Correlations for Prediction of Non-evaporating Diesel Spray Penetration

Soo-Young No†

Key Words: Diesel spray penetration, DME, Liquid-phase penetraution

Abstract

The prediction of diesel spray penetration has been the subject of several works and intensive investigations are still underway by many researchers. It is required to summarize the correlations developed before 1990 days and to introduce the correlations reported recently in the literature. The existing zero-dimensional models for the prediction of diesel fuel spray penetration can be classified as theoretical and empirical correlations. Of various correlations, the models considered in this paper were selected as based on the evaluation results of previous reviews and the recently published works in the literature. The existing theoretical correlations can be classified into seven categories and the existing empirical ones as two categories in this review. 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 and time after the start of injection. Especially, the definition for the measurement of spray angle is different with researchers. It is required to evaluate the existing spray tip penetration models for the very high injection pressure and other fuel sprays such as DME. It is also required to evaluate the correlations for the prediction of diesel spray penetration with the connection of liquid-phase penetration.

Nomenclature

A : nozzle parameter
C_a : area coefficient
C_d : discharge coefficient
C_v : velocity coefficient
d_0 : nozzle diameter
ΔP : pressure drop across nozzle
Re_l : Reynolds number based on injected fuel properties and nozzle diameter
T_g : absolute temperature of chamber gas
t : time after start of injection
U_0 : initial velocity
U_{th} : theoretical velocity
We_l : Weber number based on liquid properties
α_d : volume fraction of droplets in the spray
ρ_a : density of air
ρ_l : density of liquid
θ : spray angle

1. Introduction

The purpose of research regarding the fuel injection process in a direct injection engine is the preparation of a fuel-air mixture to accomplish a clean and efficient combustion process. The fuel-air mixture process is strongly influenced by the spray characteristics. The spray characteristics include the macroscopic, microscopic and atomization characteristics. The spray penetration belongs to one of the macroscopic characteristics. The prediction of spray penetration is of considerable practical importance in many fields such as diesel and gasoline direct injection engines. The spray penetration is a strong function of several engine operating parameters such as nozzle geometry, injection conditions and in-cylinder

---

(2007년 9월 5일 접수 ~2007년 9월 12일 심사완료)

†Department of Biosystems Engineering
Chungbuk National University, Cheongju, 361-763, Korea
E-mail : sooyoung@chungbuk.ac.kr

conditions.

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 equations with submodels for breakup, evaporation, drag, interphase transport, turbulence and the initial injection boundary conditions(1). This leads to the complexity and time-consuming. This model requires a very crucial decision for the selection of an initial representative droplet size. The prediction of spray penetration by multidimensional model is beyond the scope of this paper.

However, there were numerous research efforts for the prediction of diesel spray penetration which would combine simplicity and accuracy by introducing the zero-dimensional models. Detailed comparisons between different correlations for spray penetration published before 1971 and experimental results were published by Dent(2). In 1972, Hay and Jones(3) reported a critical review on the twelve zero-dimensional models available in the contemporary literature and recommended the two correlations proposed by Wakuri et al.(4) and Dent(2). In 1985 Hiroyasu(5) summarized the existing correlations including the works by Japanese researchers. The research results on the prediction of spray penetration up to 1989 have been reviewed by Lefebvre(6). Since these reviews, Naber and Siebers(7) mentioned the several other investigations of spray penetration appeared in the literature before 1996 in their study regarding the derivation of theoretical penetration correlation. It is required to summarize the correlations developed before 1990 days and to introduce the correlations reported recently in the literature.

Even though many studies on the measurement and the prediction of liquid-phase penetration of evaporating diesel fuel jets have been conducted from around ten years ago by virtue of the development of planar laser-based diagnostics(8), the prediction of spray penetration has been the subject of several works and intensive investigations are still underway by many researchers.

The purpose of this paper is to review and classify the recent literature related to the correlations for predicting the spray penetration in non-evaporating diesel engine conditions and to suggest the future works. The prediction of liquid-phase penetration of diesel fuel jets will not included in this paper.

2. Review of existing zero-dimensional models

Existing zero-dimensional models for the prediction of diesel fuel spray penetration can be classified as theoretical and empirical correlations. Of the various existing correlations, the correlations considered in this paper was selected as based on the evaluations results of previous reviews and the recent works in the literature.

2.1. Theoretical correlations

2.1.1 Fuel spray model

Wakuri et al.(4) 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.

$$S = 1.189 C_d^{0.25} \left(\frac{\Delta P}{\rho_a}\right)^{0.25} \left(\frac{d_0 t}{\tan \theta/2}\right) \qquad (1)$$

Naber and Siebers(7) proposed the following modified fuel spray model for the non-vaporizing transient spray penetration by introducing a proper scaling of length and time. Their derivation followed the spray penetration analysis of Wakuri et al.(4), but with several modification. The spray tip penetration and the time were made non-dimensional by using the length scale S+ and the time scale t+ defined as

$$\tilde{t} = \frac{\tilde{S}}{2} + \frac{\tilde{S}}{4} b + \frac{1}{16} \ln(4\tilde{S} + b) = b(1 + 16\tilde{S}^2)^{0.5} \qquad (2)$$

$$\tilde{t} = t/t^+ \qquad t^+ = \frac{d_f \tilde{\rho}^{0.5}}{a \tan(\theta/2) U_f}$$

$$\tilde{S} = S/S^+ \qquad S^+ = \frac{d_f \tilde{\rho}^{0.5}}{a \tan(\theta/2)}$$

where $\rho = \rho_l/\rho_a$ is the fuel and ambient gas density ratio, $d_f = Ca^{0.5}\, d_o$ is the effective diameter, θ is the spray angle, the constant a is 0.66. The fuel velocity at the nozzle orifice exit is $U_f = C_v\sqrt{2(P_f - P_a)/\rho_l}$ where Cv is the velocity coefficient, Pf and Pa are the fuel pressure in the injector and the ambient gas pressure, respectively.

It should be clear that this correlation assumes a uniform velocity profile and is correlated to non-vaporizing and non-reacting jet penetration data. They pointed out that this correlation over-predicts the penetration of vaporizing jets up to 18%. Even though the spray half angle θ/2 was reported to correlate with the normalized density only, it can not be universal because the constant c in the correlation should be changed with the nozzle orifice diameter.

This correlation had been introduced by Araneo et al.(9) for the study of gas density effects on diesel spray penetration and entrainment. In their work, they suggested the slightly modified non-dimensional length scale and time scale without using tan (/2) and obtained the different value of power of gas to fuel density ratio with that of Naber and Siebers(7).

In addition, the constant 'a' is given by them as a= 0.66, but it has since been suggested by Siebers et al.(10) that a=0.75 is more appropriate. This value was introduced by Asay et al.(11) to develop an empirical, mixing-limited, zero-dimensional model for diesel combustion.

Recently, Desantes et al.(12) proposed the following correlation by performing a dimensional analysis with the variables such as ambient gas density, time after the start of injection and instantaneous momentum flux for high injection pressure and small nozzle orifice diameter.

$$S = k\left(\frac{\Delta P}{\rho_a}\right)^{0.25}(d_o t)^{0.5} \qquad (3)$$

This correlation is basically same with Eq.(1), the fuel spray model by Wakuri et al.(4) They concluded that even though the correlation proposed by them predicts the spray tip penetration with a high degree of accuracy even if the angle is not known, a better level of confidence can be obtained if spray cone angle is considered.

Based on the jet entrainment law and momentum conservation, a new correlation for the spray tip penetration was suggested by Chen and Veshagh(13) as follows.

$$S = \left(\frac{2}{k}\right)^{0.5}\left(\frac{\rho_l}{\rho_a}A_0\right)^{0.25}(U_0 t)^{0.5} \qquad (4)$$

where A_0 is the orifice area, k is the entrainment coefficient which was found to have a value of 0.282 for free round jets into quiescent surroundings, irrespective of the densities of the injected and ambient fluids and U_0 is the initial velocity of the jet.

2.1.2. Jet mixing model

The jet mixing model based on gas jet mixing theory was proposed by Dent(2) as

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

This model is different with other models for considering the temperature effects via a gas density correction term. Hay and Jones(3) concluded in their critical review that this model is one of two best correlations. However, Schihl et al.(14) evaluated several different correlations and concluded that this model consistently over-predicted spray penetration in their test case.

2.1.3 Cone model

Schihl et al.(14) analyzed the existing spray penetration model and proposed a phenomenological cone penetration model as follows.

$$S = 1.414\left(\frac{C_d^{0.5}}{\tan\theta}\right)^{0.5}\left(\frac{\Delta P}{\rho_a}\right)^{0.25}(d_0 t)^{0.5} \qquad (6)$$

where

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

For the calculation of spray cone angle, they employed the modified Ranz model suggested by Ruiz and Chigier(15).

2.1.4 Two-phase flow model

In a recent work by Sazhin et al.(16), analytical expressions for the prediction of spray penetration were derived based on equations for conservation of mass and momentum for a two-phase flow. They assumed a two-phase flow with a zero relative velocity between air and droplets. The following correlation is one of analytical expressions which can be categorized into two-phase flow model.

$$S = 1.189\left(\frac{1}{(1-\alpha_d)^{0.5}}\right)^{0.5}\left(\frac{C_d}{\tan\theta/2}\right)^{0.5}\left(\frac{\Delta P}{\rho_a}\right)^{0.25}(d_0 t)^{0.5} \tag{7}$$

The spray angle can be estimated based on available theoretical formulae by Lefebvre(6) 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.(16) 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. In addition, Eq.(7) is entirely same with Eq.(1) if the volume fraction of droplets in the spray is not considered.

Instead of assuming that the density of mixture of gas and droplets is constant in the planes perpendicular to spray axis inside the spray in the derivation of Eq.(7), Pozorski et al.(17) assumed that it depends on the distance from the spray axis in the same way as at the initial stage of spray and proposed the following analytical correlation.

$$S = \frac{U_0}{4}\left(\frac{9d_0^2}{(1-\alpha)\tilde{\rho}_a D_t}\right)^{\frac{1}{3}} t^{\frac{2}{3}} \tag{8}$$

where $\tilde{\rho}_a = \rho_a/\rho_l$, and D_t is the turbulent diffusivity coefficient. They concluded that spray penetration at large distances from the nozzle is expected to be proportional to $t^{2/3}$ instead of $t^{1/2}$. It should be noted that even though $t^{2/3}$ law was supported by the experimental spray penetration for injection pressure of 100 MPa and air density of 49 kg/m^3, the more experimental data are required to compare.

2.1.5. Quasi-steady jet model

The correlation for the prediction of spray penetration obtained from the quasi-steady jet theory was suggested by Abraham(18) as follows.

$$S^2 = 2((0.7)3d_e U_0 t)/(16\pi^{0.5}C_t) \tag{9}$$

where d_e is the effective diameter[$=do(\rho_l/\rho_a)^{0.5}$], U_0 is the injection velocity and C_t is a constant, respectively. The value of the predicted penetration by this correlation depends on the value of a constant, C_t and an arbitrary definition of the tip. C_t= 0.0161 is a value suggested in the literature. The penetration is defined as the position of the point where the instantaneous centerline velocity has reached 70% of the local steady centerline velocity.

2.1.6. Momentum flux conservation model

More recently, the theoretical prediction model of spray penetration based on momentum flux conservation along the spray's axis was suggested by Desantes et al.(19) as

$$S = k_p\left(\frac{\dot{M}_o}{\rho_a}\right)^{0.25}\left(\frac{t}{\tan\theta/2}\right)^{0.5} \tag{10}$$

where k_p was considered a constant value as 1.26 independent of injection conditions or nozzle geometry. However, a value for k_p equal to 1.32 has been found for a quite big set of nozzle diameters and injection conditions(20).

In this correlation, the tendencies found for ambient density, time and spray cone angle are similar to those existing correlations discussed in the above. However, the momentum flux M_0 is included which can not be available in advance.

This model requires the experimental data of momentum flux and spray cone angle in order to predict axis velocity and spray penetration. Spray angle is considered as the cone angle which is formed by the spray considering 60% of the penetration as justified by Pastor et al.(21).

When the experimental data of momentum flux at the orifice outlet is not available, the following correlation of non-dimensional spray penetration can be incorporated.

$$\frac{S(t)}{D_{eq}} = k_p(C_a^{0.5}C_v)^{0.5}\left[\frac{U_{th}}{D_{eq}\tan\left(\frac{\theta}{2}\right)}\right]^{0.5} t^{0.5} \tag{11}$$

where $D_{eq} = D_o(\rho_l/\rho_a)^{0.5}$

It should be noted that the different values of the stabilized spray cone angle for different nozzle diameters and injection pressures were introduced for obtaining the values of $k_{p.}$

2.1.7. Non-dimensional parameters model

Varde and Popa(22) had derived the analytical model based on non-dimensional parameters for predicting diesel spray tip penetration as follows.

$$S = 1.1(A_1)^{0.3}(A_2)^{-0.008}(A_3)^{0.5}(A_4)^{0.16}t^{0.55} \quad (12)$$

where $A_1 = \Delta P\rho_l d_0^2/\mu_l^2 \approx Re^2$

$$A_2 = \rho_l\sigma_l d_0/\mu_l^2 = Re^2/We = 1/oh^2$$

$$A_3 = \rho_l/\rho_a$$

$$A_4 = L/d_0$$

This correlation shows the dependency of spray penetration on non-dimensional parameter A_2 to be small. This means that the degree of atomization has some relatively small effect on spray penetration. It is clear from this correlation that besides the time factor, spray penetration largely depends on the pressure drop across the nozzle orifice and density ratio of liquid to ambient gas. In addition, this correlation also shows spray penetration to depend on the nozzle length to diameter ratio. They found that while the jet mixing model by Dent(2) agrees well for the medium L/d_0 ratio nozzle, it underpredict for large L/d_0 ratio nozzle and overpredicts for low L/d_0 ratio. They concluded that the spray penetration obtained from this correlation match very well with the experimental data for all the nozzles.

Based on the analytical model for spray tip penetration developed by Varde and Popa(22) for single hole nozzles, Renner and Maly(23) proposed the analytical model for technical diesel nozzles as follows.

$$S = K(A_1)^{0.3}(A_2)^{-0.008}(A_3)^{0.2}(A_4)^{0.16}(A_5)^{0.6}\left(\frac{t}{t_0}\right)^{0.4} \quad (13)$$

where K=0.065 for multi hole nozzles and K=0.069 for pintle nozzles.

$$A_1 = \Delta P\rho_l d_{eff}^2/\mu_l^2 \approx Re^2$$

$$A_2 = \rho_l\sigma_l d/\mu_l^2 = 1/oh^2$$

$$A_3 = \rho_l/\rho_a$$

$$A_4 = L/d$$

$$A_5 = \mu_l/\mu_a$$

where d_{eff} is the effective hydraulic diameter due to flow contraction. It is slightly smaller than the corresponding geometrical hole diameter d. However, this universal model requires the details of the inside geometry of the injector which is only available for the limited researchers. It should be pointed out that the viscosity ratio of liquid to gas phase during spray breakup is considered as a major parameter in determining the spray penetration.

2.2. Empirical correlations

2.2.1. Jet breakup model

As a most widely cited empirical correlation, the jet breakup model by Hiroyasu et al.(24) was derived from the liquid jet disintegration theory done earlier by Levich(25). 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

$$\begin{aligned} &S = 0.55\left(\frac{\Delta P}{\rho_a}\right)^{0.5}_t \qquad 0<t<t_b \\ &S = 2.95\left(\frac{\Delta P}{\rho_a}\right)^{0.25}(d_o t)^{0.5} \qquad t>t_b \end{aligned} \quad (14)$$

where t_b is the jet breakup time.

This model is one of the most commonly quoted empirical correlations called sometimes two-zone penetration model..

However, Han et al.(26) had compared the measured spray tip penetration of a wide range of minisac and valve-covered-orifice nozzles using a high pressure diesel common-rail system with calculated one based on this empirical model. They pointed out that the model tends to overpredict the early phase of the penetration and underpredict that of the later phase. The calculated penetration of common-rail sprays with injection pressure of 300 bar is far less than the measured data, which may indicate that the model does not apply to injection with low needle lift and low injection rate.

In the jet breakup model, the constant line pressure was used as the injection pressure because it is difficult to measure the sac chamber pressure directly. By considering the effects of injection pressure variation and needle lift, modified jet breakup model was, therefore, suggested by Xu et al.(27) However, this modified one was rarely used for the prediction of diesel spray penetration.

2.2.2 Break-up time and length model

Yule et al.(28) proposed the following empirical correlations for the intact liquid core break-up time and liquid core penetration length, respectively.

$$S = 3.8\left[\left(\frac{\Delta P}{\rho_a}\right)^{0.5} d_0 t_b\right]^{0.5} \qquad (15)$$

where

$$t_b = \frac{3.75 \times 10^5}{d_0^{0.28} \rho_a^{0.05} \Delta P^{1.37}}$$

This correlation is much similar with jet breakup model by Hiroyasu et al.(24) However, it should be noted that a single equation can cover the whole spray flow field, rather than the two equations, two-zone approach used in jet breakup model. This correlation was introduced by Gulder(29) for the assessment of intact liquid core length with the pressure drop across the nozzle. It should be noted that he used the constant 2.9 instead of 3.8 in Eq.(15).

4. Discussion

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

The spray angle was considered as a major factor in the most of the correlations considered in this study. Especially, the definition for the measurement of spray angle is different with researchers. The existing definitions and correlations for the measurement and prediction of spray angle can be found from the recent work by No(30).

It should be noted that two-phase flow model and momentum flux conservation model are basically similar to fuel spray model.

The spray penetration dependence on ambient gas density reported in the all theoretical correlation is $\rho_a^{-0.25}$ with two exceptions. Those exceptions were the works of Naber and Siebers(7) and Varde and Popa(22) with a gas density dependence of $\rho_a^{-0.5}$.

It is well known that correlations predicting the spray penetration to be proportional to the square root of time are in good agreement with experimental results. However, there is an opinion that at shorter times, spray penetration is proportional to time t and at large distances from the nozzle, it is expected to be proportional to $t^{2/3}$. More studies are required to obtain the general conclusion regarding the proportionality of time with spray penetration.

5. Conclusions

The existing zero-dimensional models for the prediction of diesel fuel spray penetration can be classified as theoretical and empirical correlations. Of various correlations, the models considered in this paper were selected by considering the evaluation results of previous reviews and frequently cited works in the literature.

The existing theoretical correlations can be categorized into seven groups; fuel spray model, jet mixing model, cone model, two-phase flow model, quasi-steady jet model, momentum flux conservation model and non-dimensional parameters model. The existing empirical correlations can be also categorized into two groups; jet breakup model and break-up time and length model.

All the correlations discussed in this paper include the same parameters such as ambient gas density, time after the start of injection, pressure drop, diameter of nozzle orifice with more or less the same weight. The spray angle was considered in all the theoretical correlations except the jet mixing model and the non-dimensional parameters model. Therefore, it is clear that the selection of correlation for spray angle will affect the prediction of spray penetration.

It is required to evaluate the applicability of existing spray penetration models for the very high injection pressure and other fuel sprays such as DME and biodiesel fuel. The parametric analysis in relation to the correlation for spray angle in the prediction of spray tip penetration by the theoretical correlations is also required.

References

(1) V. A. Iyer, S. L. Post and J. Abraham, Is the liquid penetration in diesel sprays mixing controlled?. *Proceedings of the Combustion Institute* 2000, Vol. 28, pp. 1111~1118, 2000.

(2) J. C. Dent, A basis for the comparison of various experimental methods for studying spray penetration. *SAE paper* 710571, 1971.

(3) N. Hay and P. L. Jones, Comparison of the Various Correlations for Spray Penetration, *SAE paper* 720776, 1972.

(4) Y. Wakuri, M. Fujii, T. Amitani and R. Tsuneya, Studies on the penetration of fuel spray in a diesel engine. *Bulletin of JSME*, Vol. 3(9), pp.123~130, 1960.

(5) H. Hiroyasu, Diesel Engine Combustion and Its Modeling, COMODIA 85, pp.53~75, 1985.

(6) A. H. Lefebvre, *Atomization and Sprays*. London: Taylor and Francis,1989.

(7) J. D. Naber and D. L. Siebers, Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays, *SAE paper* 960034, 1996.

(8) C. Espey and J. E. Dec The Effect of TDC Temperature and Density on the Liquid-Phase Fuel Penetration in a DI Diesel Engine, *SAE paper* 952456, 1995.

(9) L. Araneo, A. Coghe, G. Brunello and G. E. Cossali, Experimental Investigation of Gas Density Effects on Diesel Spray Penetration and Entrainment, *SAE paper* 1999-01-0525, 1999.

(10) D. Siebers, B. Higgins and L. Pickett, Flame Lift-Off on Direct-Injection Diesel Fuel Jets: Oxygen Concentration Effects, *SAE paper* 2002-01-0890, 2002.

(11) R. J. Asay, K. I. Sevensson and D. R. Tree, An Empirical, Mixing-Limited, Zero-Dimensional Model for Diesel Combustion, SAE paper 2004-01-0924, 2004.

(12) J. M. Desantes, R. Payri, F. J. Salvador, and V. Soare, Study of the Influence of Geometrical and Injection Parameters on Diesel Sprays Characteristics in Isothermal Conditions, SAE paper 2005-01-0913, 2005.

(13) C. Chen and A.Veshagh, A Simple Unified Fuel Spray Model, SAE paper 930923, 1993.

(14) P. Schihl, W. Bryzik and A. Atreya, Analysis of current spray penetration models and proposal of a phenomenological cone penetration model, *SAE paper* 960773, 1996.

(15) F. Ruiz and N.Chigier,Parametric Experiments on Liquid Jet Atomization Spray Angle, *Atomization and Sprays*, Vol.1, pp.23-45, 1991.

(16) S. S. Sazhin, G. Feng and M. R. Heikal, A model for fuel spray penetration, Fuel, Vol. 80, pp.2171~2180, 2001.

(17) J. Pozorski et al., Spray Penetration in a Turbulent Flow, Flow, Turbulence and Comubustion, Vol. 68, pp.153~165, 2002.

(18) J. Abaraham, Entrainment Characteristics of Transient Gas Jets, Numerical Heat Transfer, Vol. 30, pp.347~364, 1996.

(19) J. M. Desantes, R. Payri, F. J. Salvador, and Gil, Development and validation of a theoretical model for diesel spray penetration, Fuel, 85, pp.910~917, 2006.

(20) J. M. Desantes, J. V. Pastor, R. Payri and J. M. Pastor, Experimental Characterization of Internal Nozzle Flow and Diesel Spray Behavior. Part I: Nonevaporative Conditions, *Atomzation and Sprays*, 15, 2005, 489~516.

(21) J. V. Pastor, J. Arregle and A. Palomares, Diesel spray image segmentation with a likelihood ratio test, Applied Optics, Vol. 40(17), 2876~2885, 2001.

(22) K. S. Varde and D. M. Popa, Diesel Fuel Spray Penetration at High Injection Pressure, SAE paper 830448, 1983.

(23) G. Renner and R. R. Maly, A universal model for spray characteristics of technical diesel sprays. International Symposium COMODIA 94, pp.385~390, 1994.

(24) H. Hiroyasu, T. Kadota and M. Arai, Fuel Spray Characterization in Diesel Engines, in Combustion Modeling in Reciprocating *Engines* (edited by Mattavi J. N. and Amann C. A., Plenum Press), pp.369~408, 1980.

(25) V. G. Levich, *Physicochemical Hydrodynamics*. Prentice-Hall Inc.,1962.

(26) J-S. Han, T.C.Wang, X. B. Xie, M-C Lai, N. A. Henein, D. L. Harrington, J. Pinson and P. Miles, Dynamics of Multiple-Injection Fuel Sprays in a Small-bore HSDI Diesel Engine, SAE paper 2000-01-1256, 2000.

(27) M. Xu, K. Nishida and H. Hiroyasu, A practical calculation method for injection pressure and spray penetration in diesel engines. *SAE paper* 920624, 1992.

(28) A. J. Yule, M. R. Mirza and I. Filipovic, Correlations for Diesel Spray Penetration Including the Effects of the Break-up Zone, *Proceeding of ICLASS-91*, Gaithersburg, MD, USA, pp.267~274, 1991.

(29) O. L. Gulder, Structure of Dense Diesel Sprays, *Atomization and Sprays* 2000, Workshop Proc., July 19, Gaithersburg, MD, USA, pp 103~111, 1991.

(30) No, S.Y., Definition and Correlation for Spray Angle in Plain-Orifice Atomizers, *Journal of ILASS-Korea*, Vol. 11(4), pp.244~250, 2006 or *Proc. of ILASS-Japan Conference*, 21~22 Dec.2006, Yokohama, Japan, pp. 141~146, 2006.