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A Numerical Study on the Spray-to-Spray Impingement System

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The present article aims to perform numerical calculations for inter-spray impingement of two diesel sprays under a high injection pressure and to propose a new hybrid model for droplet collision on the basis of literature findings. The hybrid model is compared with the original O'Rourke's model, which has been widely used for spray calculations. The main difference between the hybrid model and the O'Rourke's model is mainly in determination of the collision threshold condition, in which the preferred directional effect of droplets and a critical collision radius are included. The Wave model involving the cavitation effect inside a nozzle is used for predictions of atomization processes. Numerical results are reported for different impingement angles of 60° and 90° in order to show the influence of the impinging angle on spray characteristics and also compared with experimental data. It is found that the hybrid model shows slightly better agreement with experimental data than the O'Rourke's model.

Key Words : Inter-Spray Impingement, Wave Model, Atomization, Collision, Sauter Mean Diameter

Nomenclature

E_{boun}	: Probability of bouncing collision
E_{coal}	: Probability of coalescence collision
D	: Droplet diameter
$D_{1,2}$	: Distance between two parcels
L_{tip}	: Spray tip penetration length
N	: Number of collisions per time step
$N_{c,boun}$	: Cumulative number of bouncing collisions during a total time duration
$N_{c,coal}$	: Cumulative number of coalescence collisions during a total time duration
$N_{c,sep}$	: Cumulative number of separation collisions during a total time duration
N_c	: Cumulative number of collisions ($=N_{c,boun}+N_{c,coal}+N_{c,sep}$) during a total time duration
n	: Number of drops in a parcel
P_0	: Probability of no collision
P_n	: Poisson distribution
r	: Radius of drops
R_c	: Ratio of a total number of cumulative collisions to a total number of injected parcels
R_{crit}	: Critical radius of collision
S_z	: Distance from the nozzle tip to the impingement point
t	: Time
U	: Velocity of drops
We	: Weber number
X	: Location of droplet parcel
XX	: Random number
Z_t	: Distance from the impingement point to

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the spray tip
γ : Ratio of collector drop diameter to colliding drop diameter
ν : Collision frequency
$\forall$: Volume of computational cell

Subscripts

1 : Collector drop
2 : Colliding drop
boun : Grazing bounce regime
coal : Coalescence regime
sep : Separation regime

1. Introduction

It is well known that inter-spray impingement may be effective to enhance liquid atomization in many industrial applications such as furnace combustion and internal combustion engines and also can make clear the physics of coalescence and separation of colliding droplets in actual sprays. In particular, it may be applied to control the spatial distributions of a fuel spray in a direct injection (DI) engine for reduction of emissions. For understanding of the fundamental behavior of droplet collision, Orme (1997) reviewed droplet collisions, bounce, coalescence, and disruption to explain the difference in behavior between water droplet collisions and fuel droplet collisions and to present a unified explanation of the collision outcomes. Brenn et al. (1997) studied the effects of impact velocity, droplet size and collision parameter on collision phenomena of two equal propanol droplets. They showed that new drops may be produced either by merging of two colliding drops or by the breakup of liquid bridges formed between drops after non-central collisions. Meanwhile, some researchers have performed experimental works for spray-to-spray impingement from a practical point of view. Yuteri et al. (1993) investigated spray impingement using solid-cone atomizers and showed the influence of the intersection angle and air pressure on the droplets size. In addition, Arai and Saito (1999) and Chiba et al. (2000) performed the experiments using inter-spray impingement applied to the mixture formation process of a DI diesel engine as the first step towards controlling a diesel spray. Nevertheless, majority of previous works focused on the fundamental phenomena of droplet collisions and there have been still lacking in understanding of the atomization characteristics in spray impingement. In particular, numerical works for the present topic have been rarely carried out in spite of an outstanding advance of computer performance.

As a matter of fact, it is clear that there have been few efforts such as numerical modeling or calculations for better prediction of droplet collisions. As a pioneering work of numerical modeling, O'Rourke (1981) modeled the droplet collision between two droplet parcels using a statistical method. His model has been widely used in many commercial or in-house codes even to date. O'Rourke's model may be suitable for homogeneous two phase flows, where the void fraction is relatively constant and a large number of particles because this model uses the concept that the probability of two parcels colliding is a function of their swept volume relative to the cell volume. However, as referred by Nordin (2000), this approach is not suitable for the type of sprays where the variation in the void fraction is large even inside one cell, leading to a grid sensitive problem for predicting spray behaviors. Moreover, the O'Rourke model inherently fails to describe the spray behaviors effectively, in such case as a spray-to-spray impingement system where impinging droplets have a strong preferred direction. This may be due to the fact that there is no collision criterion for the directions of droplets in the O'Rourke model. As a revision of the O'Rourke's model for this problem, Gavaises (1997) has suggested a new critical collision distance, inside which the collision between droplets occurs in order to resolve grid dependency on the solutions. Meanwhile, Nordin (2000) proposed a new condition of the collision threshold in terms of the relative direction and velocity vector of colliding droplets and also made a new relationship for the collision probability in separated spatial and time spaces in different way from that of the O'Rourke's model. Actually, numerical studies for inter spray impingement phenomena are rare in spite of the applications to a variety of industrial fields. It is also difficult to find relevant experimental data for comparison with the relevant numerical models in literature. Hence, more elaborate experimental studies as well as developing a numerical model are important for better understanding of the atomization characteristics of colliding sprays. It is an aim of this study to perform numerical calculations for spray-to-spray impingement of two diesel sprays under a high injection pressure and also to suggest a new hybrid model for droplet collisions. The hybrid model for drop collision is devised on the basis of literature findings as a modification of the O'Rourke's model. Different angles of 60° and 90° between two impinging sprays axis are adopted for the present simulations and the predicted results are compared with the experimental data of Chiba et al. (2000).

2. Theoretical Models of Droplet Collision

2.1 O'Rourke model

In the O'Rourke model, binary collision of two droplet parcels is defined as a process in which all the droplets in the parcel with a larger diameter, called 'collector', undergo collisions with smaller droplets, called 'droplets', in the other parcel, satisfying the condition that the number of parcels after collision either remains the same or is reduced by one if the droplets are all absorbed by the collectors. This model is based on the following assumptions. First, a given parcel may collide with another parcel only if these two parcels lie in the same computational cell. Second, it is assumed that the droplets in each parcel are uniformly distributed throughout the computational cell in which they are located. Third, the binary collision dynamics of two parcels is not affected by the presence of the other parcels in the same computational cell. Under above assumptions, the collision frequency E_{12} has been introduced to account for the fact that the drops do not follow straight-line trajectories, but instead are deflected due to their interaction with the surrounding gas flow. The collision frequency of a collector drop with all droplets in the other parcel is given by:

$$\nu=\pi(r_1+r_2)^2|U_1-U_2|E_{12}N_2/\forall_{cou} \qquad (1)$$

To facilitate the description, subscripts 1 and 2 refer to the properties of collectors and droplets, respectively. The probability that a collector undergoes n collision with droplets during a time interval is assumed to follow a Poission distribution:

$$P_n=e^{-\bar{n}}(\bar{n}^{-\bar{n}}/n!) \qquad (2)$$

with mean value: $\bar{n}=v\delta t$ and the probability of no collision is $P_0=e^{-\bar{n}}$. To determine whether collision take place between collectors and droplets, a random number XX is chosen in the range of from 0 to 1. If $XX<P_0$, then no collision occurs. Consequently, the collision occurs if two conditions are satisfied simultaneously. One of which is the condition that two parcels lie in the same computational cell, and the other is that collision probability is greater than the probability of no collision. If collision occurs, five different types of collision regimes will be possible as referred in Bai (1996), but in the O'Rourke model, only three of them are accounted for. They are separation, permanent coalescence, and grazing bounce. The transition criterion from permanent coalescence to separation has been established by Brazier-Smith et al. (1972) as follows.

$$E_{coal}=\min\left[1, \frac{2.4f(\gamma)}{We_s}\right] \qquad (3)$$

where $f(\gamma)=\gamma^3-2.4\gamma^2+2.7\gamma$ and $\gamma=D_1/D_2$. If $XX<E_{coal}$, coalescence occurs, and separation occurs otherwise. Meanwhile, Brazier-Smith et al. (1972) observed grazing bouncing when equally -sized water drops collide at low relative velocity. They suggested a critical Weber number $We_{sc}(=2.12)$ below which grazing is only possible and a critical collision parameter E_{bounce}, above which grazing bouncing is only possible. In O'Rourke model, E_{bounce} is determined as follows.

$$E_{bounce}=\min\left[1, \left(\frac{We_s}{2.4f(\gamma)}\right)^{1/3}\right] \qquad (4)$$

Thus grazing bounce collision occurs if $We_{sc}<2.12$ and $XX>E_{bounce}$. For more details, good summary for each regime are well documented in Bai (1996).

2.2 A hybrid model

According to Gavaises (1997), the first assumption of the O'Rourke's model referred above is a bit dubious because collision between two spatially very close parcels which reside in different computational cells is a priori excluded, in contrast to a pair of possibly far distant parcels in the same computational cell. Under this assumption, the collision model is strongly dependent on the computational mesh used. From another point of view, Nordin (2000) indicated that the O'Rourke's approach is not suitable for sprays, where the variation in void fraction is large, even inside a single cell, and the parcels have a 'preferred direction'. Consequently, as well as the grid dependency problem, an inherent problem that the model can not describe a preferred directional effect of sprays may occur, especially for the spray-to-spray impingement system in the present study. To resolve grid dependency problem, Gavaises (1997) assumed that two parcels may collide if their distance is smaller than a critical value in terms of the number of droplets in both parcels and determined this value simply as an algebraic sum for two parcels. In addition, Nordin (2000) suggested a new model for drop collisions by considering the directional effect of droplets.

On the basis of the previous literature findings, a new hybrid model for droplet collision is introduced in the present work by modifying the original O'Rourke's model for better prediction of the inter-spray impingement phenomena. The critical radius, R_{crit}, instead of the first assumption of the O'Rourke model referred above, is newly proposed to determine whether collisions occur or not. In the hybrid model, it is assumed that the collision occurs only when the distance between two parcels is smaller than a critical radius.

$$D_{1,2} \leq R_{crit} = \frac{2(r_1N_1 + r_2N_2)}{N_1N_2} \tag{5}$$

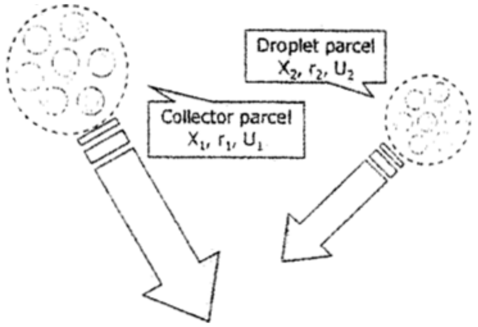


Fig. 1 Two parcels traveling towards each other

$$D_{1,2} = \sqrt{(x_1-x_2)^2 + (y_1-y_2)^2 + (z_1-z_2)^2} \tag{6}$$

As indicated previously, the droplet parcels may be of such a preferred direction, especially in a spray-to-spray impingement system. Once the above conditions are met, the directional effect of two parcels should be considered because two directions of the parcels may affect the collision probability. From Fig. 1, the second condition can be deduced, in order for two parcels to collide, they have to travel towards each other, or $U_{12} > 0$, where

$$U_{12} = (U_1 - U_2)\frac{X_2 - X_1}{|X_2 - X_1|} \tag{7}$$

The following third condition indicates that the parcels' relative displacement must be larger than the distance between them.

$$U_{12}\Delta t > |X_2 - X_1 - (r_1 + r_2)| \tag{8}$$

Therefore, if the three conditions in the above are satisfied simultaneously, a collision occurs. Our main concern in the hybrid model is mainly focused on proposition of more appropriate conditions for the collision threshold. In other words, the only difference between the O'Rourke's model and the present model is in determination of the collision criteria. Thus, the hybrid model is basically of three different regimes, which are identical to those of the O'Rourke's model. In addition, several transition criteria among these regimes as well as post-collision properties i.e. drop mass, momentum and energy are determined through the same ways as the O'Rourke's model.

3. Numerical Method

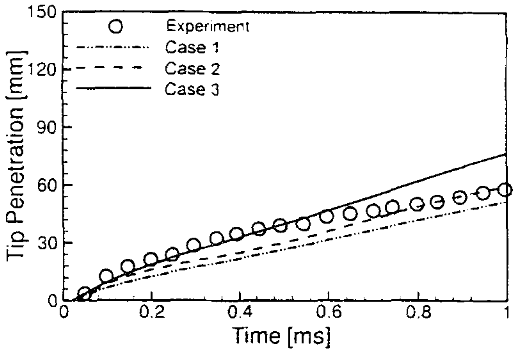
The gas phase equations are derived in terms of Eulerian conservation equations, and turbulent transport is modeled by the modified k-ε model of Reynolds (1980). To couple gas-phase velocity and pressure field, the implicit and non-iterative PISO algorithm is used in the present study. The gas-phase transport equations are discretized by a finite volume method. With this process, the Euler implicit method is used for the transient term, and a hybrid upwind/central difference scheme is used to approximate the convection and diffusion terms. The droplet parcel equations of trajectory, momentum, mass and energy are written in the Lagrangian form. Ordinary differential Lagrangian equations for droplets are also discretized in the Euler implicit manner. Particle-eddy interactions are considered in this work using the model from Gosman and Ioannides (1983). Liquid atomization and droplet breakup processes are simulated by the Wave model (Reitz, 1987), with the breakup time constant B_1 of 10. The model of Sarre et al. (1999) was used for cavitation in the nozzle. For more details of the computational methods, see Lee and Ryou (2000).

4. Results and Discussions

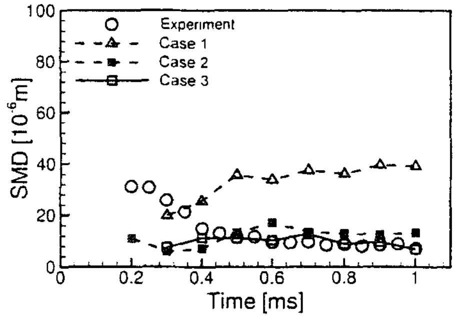
4.1 The non-evaporating free spray simulation

Table 1 Test cases for the preliminary test

TEST CASE	Atomization Model	Reference
1	R&D model	Reitz and Diwakar (1986)
2	Wave model	Reitz (1987)
3	Combined model	Reitz (1987), Sarre et al. (1999)



(a) Tip penetration



(b) SMD at 20 mm downstream from nozzle exit

Fig. 2 Comparisons of the predicted tip penetration and SMD with experimental data (Allocca et al., 1992) for single free spray

Before performing main simulation for the inter-spray impingement system, it is necessary to carry out a preliminary test to validate the present code and also to select an appropriate atomization model among earlier published models. Thus, non-evaporative free sprays through a single nozzle are simulated and the results are compared with the experiment data of Allocca et al. (1992) for tip penetration length and Sauter mean diameter (SMD). The fuel is tetradecane which is injected with the maximum injection pressure of 98MPa from the nozzle with the orifice diameter, d_{nozzle}, of 0.2 mm into a constant-volume chamber filled with nitrogen at 300 K and pressure P_g of 1.7 MPa. As seen in Table 1, there are three different test cases to choose the most appropriate model among earlier published models, i.e. Reitz and Diwakar's model, the Wave model of Reitz (1987) and finally the combined model. The third model is based on the original Wave model, but devised to mimic cavitation phenomena occurring inside the nozzle. In addition, the combined model describes the cavitation phenomena with several algebraic relationships suggested by Sarre et al. (1999). Figure 2 shows the calculated tip penetration and

SMD distributions at 20 mm downstream from the nozzle exit. In the case 3, good agreement is shown between the calculated results and the experimental data for the tip penetration length at an early stage of injection, but slightly overpredicted after $t=0.6$ ms. However, cases 1 and 2 show underestimated tip penetrations during injection. For SMD distributions, both cases 2 and 3 are in better agreement with experimental data than case 1. When the cavitation effect is considered, it can be seen that the tip penetration length increases and consequently the SMD decreases, compared with the results of case 2. This is because the cavitation model effectively considers the increasing injection velocity and the corresponding decrease of the effective nozzle diameter, resulting from cavitation effects inside the nozzle for high-pressure injection. As a result, it is concluded that case 3 with the combined model yields the best predictions among the three models in the present work. Thus, only the combined model is used to calculate liquid atomization and secondary drop breakup processes for spray-to-spray impingement, as will be discussed in the following.

4.2 Spray-to-spray impingement simulation

Numerical simulations for the spray-to-spray impingement are performed using the new droplet collision model. Test cases are selected from the Chiba et al. (2000)'s experiment. Light oil is used as a fuel. The fuel is injected from two single-hole nozzles into the high-pressure vessel filled with nitrogen gas. The diameter of the nozzles is 0.25 mm and the pressure in the vessel is kept constant at 1.0 MPa. The injection pressure of fuel spray is 19.6 MPa. Impingement angles of 90° and 60° are achieved by the impingement of these sprays. As shown in Fig. 3, the computation domain for all cases consists of $52\times52\times52$ (x, y and z respectively) grids, determined from the grid independent test. A time step 20 μs is adopted and a total of 3000 droplet parcels is introduced through injection duration time. The predicted results using the new collision model are compared with experimental data and the computational results using the original O'Rourke (1981) model. The main parameters such as spray shape, tip penetration length and SMD are analyzed.

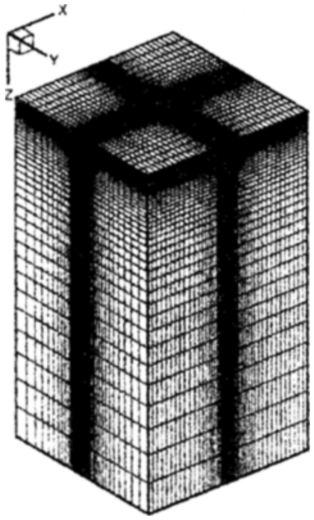
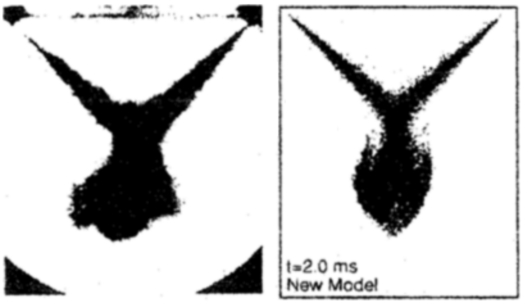


Fig. 3 Computational grid system

Figure 4 compares the spray patterns for the case of impingement angle of 90° at $t=2.0$ ms after injection start. As seen in the figure, the new swelled spray is formed by the impingement and the atomization of spray is increased at downstream of the impingement point. The new model shows the good agreement compared with the experimental photograph for the overall spray shape. In particular, the increase of spray width after the impingement point is well predicted, suggesting that the new model can predict the droplets collision effectively. On the other hand, the O'Rourke (1981) model significantly underpredicts the spray width. These may be due to the difference of collision frequencies between two collision models, as will be discussed below. Figure 5 shows the spray patterns for the case of impingement angle of 60° at $t=2.0$ ms after injection start. Contrary to the case of 90°, the two sprays merge with each other smoothly and also the spray width does not become wider after impingement. According to Chiba et al. (2000), possible explanations are as follows. The intense turbulence near the impingement position may result in the generation of larger volume of



(a) Experiment (b) New model

(c) O'Rourke model Figure

Fig. 4 Comparison of the predicted spray shape with the experiment (Chiba et al., 2000) for the case of impingement angle of 90°

sprays. As impingement angle increases, high turbulence intensity and larger eddy structures may occur and consequently give rise to a large amount of air entrainment. Therefore, it can be seen that the behaviors of the impingement spray are highly affected by the impingement angles.

Meanwhile, some parameters are newly introduced in the present work for better analysis of inter-spray impingement system. Since both new model and O'Rourke's model consider three different collision regimes, i.e. , coalescence, bounce and separation, we should define three different collision ratios for each regime as listed in Table 2. A total collision ratio is also a sum of three collision ratios as follows.

$$
\begin{aligned}
R_c &= \frac{N_c}{N_{total}} = \frac{N_{c,coal} + N_{c,boun} + N_{c,sep}}{N_{total}} \\
&= R_{c,coal} + R_{c,boun} + R_{c,sep} \qquad (9)
\end{aligned}
$$

Table 2 Definitions of the collision numbers for three different collision regimes

Collision Regime	Collision Ratio	Definition
Bounce	$R_{c,boun}$	$N_{c,boun}/N_{total}$
Coalescence	$R_{c,coal}$	$N_{c,coal}/N_{total}$
Separation	$R_{c,sep}$	$N_{c,sep}/N_{total}$

(a) Experiment

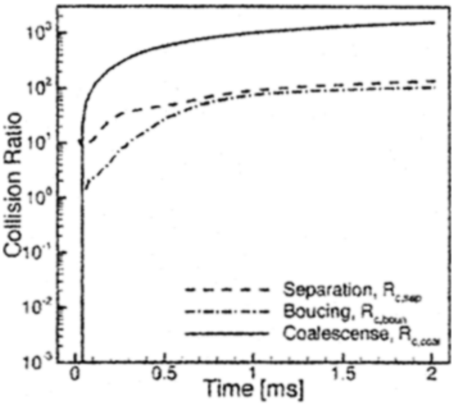
(b) New model

(c) O'Rourke model

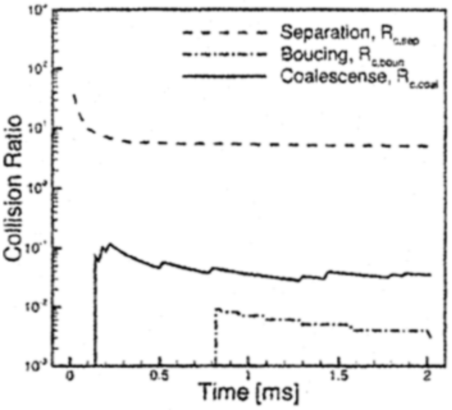
Fig. 5 Comparison of the predicted spray shape with the experiment (Chiba et al., 2000) for the case of impingement angle of 60°

So called the collision ratio means the ratio of the cumulative collision number for a collision regime to the total number of introduced parcel from injectors N_{total}. Figure 6 shows the variation of three different collision ratios, i.e., $R_{c,coal}$, $R_{c,boun}$ and $R_{c,sep}$, in coalescence, bounce and separation regimes respectively, with time since injection starts for both models in the case of 90 °. The collision ratios of O'Rourke's model are much larger than those of the new model, suggesting much higher frequency of collisions. This occurs due to the fact that there is an equal probability for collision in O'Rourke's model, regardless of whether the parcels are moving towards or away from each other. In particular, O' Rourke's model predictions show that the coalescence brings out more frequently than do other regimes. It can be expected from these results that much larger droplet size can be produced by coalescence process. Unlike the O' Rourke model, it is found from Fig. 6(b) that the separation collision is the most dominant process among three collision regimes in the new model. In fact, it is well-known fact that the separation is very important and dominant process in the spray-to-spray impinging phenomena under the condition of high injection pressure, as referred by Arai and Saito (1999). As injection pressure increases, injected droplets being of high momentum collide each other more strongly and thus the probability for separation collision between two droplets is higher than that of coalescence or grazing bounce. A total collision ratio R_c defined above is shown in Fig. 7 where there is much smaller collision frequency in the new model than that of the O'Rourke model as discussed previously. Decreasing frequency of collision results from the directional effect of droplets considering in the new model and thus indicates the decrease of momentum loss corresponding to the increase of the droplet breakup process. These are why the new model shows the wider spray shape than the O'Rourke model as seen in Fig. 4. From these results, it may be concluded that the O'Rourke model over-predicts the occurrence of the droplet collision and it cannot predict spray-to-spray impingement system effectively where the droplet parcels are of such a preferred direction. As seen in Fig. 7, there are little differences between two different angles of 60° and 90° suggesting that there is little dependence of impingement angles on the droplet collision frequencies.

Definitions of the spray tip penetration for the inter-spray impingement is shown Fig. 8. S_z is the distance from the nozzle tip to the impingement point and Z_t is the distance from the impingement point to the spray tip. The sum of



(a) O'Rourke model



(b) New model

Fig. 6 Comparison of three different collision ratios for O'Rourke and new models in the case of 90°

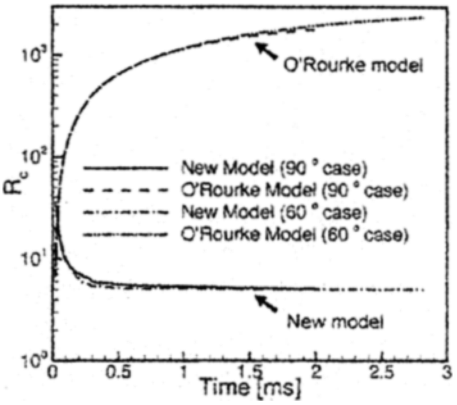


Fig. 7 The ratio of the cumulative collision number to the total number of injected parcels

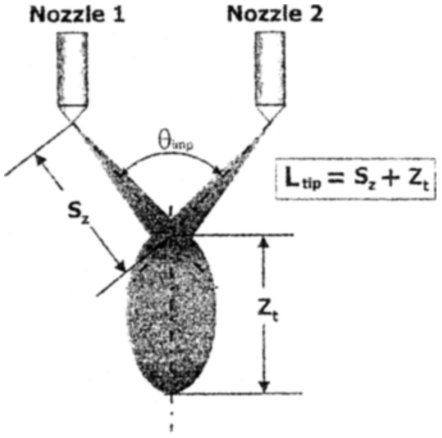


Fig. 8 Schematic diagram of impingement spray

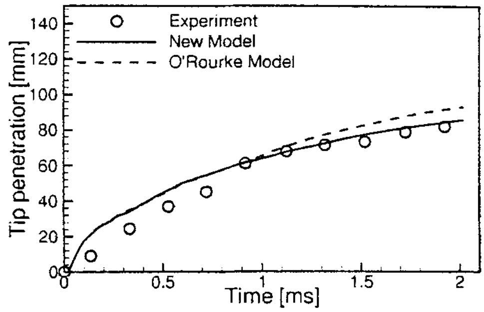


Fig. 9 Comparison of the predicted tip penetration length with experimental data (Chiba et al., 2000) for the case of impingement angle of 90°

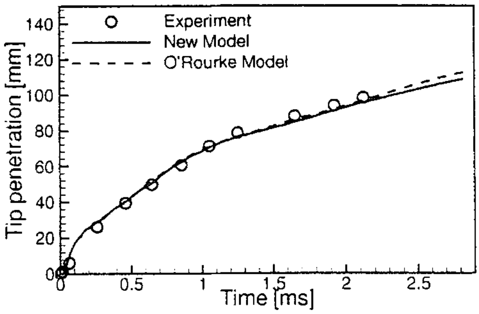
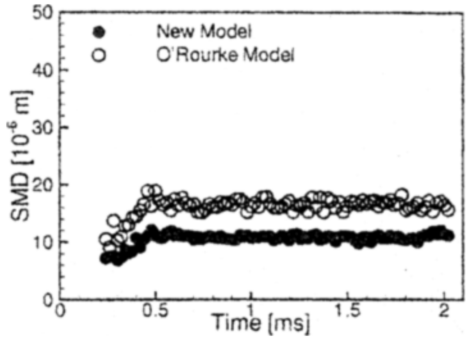
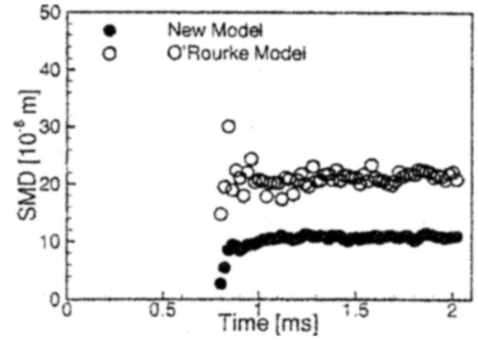


Fig. 10 Comparison of the predicted tip penetration length with experimental data (Chiba et al., 2000) for the case of impingement angle of 60°



(a) Before impingement at 20 mm downstream from nozzle exit

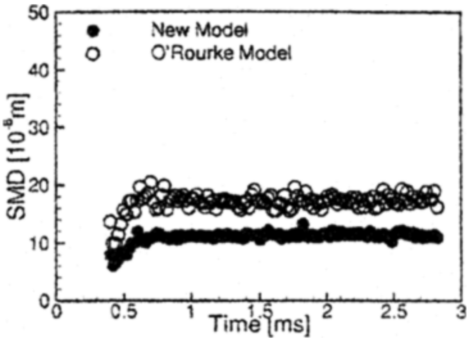


(b) After impingement at 40 mm downstream from nozzle exit

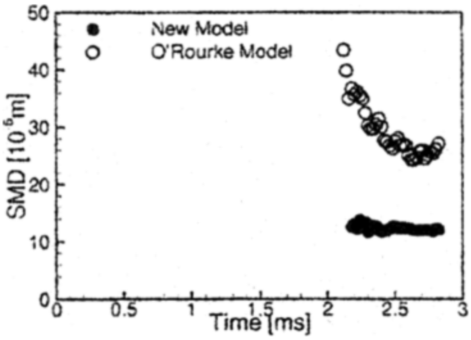
Fig. 11 Comparison of the predicted local SMD between the new model and O'Rourke model for the case of impingement angle of 90°

these two scalars $S_z + Z_t$ is defined as the spray tip penetration length L_{tip} of the impingement spray. Figures 9 and 10 show the comparison between the predicted tip penetrations and experimental data for the cases of impingement angles of 90° and 60°, respectively. As seen in these figures, the tip penetration of the case of 90° is smaller than the case of 60°. This is because the momentum loss due to the impingement increases with increasing impingement angles. Both the new model and the O'Rourke model show good agreements with experimental data, although the calculated tip penetration by the O'Rourke model slightly over-predicts the tip penetration length at the later stage of duration time. This is attributed to the fact that the tip penetration rarely depends on frequencies of collision occurrence because it is determined by the location of droplets impinged at the earliest stage.

Figures 11 and 12 present the local SMD distributions for the cases of impingement angles



(a) Before impingement at 40 mm downstream from nozzle exit



(b) After impingement at 80 mm downstream from nozzle exit

Fig. 12 Comparison of the predicted local SMD between the new model and O'Rourke model for the case of impingement angle of 60°

of 90° and 60°, respectively. Only the predicted results are presented because unfortunately relevant experimental data cannot be found in the reference of Chiba et al. (2000). Compared with the tip penetration results, it is seen that there are considerable differences in SMD predictions between the new hybrid model and the O'Rourke model. This indicates that it is very important to determine an appropriate collision model for better predictions of SMD rather than tip penetration length. These differences already occur before impingement of two sprays and become larger after impingement. These differences are associated with different collision frequencies between two collision models as previously mentioned in Figs. 6 and 7. That is, the increase of the collision frequency promotes the droplet coalescence and consequently the sizes of droplets also increases gradually. Meanwhile, another fact we should note is as follows. The main purpose of inter-spray impingement method is to yield better atomization which consequently produces the decrease of SMD due to impingement. However, it can be seen from Fig. 12(b) that the predicted SMDs significantly increase in case of the O'Rouke's model, especially near $t=2.0$ ms, because O'Rourke' model overpredicts the coalescence process, followed by the fact that increasing droplet size after impingement. This result is somewhat odd and incompatible with the practical aim of inter-spray impingement system. Unlike this, the present model shows better atomization relative to O'Rourke's model, showing the collision model can play an important role in predicting droplet sizes in the present type of spray system.

5. Conclusions

Numerical simulations for spray-to-spray impingement of two diesel sprays under high injection pressures are performed for two different impinging angles of 60° and 90°. A new hybrid model for droplet collision is suggested on the basis of literature findings as a modification of the O'Rourke model.

In case of 90°, it is seen that two impinging sprays form a new swelled spray and atomization increases downstream from the impingement point. In case of 60°, the two sprays merge smoothly and the spray width does not increase after impingement. The predicted results by the new model show better agreement with experimental data than those of the O'Rourke model for both overall spray shape and tip penetration length. This may be because the new model predicts a much lower collision frequency than the O'Rourke's model. This difference of the collision frequency also seems to significantly affect the predictions of local SMDs. It is concluded from these results that the new hybrid model for drop collision is better for simulation of spray-to-spray impingement than the O'Rourke's model. It should be noted, however, that more elaborate studies for validation and modification of the new model are required in order to obtain more accurate predictions.

References

Allocca, L., Belardini, P., Bertoli, C., Corcione, F. E. and De Angelis, F., 1992, *Experimental and numerical analysis of a diesel spray*, Society of Automotive Engineers Paper 920576.

Arai, M. and Saito, M., 1999, *Atomization Characteristics of Jet-to-Jet and Spray-to-Spray Impingement Systems*, Atomization and Sprays, Vol. 9, pp. 399～417.

Bai, C., 1996, *Modeling of Spray Impingement Processes*, Ph. D. Thesis, Imperial College of Science and Technology and Medicine, Department of Mechanical Engineering, University of London.

Brazier-Smith, P. R., Jennigs, S. G. and Latham, J., 1972, *The Interaction of Falling Water Drops: Coalescence*, Proceedings of Royal Society of London A., Vol. 326, pp. 393～408.

Brenn, G., Kalenderski, St. and Ivanov, I., 1997, *Investigation of the Stochastic Collisions of Drops Produced by Rayleigh Breakup of Two Laminar Liquid Jets*, Physics of Fluids, Vol. 9, pp. 349～364.

Chiba, T., Saito, M., Amagai, K. and Arai, M., 2000, *Inter-Spray Impingement of Two Diesel Sprays*, ICLASS2000, CA, USA, July.

Gavaises, M., 1997, *Modeling of Diesel Fuel Injection Processes*, Ph. D. Thesis, Imperial College of Science and Technology and Medicine, Department of Mechanical Engineering, University of London.

Gosman, A. D. and Ioannides, E., 1983, *Aspects of Computer Simulation of Liquid-Fuelled Combustors*, Energy, Vol. 7, No. 6, pp. 482～490.

Lee, S. H. and Ryou, H. S., 2000, *Comparison of Spray/Wall Impingement Models with Experimental Data, J. of Propulsion and Power*, Vol. 16, No. 6, pp. 939～945.

Nordin, N., 2000, *Complex Chemistry Modeling of Diesel Spray Combustion*, Ph. D. Thesis, Chalmers University of Technology, Sweden.

O'Rourke, P. J., 1981, *Collective Drop Effects on Vaporizing Liquid Sprays*, Ph. D. Thesis, Mechanical and Aerospace Engineering, Princeton University, USA.

Orme, M., 1997, *Experiments on Droplet Collisions, Bounce, Coalescence and Dispersion*, Prog. Energy Combustion Sci. , Vol. 23, pp. 65～79.

Reitz, R. D. and Diwakar, R., 1986, *Effect of Drop Breakup on Fuel Sprays*, Society of Automotive Engineers Paper 860469.

Reitz, R. D., 1987, *Modelling Atomization Process in High Pressure Vaporizing Sprays*, Atomization and Spray Technology, pp. 309～337.

Reynolds, W. C., 1980, *Modeling of Fluid Motions in Engines and Introductory Overview, in Combustion Modeling in Reciprocating Engines*, Ed. J. N. Mattavi and C. A. Amann Plenum Press, NY.

Sarre, C. K., Kong, S. -C. and Reitz, R. D., 1999, *Modeling the Effects of Injector Nozzle Geometry on Diesel Sprays*, Society of Automotive Engineers Paper 1999-01-0912.

Yurteri, C. U., Kadambi, J. R. and Arik, E., 1993, *Spray Characterization and Droplet Interactions Study Using Particle Dynamic Analyzer*, Proceedings of 5th Int. Conf. On Laser Anemometry, Advances and Applications, pp. 145～152.