Transient Characterisation of High-Pressure Diesel Sprays

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ABSTRACT
An experimental and numerical study was carried out to characterise the transient valve-covered-orifice diesel spray behaviour. In the experiments, both a microscopic observation (spray angle close to nozzle exit) and a macroscopic measurement (penetration) were conducted to obtain the temporal change in spray structures. In the calculations, several spray models are examined and compared to the spray growth from the experimentally measured penetration. Present paper discusses the results on two injection rate shapes, namely a single stage injection and a multiple stage injection. The former one is examined by the calculation of KIVA-2 code in variation of the spray sub-models. The latter one is analysed by the spray visualization and the simulations. Evaluation of the various models and potential extension to take into account transient flow characteristics are discussed.

INTRODUCTION
Diesel fuel injection is one of the most dominant flow processes in Compression Ignition (CI) engines, since it controls the fuel/air mixing, and the subsequent ignition, flame propagation, and pollutant formation processes. Due to the flexibility in controlling injection timings, such as the common rail system, there are several trials to examine and investigate combustion performances with a multiple stage fuel injection strategy. One of the methodologies is the multiple injection that uses the combination of the early fuel injection (almost at bottom dead center) and the subsequent main injection (around at top dead center).

Primary turbulent breakup of diesel sprays was examined in the previous paper of Dan and Lai [1] using VCO spray injected into a atmospheric ambient condition. And it was shown successfully for the case of single stage fuel injection case. In this study, the computation of non-evaporating fuel spray was done with various atomisation models, including TAB and WB for the cases of pressurised ambient condition. Modified distribution function method is also introduced both in TAB and in pre-atomised spray modelling. The initial size of atomised droplets (Sauter mean radius) is derived from the empirical equation of Hiroyasu et al. [2].

Spray visualization is also carried out to investigate the transient spray structure. In addition to conventional spray visualisation using stroboscope and 35-mm film still camera, microscopic visualisation at the nozzle hole vicinity was also conducted with a long-distance microscope and magnified on a 35-mm film drum camera using a copper-vapour laser as the optical shutter.

ANALYSED CONDITIONS
Spray Modeling
KIVA-2 code [3] was used and several spray sub-models were implemented in this study. Table 1 show the summary of numerical conditions.

<table>
<thead>
<tr>
<th></th>
<th>Single stage</th>
<th>Multiple stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>Diesel fuel No. 2 (DF2)</td>
<td></td>
</tr>
<tr>
<td>(298 K)</td>
<td>840 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Ambient</td>
<td>Nitrogen gas (N₂)</td>
<td></td>
</tr>
<tr>
<td>(298 K)</td>
<td>17.2 kg/m³</td>
<td>19.4 kg/m³</td>
</tr>
<tr>
<td>Injection hole</td>
<td>1 (number of hole)</td>
<td></td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>0.19 mm</td>
<td>0.162 mm</td>
</tr>
<tr>
<td>Injection duration</td>
<td>1.8 ms</td>
<td>0.35/0.45/0.80 ms (pilot/dwell/main)</td>
</tr>
<tr>
<td>Discharge coeff.</td>
<td>0.50</td>
<td>See Fig. 7</td>
</tr>
<tr>
<td>Injection velocity</td>
<td>265 m/s</td>
<td></td>
</tr>
<tr>
<td>Parcel number</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Model in use</td>
<td>DDM, TAB, WB, MF *</td>
<td>TPB (original and MF) WB *</td>
</tr>
</tbody>
</table>

* DDM : pre-atomised method, TAB : KIVA original breakup model, WB : wave breakup model, MF : modified distribution function method, TPB : turbulent primary breakup model

At first, pre-atomised spray modelling, that is the original method in KIVA code [4], is examined in variation of distribution function [5]. Here, Φ = 2 (original) and 6 (modified) are adopted in the same input value of Sauter mean diameter which is derived from the empirical equation. Second, atomisation sub-models are investigated for TAB model [6] and KH wave model [7]. In TAB model, the modification in distribution function is also considered. Finally in the last section of this paper, the turbulent primary breakup model, which is introduced in the previous report of the authors is implemented to compare with the experimental
Experimental Conditions

Figure 1 shows the experimental set-up of spray visualisation. A six-hole VCO nozzle is used with a common rail injection system for the injection control. Diesel fuel No. 2 was used at a room temperature (298 K). Nitrogen gas was used at the high ambient gas density condition in the constant volume vessel.

NUMERICAL METHODOLOGY

There are several spray atomisation models that are proposed and implemented to the KIVA codes. Their detail procedures are available in each literature, therefore short descriptions are noted in the followings for brevity.

Taylor Analogy Breakup (Original KIVA)

The TAB method solves an oscillating and distorting motion of fuel drop as the displacement of drop's surface from the state, i.e. the sphere. The displacement, $x$, is normalised with drop radius, $r$, and defined to be $y$ as,

$$y = \frac{x}{Cr}$$

where $Cr (= 1/2)$ is model constant. The time history of this normalised displacement $y$ is evaluated by the following equations.

$$y(t) = \frac{C_F}{C_k C_b} W_{e} + \left[ \exp \left( -\frac{t}{t_d} \right) \right] \cdot \left[ y_0 - \frac{C_F}{C_k C_b} W_{e} \right] \cos \omega t + \frac{1}{\omega} \left[ y_0 + \frac{C_F}{C_k C_b} W_{e} \right] \sin \omega t$$

and

$$W_{e} = \frac{\rho_u u^2 r}{\sigma}, \quad \frac{1}{t_d} = \frac{C_d}{2} \frac{\mu}{\rho r^2}, \quad \omega = \sqrt{\frac{C_i \sigma}{\rho u^3}} \frac{1}{t_d^2}$$

where $C_F (= 1/3)$, $C_i (= 8)$ and $C_d (= 5)$ are model constants derived from the critical Weber number ($W_{e, cr} = 6$) for breakup. $u$ is relative velocity between fuel and gas, $r$ drop radius, $\rho$ density, $\sigma$ surface tension and $\mu$ viscosity, respectively. Subscript $l$ indicates for liquid fuel and $a$ for ambient gas.

Turbulent Primary Breakup

The amplitude of droplet oscillation at nozzle exit can be correlated to the turbulent feature of the liquid jet at the nozzle hole. The disturbance of drops injected from the nozzle is given by the non-dimensional initial amplitude parameter, $amp0$, in the TAB method as,

$$\dot{y}_0(0) = amp0 \cdot \omega$$

If it is assumed that the turbulence of fuel flow at nozzle hole is isotropic and its magnitude acts as the deforming rate, one can obtain the following correlation between the deformation and the turbulent kinetic energy.

$$x = \frac{2}{\sqrt{3}} k_0$$

where $x$ dot is deforming rate of drop, $k_0$ is kinetic turbulent energy of drop, namely the turbulent energy of fuel jet at nozzle exit. Then, the initial non-dimensional displacement can be derived from Eqn. (1) as,

$$\dot{y}_0(0) = \frac{x}{C_b r_0}$$

where, $r_0$ is initial drop radius. Substituting Eqn. (6) into Eqn. (7), and comparing with Eqn. (5), we can obtain the correlation of TPB method as,

$$amp0 = \frac{2}{\sqrt{3}} \frac{k_0}{C_s r_0 \sqrt{C_i \frac{\sigma}{\rho u^3} - \left( \frac{C_F \mu}{2 \rho r_0^2} \right)^2}}$$

where $a_b$ is derived from the relations in Eqn. (3). Here, the parameter $amp0$ is made to be consistent with the turbulent energy $k_0$. In this article, $amp0 = 20.0$ for a room temperature Diesel fuel was used, where it means $k_0 = 352$ m$^2$/s and $x$ dot = 15 m/s.

Modified Function Method

Modification in drop's distribution function that are used in KIVA codes can assess the wider range distribution in particle number density. In the computation of TAB method, Sauter mean radius of atomised particles, $r_{32}$, is evaluated through the energy conservation of particle's states before and after the disintegration process as follows.

$$r_{32} = \frac{r}{\left[ \frac{8}{20} \frac{K}{K + 6 \frac{K - 5}{120} \left( \frac{\rho_r^2}{\sigma} \right)^2} \right]}$$

where $r$ is particle radius before breakup and $K$ is the ratio of deforming motion energy to the total energy. The particle radius after breakup is defined with the evaluated $r_{32}$ according to the cumulative distribution function $h(r)$ which is derived from the weight distribution function $g(r)$, $g(r)$ is consistent with the size distribution function $f(r)$, i.e. the $\chi$-square distribution function. For the degree of freedom $6$, those functions are given as,
\[
f(r) = \frac{r^2}{6\pi^3} \exp\left(-\frac{r}{\bar{r}}\right) \tag{10}
\]
\[
g(r) = \frac{r^5}{120\pi^5} \exp\left(-\frac{r}{\bar{r}}\right) \tag{11}
\]
\[
h(r) = \int_0^r g(r)dr = 1 - \left[\exp\left(-\frac{r}{\bar{r}}\right)\right]^3 \tag{12}
\]
where, \(\bar{r}\) is arithmetic mean radius of particles (= \(r_{10}\)) that is related to SMR by \(r_{10} = 3r_{32}/5\) (while \(r_{10} = r_{32}/3\) for the case of freedom 2). \(h(r)\) is given randomly within the range between \(r = 0\) to \(21\bar{r}\) (\(r = 0\) to \(12\bar{r}\) for freedom 2). \(K\) is also justified to be \(K = 1.0\) for calculations with usage of the coalescence between droplets.

**Wave Breakup (Kelvin-Helmholtz)**

The KH-WB model is based on the stability analysis in perturbations to a cylindrical liquid surface, and the most unstable wave is described with curve-fit to solutions derived from the Orr-Sommerfeld equations. Breakup phenomena is evaluated by wave's growth frequency and its length which can be given for the most unstable, i.e. the fastest growing one as,

\[
\Omega = \frac{0.34 + 0.38We^{1/3}}{(1+Z)(1+1.47\sigma^3)} \sqrt{\frac{\nu}{\rho_1r_0^5}} \tag{13}
\]

\[
\Lambda = 9.02r_0 \left(\frac{1+0.45Z^3}{1+1.47\sigma^3}\right)^{1/6} \left(\frac{1+0.87We^{1/2}}{1+0.87We^{1/2}}\right)^{1/6} \tag{14}
\]

where \(\Omega\) and \(\Lambda\) are the fastest growing wave's frequency and length respectively, and \(r\) is drop radius before breakup. \(We\) is gas phase *Weber* number as the same definition noted in Eqn. (3), \(Z\) is *Ohnesorge* number and \(T\) is *Taylor* number which are defined as,

\[
Z = \frac{\sqrt{We}}{Re} = \frac{\mu_1}{\sqrt{\rho_1\sigma}}, \quad T = Z \sqrt{We} = \sqrt{\frac{\rho_0}{\rho_1}} \frac{\mu_1}{\sigma} \tag{15}
\]

In calculations, it is assumed that drops will disintegrate when the breakup time, \(\tau\), falls within the interested time duration (i.e. computational time step). Diameter of atomised droplets, \(r_c\), is considered to be proportional to the most unstable wave length. Those characteristic time and length scales in breakup are given by,

\[
\tau = \frac{3.726r}{\Lambda\Omega} \tag{16}
\]

\[
r_c = B_0\Lambda, \quad (B_0\Lambda \leq r) \tag{17}
\]

where \(B_0 = 0.6\) is model constant for drop-size, and \(B_1\) is also constant for breakup time that should be regarded as an adjustable model constant. The magnitude of \(B_1\) depends on the breakup regime and feature of jet. \(B_1\) is chosen to be 30 in the paper of the Ref. [8].

**RESULT AND DISCUSSION**

**Spray Modeling**

Figure 2 shows the spatial parcel distribution calculated by KIVA-2 code (Single stage in Table 1). Each diagram shows the result at \(t = 1.0\) ms after injection start, and parcels are depicted with circles according to the particle diameter. In the two diagrams (Left), the sprays are assumed to be fully breakup at nozzle exit. It is clearly shown that change in the particle distribution function can give the difference in parcel sizes. That is, the larger in the freedom (\(\phi\)), the spray consist of larger droplets.

The transient change in spray structure is shown in Fig. 3 (\(amp = 0.0\)). Here, the cases of original KIVA breakup model (TAB) and function (MF) method were shown. The TAB (Upper) assumes unbroken drops at close to nozzle exit, where the MF assesses the prompt breakup (only the case of \(t = 0.2\) ms remains the unbroken drops). On the other hand, TAB assumes smaller droplets after breakup than the MF. This aspect gives the difference in spray boundary shape.

In Fig. 4, the change in spray tip penetration history were shown for three atomisation models. There is significant difference in the models. That is, the growth rate in the penetration is different from model to model. The WB model predict the fastest penetration in the early time period (\(t < 0.25\) ms), and the TAB calculates that of the largest in the later time period (\(t > 1.0\) ms). This tendency is attributed by the atomised droplets size (See Fig. 2).

![Fig. 4 Calculated penetration (Single stage)](image)

**Microscopic Spray Behaviour**

Figure 5 shows the spray visualization results in the spatial range from nozzle exit to 1.3 mm downstream. In experiments, the copper vapour laser was operated at the frequency of 25 kHz, *i.e.* each frame is 40 μs apart. From Frame 1 to 9, the sprays of pilot injection period are shown, and those of main injection are given from Frame 13. It is obvious that the sprays spread widely at the start of injection for both injection stages. And there can be observed the atomised droplets around spray cone in this spatial region vicinity to nozzle exit (\(z = 0 - 1.3\) mm). It means that spray already breaks up at the exit.

Transient change in spray dispersion is defined with spray angle, and the result is shown in Fig. 6. Frame numbers correspond to the photographs of Fig. 5. It is induced that the spray angles at the start of injection are larger than those of during injection periods. Moreover, the angles at the just before injection are also larger for both cases of injection stages. This is attributed to the nozzle internal flow turbulence which is enhanced by the needle lift change[9] and needle lift oscillation.

**Spray Growth Calculation**

Spray penetration of the multiple stage injection (See Table 1) is calculated using the turbulent primary breakup
model, and the results are compared with the experimental results in Fig. 7(b). Also, it is shown for the injection velocity history (Fig. 7(a)). The injection velocity was derived from the injection rate measurement with Bosch type instrument. This history was used in the calculation, and the results were shown for the case of original TAB \((\text{amp}0=20.0)\), modified TAB \((\text{amp}0=20.0)\) and Kelvin-Helmholtz model (variation in set cone angle). As the same trend in the single injection case (shown in Fig. 4), K-H model gives larger penetration compared to those of TAB models. Penetrations measured in experiments show the variation in hole to hole, and it was shown for the case of fastest growth one (denoted hole \#2) and the case of slowest one (hole \#5). From the comparison between calculation and experiment, the slowest penetrations (\#5) are simulated well in early time stage, but the deference becomes large with time elapsed. These aspects suggest that it needs to be improved in the numerical simulation scheme, especially in the later time period of multiple injection sprays.

CONCLUSION

In this study, both spray visualization close to nozzle exit \((z<1.3 \text{ mm})\) is observed, and numerical simulation with several spray atomization models are conducted in order to discuss the transient spray characteristics. The conclusions derived from this study are as follows:

1. The broken up droplets already exist around spray periphery very close to the nozzle exit (Fig. 5).
2. Spray usually spreads wider at both injection start and end times.
3. This phenomena can also be observed for multiple fuel injection sprays (Fig. 6)

It is also drawn that the spray modelling for the multiple fuel injection needs to be improved.

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REFERENCES


Fig. 6 Transient change in spray angle (Defined on Fig. 5)

Fig. 7 Comparison in spray tip penetration (Multiple stage)
Fig. 2 Comparison in parcel spatial distribution with atomisation models (Single stage, t = 1.0 ms)

Fig. 3 Transient change in parcel spatial distribution
Fig. 5 Spray close to nozzle exit (Multiple stage injection, drum camera with Cu vapour laser)
; Injection pressure 135 MPa, pilot/dwell/main time duration are 0.2/1.0/0.8 ms respectively,
nozzle hole diameter is 0.162 mm, and every 40 μs spray photograph is shown, spray is injected
from top to bottom in the figures (magnified ratio 16 on 35-mm black & white negative film)