

## SPRAY CHARACTERISTICS OF DME AND DME BASED FUELS IN COMPRESSION IGNITION ENGINES- A REVIEW

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### ABSTRACT

It is well known that dimethyl ether(DME) is a very promising alternative fuel for compression ignition engine which provides extremely low particulate matter emissions, while NO<sub>x</sub> emissions are compatible to those from current diesel fuel under the same engine operating conditions. A brief review of recent works related to the spray characteristics of neat DME and various DME based blends in compression ignition engines is presented. Recent production technologies of DME are introduced. The application of DME as a fuel except diesel engine and as the other fields is also introduced. Problems in DME fuelled compression ignition engines such as low lubricity, poor elasticity, high vapour pressure and low energy content are included. In this review, spray characteristics include the spray structure, spray angle, spray tip penetration, and SMD. Recent works for the prediction of spray characteristics in DME fuelled diesel engines are also discussed. The possibility of applying the existing correlations for the prediction of diesel spray characteristics to DME spray characteristics is discussed. Future works related to DME spray characteristics are suggested.

### INTRODUCTION

Compression ignition engines are widely used in vehicles because they provide better fuel economy, longer life and safer operation than do gasoline fuelled spark ignition engines. However, compression ignition engines are a significant source of pollutant emission, typically NO<sub>x</sub> and particulate matter. One of reduction methods of pollutant emissions in compression ignition engine is the development of suitable alternative and renewable fuels or blends. Several oxygenated fuels are known to have the potential for use as the alternative diesel fuel. Those oxygenates include alcohol (methanol and ethanol), ether, ester, carbonate and acetate compounds. Of such oxygenates, the leading candidate for alternative fuel as the ether compounds include dimethyl ether (DME), diethyl ether(DEE), dimethoxy methane(DMM) and glycol ether such as monoglyme and diglyme etc.[1]

A review of development up to 2000 related to the application of DME in compression ignition engine was reported by Sorenson [2]. A comparative review of leading alternative fuel candidates had been conducted by Semelsberger et al. [3] for demonstrating the viability of DME as an alternative fuel. Recently Arcoumanis et al. [4] presented a comprehensive review of the technical feasibility of DME as a candidate fuel for environmentally-friendly compression ignition engines independent of size and application. It is well known that spray characteristics of DME due to its inherent properties plays an important role in engine's performance and exhaust emissions in compression ignition engine. Therefore, it is required to demonstrate the comprehensive review of spray characteristics of DME applied to compression ignition engines.

This paper reviews the spray characteristics of dimethyl ether (DME) as an alternative fuel for compression ignition engines. In this review, several recent production methods of

DME are introduced. The application of DME except as diesel fuel is also introduced. Problems in DME fuelled compression ignition engines such as low lubricity, poor elasticity, high vapour pressure and low energy content are included. In this review, spray characteristics include the spray structure, spray angle, spray tip penetration, and Sauter mean diameter(SMD). Recent works for the prediction of spray characteristics in DME fuelled diesel engines are also discussed. The possibility of applying the existing correlations for the prediction of diesel spray characteristics to DME spray characteristics is discussed. Future works related to DME spray characteristics are suggested.

### PRODUCTION OF DME

Conventionally, DME has been produced in a two step process where syngas typically generated from steam reforming of methane in natural gas is first converted to methanol-followed by methanol dehydration to DME. As DME is traditionally produced via methanol dehydration catalyzed by liquid sulphate acid and/or solid acids, a lot of researches have been focused on finding better catalyst that have higher selectivity for the DME formation and less tendency to generate undesirable by-products [3, 5].

Natural gas is not the only feedstock that can be used to produce syngas. Coal, biomass and hydrates can also be used. Production of DME from coal in remote areas was studied and an innovative process of direct synthesis of DME from syngas in a slurry phase reactors has been developed [6].

The evaluation of systems for making an organic farm self-sufficient of renewable fuel was recently reported by Ahlgren et al.[7] The land use, energy balance and environmental impact of systems based on DME produced from either straw or short-rotation willow coppice were investigated. Gasification is essential for producing DME from

biomass and it can be carried out with different methods and with different oxidation media, pressure and temperatures. Refining the woody biomass to motor fuels such as methanol, DME and ethanol and to fuel pellets are compared in terms of CO<sub>2</sub> reduction rate and specific cost of reduction[8]. For economical development of gas hydrates located in permafrost and deep sea locations, conversion of this resource into DME at the feed location is considered [9].

Recently, polygeneration system producing DME and electricity based on natural gas was widely investigated [10]. In addition, co-feed(coal and natural gas) and co-production(electricity and DME) system was proposed and evaluated [11].

## OTHER APPLICATIONS OF DME

DME was used mainly as a propellant of paint, agricultural chemicals and cosmetics, etc[12]. The successful application of DME as a starting aid for methanol-fueled SI engines at low temperatures are reported[13]. The first diesel engine application of DME is related to its use as an ignition improver in connection with methanol fuelled diesel engine[14].

The new engine design concepts such as low compression ratio direct injection compression ignition(LCR DI-CI) engine[15], controllable premixed combustion(CPC) engine[16], and homogeneous charge compression ignition(HCCI) engine[17] have been studied using DME as an alternative fuel.

The concept of using DME as fuel in DI diesel engine with a low compression ratio was investigated to find a combustion regime with the highest thermal efficiency[15]. Even though DME fuelled LCR DI-CI engine was superior to the conventional diesel engine in terms of thermal efficiency, emissions and engine noise, NO<sub>x</sub> emissions was inevitably high.

In order to control NO<sub>x</sub> emissions and solve the problems in fuel injection system of DME fuelled diesel engine, the controllable premixed combustion (CPC) system fuelled with DME was newly proposed by adding a premix chamber to the diesel engine fuelled with DME[16]. However, they pointed out that further study is required to reduce THC and CO emissions from DME fuelled CPC engine.

The researches on the application of DME as a fuel for HCCI engine were widely undertaken [17,18]. DME is also one of the most promising fuels for both direct and indirect type fuel cells [19-21]. Many studies have been conducted to apply DME as an alternative fuel for gas turbine [22,23]. In a natural gas dual-fuel diesel engine application, it is reported that DME would be expected to give lower NO<sub>x</sub> and smoke emissions than diesel fuel[24].

DME is largely used in the chemical industry as an assistant solvent, as a propellant gas in aerosol products and as a refrigerant. Recently it is proved that DME could be a useful solvent for industrial scale up of rapid expansion of supercritical solution process (RESS) used for generation of particles for the pharmaceutical industry[25]. The synthesis of cetane number improver from conversion of DME using dielectric barrier discharges is reported [26]. Application of DME as a reductant in selective catalytic reduction of NO<sub>x</sub> in compression ignition engines has been suggested [27,28]. DME also shows good ignition quality as an ignition additive in HCCI engine fuelled with liquefied petroleum gas(LPG) [29].

## PROBLEMS IN DME FUELLED COMPRESSION IGNITION ENGINE

The most challenging problems of DME fuelled compression ignition engines are related to its physical properties and not to its combustion characteristics. Typical examples include low viscosity, low lubricity, poor elasticity, high vapour pressure, low energy content of DME.

DME has an inherently low viscosity, an order of magnitude lower than that of diesel fuel.(2.482 cSt for No.2 diesel and 0.225 cSt for DME at 40 °C). Due to its low viscosity, currently available fuel injection systems are not suitable for DME because of wear and leakage problems in pumps and fuel injectors. However, the additives suggested for enhancing viscosity include diesel fuel, dimethyl carbonate and fatty acids. In addition, for the estimation of viscosity of DME as a function of temperature, three different equations were suggested[30-32]. Evaluation of viscosities calculated from those equations is required.

Even though viscosity of fuel is a dominant property in the hydrodynamic lubrication regime, lubricity of fuel is important in the boundary lubrication regime[33]. The lower lubricity of DME than that of diesel fuel leads to premature wear and eventual failure of pump and fuel injectors. Several additives such as Lubrizol, Hitec, Infinem R655 and castor oil have been introduced to increase the lubricity of DME.

DME is also highly chemically corrosive, attacking most common polymers found in o-ring seals. Special highly fluorinated materials must be substituted in order to use DME in current engine configurations.[34]

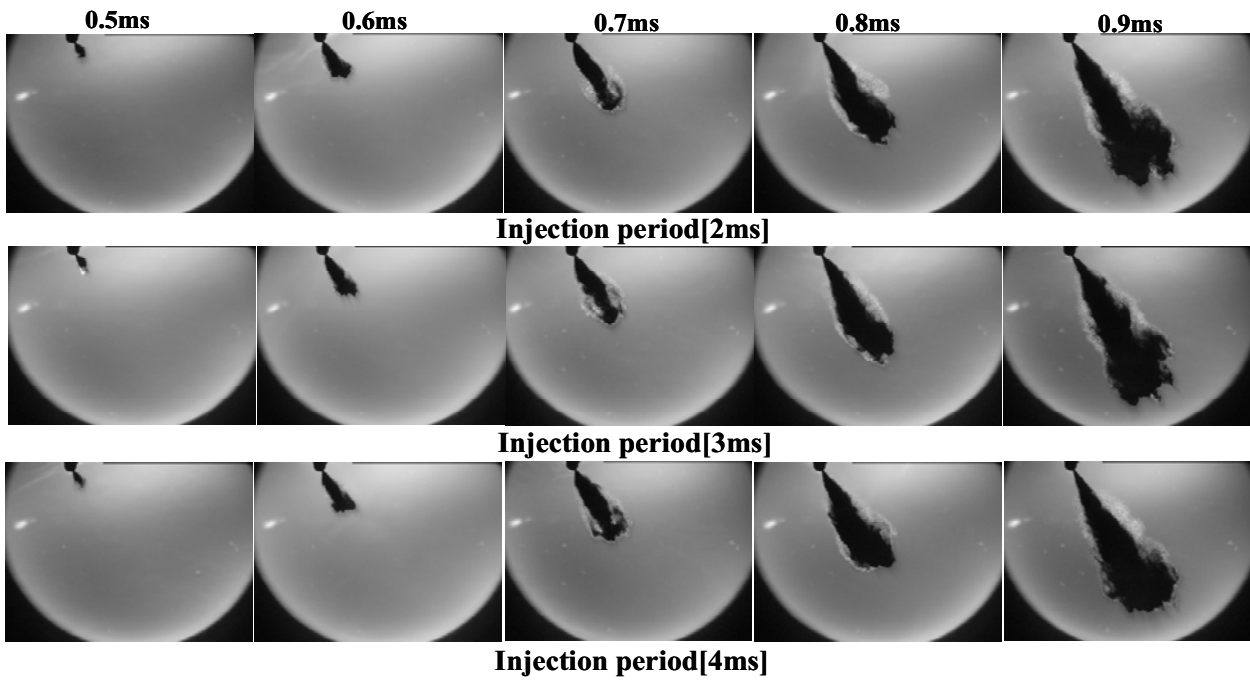
Fuel injection of DME can be achieved through both conventional mechanical and current common-rail systems but requires slight modification of the standard system to prevent corrosion and overcome low lubricity[4].

## SPRAY CHARACTERISTICS OF DME

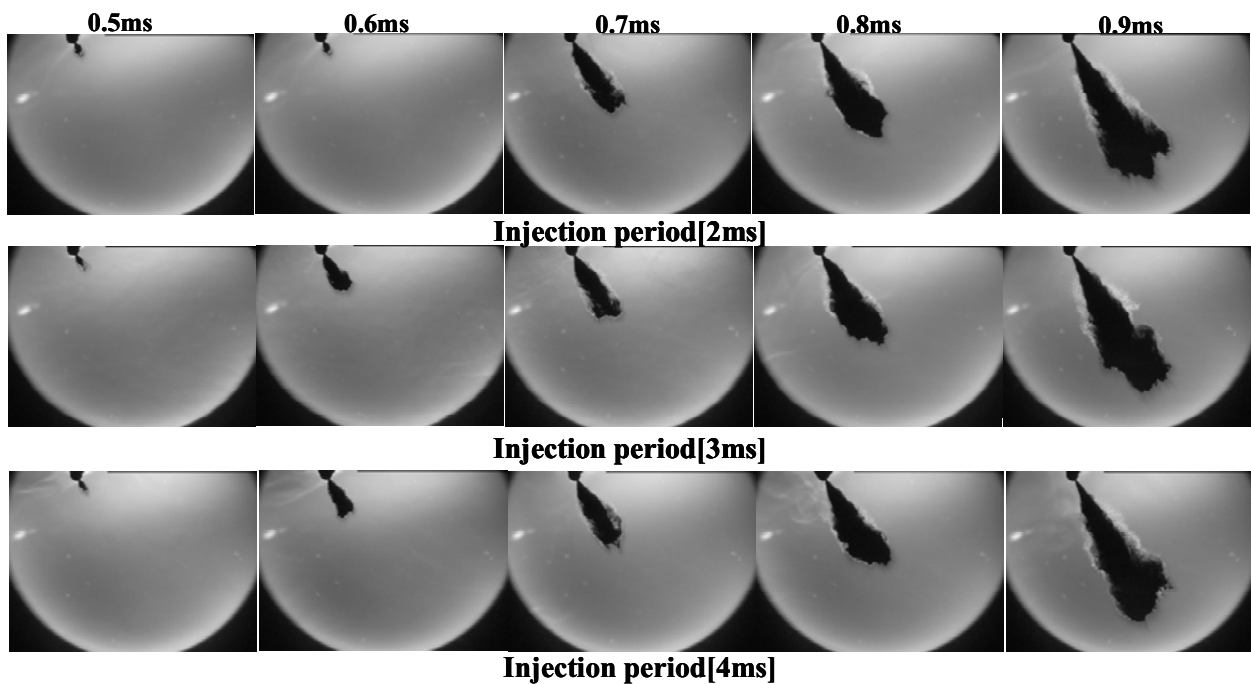
In this review, spray characteristics of DME include the spray structure, spray angle, spray tip penetration, and mean diameter of droplet, particularly Sauter mean diameter(SMD). The prediction of DME spray characteristics will also be discussed.

## SPRAY STRUCTURE

Fig. 1 shows the typical photographs of spray structure emerged from the single hole nozzle having diameter of 0.4 mm and taken by shadowgraphy technique in the injection pressure of 35 MPa and in the ambient pressure of 0.6 and 1.0 MPa, respectively[35]. For both cases of ambient pressures, irregular shape of spray can be observed immediately after start of injection. The evaporation starts to occur mainly in the head of spray at 0.7 ms after start of injection. The rapid lateral spreading of the spray or side jets at the very start of injection were observed for injection pressures of 20 MPa at ambient pressure of 4 and 5.5MPa, but not at pressures between 1.5 and 2.5 MPa[36, 37]. However, this phenomenon could not be found in these photographs. This may be due to the higher injection pressure and the lower ambient pressure than those of former works



a) injection pressure: 35 MPa, ambient pressure: 0.6 MPa



b) injection pressure: 35 MPa, ambient pressure: 1.0 MPa

**Fig. 1 Typical photographs of DME spray structure**

There are portions of the spray tip that tend to break off the spray during the injection process. These chunks of spray

rapidly decelerate as the main body of spray penetrates past them in the usual manner. This observation is exactly same as in the case of Sorenson et al.[36,37]. This may be due to the intrinsic physical properties of DME and air entrainment characteristics. In addition, it should be pointed out that the DME spray is not axi-symmetric and this leads to the serious problem in the measurement of spray angle. In the continuous spray development, intermittent hesitating DME spray was observed under the injection pressure of 25 to 55 MPa and the ambient pressure of 3MPa[38].

It is well known that the shape of DME spray was wide and short compared to the diesel spray[39]. Compared with diesel fuel, DME spray displays a slower penetration, much faster evaporation and wider spray angle by a factor of about 2. Its breakup time is 0.2 – 0.4 ms, which is shorter than that of diesel[40].

## SPRAY ANGLE

DME spray spreads widely with short penetration regardless of similar sac pressure and higher flow velocity in the hole with diesel fuel[30]. Under the same injection conditions, a wider spray angle is observed with DME spray compared to diesel spray[39-42]. In the comparative study of spray characteristics of diesel fuel and DME conducted on the basis of momentum conservation, it is pointed out that the spray angle of DME may be larger than that of diesel fuel by 15-20 % [42].

Spray angle for DME increases with increase in ambient pressure for 1.0 and 1.5 MPa[43], and 2.0 to 4.0 MPa[39], which is similar tendency of diesel fuel spray. The initial spray angles at the three injection pressures(10,13, and 16 MPa) shows nearly the same value[39]. As the injection pressure increases, the spray angle for DME decreases.[44]

When the orifice diameter of the nozzle was increased from 0.5 to 1.2 mm, the spray angle is increased[39]. More precise results were noticed in the study of Xu et al.[45]. In the beginning and the end of injection, with the decreasing the orifice diameter with 0.25, 0.28 and 0.34 mm, the spray angle decreased. However, in the middle of injection processes, the orifice diameter almost had no effect on the spray angle. In addition, they pointed out that further study at elevated ambient temperatures is required to confirm the effect of ambient temperature on spray angle.

Yu et al.[46] have studied the hole-to-hole variation of spray angle in the case of multi-hole nozzle. They found that hole-to-hole variation of spray angle for DME spray was lower than that of diesel spray, regardless of chamber pressure because of the high compressibility of DME.

The spray 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  $60d_0$  ( $d_0$  is the orifice diameter) downstream of the nozzle. According to the droplet evaporation analysis[47] and experimental studies[35,48,49], many small droplets vaporize completely even before reaching the  $60d_0$  distance where the spray angle is defined for diesel fuel. From the experimental work for the measurement location of spray angle of DME spray, the distance between  $30d_0$  and  $45d_0$  from the nozzle tip is newly suggested for DME spray[48,50]. For the DME spray injected under atmospheric ambient pressure, the longitudinal spray dispersion was quite remarkable and the spray boundary had a smaller curvature so that two lines to define the spray angle cannot adequately follow the spray boundary[38]. In their work, the spray angle was, therefore, defined near the nozzle tip following the spray boundary from the nozzle. It is clear from the above investigations that spray angle defined for diesel spray is not appropriate for DME spray. It is, therefore,

required to develop the definition of spray angle for DME spray.

An increased proportion of DME in blends of DME and diesel fuel leads to the increased spray angle[51]. In addition, DME- propane blend fuel shows the wider spray angle than that of diesel fuel[52]. Spray angle of DME-biodiesel of 50% blends shows nearly the same value compared to that of diesel fuel[53]. In the work of biodiesel blends with different proportions of DME(25, 50 and 75%), the ratio of DME does not affect to spray angle[54]. In addition, it is clear that spray angle of DME-vegetable oil blend fuel shows the nearly same value of diesel fuel[53,54]

## SPRAY TIP PENETRATION

The spray penetration for DME is shorter than or almost the same as that for diesel fuel at the same injection conditions.[4,47,55]. The weak penetration was measured and reported at the ambient pressures of 0.1 and 1.5 MPa[56], 0.1 MPa[57], and 2~2.6 MPa[45], respectively. This weak penetration could be explained with the state change of DME[30].

Spray tip penetration of DME decreased with increase in ambient pressure and orifice diameter which is similar to the variation of diesel spray[39,55]. Their data showed that the spray tip penetrating speed of DME is slower and more smaller effect of ambient pressure difference than those of diesel fuel.

In addition, spray tip penetration decreased with decrease in injection pressure[39]. The higher the injection pressure ranging from 20 to 35 MPa, the longer the spray penetration[58]. It should be pointed out that spray penetration increased as ambient temperature increased[55].

Sorenson et al.[36] had measured spray penetration of DME at  $P_a=4$  and 5.5 MPa and  $P_i=20$ MPa and compared with the predicted penetration by the empirical correlation for diesel fuel. The results show that only the slope of the curves for both ambient pressures agree well.

In the same conditions, the spray penetration of DME was two times slower than that of diesel fuel[45]. Investigation have been done in engine-like ambient temperature ranging from 573 K -773 K, in which no remarkable change in the spray penetration was found with increase either in the ambient temperature or in the ambient density. In addition, it is found that the spray penetration decreased with decrease in the orifice diameter of 0.25 to 0.34 mm.

Spray penetration of DME was shorter than that of diesel fuel at injection pressure of 25 MPa and ambient pressure of 0.1MPa. However, the similar spray penetration of DME with diesel could be obtained at injection pressure of 55 MPa and ambient pressure of 3.0 MPa[46]. It is confirmed that the effect of ambient and injection pressures on DME spray penetration is coincident with the trend of diesel spray.

According to the theoretical and comparative study of characteristics of diesel fuel and DME sprays on the basis of momentum conservation, the penetration of DME spray tends to be longer than that of diesel fuel for reaching the diesel-fuel equivalent output due to longer injection duration of DME[42].

Although the presence of gaseous and liquid spray is not clear, DME spray penetration is obviously shorter than that of diesel fuel. Wakai et al.[56] reported that the liquid spray penetration(liquid length) is also shorter than that of diesel fuel. Lee et al.[59] reported that the liquid length decreases with increase in ambient temperature and pressure. It is also pointed out by them that the evaporation process of DME sprays should be investigated more precisely.

Spray penetration of DME blended with biodiesel of 50% initially shows nearly the same value with diesel fuel up to 34

ms after start of injection. However, spray penetration of DME blended with biodiesel is longer than that of diesel fuel after greater than 34 ms[53]. In the work of biodiesel blends with different proportions of DME(25, 50, and 75 %) the effect of DME ratio on spray penetration is negligible[54]

Spray penetration of DME -diesel blend fuel was reported that it is decreased with increase in proportion of DME[51]. However, the effect of ambient pressure on the spray characteristics for blends of DME and diesel fuel was not undertaken. As same as in the case of neat DME, DME-propane blend fuel reveals the shorter spray tip penetration than that of diesel fuel[52].

## SMD

In the case of injection pressure of 5.0 MPa into the ambient pressures of 1.0 and 1.5 MPa, SMD for  $P_a=1.0$ MPa is slightly larger than that of  $P_a=1.5$  MPa. SMD is decreased remarkably with the increase in the axial distance from the nozzle tip up to  $z=20$ mm[43]. The same tendency can be found in the case of the higher injection pressures of 4, 50, and 60 MPa[55].

In the case of ambient pressure of 0.5 MPa with the injection pressure of 2.0 and 4.0 MPa, SMD for  $P_{inj}=4.0$ MPa is slightly larger than that of  $P_{inj}=2.0$  MPa up to  $z=20$  mm, whereas the distance more than  $z=20$  mm demonstrates the opposite tendency[53,60,61]

SMD is decreased with the increase of injection pressure(1.0, 3.0 and 5.0 MPa) and the distance from the nozzle tip(30 to 100 mm) [62]. However, there is no apparent difference of SMD for  $P_i=3.0$  MPa and  $P_i= 5.0$  MPa after the distance from the nozzle tip of 60 mm.

At  $z=20$  mm, SMD of DME spray decreased with increase in ambient pressures of 0.5, 1.0, 1.5 and 2.0 MPa for the injection pressure of 5.0 MPa. However, the same tendency is not shown in the other axial distance from the nozzle tip up to 40 mm[63].

Qiao et al.[64]demonstrated that DME produces much smaller drops, more uniform drop size distribution than diesel fuel according to the data of the radial distribution of drop size at a distance of 54 mm from the nozzle tip.

As the ambient temperature was increased, the droplet size of DME spray became smaller[45]. It should be pointed out that the effect of high ambient temperature on SMD of DME spray should be investigated because the ambient temperature is important on evaporation of DME spray.

SMD of DME-biodiesel blends is decreased with increase in injection pressure up to 4.0 MPa and is increased as the injection pressure is elevated[53]. In addition, it is found that there exists the different optimum ambient pressures for minimum droplet size for the different injection pressures. Microscopic spray characteristics of DME-vegetable oil blends, particularly used cooking oil, was investigated by Kim et al.[60] and Hyun et al[59]. They found that the increase of blend level of DME over 50% by weight in DME-vegetable oil blends results in the decrease of droplet size and the droplet size lies in the similar size range of diesel fuel. The effect of injection pressure in the range of 1.0 and 8.0 MPa on SMD of blends of DME and vegetable oil was negligible. Droplet size was increased with the increase in ambient pressure between 0.1 to 1.0 MPa. They concluded that 50% blended level by weight of vegetable oil shows the best atomization characteristics due to micro-explosion phenomena.

## PREDICTION OF DME SPRAY CHARACTERISTICS

In this review, the prediction of DME spray characteristics includes the zero-dimensional, theoretical and empirical

correlations for the prediction of spray angle, spray tip penetration and Sauter mean diameter, respectively.

## SPRAY ANGLE

Various theoretical and empirical correlations for the prediction of spray angle in diesel fuel sprays are reported in the literature and are reviewed recently[65]. Even though there is a theoretical analysis of spray angle in connection with spray penetration of DME spray on the basis of momentum conservation[42], this study is not so enough for supplying the correlation for the prediction of spray angle for DME sprays. It is, therefore, required to conduct the research about the application or modification of those correlations developed for diesel spray to DME sprays.

## SPRAY PENETRATION

Many workers have studied the spray penetration in diesel spray and suggested the zero- or multi- dimensional and theoretical or empirical correlations for the prediction of spray penetration[66]. Most studies on the prediction of spray penetration for DME had introduced the following, zero-dimensional, and empirical correlation proposed by Hiroyasu et al.[67].

$$S = 0.55 \left( \frac{\Delta P}{\rho_A} \right)^{0.5} t \quad 0 < t < t_b$$

$$S = 2.95 \left( \frac{\Delta P}{\rho_A} \right)^{0.25} (d_0 t)^{0.5} \quad t > t_b \quad (1)$$

where  $t_b$  is the jet breakup time.

In the case of mozzle opening pressure of 2.0MPa and ambient pressure of 4 and 5.5 MPa, spray penetration calculated by the above correlation underestimated the measured one even though general tendency of spray penetration agreed well[36]. In the study of nozzle opening pressures of 12, 20 and 24 MPa and the ambient pressures of 4 and 5 MPa, respectively, the measured spray penetration was greater than the calculated one from the above correlation [68]. For the higher nozzle opening pressure of 24 MPa, there was better consistency between experimental and predicted penetrations. However, in all cases the calculated penetration underpredicted the measured penetration by as much as 40%.

On the other hand, the calculated penetration for low ambient pressure(0.1MPa) among 0.1 and 1.0 and 1.5 MPa and for valve opening pressures of 9.8 and 19.6 MPa, was considerably different with the experimental results[69]. When the ambient pressure is lower than the vapour pressure of DME(0.53 MPa at 293 K), flash boiling which results in the fine atomization of liquid DME and enlargement of spray angle must happen. However, the calculated penetration for the ambient pressure of 1.5 MPa was nearly consistent with the calculated penetration. This is the opposite results with the study of Glensvig et al.[68]which shows the inconsistency between the predicted and the measured penetrations under the much higher ambient pressures than that of this experiment.

Wakuri et al. [70] used momentum theory to develop the fuel spray model by assuming that the relative velocity between fuel droplets and entrained air can be neglected and the injected liquid droplet momentum is transferred to the homogeneous fuel droplet-entrained air mixture. Their model can be expressed by the following.

$$S = 1.189 C_d^{0.25} \left( \frac{\Delta P_L}{\rho_a} \right)^{0.25} \left( \frac{d_0 t}{\tan \theta} \right)^{0.5} \quad (2)$$

Kajitani et al.[71] proposed the following correlation for the prediction of spray penetration of DME spray by modifying the above Eq.(2) .

$$S = \left( \frac{\rho_f}{\rho_a} \right)^{0.25} \left( \frac{dU t}{\tan \theta} \right)^{0.5} \quad (3)$$

where U is the spray velocity and  $\theta$  the half angle of spray. The comparative study of the above two correlations Eq.(1) and Eq.(3) with the experimental data was undertaken and concluded that the calculated spray penetration by Eq(3) is more close to the experimental results than that by Eq.(1)[35,50]. This is attributed to the use of the constant injection pressure in Eq.(1) and the introduction of spray velocity instead of pressure and spray angle.

Recently, a two-phase flow model, for the prediction of spray penetration was suggested by Sazhin et al. [72]. This model was derived under the assumption that the droplets and entrained air form a two-phase flow. They recommend the following one of the three developed equations for modeling the spray penetration.

$$S = 1.189 \left( \frac{1}{(1-\alpha_d)^{0.5}} \right)^{0.5} \left( \frac{C_d}{\tan \theta} \right)^{0.5} \left( \frac{\Delta P}{\rho_a} \right)^{0.25} (d_0 t)^{0.5} \quad (4)$$

where  $\alpha_d$  is the volume fraction of droplets in the spray.

It should be pointed out that Eq.(2) and Eq.(4) is very similar even though they were developed from the different point of view.

The applicability of several existing spray penetration models developed for the prediction of diesel spray was analyzed for DME spray[48,73,74]. Two-phase flow model, Eq.(4), with spray angle at a distance 45do downstream of the nozzle and fuel spray model, Eq.(2) with spray angle at a distance 30do downstream of the nozzle give the reasonable prediction of DME spray penetration. This tendency is same for the prediction of spray penetration with the different nozzle diameters and ambient pressures. In addition, it was clear that both models clearly overestimate the observed spray penetration at times less than about 0.8 ms after start of injection. This reveals that the development of model valid at the initial stage of spray penetration for DME spray is required.

The jet mixing model based on gas jet mixing theory was proposed by Dent[75] for the prediction of spray tip penetration of diesel spray. This model is different with other models for considering the temperature effects via a gas density correction term as follows.

$$S = 3.36 \left( \frac{\Delta P}{\rho_a} \right)^{0.25} (d_0 t)^{0.5} \left( \frac{294}{T_g} \right)^{0.25} \quad (5)$$

In the work of DME spray characteristics in a common-rail fuel injection system[38], it was found that Eq.(5) resulted in best fit for the DME spray in the injection pressure from 25 to 55 MPa and in the ambient pressure of 3 MPa.

Recently, two empirical correlations including Eq.(1) and one theoretical correlation Eq.(4) were introduced to compare with the experimental results of DME spray penetration under the different injection pressures, ambient pressures and ambient temperatures[44,55]. Even though they mislead the theoretical

correlation Eq.(4) as empirical one, they also found that the calculated penetration provide good agreement with the experimental one, except in the early stage of spray development.

## SMD

Several correlations for the prediction of mean drop sizes derived for the diesel spray are summarized in the book[76]. Till date, no information is available on the application of drop size correlations for the prediction of SMD in diesel spray to DME spray.

## SUMMARY

DME can be produced from a variety of feedstock such as natural gas, methanol, coal, biomass and methane hydrates. Recent studies on DME production showed the potential of exploiting new production concepts such as polygeneration system and co-feed and co-production system.

DME can be used as a fuel for HCCI engine, fuel cell, gas turbine, and dual-fuel diesel engine. In addition, it can be applied to conventionally propellant gas in aerosol products, solvent used for particle generation in pharmaceutical industry, cetane number improver in diesel fuel, reductants in SCR of NOx in diesel engine, ignition additive in HCCI LPG engine.

Under the same injection conditions, spray structure of DME is widely different with that of diesel fuel. Compared to diesel fuel spray, DME spray demonstrates a slower penetration, much faster evaporation and wider spray angle.

The spray angle for DME increases with increase in ambient pressure and orifice diameter. As the injection pressure increases the spray angle decreases. The new definition of measurement location on spray angle for DME spray is required since the existing one for diesel spray is not suitable.

Spray tip penetration of DME decreased with increase in ambient pressure and orifice diameter. In addition, spray tip penetration decreased with decrease in injection pressure and ambient temperature.

SMD of DME spray decreases with increase in injection pressure and ambient pressure. As the ambient temperature is increased, the droplet size is decreased.

DME-biodiesel blend fuel can be used directly to compression ignition engine because it has nearly the same spray penetration, spray angle and good air entrainment with diesel fuel which results in homogeneous fuel-air mixture.

It is clear that the development of the correlations for the prediction of spray angle and SMD for DME sprays is required. It is also necessary to develop the correlation for the prediction of initial stage of spray penetration for DME spray.

## NOMENCLATURE

Symbol	Quantity	SI Unit
$C_d$	discharge coefficient	-
$d_0$	orifice diameter	m
$\Delta P$	pressure drop through the nozzle	MPa
$S$	spray penetration	M
$t$	time	S
$t_b$	breakup time	S
$T_g$	temperature of ambient gas	K
$U$	fuel spray velocity	m/s
$\alpha_d$	volume fraction of	-

$\Theta$	droplet in the spray	
$\rho_a$	half angle of spray	$^\circ$
	density of ambient gas	$\text{kg/m}^3$
$\rho_f$	density of fuel	$\text{kg/m}^3$

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