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# An investigation on the fuel behavior for a PFI type motorcycle engine †

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## Abstract

Recently, the electrically controlled fuel injection type motorcycle has been emphasized in order to meet regulations for exhaust emissions. However, there are many difficulties in selecting the control parameters because the pulsation phenomenon occurs in the intake port due to the higher speed operating range and the smaller layout than for a passenger car. Therefore, we investigated the injector spray characteristics which are applied to a 4-valve motorcycle gasoline engine. The spray characteristics were visualized by using a CCD camera synchronized with the stroboscope at 6000 rpm. Furthermore, we compared the simulation results using the VECTIS code with experimental results. The results showed that the trajectory of the spray was directed towards the lower wall of the intake port when the fuel was injected at closed valve timing. On the other hand, when the fuel was injected at open valve timing, a large portion of the fuel was lifted towards the upper half of the port. In addition, open valve injection makes fuel evaporation time short; this resulted in better mixture formation than a closed valve injection. From this result, we found that injection timing has a great effect on the mixture formation within a motorcycle cylinder.

*Keywords*: Motorcycle; Fuel evaporation; Equivalence ratio; Port fuel injection; CVI (closed valve injection); OVI (open valve injection); A/F (air fuel ratio)

## 1. Introduction

Due to increasing concerns regarding environmental pollution, emission regulations for motorcycles have become more stringent in various countries around the world. This is especially true in the Asian market cases where motorcycles are very popular: China has a market share of more than 50 percent, India has 20 percent, and Taiwan has 3 percent. Since motorcycles are used for essential transportation purposes in these countries, air pollution in these countries becomes a serious matter [1].

To improve air quality of each country, the emission regulations for motorcycles should be becoming more stringent. In Taiwan, new emission regulation was introduced from 2004. In Europe and Japan, the emission regulations become more stringent again from 2006. It is well known that the port fuel injection system is more efficient than the carburetor system for gasoline engine to satisfy the new emission regulations. However, the port fuel injection system has been offered only as an optional feature in some countries. In case of port fuel injection system, some amount of injected fuel cannot enter the cylinder and forms wall film. Therefore, the A/F (air fuel ratio) tends to become rich or lean. Finally, UHC (unburned hydro carbon) is increased by misfire or incomplete combustion. To meet with problems, we need the research to find the optimal injection timing which guarantees the complete combustion.

The intake air flow and mixture formation in the cylinder are important parameters that affect the

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combustion process and emission reduction of a motorcycle. Recently, various measurements of fuel behavior in an engine have been performed. However, the information derived from an experiment is limited because the engine operating condition or measurement domain has to be restricted. To get more valuable information, the application of numerical analysis is very decisive. Three-dimensional calculations are also expected to be an effective tool for engine design [2].

In this paper, the detailed features of spray behaviors and evaporation characteristics according to injection timing were analyzed by experiment and simulation. From these results, we found that open valve injection case makes fuel evaporation time short, resulting in better mixture formation than a closed valve injection case. In addition, this paper revealed that injection timing has a great effect on the mixture formation within the cylinder of the motorcycle.

## 2. Experimental set up

### *2.1 Experimental device for fuel behavior*

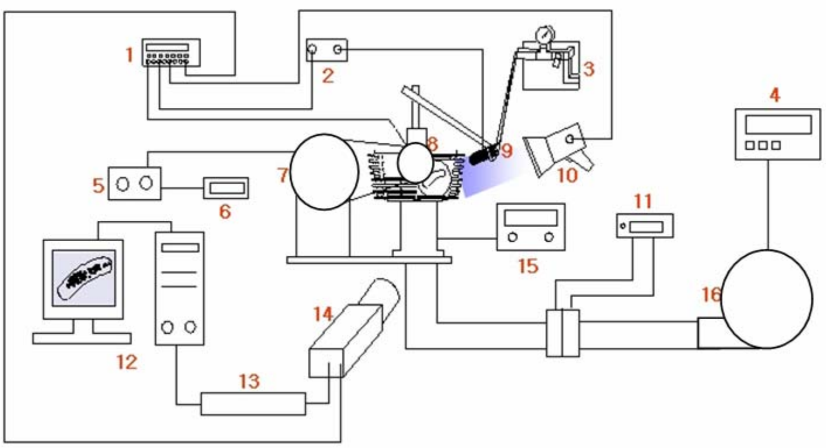
Fig. 1 shows the fuel behavior measurement device used in this study. This apparatus consists of a CCD camera for taking a picture of the fuel behavior in intake port, a stroboscope which illuminates the spray from the injector, a control unit which amplifies CCD signal, a counter board with C++ program for making images digitalized. In addition, we manufactured a visualization device that consists of encoder, DC motor, inverter, belt and gear to investigate the unsteady fuel behavior.

### *2.2 Experimental procedure*

Fuel behavior is captured by controlling the fuel injection timing at a constant engine speed of 6000 rpm. The injection duration is fixed at 4 msec and fuel was injected in two conditions according to the intake valve timing. Fuel injection timing is set up on the basis of the time needed for the fuel to reach the valve in both CVI (closed valve injection) and OVI (open valve injection) conditions. Table 1 shows the injection timing and valve timing in each condition.

Table 1. Injection timing and valve timing.

| | Start of injection |
|---|---|
| CVI | 62 CAD |
| OVI | 296 CAD |
| IVO/IVC | 296 CAD/640 CAD |
| EVO/EVC | 76 CAD /424 CAD |




| | | | |
|---|---|---|---|
| 1. DG 535 | 2. Injector Driver | 3. Fuel pump | 4.Inverter(fan) |
| 5. Inverter(DC motor) | 6.Tachometer | 7. DC Motor | 8. Encoder |
| 9. Injector | 10. Stroboscope | 11. Diff .Pressure Meter | 12. Computer |
| 13. Image Board | 14. CCD Camera | 15. Vacuum Meter | 16. Vacuum Fan |

Fig. 1. Schematic diagram of fuel behavior measurement device.

## 3. Numerical analysis

### *3.1 The condition and spray model for numerical analysis*

The numerical simulation of spray and flow field was conducted by using the VECTIS 3.7 program (Ricardo Co. Ltd). The convergence condition is less than $1\times10^{-6}$ of residual point at the observation point. Time step is set to the 0.1° for precision of calculation and the number of PISO correction steps is set to 5 times. In addition, the PISO algorithm is used for coupling pressure and velocity field of the air-fuel flow in the cylinder [3-4].

The intake flow analyses were performed by solving the three momentum equations such as continuity equation, energy equation and k-ε model for turbulence. In addition, the injection velocity was calculated by using the result of the injection quantity that was injected 1,000 times during equal spray duration.

An initial SMD was assumed to be nozzle hole diameter and an initial spray diameter distribution was calculated by using the Rosin-Rammler distribution function [5].

Boundary conditions were employed by complete 1-D simulation of the engine using commercial WAVE software.

We also used the breakup model developed by the Reitz and Diwakar [6]. The breakup of the injected liquid was divided into the Bag and Stripping breakup process according to the Weber number [7]. Bag breakup occurs when:

$$We = \frac{\rho U^2 D}{2\sigma} \geq 6 \tag{1}$$

The life time of unstable drop is:

$$\tau_b = \frac{\pi}{2}\left(\frac{\rho_l D^3}{\sigma}\right)^{\frac{1}{2}} \tag{2}$$

Stripping breakup happens when:

$$\frac{We}{\sqrt{\mathrm{Re}}} \geq 0.5 \tag{3}$$

The stripping breakup lifetime is:

$$\tau_b = 5\left(\frac{\rho_l}{\rho_g}\right)^{\frac{1}{2}} \frac{D}{U} \tag{4}$$

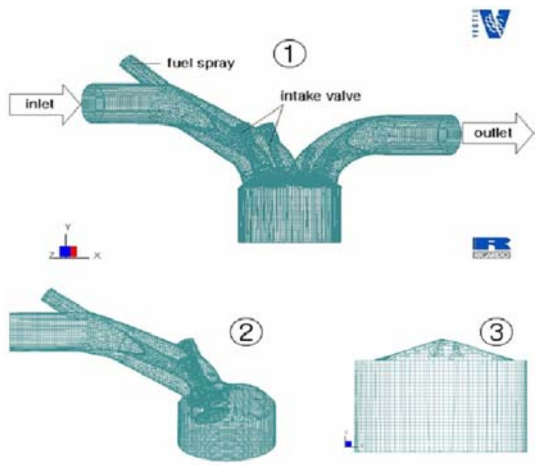


Fig. 2. Mech generation.

The spray impingement model proposed by Gosman et al. [8] was used to evaluate spray characteristics. The stick, rebound, spread, and splash conditions occurred after spray impingement according to $We_{in}$ and $T_{Leid}$. The roughness effect of the combustion chamber was ignored.

### *3.2 Mesh generation*

The moving mesh technique was adopted in this paper. And, in order to increase the accuracy of calculations at the neighborhood of the intake valve, the mesh structure was refined at this region. The mesh structure had 575,600 cells at BDC. To improve accuracy and to reduce the calculation time, three kinds of mesh were used.

Fig. 2 shows the mesh used for this study. Mesh ① was used for the section until the end of the valve overlap from the end of the compression stroke. In addition, mesh ② was used for the section of the last inhalation and initial compression stroke. Finally, mesh ③ was used for the section of end of compression stroke.

## 4. Results and discussion

Fig. 3 shows a comparison of the spray developing process between experiment and simulation when the fuel is injected for 4 msec. Immediately after injection, the droplet is observed to be broken up owing to vibration which is caused by air friction. From this figure, we found that both results obtained from experiment and simulation are considerably well matched.

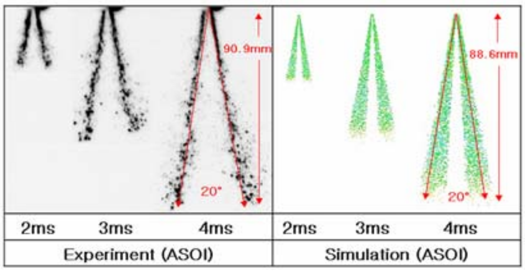



Fig. 3. Comparison of spray pattern between experiment and simulation (ASOI = After Start of Injection).

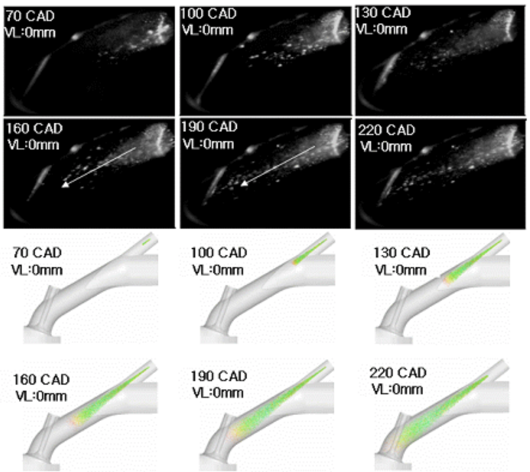



Fig. 4. Spray images for CVI (VL = Valve Lift).

Fig. 4 shows the fuel behavior when the fuel was injected in closed valve condition. We compared the image from visualization experiment with the simulation result. Injected fuel was directed to the lower part of valve fillet and intake port, which was previously settled to the targeting point without any effect of air flow. After injection, many droplets were observed at the case of 3.5 msec, which corresponds to 190CAD, through a transparent window. As a result of simulation, large droplets were observed to be conflicted firstly at the lower part of valve and port from the 130CAD with initial injection velocity.

Fig. 5 shows total injected fuel amount, wall stuck amount and non-evaporation amount obtained by calculation. The amount of evaporated fuel in the wall is almost same as the amount of evaporated fuel in intake port or cylinder without wall collision. On the other hand, the amount of evaporated fuel on the wall is the same as the amount of evaporated fuel among the fuel which sticks on the wall after collision. Before the intake valve is opened, injected fuel is first

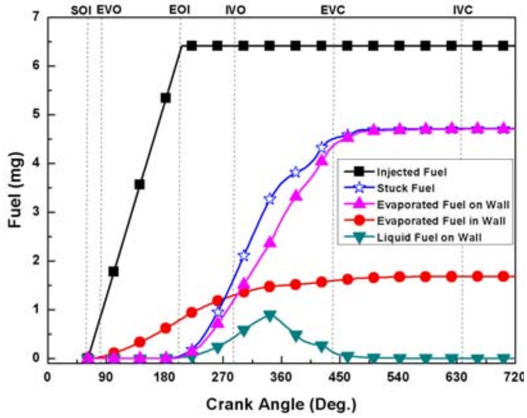



Fig. 5. Distribution of injected fuel amount for closed valve injection case.

evaporated in the intake port, and as the intake valve opens, most of non-evaporated fuel is stuck on the wall with collisions.

In addition, most impinging fuel on the wall is evaporated secondly. This is caused by the high temperature of the wall, strong air flow caused by high engine speed and residual gas within the cylinder caused by long valve overlap. On the other hand, the amount of evaporated fuel on the wall is remarkably high compared to the amount of evaporated fuel in the wall. However, in this case, not only non-enough fuel evaporation but also a great quantity of UHC exhaust is produced because of low temperature in cylinders at cold starting condition.

As the fuel injection timing advances and the amount of evaporation is increased in the intake port, UHC emission can be decreased. However, there is a limit to making fuel injection timing advance because most motorcycles are driven at the high engine speed above 4000 rpm. Therefore, it is necessary to study the fuel behavior when fuel is injected at valve open condition for analyzing the high speed region.

Fig. 6 shows the distribution of A/F in the combustion chamber from 640CAD to 0CAD. This time corresponds to the period that the intake valve is closed completely. As the compression stroke progresses, the rich (A/F=0~8) and the lean (A/F=16~50) regions are continuously decreased. An approximately theoretical stoichiometric A/F region is observed in this case.

Fig. 7 shows fuel behavior obtained from CCD camera and simulation. The spray image is captured when the fuel is injected while intake valve is opened.

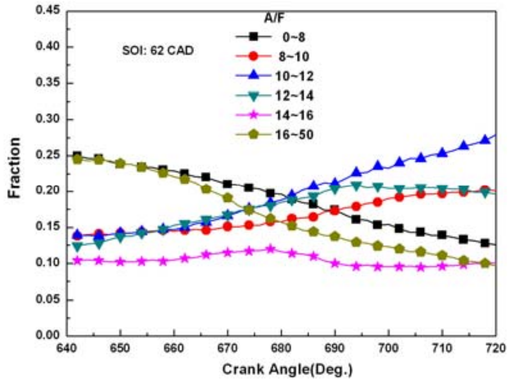



Fig. 6. Distributions of A/F for closed valve injection case.

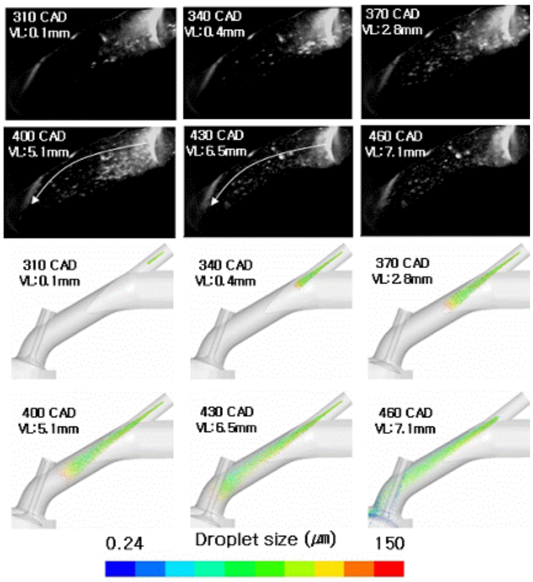



Fig. 7. Spray images for OVI.

After injection, the fuel behavior is nearly not affected by induction air flow until 370 CAD. After that, droplets fly to the part of valve fillet like CVI case. However, we found that the droplets fly leaning to the higher part of intake port from the time of 400 CAD due to the effect of air flow. As the crank angle is progressing, more droplets are directed to the same part and may be evaporated. This situation is caused by the Stokes number [9]. When the injected fuel droplet size is bigger than 25 μm, a droplet doesn't follow with the air flow. This kind of situation was proved experimentally by Heywood [7].

Fig. 8 shows the total injected fuel amount, evaporation amount, stuck amount and non-stuck and evaporated fuel amounts. Flying with regular speed,

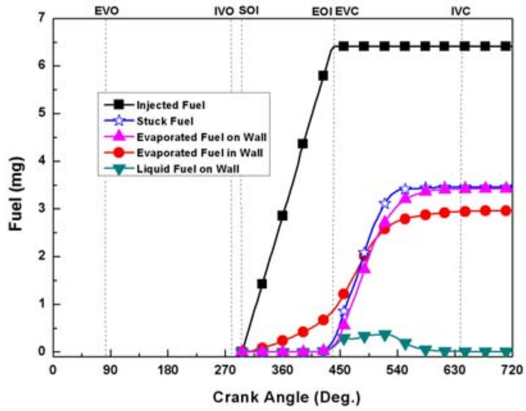



Fig. 8. Distribution of injected fuel amount for open valve injection case.

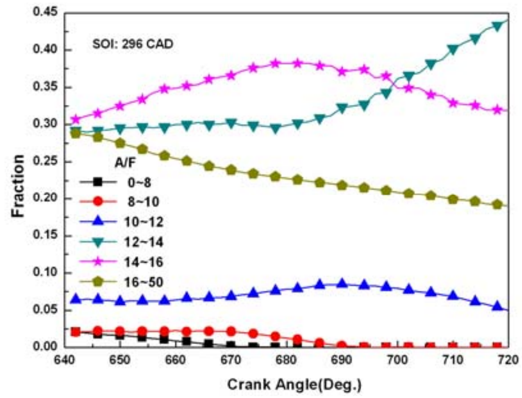



Fig. 9. Distributions of A/F for OVI.

the injected fuel is evaporated in the intake port. As mentioned in Fig. 7, a droplet starts to reach the valve fillet from the point of 430 CAD and evaporation is dramatically increasing. In addition, for strong air flow and high temperature of cylinder, a great quantity of evaporation occurs in the intake port and cylinder until the point of 540 CAD, which is the induction stroke. Compared with evaporated fuel on the wall and evaporated fuel in the wall, it is less than 0.5 mg. This value gap is declining because of the strong air flow as the engine speed is increasing. As this result makes fuel evaporation time short, it will be better than CVI with high speed driving and abrupt acceleration.

Fig. 9 shows the A/F distribution in the combustion chamber from 640CAD to 0CAD after the intake valve is completely closed in the open valve injection case. Both CVI and OVI have the highest ratio when it is near to stoichiometric A/F, from 12

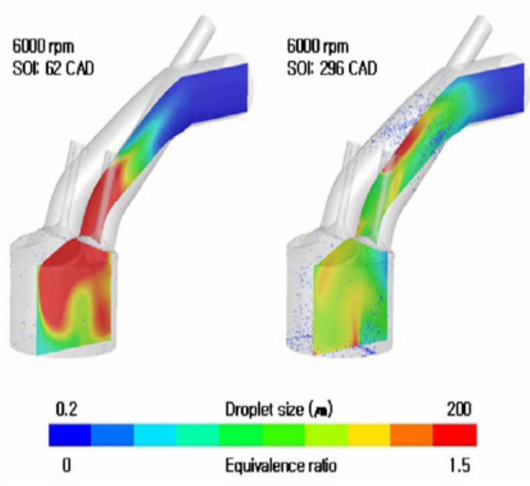



Fig. 10. Comparison of equivalence ratio between CVI and OVI.

to 16. Compared with Fig. 6, A/F is in a high ratio because the resident fuel amount in the intake port is large.

Fig. 10 shows equivalence ratio characteristics while the intake valve is completely closed (640CAD) in both cases of CVI and OVI. Droplet size is magnified 10 times. In case of 62CAD, most injected fuel is evaporated and it is difficult to find droplets in the intake port. Thus, it shows relatively high equivalence ratio range, which means lean mixture condition. However, non-evaporated fuel is observed to be stay in the higher part of intake port and inside of the cylinder.

In both cases, a large amount of fuel flows backward to the intake port during the compression stroke and a huge amount of mixture is observed inside a cylinder as well as intake port. In case of 296 CAD, quite a bit of fuel stays in intake port and is evaporated at the higher part of the intake port. In both cases of CVI and OVI, we found that 0.61 mg and 1.58 mg among the total injected fuel (6.41 mg) stay in intake port. After all, a little amount of injected fuel stays in intake port because of the intake valve switch timing effect.

Fig. 11 shows the distribution of fuel mass fraction of the vapor in each case of different crank angle when the fuel is injected at 62CAD. Most evaporated fuel stays near the higher temperature wall during the intake stroke. However, the fuel stays near the cylinder head intensively during compression stroke. This fuel range will enhance the ignition and flame propagation speed during combustion.

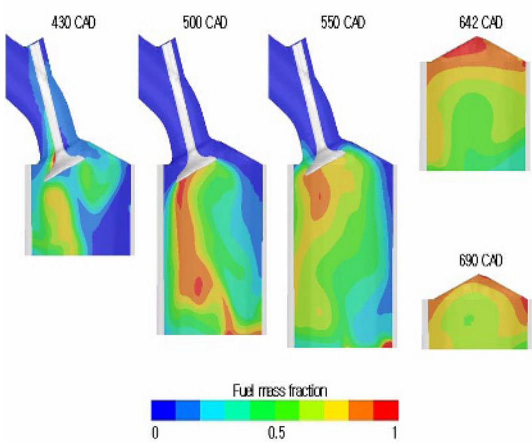



Fig. 11. Distributions of fuel mass fraction of the vapor.

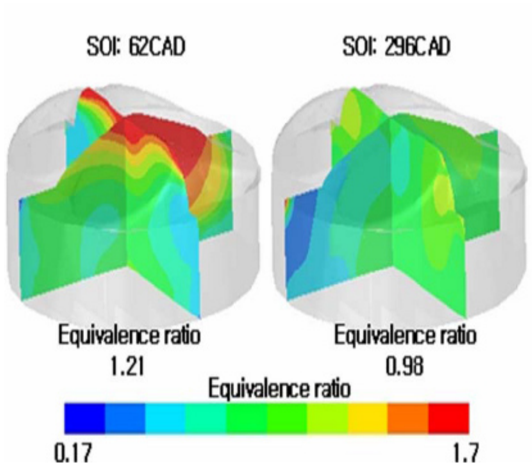



Fig. 12. Distribution of equivalence ratio at 690 CAD.

Fig. 12 shows the equivalence ratio distribution in a cylinder. It occurs in the condition of the end of compression stroke according to injection timing. As shown in Fig. 11, a high equivalence ratio distribution is observed in the part of cylinder head when the fuel is injected at 62CAD. In addition, as the amount of fuel flows into the cylinder more than the fuel injected at 296 CAD, high equivalence ratio range appears.

When the fuel is injected at 296 CAD, the equivalence ratio range is evenly distributed within the cylinder. However, a relatively rich fuel distribution is observed at the intake part of the cylinder. This is because most of the fuel in case of OVI flows into the exhaust part of a cylinder and relatively small amount of fuel flows into the intake part of a cylinder.

## 5. Conclusions

To confirm the fuel behavior and evaporation characteristics of a fuel injection type motorcycle engine according to the injection timing, spray visualization and simulation were conducted in this research. The main conclusions may be summarized as follows:

- CVI case -

(1) The trajectory of the droplets was unaffected by flow in the intake port and towards the lower port wall and valves where droplets coalesced into a film.
(2) Evaporation was promoted by a backflow phenomenon within the intake port during valve overlap duration. But, the UHC exhaust is predicted because mixture was discharged to the exhaust port during long valve overlap duration.

- OVI case -

(1) A large portion of the fuel was lifted by the intake air flow towards the upper intake port.
(2) OVI is likely to be advantageous under rapid changes of engine speed and cold starting condition because the droplets passed the upstream of the port and re-evaporated into many small droplets with almost no film formation due to the high velocity of the flow.

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