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The Influence of Port Fuel Injection on Combustion Stability

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Abstract

The demands on internal combustion engines for low emissions and fuel consumption are increasing year by year. On the other hand, engines to be used in motorcycles need to provide high output and quick response to meet user desire. In order to realize low fuel consumption while keeping high performance, it is necessary to properly understand cyclic variations during combustion as well as the influence of the injection system on fuel control during transient periods.The current paper reports on the results of a study in the influence of port fuel injection on combustion stability in a small displacement motorcycle engine, using both a series of experiments and CFD. The parameters of the injection systems under study are injection targeted area, injection timing, and fuel droplet size. Considering experimental results and CFD results, it is shown that the cyclic variations of combustion can be correlated with the inhomogeneiety of the mixture distribution in the cylinder and around the spark plug.

1 Introduction

The demands on internal combustion engines with regard to fuel efficiency [1] are getting more severe due to concerns for the environment and energy conservation. The lean burn concept is a well known approach aimed at achieving low fuel consumption in port fuel injection engines. However, cyclic variations of the combustion process impose a limit on the range where lean burn is possible [2]. This makes increased combustion stability highly desirable. Exploring the causes of combustion instability therefore is an essential prerequisite for extending the limits of lean combustion.

In the field of automotive engines, there have been many reports [3-5] investigating topics ranging from in-cylinder flow to mixture formation and flame propagation structure, by means of optical visualization technology and numerical modeling techniques using computers. However, little work has been done in this area with regard to motorcycle engines.

In motorcycle engines, the layout of injection systems is subject to various potential limitations owing to the reasons for requiring the engine to be mounted in a narrow space. For sports type motorcycles, the need for high specific output power brings with it a need for operating at high revolution speeds. A short-stroke layout is therefore often used, which in turn makes it difficult to achieve stable combustion under low load conditions. Since acceleration is an important sales point for sports type motorcycles, it is vital to examine the influence of the injection system on cyclic variations in combustion and fuel control during transient periods.

For the current study, the influence of port fuel injection on combustion stability characteristics in a small displacement motorcycle engines was examined using both a series of practical experiments and the principles of computational fluid dynamics (CFD). The parameters of the injection systems under study are as follows: (1) injection targeted area (intake port upstream wall, dual intake ports, or single intake port valve face), (2) injection timing (fuel spray passing intake valve slit directly or when intake valve is closed), (3) fuel droplet size (low or high pressure injector).

2 EXPERIMENTAL APPARATUS

The current study used a liquid-cooled 4-cycle single-cylinder engine based on a production model. The main specifications of the test engine are listed in **Table 1**. Four types of injection systems were tested. Their main parameters are listed in **Table 2**, and **Figure 1** shows a schematic view.

Table 1 Engine Specification

Bore × Stroke	73.0 mm × 59.6 mm
Connecting-rod length	116.0 mm
Displacement Volume	249.4 cm^3
Compression Ratio	9.7
Valve Overlap period	48 deg
Numbers of Valves	Intake 2 & Exhaust 2

Table 2 Specifications of Injection Systems

Injection System	1	2	3	4
Target Area	Upstream Wall	Dual Intake Valve Faces	Single Intake Valve Faces	Upstream Wall
Spray Type	1-Jet	2-Jet	1-Jet	Hollow Cone
Injection Angle	-	18.5deg	-	-
Spray Angle	5deg	5deg	5deg	45deg
Injection Pressure	0.3 MPa	0.3 MPa	0.3 MPa	7.0 MPa
SMD	120 μm	130 μm	120 μm	30 μm

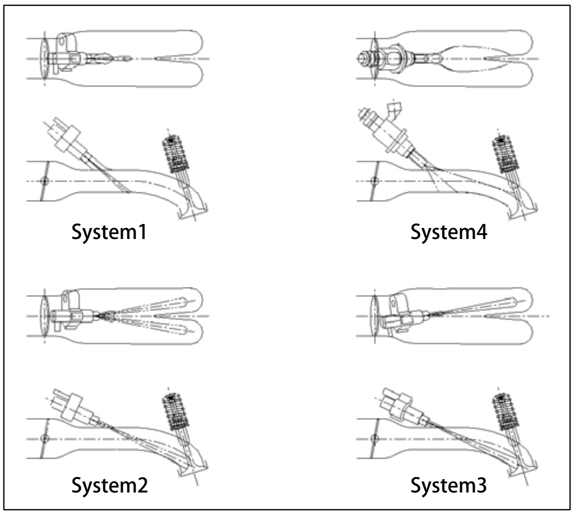


Figure 1 Schematic View of Injection Systems

Injection systems 1, 2, and 3 use a conventional PFI type injector, while system 4 uses an injector with good atomizing properties. With systems 1 and 4, the fuel spray is aimed at the wall upstream of the intake port. Injection system 2 directs the fuel spray at the intake valve face of both intake ports. In injection system 3, the fuel spray is aimed only at the intake valve face of one intake port.

The initial averaged droplet diameter of the fuel spray is the SMD (Sauter Mean Diameter) at 50 mm below the injection hole, as determined using the LDSA 1500A (Laser Diffraction Sizing Analyzer) from TOHNICHI COMPUTER APPLICATIONS.The internal pressure in the cylinder was measured with a KISTLER 6053C non-cooled combustion chamber pressure sensor, and the combustion analysis system DS-228 from ONO SOKKI was used to analyze the combustion process. Combustion stability in the tests was evaluated by the coefficient of variance (COV) in net mean effective pressure (NMEP).

The test results for the current study as reported in **Table 3** refer to a partial load range at 4000 [rpm]. The intake quantity was adjusted with the throttle valve. Unless specified otherwise, the injection timing was set to 240 [deg] before the compression top dead center (BCTDC). This was determined through preliminary tests as a parameter where combustion stability is least affected by injection timing. The ignition timing was MBT for the respective operation mode.

Table 3 Experiment Conditions

Engine Revolution	4000 [rpm]
Load	NMEP 300 ～ 700 [kPa]
AFR	13 , 14.5 , 16
Coolant Temperature	30, 80 [℃]
Ignition Timing	MBT
SOI	240 [deg] BCTDC

3 NUMERICAL ANALYSIS OF MIXTURE AND WALL FILM BEHAVIOR

In order to assess the differences in air-fuel mixture distribution in the engine depending on the injection system used, injection timing and coolant temperature, CFD was employed to analyze droplet and wall film behavior as well as mixture distribution. Among the test parameters shown in Table 3, seven conditions listed in **Table 4** were determined in which the influence on combustion stability was significantly large in experiment.

Table 4 Calculation Specifications

Case Name	Injection System	Coolant [℃]	Start of Injection [deg] BCTDC	Ignition Timing [deg] BCTDC
A	1	80	240	60
B	1	↑	380	60
C	2	↑	240	66
D	2	↑	390	66
E	2	30	240	64
F	3	80	240	64
G	4	↑	150	62

VECTIS program from Ricardo was used for simulation, and droplet behavior was analyzed according to the DDM (Discrete Droplet Method). The Bai-Gosman model was used to represent spray impingement onto the wall and wall film behavior. A $k-\varepsilon$ standard model was used as the turbulence model.

The engine model and calculation procedure were as follows. For the engine model, the intake pipe downstream from the throttle valve position, intake port, combustion chamber, and exhaust port were modeled (see **Figure 2**). The shape of the throttle valve itself was not modeled. Instead, the inlet boundary for calculation was set at the throttle valve position. The boundary conditions were obtained by one-dimensional simulation as well as initial conditions.The injector spray model used for calculation was validated based on a combination of direct imaging and LDSA measurement.

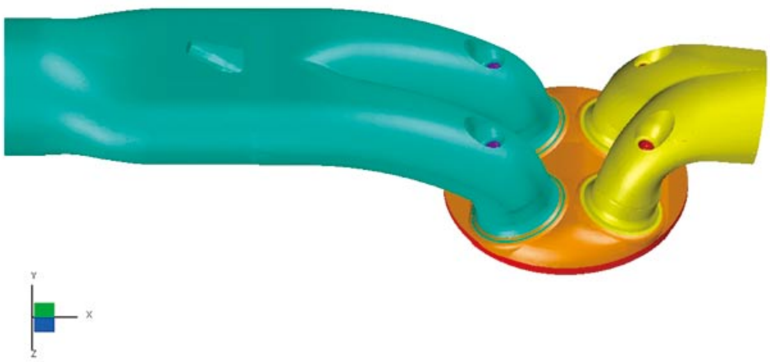


Figure 2　Overview of Simulation Model

4 RESULTS AND DISCUSSIONS

4.1 COMBUSTION STABILITY

Figure 3 shows the COV of NMEP for injection systems 1, 2, 3 and 4 with AFR of 14.5. In system 3, where fuel is injected to a single port only, combustion stability is worse than with other specifications, as can be expected. It is worth noting that system 4, which uses an injector with good atomizing properties, does not show better combustion stability under these conditions than others.

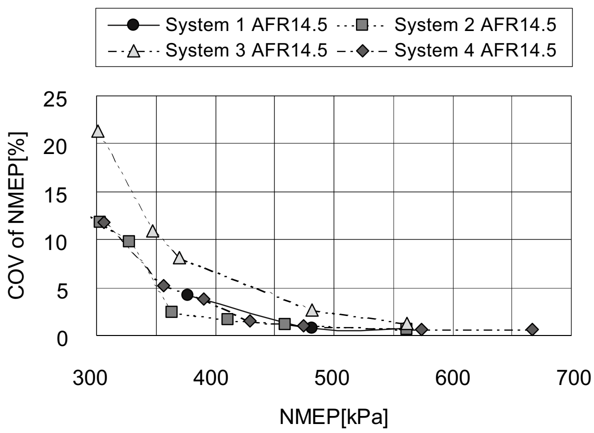
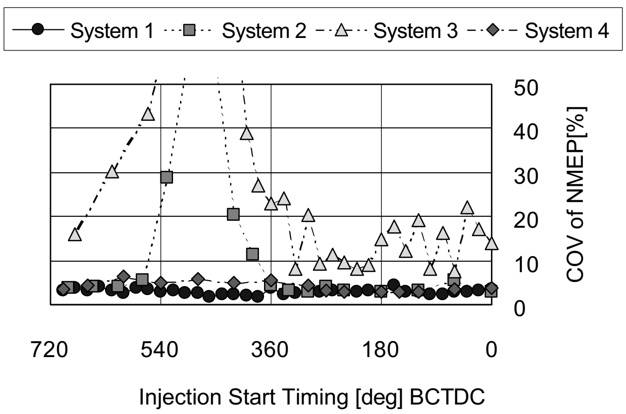


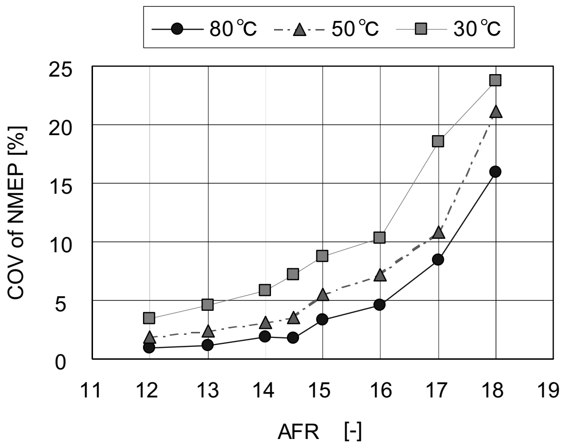
Figure 3　Influence of Engine Load

Figure 4 plots the influence of injection timing on the COV of NMEP at NMEP of 380 [kPa] and AFR of 14.5. System 1, with injection aimed at the upstream wall, the COV of NMEP is low and remains roughly constant, regardless of injection timing. System 2 and 3, with injection aimed at the intake valve face, there is a region where the COV of NMEP rises drastically depending on injection timing. Considering the spray velocity and distance between the injection nozzle and intake valve, this is related with the conditions in which the injection timing is set so that the fuel spray is inducted directly into the cylinder during the intake stroke. With other injection timing settings, the influence of injection timing on combustion stability at low load is small. In system 4, which uses an injector with good atomizing properties, injection timing where the injected spray is introduced directly into the combustion chamber during the intake stroke results in slightly worse combustion stability at low load.

Figure 5 shows the influence of coolant temperature on the COV of NMEP in system 2 in which injection is aimed at the intake valve face. Combustion stability is markedly worse with low wall temperature, especially under lean conditions.



NMEP 380 kPa, AFR 14.5, Coolant Temp. 80℃
Figure 4 Influence of Injection Timing



NMEP 380[kPa], AFR 14.5, System2
Figure 5 Influence of Coolant Temperature

4.2 COMBUSTION DURATION

The relation between combustion duration and combustion stability was investigated. The results shown here contain all test points. **Figure 6** shows the relationship between COV of NMEP and the MFB 0-10% duration. As the MFB 0-10% duration becomes longer, combustion stability deteriorates. At the same time, the COV of NMEP range is relatively wide for the MFB 0-10% duration. **Figure 7** shows the relationship between COV of NMEP and the MFB 10-90% duration. Again, combustion stability deteriorates as the 10-90% duration becomes longer. Compared to the MFB 0-10% duration, the COV of NMEP range for the MFB 10-90% duration is narrower.

From these results, it becomes clear that longer initial combustion durations with MBT setting do not necessarily degrade combustion stability. In other words, some conditions exist in which long duration is required before main combustion starts, though there is little fluctuation in this required interval, and this causes good combustion stability. However, it is common behavior that when the initial combustion duration is extended over a certain point, combustion stability suddenly deteriorates notably. On the other hand, longer combustion durations for the main combustion phase always lead to poor combustion stability, demonstrating the clear effect that this parameter has upon combustion stability.

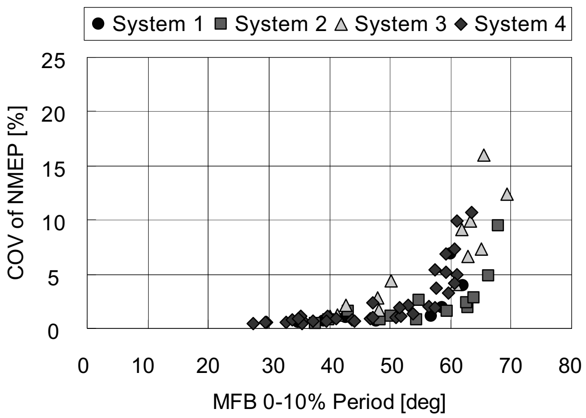


Figure 6 Relationship between MFB 0-10% Duration and Combustion Stability

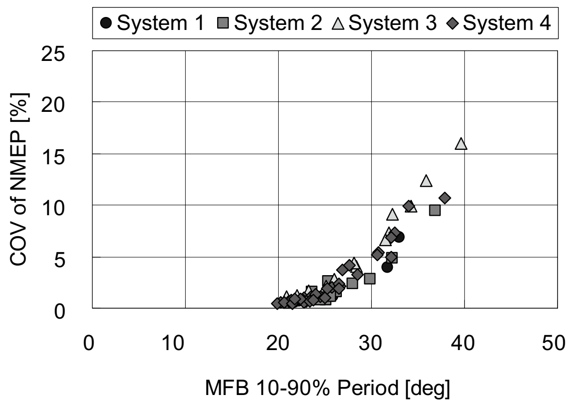


Figure 7 Relationship between MFB 10-90% Duration and Combustion stability

4.3 MIXTURE DISTRIBUTION

The experimental results demonstrated that the injection system configuration, injection timing and coolant temperature exert an influence on combustion stability and duration. Change of injection affects mixture formation in the intake port, wall film location and amount, size and amount of droplets, and finally mixture distribution in the combustion chamber. Therefore, it seems reasonable to relate the difference of combustion resulting from the injection system used to the mixture distribution. To examine this aspect, CFD simulation was employed to analyze the mixture distribution in the cylinder.

Figure 8 shows the fuel air ratio (FAR) distribution in the combustion chamber around the ignition timing for each experiment. The corresponding COV of NMEP data obtained in the experiment are also indicated. The green in the contour corresponds to stoichiometry around AFR 14.5. The spark plug is located in the center of the combustion chamber but this is not reflected in the shape of the calculation model.

In cases A, B, and G, the mixture uniformity appears to be high. The COV of NMEP under these conditions was comparatively low, with 1.8 [%], 3.1 [%], and 3.9 [%] respectively. On the contrary, cases D, E, and F, in which condition COV of NMEP was relatively high (11.4, 7.1, and 8.6% respectively), show low uniformity of the mixture. It can be stated from these facts that high uniformity of mixture results in low COV of NMEP and high COV of NMEP can be related to low uniformity of mixture.

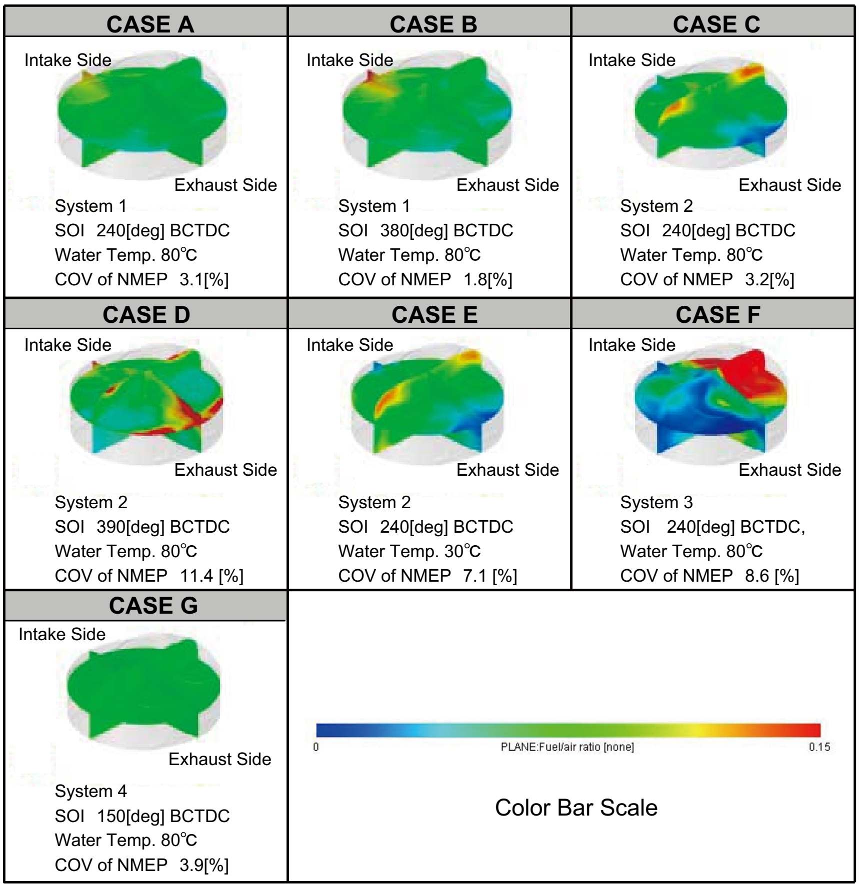


Figure 8 Distribution of FAR in the cylinder at around the Ignition Timing

Let us investigate the results of each injection system in more detail. For injection system 1, with injection targeted at the upstream wall, combustion was stable regardless of injection timing in the experiment. This can be explained by the fact that the mixture distribution in the combustion chamber for case A seems almost the same as that for case B. This fact also indicates that spray targeting onto the wall upstream of the intake port can enhance uniform mixture formation by the impingement of fuel droplets that can cause atomization.

For injection system 4, simulated as case G, fuel spray with small SMD is injected into the intake port, which aids fuel vaporization and air-fuel mixing in the port. This mixture with high uniformity is introduced into the cylinder from the intake port.

For injection system 2, where injection is aimed at the intake valve face, injection timing has severe effect on combustion in the experiment. In case D, in which the injection timing is set so that combustion stability is poor, the mixture is lean in the center of the cylinder and rich near the cylinder wall, particularly on the exhaust side. On the contrary, in case C, in which the injection timing is set so that combustion stability is good, the mixture is stoichometric in the center of the cylinder. Moreover, the fact that the mixture near the cylinder wall on the exhaust side is lean shows it to be totally different from that in case D.

In order to explain how the difference of the mixture distribution is caused, FAR distribution is shown in **Figure 9** for cases C and D at IVC (intake valve closed), with droplet distribution and wall film thickness on a cross section of the intake valve axis. The biggest difference between them is that droplets are found in the cylinder in case D while droplets are only in the port in case C. Wall film is also seen in case D on the cylinder wall below the exhaust valve, though not in case C. Rich mixture found below the exhaust valve in case D at ignition timing is presumably due to vaporization from this wall film. These facts allow the conclusion that the fuel introduced in the cylinder as droplets and wall film generated on the exhaust side cannot fully mix in the cylinder, so that uneven distribution leads to combustion variations.

CASE C：System 2, SOI 240[deg]BCTDC, Water Temperature 80[℃]
CASE D：System 2, SOI 390[deg]BCTDC, Water Temperature 80[℃]

Figure 9 FAR distribution on a plane passing through the axis of the intake valve, and wall film distribution in the calculation domain at IVC

Considering the spray velocity and distance between the injection nozzle and intake valve, the timing at which the fuel spray reaches the intake valve and enters the cylinder becomes as shown in **Figure 10**. In the case when SOI is 530 [deg] BCTDC, the fuel spray begins to reach the intake valve at almost IVO. In the case when SOI is 390 [deg] BCTDC, the arrival of fuel spray to the intake valve mostly ends before IVC. As mentioned before (see **Figure 4**), the COV of NMEP deteriorates in the case of the above 2 timings. Then, the injection timing when combustion stability gets worse is related to the conditions in which the fuel spray is inducted directly into the cylinder during the intake stroke.

When the water temperature is low (case E), the mixture distribution trend is the same as for high water temperature (case C), but the variance in mixture distribution is more pronounced. It can be concluded that this severe inhomogeniety of mixture makes the combustion stability poor.

Therefore, with considering the mixture distribution of CFD results, it seems likely that in an injection system injection aimed at the intake valve face, the worsening of combustion stability during the intake stroke is connected with specific injection timings and low wall temperature results from the mixture distribution as described above.

Injection system 3 by case F shows mixture distribution by CFD results that are strongly skewed towards the intake port from which the fuel was introduced. Uneven distribution also existed in the vicinity of the spark plug. This data along with the test results allow the conclusion that with fuel injection to a single port, uneven mixture distribution in the vicinity of the spark plug and in the cylinder lead to cyclic variations in combustion.

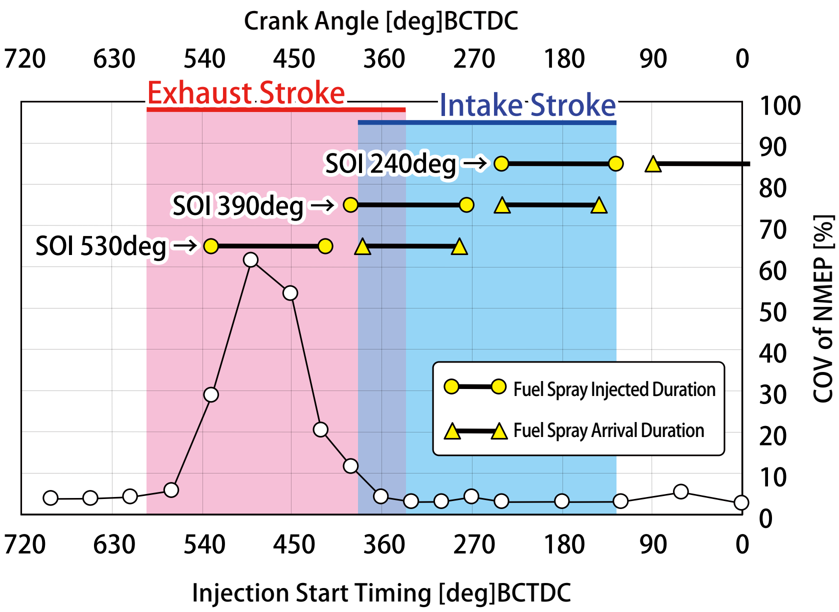


Figure 10 Relationship between the Timing at which Fuel Spray arrives to Intake Valve and Injection Start Timing at which Combustion Stability deteriorates

4.4 WALL FILM AMOUNT

The injection system not only affects combustion stability but also has severe effect on transient behavior. In order to quantitatively assess such influences, CFD results are analyzed to get information on wall film behavior in the engine.

Figure 11 illustrates the transition of wall film quantity inside a port. With injection systems aimed at the upstream wall (cases A and B), wall film quantity in the port is relatively high, regardless of injection timing. It is not converged yet. This can be related to poor transient behavior. As an example for wall film distribution, **Figure 12** shows the situation at the timing of IVO. It can be seen that wall film exists in the area from the target location of the injection to the intake port branch section. On the other hand, with injection systems aimed at the valve face (cases C, D, F), the wall film quantity in the port is relatively low, which is likely to result in good transient behavior. However, at low wall temperature (case E), the wall film quantity in the port is relatively high, which points to a possible deterioration of transient behavior. When using an injector with good atomizing properties, the wall film quantity in the port is lower than with a conventional PFI type injector. Transient behavior can therefore be expected to be better.

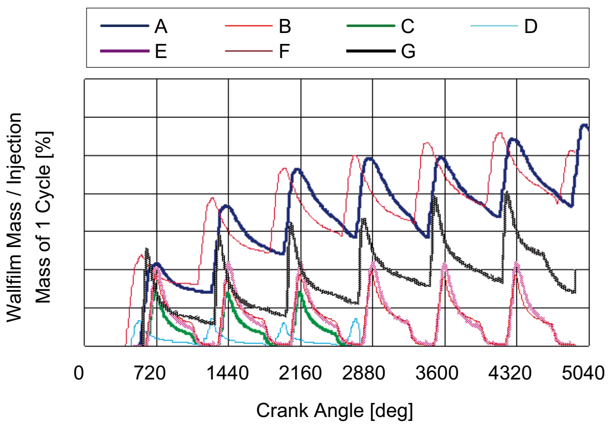


Figure 11 Ratio of Wall Film Mass to Injection Mass of 1 Cycle

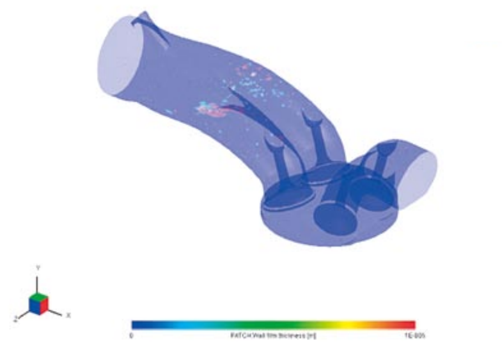


Figure 12 Distribution of Wall film thickness at around the timing of IVO in the case A

5 SUMMARY

The current study examined the influence of PFI injection systems on combustion stability in a small displacement motorcycle engines, using both experimental testing and CFD simulation. The following conclusions have been obtained.

1.Combustion stability at low load is affected strongly by the mixture distribution in the cylinder.

2.Even with a port fuel injection system, the mixture distribution in the cylinder is influenced by the injection system.

3.The effect of the injection system on combustion stability can be explained qualitatively by the mixture distribution seen in CFD results.

4.Injection systems tested show properties as follows :

●With injection systems aimed at the upstream wall, the influence of injection timing on combustion stability is small. This is thought to be due to the fact that mixture distribution inside the cylinder at the ignition timing is fairly even. However, the wall film quantity inside the port is relatively high, which may have a negative effect on transient behavior.

●With injection systems aimed at the valve face, the influence of injection timing on combustion stability at low loads is relatively small, provided that the timing is set so that the fuel spray is not introduced directly into the cylinder during the intake stroke. The wall film quantity inside the port is relatively low, which can be expected to have a positive effect on transient behavior.

●When the injection timing is set so that the fuel spray is introduced directly into the cylinder during the intake stroke, injection systems aimed at the valve face cause a degradation of combustion stability at low loads. With this injection timing, combustion stability at low loads will deteriorate slightly even when using an injector with good atomizing properties. This is thought to be due to the mixture distribution in the cylinder and an increase in droplet quantity. However, the wall film quantity inside the port is relatively low, which can be expected to have a positive effect on transient behavior.

- With injection systems aimed at the valve face, combustion stability at low loads deteriorates at low wall temperatures, particularly when the AFR is leaner than stoichiometric AFR. This is thought to be due to the mixture distribution in the cylinder and an increase in droplet quantity. Also, because the wall film quantity inside the port is relatively high, a negative effect on transient behavior can be expected.
- With injection systems using only a single port, combustion stability is impaired. This is thought to be due to uneven mixture distribution in the vicinity of the spark plug.
- An injection system with small SMD gives good combustion stability and a small amount of wall film.

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