Analysis of existing spray penetration models for dimethyl ether spray

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The prediction of spray penetration is of considerable practical importance in many fields such as diesel and gasoline direct injection engines. The applicability of existing spray penetration models developed for the prediction of diesel spray was analyzed for DME spray. It can be found that the existing spray penetration models can be used for the prediction of DME spray penetration. For modeling the spray penetration of DME, Wakuri et al's and Sazhin et al's model are recommended. In the selection of spray angle for both models, the measurement location of 30do for Wakuri et al's model and 45do for Sazhin et al's model are suggested. The discrepancy between the predicted and the observed penetration becomes smaller with increase in ambient pressure at the given orifice diameter. The spray penetrations predicted by the existing penetration models are not in good agreement with the observed penetration with increase in orifice diameter. It is required to develop the correlation valid at the initial stage of penetration.

1. Introduction

DME (Dimethyl Ether) has been known as a very promising alternative oxygenate fuel which gives low emissions and good economy in the application of direct injection diesel engine.
Sorenson et al. [1] reported the spray tip penetration and spray angle of DME spray under the high pressure injection from hole and pintle type nozzles into nitrogen using conventional jerk pump injection system. By using the dynamic injection line pressure, spray penetration of DME spray can be predicted with methods developed for diesel fuel by Hiroyasu and co-workers at ambient pressure of 0.4 MPa. However, the comparison of spray tip penetration between experimental and calculated results was not favorable and they only suggested the possibility of prediction.
Yoshizaki et al. [2] and Wakai et al. [3] reported spay characteristics of DME with a constant volume vessel experiments. The experimental results of spray penetration were compared with the computed one from the empirical equation suggested by Xu et al [4]. The calculated results revealed reasonably good agreements with the experimental one only under high ambient pressure condition.
Hwang et al. [5] investigated the effect of ambient pressure on spray angle and penetration for DME spray in common rail injection system. The experimental results of spray penetration could be predicted more reasonably by introducing the Kajitani et al's correlation [6] than Hiroyasu and Arai's correlation [7]. They pointed out that the development of model for the prediction of DME spray penetration is required.
The problem of spray tip penetration is of considerable practical importance in design of diesel and gasoline direct injection (GDI) engines. The spray penetration is a strong function of several engine operating parameters such as nozzle geometry, spray angle, injection conditions including the injection pressure, and ambient density and temperature.
Various models developed for the prediction of diesel spray penetration belong to one of zero-

dimensional and multidimensional models. Multi-dimensional models introduce the governing physical mathematical equations with submodels for breakup, evaporation, drag, interphase transport, turbulence etc and the initial injection boundary conditions [17]. This leads to the complexity and time-consuming. This model requires a very crucial decision for the selection of an initial representative droplet size.
There were numerous research efforts for a prediction of diesel spray penetration which would combine simplicity and accuracy. The application of DME as an alternative fuel to direct injection diesel engine requires the analysis of existing zero-dimensional model for the calculation of DME spray penetration.
The purpose of this study is to investigate the applicability of the existing zero-dimensional spray penetration models for DME spray.

2. Review of existing models

Many researchers have studied the spray penetration in diesel engines and suggested expressions for penetration of diesel sprays into stagnation air. The results of these studies have been reviewed by Lefebvre [8] and Heywood [9]. However, Wakuri et al's work [10] was not included in their reviews.
Existing zero-dimensional models for the prediction of spray penetration can be classified into five categories such as fuel spray model by Wakuri et al.[10], jet mixing model by Dent [13],jet breakup model by Hiroyasu et al. [14], Cone model by Schihl et al. [11], and two-phase flow model by Sazhin et al [12].
Wakuri et al. [10] 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.

$$S = 1.189 {C_d}^{0.25} \left(\frac{\Delta P_L}{r_a} \right)^{0.25} \left(\frac{d_0 t}{\tan q} \right)^{0.5} \tag{1}$$

This model was applied by Chikashisa and Murayama [15] for diesel spray and by Kajitani et al. [6]for DME spray with different values for discharge coefficient, respectively.
The jet mixing model based on gas jet mixing theory was proposed by Dent [13] as

$$S = 3.36 \left(\frac{\Delta P}{r_a} \right)^{0.25} (d_0 t)^{0.5} \left(\frac{294}{T_g} \right)^{0.25} \tag{2}$$

This model is different with other models for considering the temperature effects via a gas density correction term. This model was analyzed by Shihl et al. [11] and consistently over-predicted spray penetration in their test case. Therefore, it will be excluded from this study.
The jet breakup model by Hiroyasu et al. [14] was derived from the liquid jet disintegration theory done earlier by Levich [16].
In this model, the spray tip penetration is divided into two zones; the initial zone consists of an intact liquid core and the latter zone consists of a mixture of liquid droplets and entrained medium as given by

$$
\begin{aligned}
S &= 0.55\left(\frac{\Delta P}{\rho_A}\right)^{0.5} t \qquad\qquad 0 < t < t_b \\
S &= 2.95\left(\frac{\Delta P}{\rho_A}\right)^{0.25} (d_0 t)^{0.5} \qquad t > t_b
\end{aligned}
\tag{3}
$$

where t_b is the jet breakup time. This model is one of widely used model for the comparison with the experimental data of spray penetration.

Schihl et al.[11] analyzed the existing spray penetration model and proposed a phenomenological cone penetration model.

$$
S = 1.414\left(\frac{C_d^{\;0.5}}{\tan\theta}\right)^{0.5}\left(\frac{\Delta P}{\rho_a}\right)^{0.25}(d_0 t)^{0.5} \tag{4}
$$

$$
\tan\theta = \frac{4\pi}{A} f\left[\left(\frac{\rho_l}{\rho_\infty}\left(\frac{\mathrm{Re}_l}{We_l}\right)^2\right)\right]\left(\frac{\mathrm{Re}_l}{We_l}\right)^{-0.25} \tag{5}
$$

For the calculation of spray cone angle, they employed the modified Ranz model.

Recently, a new model, two-phase flow model, for the prediction of spray penetration was suggested by Sazhin et al. [12]. 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.

$$
\begin{aligned}
S &= \frac{\sqrt{V_{in} d_0 t}}{(1-\alpha_d)^{0.25}\,\tilde{\rho}_a^{\;0.25}\sqrt{\tan\theta}} \\
&\times\left(1 - \frac{\sqrt{d_0}}{4\sqrt{V_i}(1-\alpha_d)^{0.25}\,\tilde{\rho}_a^{\;0.25}\sqrt{\tan\theta}\sqrt{t}}\right)
\end{aligned}
\tag{6}
$$

Eq.(6) can be further simplified if the second term in the right hand side is ignored thus giving this equation as:

$$
S = 1.189\left(\frac{1}{(1-\alpha_d)^{0.5}}\right)^{0.5}\left(\frac{C_d}{\tan\theta}\right)^{0.5}\left(\frac{\Delta P}{\rho_a}\right)^{0.25}(d_0 t)^{0.5} \tag{7}
$$

The half angle of the spray cone can be estimated based on available theoretical formulae by Lefebvre [8] or obtained from the experimental data. In the realistic spray environment, the volume fraction of droplets in the spray will be much less than 1. In the case of no entrained air, the volume fraction of droplets will be equal to one. When Sazhin et al. [12] compared the predictions of their model and the experimental results reported by two different researches, the volume fraction of droplets of 0.0001 was introduced. This reveals that the effect of volume fraction of droplets in the spray on spray tip penetration will be negligible.

Renner and Maly[18] reported a universal correlation model for simultaneous and assumption-free prediction of the temporal evolution of spray penetration, spray tip speed, spray angle, Sauter mean diameter and mean equivalence ratio of multi hole and pintle nozzles for diesel engines. However, this universal model requires the details of the inside geometry of the injector which is only available for the limited researchers, so it will be excluded from this study.

According to the review of existing models, the dominating factors for the prediction of spray tip penetration are the spray angle, discharge coefficient, pressure drop across nozzle , ambient density and orifice diameter.

3. Experimental set up

The experimental apparatus used in this study is shown in Fig. 1. It consists of high pressure chamber, common rail system injector, control unit, fuel pump (Haskel, MS-71), air compressor, pressure regulator and PMAS (Particle Analysis Motion System).
The fuel supply system in this study was organized by considering the high vapor pressure of DME. To avoid vaporization in the fuel line, it was pressurized from the fuel tank to the fuel pump (MS-71, Haskel INC, USA) by using nitrogen at 1.6 MPa
In order to protect the leakage of DME in the fuel line, a solenoid valve and sensor were used. The regulator was utilized to keep injection pressure constant and the high fuel pressure required. As DME injection required high pressure to operated, a fuel pump which was operated with air compressor and the surge tank was used instead of common rail. The surge tank can be pressurized up to 35 MPa and the DME pressurized set at 35 MPa was injected into the high pressure chamber which was filled up by nitrogen and at ambient pressures of 0.6 ,1.0 and 1.5 MPa.
The spray angle and spray tip penetration were measured by using PMAS (particle motion analysis system, V-tek Co., Korea). It consists of a spark light source with very short time duration of about 50 ns, a field lens, a CCD camera, a positioning unit, and a personal computer with an image board.
The spray angle and spray penetration was measured by using the shadowgraphy method based on the macroscopic spray measurement function of PMAS. The shadowgraphy image passes through the diaphragm of camera lens and is recorded on CCD. The qualitative observation and instantaneous images for a short period of time were obtained by the shadowgraphy technique. The edge of spray of this method was defined as a line of 80 % transmittance.

4. Result and discussion

For the comparison between predicted spray penetration with the different penetration models and experimental penetration, it is required to make clear the numerical values of parameters such as discharge coefficient and spray angle.
In the calculation of spray penetration based on Wakuri et al's model, a representative discharge coefficient of 0.6 was used according to their suggestion. In the prediction of spray penetration by Schihl et al and Sazhin et al's model, the discharge coefficient was varied as C_d= 0.793 for do = 0.2 mm, C_d = 0.804 for do = 0.3 mm, and C_d = 0.81 for do = 0.4 mm. This results came from the introduction of correlation C_d max = 0.827-0.0085 l/d [8]. In this experiment, the sharp-edged nozzle was used and l/d = 4 for do = 0.2 mm, l/d = 2.67 for do = 0.3 mm, and l/d=2 for do = 0.4 mm.
In the selection of half-angle of spray cone, the Eq.(5) is used only for Schihl et al's model. For the rest models, half-angles of spray cone measured in this study are introduced. It should be noted that half-angles of spray cone was selected at 1.8 ms after start of injection and at the axial distance of 30 do from the nozzle tip.
Fig.1 shows the comparison of measured spray penetration with predictions by different penetration models at different ambient pressures for the orifice diameter of 0.2 mm. It should be noted that Eq.(7) of two phase model was selected for the comparison because it has similar format with Wakuri et al's model. As can be seen from the figures, Wakuri et al's and Sazhin et al's models give reasonably good predictions of the observed spray penetration. However, the other three models consistently over-predict the experimental spray penetration. This may be

due to lower spray angle predicted by Eq.(5) in Schihl et al's model than the experimental one. For Hiroyasu et al's model, the constant in Eq.(3) can not properly represent the parameters such as discharge coefficient and half-angle of spray cone taken into account in the other models considered in this study for DME spray. For Dent et al's model, the constant discharge coefficient of 0.8 and gas temperature effect leads to the undesirable prediction results. This is coincident with the analysis by Schihl et al.[11]. For the higher ambient pressure shown in Fig.1(c), three models appear to be on average closer to the experimental data. It is clear from

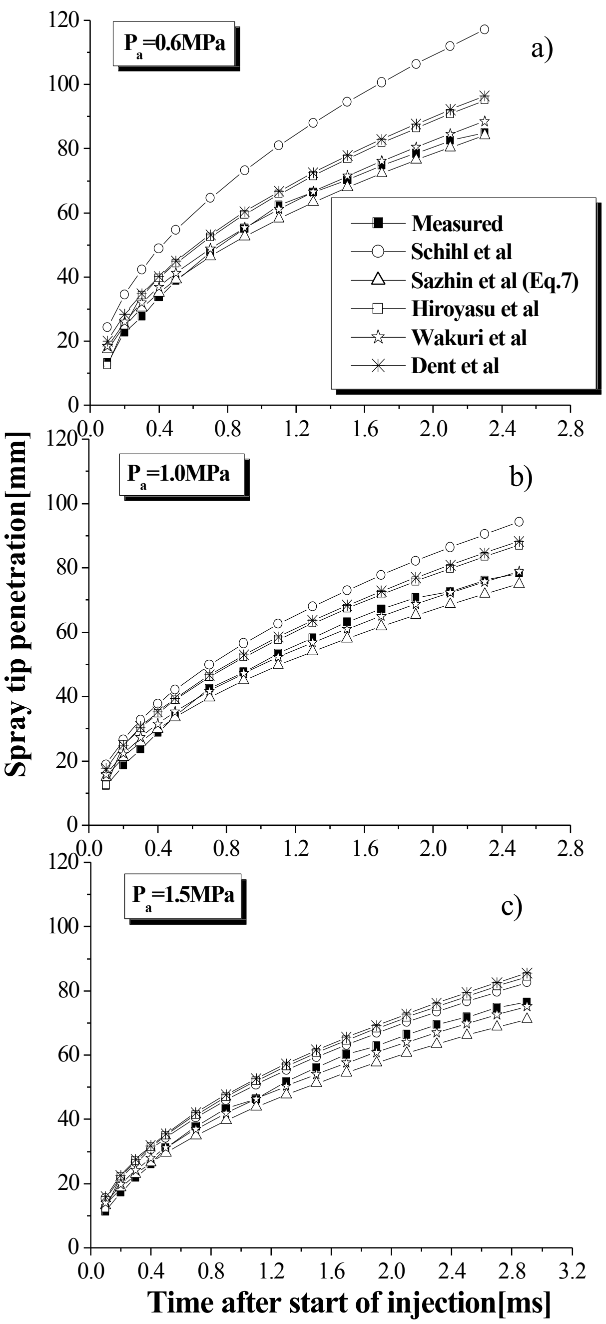

Fig. 1 Comparison of measured spray penetration with theoretical predictions (do=0.2mm, T_L=30do)

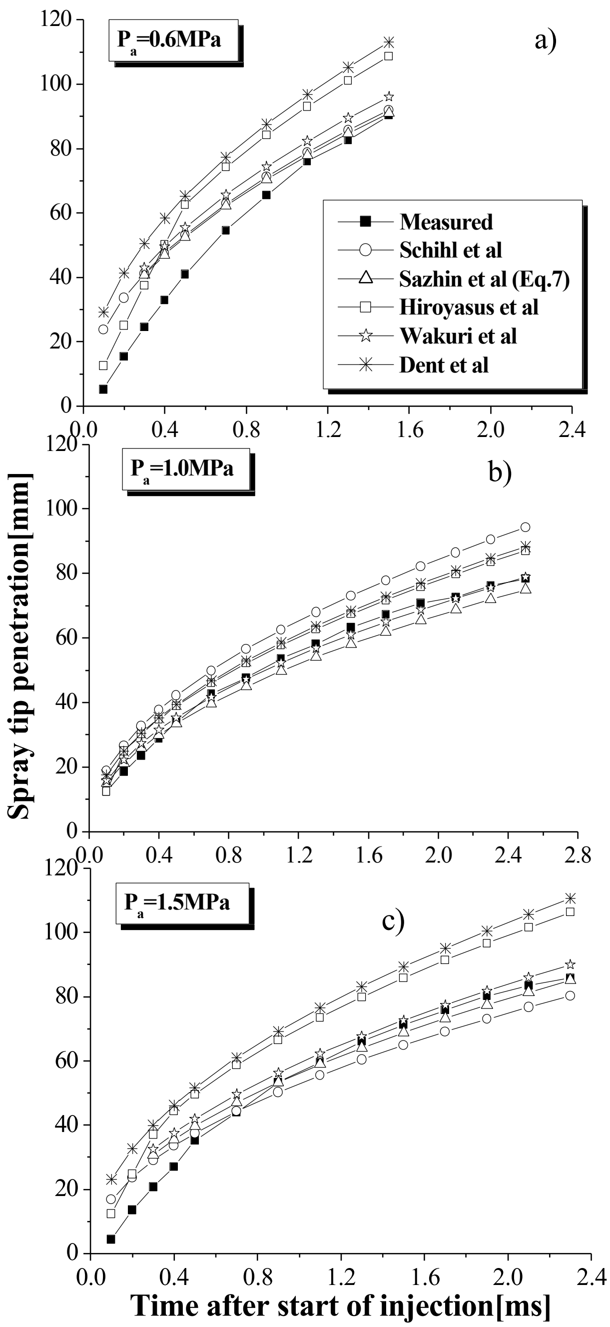

Fig. 2 Comparison of measured spray penetration with theoretical predictions (do=0.4mm, T_L=30do)

the figures that the discrepancy between observation and predictions by Wakuri et al's and Sazhin et al's models becomes larger with increase in an ambient pressure. This tendency can also be found in the spray penetration in the case of the orifice diameter of 0.3 mm.

Fig. 2 shows the comparison of the predicted spray penetration by five models and the observed spray penetration for the orifice diameter of 0.4 mm. In the lower ambient pressure as shown in Fig.2(a), all the models considered here consistently over-predict the observed spray penetration. Inspection of Fig. 2 shows good agreement between the experimental data and the calculated spray penetration provided by Wakuri et al's and Sazhin et al's models. It should be noted that Schihl et al's model gives more better predictions in the bigger orifice diameter than those in the smaller orifice diameter as shown in Fig. 1.
It is clear from the comparison of the predicted with the observed spray penetration that Wakuri et al's and Sazhin et al's models can give reasonably accurate predictions of the observed spray penetration in the experimental conditions considered here. It is clearly of interest to compare

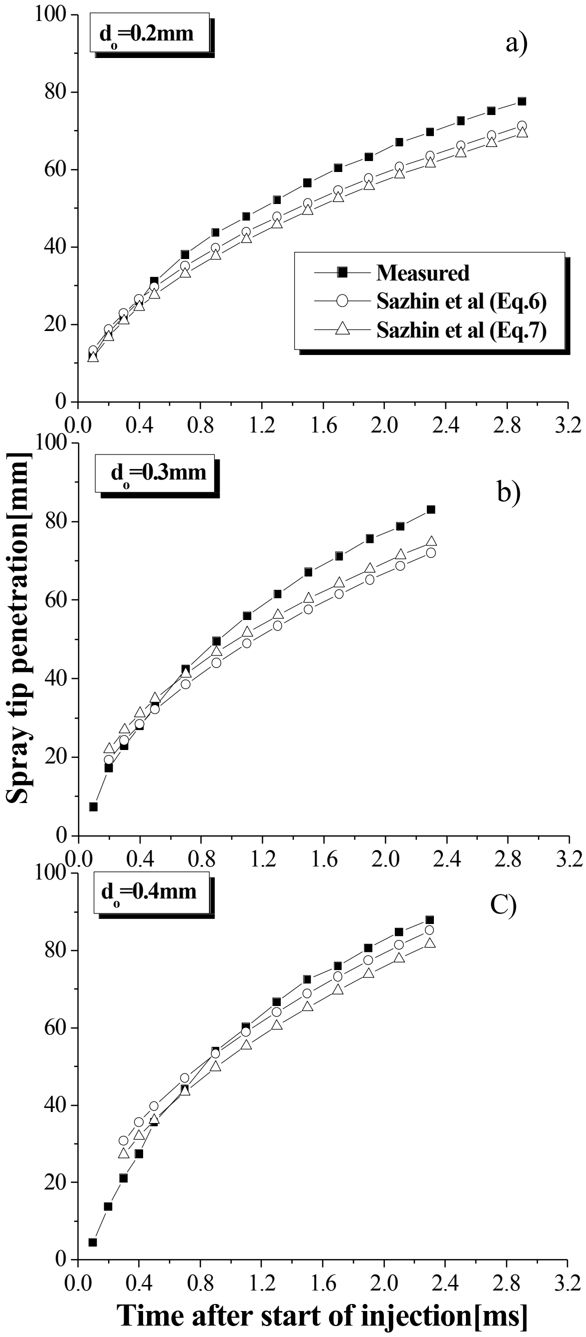

Fig. 3 Comparison of measured spray penetration with predictions based on two-phase model. (Pa=1.5Mpa)

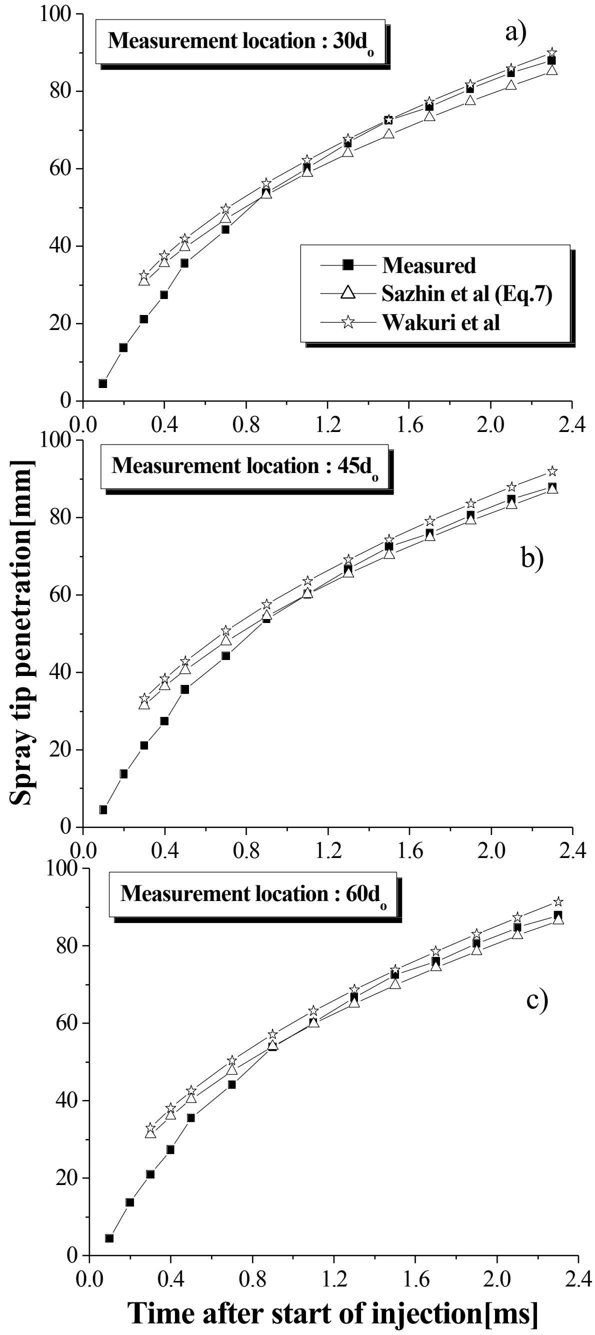

Fig. 4 Influence of measurement location for spray angle on measured and predicted spray tip penetration (d_o=0.4mm,P_a=1.5Mpa)

the measured spray penetration with the predicted one by two equations, Eqs.(6) and (7) here. The comparison of the prediction by two equations in Sazhin et al's model with the observed spray penetration for the ambient pressure of 1.5 MPa and different orifice diameters is shown in Fig. 3. The predicted results for both equations generally under-predict the observed spray penetration at times greater than about 0.5 ms after start of injection for the orifice diameters considered in this study. It is clear that Eq.(7) shows more better predictions than one by Eq.(6). It is recommended that Eq(7) of Sazhin et al's model is used for the prediction of spray tip penetration for DME spray.

It is clearly of interest to compare the Wakuri et al's model and Eq.(7) of Sazhin et al's model with the experimental penetration for the different orifice diameter and measurement location of spray angle. The effect of measured location of spray angle on the predicted spray penetration by two selected models is shown in Fig. 4. It is 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 fuel spray is required. Two models agree fairly well with the observation within the experimental error range for the different measurement location of spray angle. For Wakuri et al's model, the measurement location of 30do from the nozzle tip for spray angle is suggested and for Sazhin et al's model, the measurement location of 45do from the nozzle tip.

5. **Conclusion**

The applicability of existing spray penetration models developed for the prediction of diesel spray was analyzed for DME spray. It can be found that the existing spray penetration model can be used for the prediction of DME spray penetration. For modeling the spray penetration of DME, Wakuri et al's and Sazhin et al's model are recommended. In the selection of spray angle for both models, the measurement location of 30do for Wakuri et al's model and 45do for Sazhin et al's model are suggested. The discrepancy between the predicted and the observed penetration becomes smaller with increase in ambient pressure at the given orifice diameter. The spray penetrations predicted by the existing penetration models are not in good agreement with the observed penetration with increase in orifice diameter. It is required to develop the correlation valid at the initial stage of penetration.

6. Acknowledgement

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7. Nomenclature

A : nozzle parameter

C_d : discharge coefficient

d_0 : nozzle diameter

Re_l : Reynolds number based on injected fuel properties and nozzle diameter

T_g : absolute temperature of chamber gas

t : time

V_{in} : initial velocity

We_l : Weber number based on liquid properties

a_d : volume fraction of droplets in the spray

ΔP : pressure drop across nozzle (injection pressure less the chamber pressure)

$\widetilde{r}_a$: r_a / r_l

r_a : density of air

r_ℓ : density of liquid

r_∞ : surrounding gas density (chamber gas density)

q : half angle of the spray cone

8. References

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