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A NUMERICAL SIMULATION ON FUEL SPRAY INTERACTIONS OF TRASIENT JETS IN A MARINE DIESEL ENGINE

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ABSTRACT

The objective of this work was to investigate the behaviour of spray interactions taking place in a marine diesel engine. The spray in a diesel engine was known to be an important parameter that affects the mixing of the fuel jets, heat release, emissions, and overall engine performance. The correlation of interaction between sprays depends on the parameters of fuel injection and ambient conditions such as, angle of sprays, swirl, pressure, etc. In this work, we explored the interactive effects of droplet size, velocity, SMD, evaporation rate, mass fraction of spray with several variables using a computational analysis. The results showed that a mixing rate between fuel spray and air is significantly affected as spray angles changed, while evaporation rate and diameter of droplet were so. To facilitate the development of the multi-hole injector, it is essential to obtain a relation between spray angle and the spray behaviour, which also could depend on swirl ratio. As the swirl ratio increased, the mixing rate of spray and air was effectively improved. But excessive swirl might have adverse effect on fuel vapour development since distorted shape of spray was formed to prevent spray from collision which otherwise promoted the evaporation rate in a typical manner.

INTRODUCTION

The spray characteristics and mixing of diesel fuel injected and ambient condition in a direct injection diesel engine had a predominant effect on the mixture formation, self-ignition, combustion, and emissions emitted from an engine cylinder. Hence it was important to understand how parameters such as angle of spray, ambient pressure, swirl could interact with mixing and combustion processes. Understanding these interactions was important in the context of optimizing diesel engine performance to maximize thermal efficiency and meet stringent regulations on toxic pollutants.

The key physical processes in a liquid-fuel spray were illustrated in Fig. 1. Adequate numerical model of the dynamics of the spray within internal combustion (IC) engines must include the spray behaviour at the injector tip, primary and secondary atomization, and droplet collision and coalescence, followed by further interaction of spray with ambient environment (drag and vaporization) and combustion chamber surfaces [1]

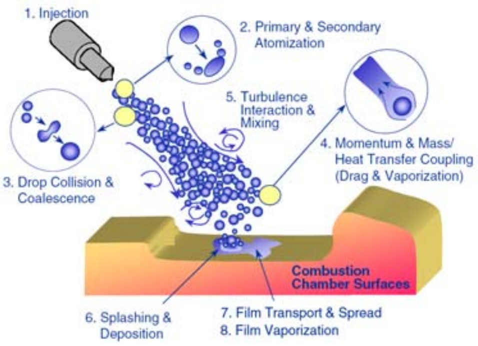

Fig. 1 Spray dynamics occurred within IC engines [1]

The observation of the spray indicated that the spray could be divided into four regions: the leading edge, the cone, the trailing edge, and the vortex cloud. These four regions were sketched in Fig 2. The leading edge region consisted of droplets formed during the beginning of fuel injection pulse. When an injector valve began to open, a liquid velocity reached a steady value. The cone region was produced during the period of steady liquid velocity. The swirl of the liquid and the design of the nozzle caused the droplets to form the shape of a hollow cone. The trailing edge region of the spray was typically produced at the time when the pintle closes. The vortex cloud region was formed by the circulating air carrying droplets from the spray. As the injection pulse ended, the vortex cloud continued to grow. This kinds of dividing regions was very useful to understand about behaviour of spray when the spray observation was made.

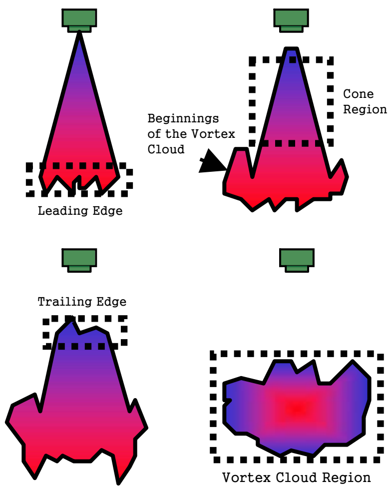

Fig. 2 Four regions of single spray [2]

The interaction between two adjacent sprays was extremely affected by angle of sprays and swirl. Nowadays, multi-hole injector had been used to reduce particulate emissions [3, 4, 5, 6]. Abraham et. al. [7] showed interactions between the jets in a multi-hole injector and between the jet and the wall may affect the fuel-air mixing processes in a direct injection diesel engine. The research on angle of spray was necessary to explore the effect of spray interaction in multi-hole injector. The effects of swirl were explored to determine how mixing, combustion, and emissions were influenced. McCracken et. al. explored effects of swirl on fuel vapour development within a single spray [8]. Mehta and Tamma have reported effects of swirl and injection conditions on combustion processes with multi-zone, quasi-steady, axisymmetric gas jet model [9]. Fuchs and Rutland employed KIVA-Ⅱ and KIVA-3 multi-dimensional CFD codes with modifications to the sub-models in a 360° grid [10]. The results showed that swirl could enhance early mixing while too high swirl ratio might deteriorate mixing in the later stage of the combustion process.

In this work, interaction of spray was investigated using 3-dimensional models when two sprays were injected into real gas conditions of a marine diesel engine. The injected sprays in cylinder was affected by surrounding conditions such as spray angle, swirl and so on. The two parameters were very important factors in interactions when two sprays injected. Finally, an interaction mechanism of between sprays and between spray and wall was proposed.

THE COMPUTATIONAL MODEL

The Star-CD engine model [11] was a computational fluid dynamics code which is capable of modelling multi-phase reacting flow. While high Reynolds Number k-ε model was used for turbulence model, it was also important to implement a proper droplet model.

Droplet break-up model

The droplets (and bubbles) break-up model used in this study was the model of Reitz and Diwakar. According to this model[12,13], droplet break-up due to aerodynamic forces occurs in one of the following modes:

① "Bag break-up", in which the non-uniform pressure field around the droplet causes it to expand in the low-pressure wake region and eventually disintegrate when surface tension forces are overcome.
② "Stripping break-up", a process in which liquid is sheared or stripped from the droplet surface.

In each case, theoretical studies have provided a criterion for the onset of break-up and concurrently an estimate of the stable droplet diameter, $D_{d,stable}$, and the characteristic time scale τ_b of the break-up process. This allows the break-up rate to be calculated from:

$$\frac{dD_d}{dt} = -\frac{(D_d - D_{d,stable})}{\tau_b} \tag{1}$$

Where, D_d is the instantaneous droplet diameter. The criteria and time scales are as follows:

Bag break-up

Here, instability is determined by a critical value of the Weber number, W_e, thus:

$$W_e \equiv \frac{\rho\left|\vec{u} - \vec{u}_d\right|^2 D_d}{2\sigma_d} \geq C_{b1} \tag{2}$$

Where, σ_d is the surface tension coefficient, and C_{b1} is an empirical coefficient having a value in the range 3.6 to 8.4. In this study C_{b1}=6. The stable droplet size is that which satisfies the equality in the above equation.

The associated characteristic time is:

$$\tau_b = \frac{C_{b2}\rho_d^{1/2} D_d^{3/2}}{4\sigma_d^{1/2}} \tag{3}$$

In which $C_{b2} \approx \pi$.

Stripping break-up

The criterion for the onset of this regime is:

$$\frac{We}{\sqrt{\mathrm{Re}_d}} \geq C_{s1} \tag{4}$$

Where Re_d is the droplet Reynolds number and $C_{s2}$is a coefficient with the value 0.5.

The characteristic time scale for this region is:

$$\tau_d = \frac{C_{s2}}{2}\left(\frac{\rho_d}{\rho}\right)^{1/2} \frac{D_d}{\left|u - u_d\right|} \tag{5}$$

Here, the empirical coefficient C_{s2} id in the range 2 to 20. In this study C_{s2}=20.

Droplet collision model

The model for droplet-droplet collisions follows that of O'Rourke[14, 15, 16]. It distinguishes the following three types of interaction:

(1) Coalescence
(2) Separation
(3) Bouncing

During these processes, droplets from the participating parcels could exchange mass, momentum and energy. A statistical, rather than a deterministic approach is used to avoid creating an excessive number of new parcels. In fact, the number of parcels remains constant, unless the smaller-diameter droplets are all absorbed by coalescence, in which case the total number of active parcels is reduced by removal of the small droplets. Once the type of collision has been resolved, then all the droplets in the parcel with the larger diameter (called the collector) undergo collisions with the droplets from the parcels with smaller diameter (donors). For each pair of parcels, collisions only occur if they lie in the same computational cell.

The droplets are considered to be uniformly distributed throughout the cell, so that the collision frequency, ν, of a collector droplet with all droplets in the other parcel is given by:

$$\nu = \frac{\pi}{4}\left(D_{d,1} + D_{d,2}\right)^2 \left|u_{d,1} - u_{d,2}\right| E_{1,2} \frac{N_{d,2}}{\delta v} \tag{6}$$

Here the subscripts 1 and 2 refer to the collector and donor parcels, respectively, $N_{d,2}$ is the number of droplets in the second parcel, and δV id the cell volume.

The collision efficiency, $E_{1,2}$, is evaluated from:

$$E_{1,2} = \left(1 + \frac{0.75\ln(2W)}{W - 1.214}\right)^{-2}; W > 1.214 \tag{7}$$

Otherwise $E_{1,2} = 0$. In this equation, W is a dimensionless parameter given by:

$$W = \frac{\rho_{d,2}\left|u_{d,1} - u_{d,2}\right| D_{d,2}^2}{9\mu D_{d,1}} \tag{8}$$

The probability that the collector undergoes n collisions with droplets from a donor parcel during the time angle δt is taken to follow a Poisson distribution, with the mean value $n' = \nu\delta t$, i.e

$$P_n = \frac{(n')^n}{n!} e^{-n'} \tag{9}$$

The case $n' = 0$ gives probability of no collisions, $P_0 = e^{-n'}$. To determine whether collision take place between individual droplets, a random number $N_{r,1}$ is chosen in the angle (0-1). If $N_{r,1} < P_0$, no collision occurs.

If a collision occurs, the probability that outcome is coalescence of the droplets id given by:

$$E_{coal} = \min\left[\frac{2.4f(\gamma)}{We_L}, 1\right] \tag{10}$$

Where $f(\gamma) = \gamma^3 - 2.4\gamma^2 + 2.7\gamma$, $\gamma = D_{d,1} / D_{d,2}$, and We_L is the droplet Weber number defined as:

$$We_L = \frac{\rho_d \left|u_{d,1} - u_{d,2}\right|^2 D_{d,2}}{2\sigma} \tag{11}$$

To determine whether an individual collision results in coalescence or separation, a second random number $N_{r,2}$ is chosen. If $N_{r,2} < E_{coal}$, coalescence occurs and the number of droplets m which take part in the coalescence with each collector droplet is:

$$\sum_{i=0}^{i=m-1} \frac{P_i}{P_o} < \frac{N_{r,1}}{P_o} < \sum_{i=o}^{i=m} \frac{P_i}{P_o} \tag{12}$$

Thus, the new number of droplets in the donor parcel is $N^2_{d,2} = N_{d,2} - mN_{d,1}$. The properties of the collector droplets are recomputed so that mass, momentum and energy are conserved. In the case when the condition $N_{r,2} < E_{coal}$ and the additional requirement $We_L < We_{bou}$ are satisfied, another type of collision called "bouncing" occurs, where We_{bou} is obtained from:

Table 1 Computational models

Computational code	Star-CD
Turbulent model	High Reynolds Number k-εmodel
Break-up model	Reitz-Diwakar model
Atomization model	Hur model
Collision and coalescence	O'Rourke model

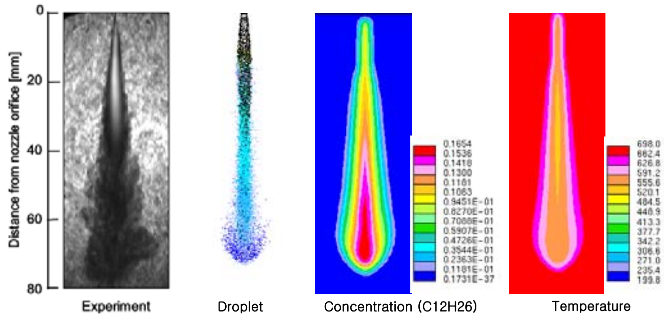

Fig. 3 The comparison of evaporative diesel spray between experiment and simulation

$$We_{bou} = 2.4f(\gamma)N_{r,2}^3 \tag{13}$$

When separation or bouncing occurs, only momentum is exchanged (and conserved overall).

It should be noted that there is a time scale associated with collision, namely the collision time. Ideally the computational time step $\triangle t$ should be smaller than the collision time. However, with the statistical approach employed here, this limit may be exceeded without the accuracy of the results being compromised, as long as only a few collisions are so affected.

COMPUTATIONAL VALIDATION

The experimental results available in Myong et al.[17] were used to validate the computational results of evaporative diesel spray. As shown in Fig. 3, liquid and vapour phase of evaporative diesel spray was photographed using Mie scattering and Shadowgraph method, respectively.

COMPUTATIONAL SETUP

A numerical simulation were conducted using marine diesel engine condition. Fig. 4 showed combustion chamber geometry at TDC used in this computation where the angle of sector is 60° and the number of cells are 210,000. The main parameters to be varied were angle of spray and swirl. The values for the temperature and pressure at the start of computation were determined by running a 0-dimensional code up to 20°BTDC and computations was done in a 60° sector. Normal dodecane($C_{12}H_{26}$) was selected as fuel because its properties are similar to those of marine diesel fuel. The conditions of angle depends on condition of multi-hole injector. Several swirl ratios were employed in the engine. The swirl ratio was defined by the angular velocity of gases in the cylinder over the angular velocity of the engine. These swirl ratios was changed from 0 to 5.0 (No-swirl, 1.5, 3, 5).

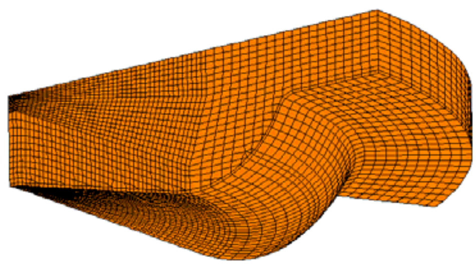

Fig. 4 60 degree sector mesh at TDC

RESULTS AND DISCUSSION

The influence of angle between spray to spray

The spray characteristics were influenced by angle between spray to spray, whether the angle was closer or farther each other. The important factors in the spray include droplet size, distribution of fuel concentration, evaporation rate and so on.

Fig. 5 showed a variation of the distribution of fuel concentration as spray angle changed. When the angle was 24 degree, two sprays looked interfered, for the angle of spray was smaller than cone angle of spray from nozzle tip. It is apparent that even liquid part of yellow colour was influenced at this the spray angle condition. The interaction of two sprays decreased as the angle became large. For example, when the angle was 30 degree, mixing of spray and air could be explored only in the vapour phase. NO interaction occurred between the sprays after angle reached 36 degree.

Fig. 6 showed to two regions at the sector to marked as yellow line in the plane where velocity and concentration of fuel would be examined in the azimuthal direction.

Fig. 7 described the velocity and concentration of fuel according to yellow line in the Region 1. The position have taken place the injection of spray explored that the velocity and fuel concentration were larger than spray surrounding. As the angle of spray increased, the region of velocity and concentration were moved to both sides, the 24 degree region mixed two sprays explored that the velocity and concentration were very big in the middle of sprays. The velocity of spray increased by about 100 m/s, for Region 1 was very close from nozzle tip where the spray injected.

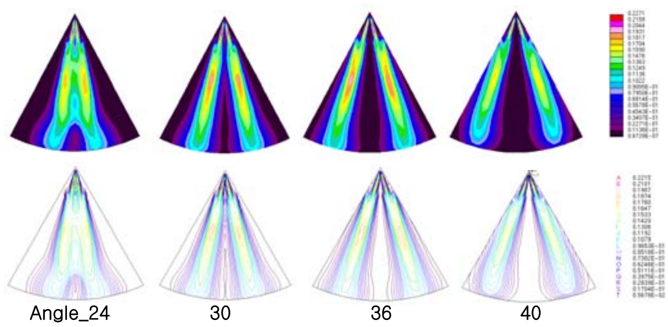

Fig. 5 The distribution of fuel concentration as a function of spray angle

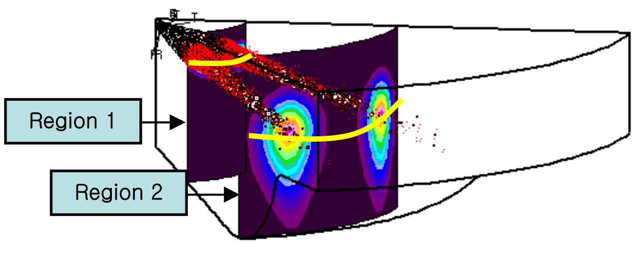

Fig. 6 Vertical position of Region 1, 2 at the cylinder

Fig. 8 described the velocity and concentration of fuel according to yellow line in the Region 2. The velocity and concentration were kind of low and the region of spray was broader in comparison with Region 1, for this region have progressed to some extent after the spray injected. When the angle was 24 degree, the spray was kept affecting according to interaction of sprays, when the angle was 30 degree, the interaction of spray was decreasing as the angle of spray was farther.

Fig. 9 showed the variation of total mass of liquid phase and evaporated mass as angle of sprays changed. In general, the mass of spray liquid increased rapidly when the spray was injected. Around BTDC 3 degree, the mass of liquid phase got decreased for the droplet was evaporated due to ambient condition driven from high pressure and temperature in the combustion cylinder. It was observed that the mass of liquid phase increased around ATDC 5 degree due to coalescence after which the liquid was collided with bowl of piston. Afterward, the mass of liquid rapidly decreased due to evaporation.

It appears that the mass of liquid injected with the angle of 40 degree was decreased faster than with the angle 24 degree, duo to increased evaporation driven from larger space which met spray and air as angle of spray was broader. The evaporation of mass was kept regularly according to CA. The difference of evaporated mass was rarely changed, for the quantity of vapour phase was far larger than quantity of liquid phase.

Fig. 10 showed the temporal variation of SMD at different angle of spray. SMD was defined as the diameter of a sphere that has the same volume/surface area ratio for a particle of interest

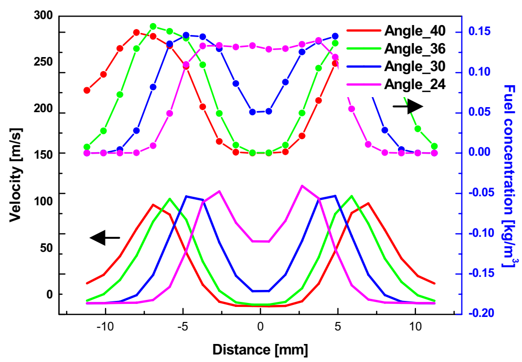

Fig. 7 Velocity and fuel concentration around spray at the Region 1 (near nozzle tip)

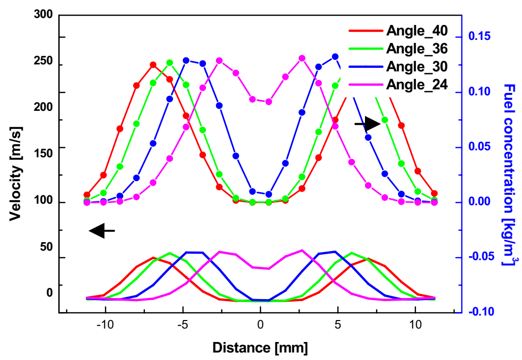

Fig. 8 Velocity and fuel concentration around spray at the Region 2 (away from nozzle tip)

$$SMD = \frac{\sum n_i d_i^3}{\sum n_i d_i^2}$$

where, i represented section of droplet size, n_i and d_i represented the number of droplet and diameter of droplet at the i respectively. As Pederson [2] defined, each region could divide to understand about the characteristics of spray. The SMD increased rapidly by BTDC 5 degree, it was decreased with break-up and evaporation of droplet. Afterward, it was increased due to coalescence of droplet after the droplet was collided with bowl of piston. There were characteristics that the SMD of angle 24 degree was smaller than those of others at the vicinity of TDC.

Fig. 11 showed droplet mass and droplet temperature which is affected by angle of spray. The mass of droplet was influenced by ambient temperature. As the initial droplet was injected, the temperature of droplet was increased due to ambient temperature. When the temperature was reached about 450K, the mass of droplet was decreased as the droplet was evaporated. After the droplet was collided with bowl of piston, the temperature was increased due to friction of droplet driven from collision.

Fig. 12 showed diameter of droplet and parcels of droplet according to angle of sprays. The diameter of initial droplet was increased rapidly after the droplet was injected, for it had not yet happened break-up of droplet. As time goes, if the droplet was broken, diameter of droplet was decreased but the number of parcels was increased. The droplet having break-up was decreased diameter as well as parcels due to evaporation by influence of ambient air.

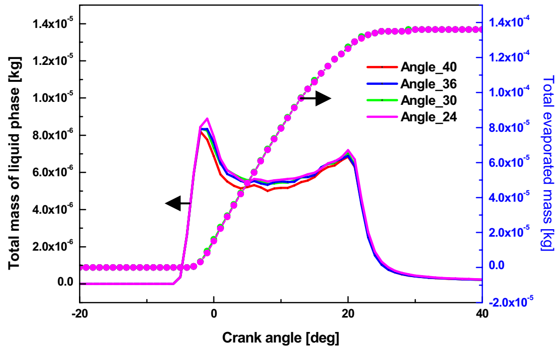

Fig. 9 Total mass of liquid phase and total evaporated mass depending on angle between sprays

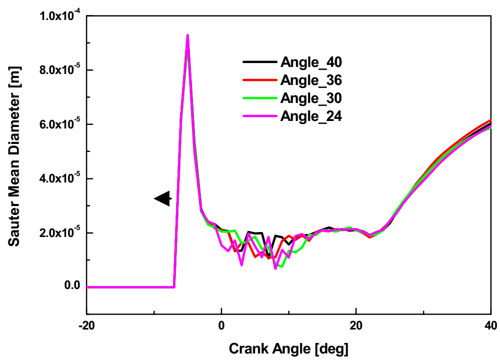

Fig. 10 Sauter Mean Diameter depending on angle between sprays

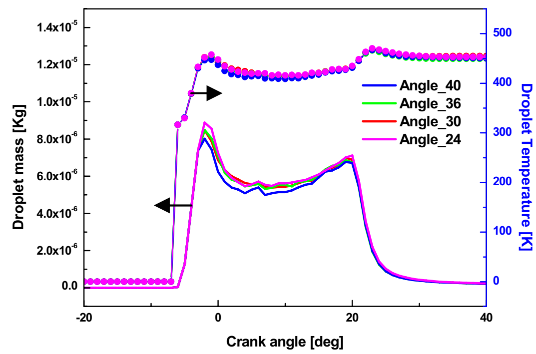

Fig. 11 Droplet mass and droplet temperature depending on angle between sprays

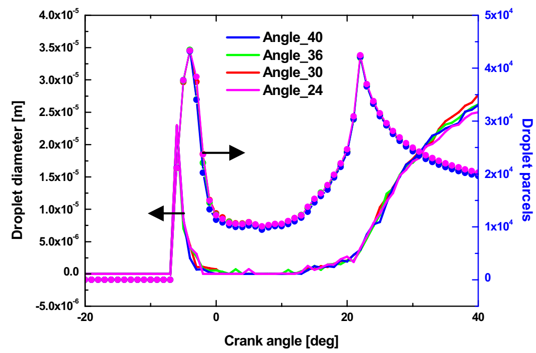

Fig. 12 Droplet diameter and droplet parcels depending on angle between sprays

After happening collision of piston bowl, the droplet was broken, the number of parcels was rapidly increased and the diameter also was increased at once due to coalescence between rebounding droplet and existing droplet. As soon as the droplet was broken, the evaporation was happened and almost of small droplet was evaporated, so the number of droplet was decreased. But the diameter was continually increased due to coalescence.

According to angle, we explored that there was characteristic taking place faster evaporate than those of others and the number of parcels were smaller than others at the angle 40 degree

The influence of swirl

The influence of swirl was significant in the cylinder as the magnitude of swirl changed from 0, 1.5, 3 to 5.

The swirl ratio is defined as below:

$$R_s = \frac{angular\ \ velocity}{engine\ \ rotational\ \ speed}$$

Fig. 13 showed the temporal profile of distribution of fuel, velocity and droplet at the swirl ratio of 1.5. It appears that the end of spray was getting curved to the direction of swirl. The shape of droplet was a little distorted by influence of swirl. As a result, mixing rate of fuel and air was more increased as the influence of swirl was stronger. It was more effective to mix because the air was flowed up to between sprays. The injection of spray was finished at the ATDC 26, the mixing was better than no swirl. The swirl influenced just tip of spray at the first stage of injection, after that the swirl influenced up to primary atomization region.

In contrast, Fig.14 showed the distribution of fuel, velocity and droplet at the swirl ratio of 3. The mixing rate was faster than swirl ratio of 1.5 because the influence of swirl was stronger than swirl ratio of 1.5. The shape of droplet was more distorted than previous condition. The mixing had almost finished at the ATDC 19, injected droplet was faster broken due to stronger swirl. Also shape of droplet was faster distorted by swirl, so the air could be more percolated to spray than swirl ratio of 1.5. The penetration of spray at the ATDC 19 degree was far shorter, for it was faster evaporated.

Fig.15 showed the distribution of fuel, velocity and droplet at the swirl ratio of 5. This condition was the strongest swirl among the condition given in this computation. The shape of droplet was rarely formed due to very strong swirl. The droplet from the tip of nozzle was mixed within very short time, the break-up and evaporation were also faster happened. The shape of droplet was getting curved completely along the direction of swirl, so this droplet was hard to be collided with bowl of piston. Also because evaporation rate was very fast, the penetration of spray was very short

Fig. 16 showed the total mass of liquid phase and total evaporated mass according to swirl ratio. The stronger swirl intensity was, the faster the mass of liquid phase was decreased. No-swirl was the slowest among the decreasing the mass of liquid phase. After the liquid had collided, the increase of swirl influence was the biggest at the swirl ratio of 3, for the interaction of droplet occurred actively between rebounding droplet and existing droplet. But because swirl ratio of 5 was very strong the influence of swirl, there was rarely collision with bowl of piston

Fig. 17 showed distribution of SMD according to swirl ratio. The shape of SMD distribution was similar by BTDC 2 degree because of initial part of injection. The spray forming some extent was influenced by swirl, the break-up of droplet was promoted for swirl ratio 5 by strong swirl, and then the SMD of droplet was decreased.

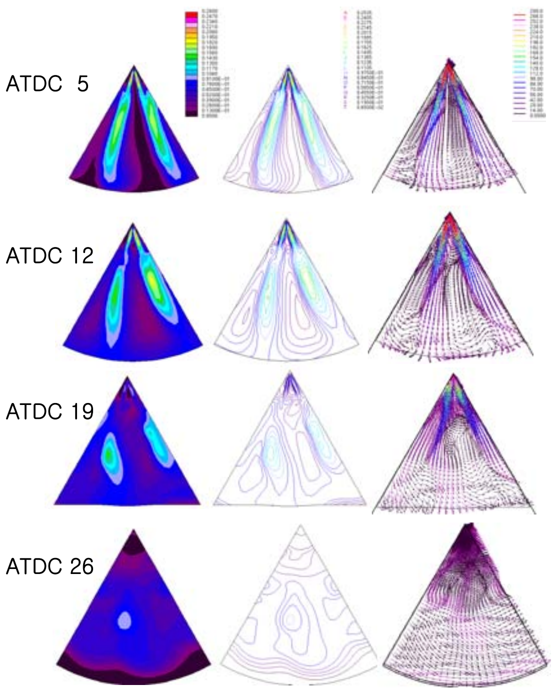

Fig. 13 The distribution of fuel concentration and velocity at the swirl ratio of 1.5

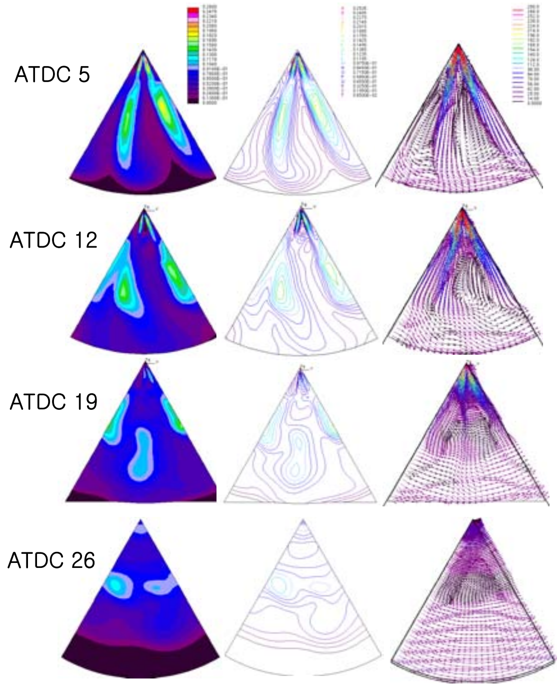

Fig. 14 The distribution of fuel concentration and velocity at the swirl ratio of 3

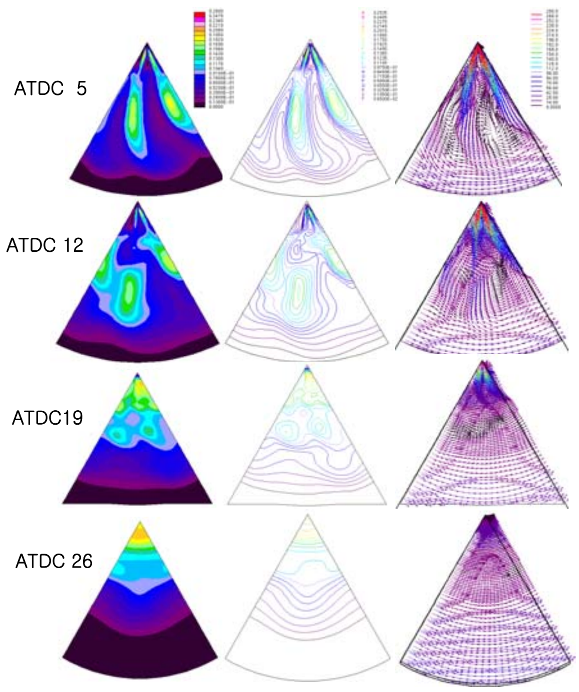

Fig. 15 The distribution of fuel concentration and velocity at the swirl ratio of 5

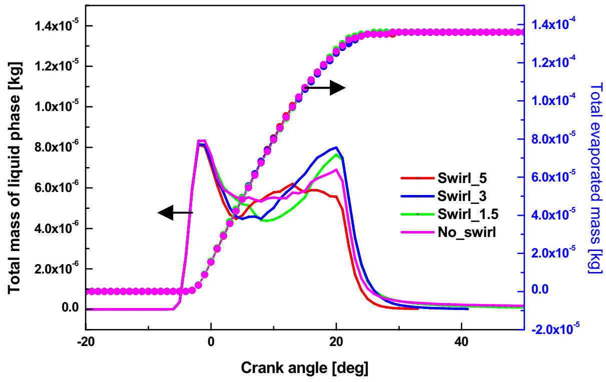

Fig. 16 The dependence of total mass of liquid phase and total evaporated mass

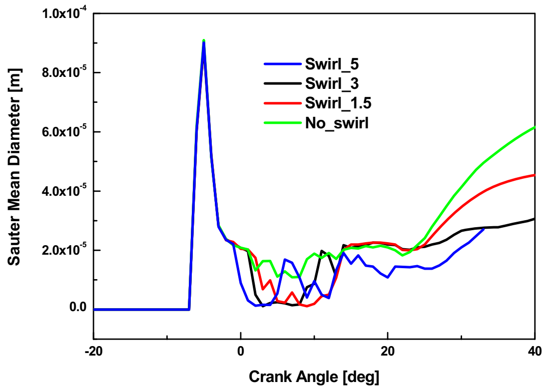

Fig. 17 Swirl ratio effect on Sauter Mean Diameter

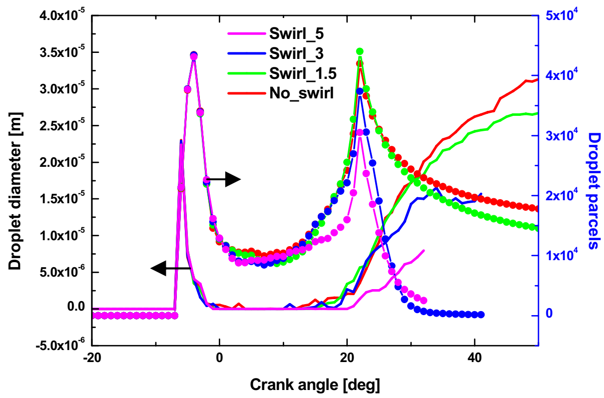

Fig. 18 Droplet diameter and droplet parcels depends on swirl ratio

Fig. 18 showed diameter of droplet and the number of parcels according to swirl ratio. Swirl ratio of 1.5 was faster evaporated than No swirl and it had less coalescence after the droplet was collided. Also the break-up of droplet was progressed actively at the swirl ratio of 1.5, so the number of parcels was better than no swirl. The break-up and coalescence of droplet was enormous influenced by swirl. The coalescence of droplet at the swirl ratio of 3, 5 after the droplet which has collided was less formed due to influence of strong swirl, for there was no enough time to have coalescence, so droplet diameter was smaller than others and the numbers of parcels was less due to evaporation driven from influence of strong swirl.

CONCLUSIONS

An interaction between spray-to-spray and between spray and wall was examined in real operating conditions of marine diesel engine using 3-dimensional numerical analysis method. The main purpose of this study was to explore the difference in spray interaction as angle of spray and swirl ratios vary.

(1) The spray injected into the cylinder was observed to undergo the following processes; the size of droplet in the first stage of injection through the quantity of droplet is small, afterward the droplet was broken with fraction of ambient environment. Broken droplet was evaporated with high temperature and pressure of surrounding air. Injected spray was continuously collided with bowl of piston due to penetration of spray. At that time, droplet was broken but afterward, rebounding droplet and existing droplet was coalesced as well as evaporation.

(2) As angle of spray became the wider, the evaporation rate was better, for the air could be percolated easier than done with small angle. If the angle of spray was changed arising from multi-hole injector implentation, the evaporation rate, droplet condition and fuel concentration was accordingly influenced by penetration distance of spray. So, it was needed optimal values about above parameters to ensure the successful operation of the multi-hole injector.

(3) The swirl between spray was very effective to improve the mixing rate of spray and air in the cylinder. The spray which added proper range of swirl ratio was good at increasing evaporation rate and break-up. But excessive swirl beyond the threshold appears to produce bad result, since the shape of spray was distorted completely suppressing the further interaction with top bowl of piston for better evaporation.

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NOMENCLATURE

D	Diameter	m
SMD	Sauter Mean diameter	m
Symbol	Quantity	SI Unit
T	Temperature	K
V	Velocity	m/s

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