. 86, 2007, pp. 1351-1357.
 - (17) A. C. Hasen, Q. Zhang, P. W. L. Lyne, Ethanol-diesel fuel blends-a review, *Bioresource Technology*, Vol. 96, 2005, pp. 277-285.
 - (18) A. H. Lefebvre, A. H., *Atomization and Sprays*, Hemisphere, 1989.
 - (19) L. Bayvel, and Z. Orzechowski, *Liquid Atomization*, Taylor & Francis, 1993.
 - (20) G. G. Nasr, A. J. Yule and L. Bendig, *Industrial Sprays and Atomization, Design, Analysis and Applications*, Springer, 2002.
 - (21) S. Y. No, Prediction of Maximum Liquid-phase Penetration in Diesel Spray: A Review, *Journal of ILASS-Korea*, Vol. 13, No. 3, 2008, pp. 117-125.
 - (22) P. Spiekemann, S. Jerzembeck, C. Felsch, S. Vogel, M. Gauding, N. Peters, Experimental and Numerical Investigation of Common-Rail Ethanol Sprays at Diesel Engine-like Conditions, *Atomization and Sprays*, Vol.19, No.4, 2009, pp. 357-387.
 - (23) S. Kumar, J. H. Cho, J. Park, I. Moon, Advances in diesel-alcohol blends and their effects on the performance and emissions of diesel engines, *Renewable & Sustainable Energy Reviews*, Vol. 22, 2013, pp. 46-72.
 - (24) D-G, Li, Z. Huang, X. Lu, W-G, Zhang, J-G. Yang, Physico-chemical properties of ethanol-diesel blends fuel and its effect on performance and emission of diesel engines, *Renewable Energy*, Vol. 30, 2005, pp. 967-976.
 - (25) Z. Q. Chen, X. X. Ma, S. T. Yu, Y. N. Guo, J. S. Liu, Physical-Chemical Properties of Ethanol-Diesel Blend Fuel and Its Effect on the Performance and Emissions of a Turbocharged Diesel Engine, *International Journal of Automotive Technology*, Vol. 10, No. 3, 2009, pp. 297-303.
 - (26) M. Lapuerta, R. Garcia-Contreras, J. Campos-Fernandez, M. P. Dorado, Stability, Lubricity, Viscosity, and Cold-flow Properties of Alcohol-Diesel Blends, *Energy Fuels*, Vol. 24, 2010, pp. 4497-4502.
 - (27) B. E. Poing, J. M. Prausnitz, J. P. O'Connell, *The Properties of Gases and Liquids*. Fifth ed. McGraw-Hill, 2001, pp. 9.77-9.80.
 - (28) E. Torres-Jimenez, M. S. Jerman, A. Gregorc, I. Lisec, M. P. Dorado, B. Kegl, Physical and chemical properties of ethanol-diesel fuel blends, *Fuel*, Vol. 90, 2011, pp. 795-802.
 - (29) S. H. Park, I. M. Youn, Y. Lim, C. S. Lee, Effect of Bioethanol Blended Diesel Fuel and Engine Load on Spray, Combustion, and Emissions Characteristics in a Compression Ignition Engine, *Energy Fuels*, Vol. 26, 2012, pp. 5135-5145.
 - (30) S. Parala, M. K. Le, S. Kook, E. R. Hawkes, Imaging Diagnostics of ethanol port fuel injection sprays for automobile engine applications, *Applied Thermal Engineering*, Vol. 52, 2013, pp. 24-37.
 - (31) R. Stone, *Introduction to Internal Combustion Engines*, 2nd Ed., Macmillan, 1992, p. 88.
 - (32) H. J. Kim, H. K. Suh, S. H. Park, C. S. Lee, An Experimental and Numerical Investigation of Atomization Characteristics of Biodiesel, Dimethyl Ether, and Biodiesel-ethanol Blended Fuel, *Energy Fuels*, Vol. 22, 2008, pp. 2091-2098.
 - (33) P. I. Lee, X. Xie, M. C. Lai, Effect of ethanol-biodiesel blend ratio on fuel properties and spray behaviors, *ILASS-Americas, 23rd Annual Conf. on Liquid Atomization and Spray Systems*, Ventura, CA, May 2011.
 - (34) P. Kwanchareon, A. Luengnaruemitchai, S. Jai-In, Solubility of a diesel-ethanol blend, its fuel properties

- and its emission characteristics from diesel engine, *Fuel*, Vol. 86, 2007, pp. 1053-1061.
- (35) N. Ashgriz, *Handbook of Atomization and Sprays: theory and applications*, Springer, 2011.
- (36) P. Spiekermann, S. Jerzembeck, S. Vogel, C. Felsch, N. Peters, *Experimental and Numerical Investigation of Common-Rail Ethanol Sprays at Diesel Engine-Like Conditions*, ILASS-Americas, 20th Annual Conf. on Liquid Atomization and Spray Systems, Chicago. IL., May 2007.
- (37) M. A. Reddemann, F. Mathieu, D. Martin, R. Kneer, *Experimental Investigation of Spray Propagation and Mixture Formation of Tailor-Made Fuels under Engine-Relevant Conditions*, ICLASS 2009, 11th Triennial Int'l Conf. on Liquid Atomization and Spray Systems, Vail, Colorado, USA, July 2009.
- (38) G. Nagarajan, A. Rao, T. Jagadeesan, S. Renganara-yanan, *Review of Ethanol in Compression Ignition Engine*, Institute for Energy Studies, Anna University, India.
- (39) C. F. Lee, K. T. Wang, W. L. Cheng, *Atomization Characteristics of Multi-component Bio-fuel Systems under Micro-explosion Conditions*, SAE paper 2012-012-1740, 2012.
- (40) H. Rahimi, B. Ghobadian, T. Yusaf, G. Najafi, M. Khatamifar, *Diesterol: An environment-friendly IC engine fuel*, *Renewable Energy*, Vol. 34, 2009, pp. 335-342.
- (41) S. Fernando and M. Hanna, *Development of a Novel Biofuel Blending Using Ethanol-biodiesel-Diesel Micro-emulsions: EB-Diesel*, *Energy Fuels*, Vol. 18, No. 6, 2004, pp. 1695-1703.
- (42) G. Gonca, *Investigation of the effects of steam injection on performance and NO emissions of a diesel engine running with ethanol-diesel blend*, *Energy Conversion and Management*, Vol. 77, 2014, pp. 450-457.
- (43) M. Lapuerta, O. Armas, R. Garcia-Contreras, *Effect of Ethanol on Blending Stability and Diesel Engine Emissions*, *Energy Fuels*, Vol. 23, 2009, pp. 4343-4354.
- (44) J. Liu, S. Liu, Y. Wei, Y. Li, G. Li, H. He, *Diesehol CI Engine Performance. Regulated and Nonregulated Emissions Characteristics*, *Energy Fuels*, Vol. 24, 2010, pp. 828-833.
- (45) S. A. Shahir, H. H. Masjuki, M. A. Kalam, A. Imran, I. M. Rizwanul Fattah, A. Sanjid, *Feasibility of diesel-biodiesel-ethanol/bioethanol blend as existing CI engine fuel: An assessment of properties, material compatibility, safety and combustion*, *Renewable & Sustainable Energy Reviews*, Vol. 32, 2014, pp. 379-395.
- (46) A. V. Pantar, K. C. Corkwell, *E Diesel: A Viable Alternative Fuel*, SAE paper 2004- 28-0074, 2004.
- (47) M. J. Cardenas, D. Cordes, R. Kneer, *Experimental investigation of spray characteristics of fuel blends having low cetane number and high volatility in a diesel fuel injection system*, ICLASS 2012, 12th Int'l Conf. on Liquid Atomization and Spray Systems. Heidelberg. Germany, Sept. 2-6, 2012.
- (48) Y. Di, C. S. Sheung, Z. Huang, *Comparison of the Effect of Biodiesel-Diesel and Ethanol-Diesel on the Particulate Emissions of a Direct Injection Diesel Engine*, *Aerosol Science and Technology*, Vol. 43, 2009, pp. 455-465.
- (49) C. S. Cheung, Y. Di, Z. Huang, *Experimental Investigation of regulated and unregulated emissions from a diesel engine fueled with ultralow-sulfur diesel fuel blended with ethanol and dodecanol*, *Atmospheric Environment*, Vol. 42, 2008, pp.8843-8851.
- (50) X. Wang, C. S. Cheug, Y. Di, Z. Huang, *Diesel engine gaseous and particle emissions fueled with diesel-oxygenate blends*, *Fuel*, Vol. 94, 2012, pp. 317-323.
- (51) J. Huang, Y. Wang, S. Li, A. P. Roskilly, H. Yu, H. Li, *Experimental investigation on the performance and emissions of a diesel engine fueled with ethanol-diesel blends*, *Applied Thermal Engineering*, Vol. 29, 2009, pp. 2484-2490.
- (52) H. Chen, J. X. Wang, S.-J. Shuai, X.-L. An, W.-M. Chen, *Effects of Ethanol in Ester-Ethanol-Diesel Blended Fuelson Spray Behavior and PM Emission*, SAE paper 2006-01-0236, 2006.
- (53) S. H. Park, S. H. Kim, C. S. Lee, *Mixing Stability and Spray Behavior Characteristics of Diesel-Ethanol- Methyl Ester Blended Fuels in Common-rail Diesel Injection System*, *Energy Fuels*, Vol. 23, 2009, pp. 5228-5235.
- (54) S. H. Park, I. M. Youn, C. S. Lee, *Influence of ethanol blends on the combustion performance and exhaust emission characteristics of a four-cylinder diesel engine at various engine loads and injection timings*, *Fuel*, Vol. 90, 2011, pp. 748-755.
- (55) S. Y. No, *Definition and Correlation for Spray Angle in Non-Reacting Diesel Fuel Sprays*, *ILASS-Korea Journal*, Vol. 11, No. 4, 2006, pp. 244-250.
- (56) K. Jeong, S. H. Park, C. S. Lee, *Injection spray and emissions characteristics in a diesel engine using diesel-*

- bioethanol blended fuel, ILASS-Europe 2011. 24th European conf. on Liquid Atomization and Spray Systems, Estoril, Portugal, Sept. 2011.
- (57) C. Shen, W. L. Cheng, K. Wang, C. F. Lee, Estimating the Secondary Droplet Size Distribution after Micro-Explosion of Bio-fuel Droplets, ILASS-Americas 2010, 22nd Annual Conf. on Liquid Atomization and Spray Systems, Cincinnati, OH, May, 2010.
- (58) S. H. Park, H. K. Suh, C. S. Lee, Nozzle flow and atomization characteristics of ethanol blended biodiesel fuel, *Renewable Energy*, Vol. 35, 2010, pp. 144 -150.
- (59) S. H. Park, H. K. Suh, C. S. Lee, Effect of Bioethanol-Biodiesel Blending Ratio on Fuel Spray Behavior and Atomization Characteristics, *Energy Fuels*, Vol. 23, 2009, pp.4092-4098.