技術論文

Influence of Injection and Flame Propagation on Combustion in Motorcycle Engine – Investigation by Visualization Technique –

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要旨

二輪車のポート噴射SIエンジンにて、燃焼と混合気形成との相関を調査すべく、燃料噴霧・液膜や初期火炎の伝播挙動について可視化観察した。同可視化観察には、ボアスコープ方式を採用した。混合気形成の影響を調査するため、噴射系のパラメータとして、噴射方向・噴射タイミング・燃料噴霧粒径を変更した。その結果、低負荷での燃焼安定性は、混合気の不均一性に大きく影響されることが分かった。これは、大粒径の燃料噴霧が燃焼室へ直接流入すること、あるいは吸気管内の混合気が不均一であることにより引き起こされていた。燃料噴霧の燃焼室直接流入による輝炎発生は、低負荷・全負荷の両条件で見られた。液膜による過渡応答の問題を最低限に減らし全開で混合気均一性を保ちつつ、低負荷での燃焼安定性を保つためには、微粒化インジェクターにて、吸気行程に燃料噴霧が燃焼室内へ直接流入するタイミングで噴射する手法が有効であると考えられる。

Abstract

This paper reports visualization of behavior of spray, wall film, and initial flame propagation in an SI engine with port fuel injection system for motorcycle in order to directly investigate their influences on combustion and relations among them. Borescopes were used to visualize the flame propagation in the combustion chamber and wall film in the intake port. Various injection systems and injection parameters were tested: injection direction, timing, and size of droplets to investigate the effect of mixture formation. It is concluded that combustion stability under low load condition is greatly influenced by mixture inhomogeneity in the combustion chamber whose evidence is the luminous emission. It is caused by direct induction of considerable amount of liquid fuel with large size of droplets into combustion chamber or too inhomogeneous mixture in the intake port. Luminous emission in the flame was also seen under wide open throttle condition due to direct introduction of wall film into combustion chamber. Finally, great potential of highly atomized spray to keep combustion stability under low load condition and homogeneity under high load condition without defect of transient behavior due to wall film has been shown with injection timing of IVO.

1 INTRODUCTION

Reduction of fossil fuel consumption is necessary with regards to global warming and energy security. Motorcycle has great potential to play an important role for these demands due to its light weight. Reduction of environmental impact is also an important factor as well as the fuel efficiency. Mixture formation is one of the key issues for both aspects. Port fuel injection system is getting popular due to better control ability of fuel supply than by carbureter that is still used widely due to the benefit of cost and simplicity. Port fuel injection system is widely used for automotive application in many years. Compared to automobile, motorcycle has severe limitations about cost and space. Demand for specific power is higher instead of less stringent emission regulation. Considering these differences, it is important to establish appropriate guide for motorcycle applications with regard to injector layout and injector specification to satisfy regulation for environment without deterioration of advantages.

One of the most important issues is generation of wall film. It is enhanced by shorter distance between injection hole and wall against it, shorter duration to evaporate due to higher engine speed, and lower evaporation rate by higher pressure in the intake system due to smaller volume downstream of throttle. This may cause combustion instability under stoichiometric operation, in conjunction with longer valve overlap due to high specific power demand. Limitation by the cost makes it difficult to add devices to enhance combustion stability, such as variable valve timing system and tumble generation valve, which are widely used for automotive application. Large amount of wall film is also an important issue with regard to transient behavior. It may spoil quick response of motorcycle, which is one of the most attractive features of motorcycles.

Dealing with these issues, many research activities have been reported in the past. Enhancement of combustion with rather simple devices has been reported [1-4]. More fundamental phenomena such as wall film behavior inside the intake port was explored and reported by using simple test rigs [5-8]. The influence of port fuel injection on combustion in a small displacement engine was analyzed by computational fluid dynamics (CFD) [9-10] with performance test. Investigation by measurement is necessary to support CFD simulation. There are lots of papers about flame propagation [for example, 11-12] if we search for it not within the range of motorcycle application. It is rare, however, to find a paper to investigate the relation between mixture formation and flame propagation, especially in a small engine, directly by visualization method. Optical engine with transparent parts is traditional system to observe flame behavior in the combustion chamber, while the limitation of operating condition, especially engine speed, is very severe to apply this under realistic condition of motorcycle operation. Borescopes have the ability to operate under relatively high engine speed only with small modification of the engine.

This paper reports visualization results of spray, wall film, and initial flame propagation in order to directly investigate their influences on combustion and relation among them. Combustion stability under low load condition is within our scope. Luminous flame emission, which is an index of mixture property, is also investigated under low load and wide open throttle condition. Moreover, possibility of highly atomized spray to improve both combustion stability and transient behavior is also discussed.

2 EXPERIMENTAL APPARATUS

ENGINE CONFIGRATION

This study was conducted in a water-cooled 4-cycle single-cylinder engine based on motorcycle application. The main specifications of the test engine are listed in Table 1. These are the same as in the previous report from our group [9].

Table 1: Engine specification

Cylinder Bore	73.0 mm
Stroke	59.6 mm
Displacement Volume	249.4 cm^3
Compression Ratio	9.7
Numbers of Valves	Intake 2, Exhaust 2

INJECTION SYSTEM

Injection systems shown in Table 2 and Figure 1 were tested in this research. These are also the same as in the previous report from our group [9]. SMD of the injector was measured at 50 mm below the injection hole by LDSA 1500A (Laser Diffraction Sizing Analyzer) from TOHNICHI COMPUTER APPLICATIONS. System 1 is a typical layout of motorcycle to represent that an injector is installed far upstream and aims at wall. System 2 is another typical layout to represent that an injector aims at both intake valves. The injector in System 3 is the same as in System 2, but aims at one side of intake port. System 4 is a system to see how an injector targeting the wall with small SMD behaves and affects to combustion.

Table 2 Specification of injection system

Injection System No.	Target Area	Spray Type	Injection Angle [deg]	Spray Angle [deg]	Injection Pressure [MPa]	Initial SMD [μm]
1	Upstream Wall	1-Jet		5	0.3	120
2	Dual Intake Valve faces	2-Jet	18.5	5	0.3	130
3	Single Intake	1-Jet		5	0.3	120
4	Upstream Wall	Hollow Cone		45	7.0	30

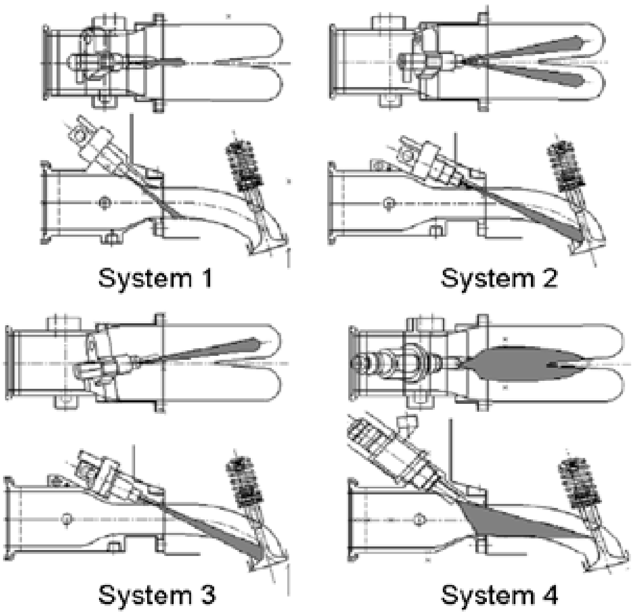


Figure 1 Schematic view of injection system.

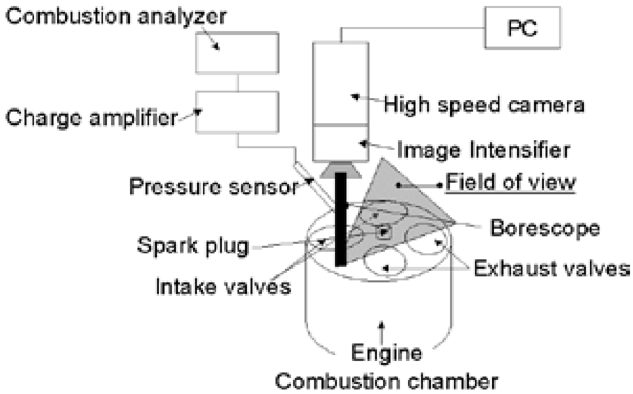


Figure 2 Pattern diagram of setting for observation in combustion chamber.

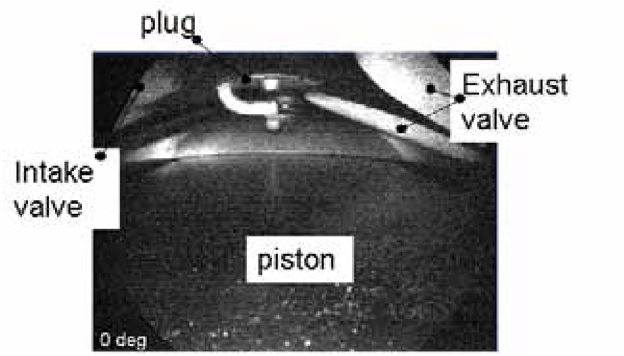


Figure 3 Actual field of view of combustion chamber.

Promotion of evaporation by fuel droplets impingement on upstream wall and big amount of wall film is expected in System 1. In System 2, aiming at intake valve, smaller amount of wall film and inhomogeneous mixture distribution is expected. In System 3, asymmetric and extreme inhomogeneity of mixture is expected. Better balance between homogeneity and amount of wall film is expected in System 4.

MEASUREMENT TECHNIQUES

The pressure in the combustion chamber was measured with a KISTLER non-cooled combustion chamber pressure sensor. Combustion analysis system DS-228 (ONO SOKKI) was used to analyze the combustion process. Coefficient of variation (CoV) of net mean effective pressure (NMEP) and combustion duration was calculated from the data of 500 consecutive cycles. However, cycles with less than 100 kPa of NMEP were considered misfires and were eliminated from the parent population of combustion duration evaluation.

Two types of borescope, one is for flame observation in combustion chamber, the other is for observation of spray and wall film in intake port, were equipped to the test engine.

Visualization configuration of flame

Shown in Figure 2 is the layout of the borescope assembled on the engine. Area of view of this system is shown in Figure 3. All images of flame in this paper were taken with the same direction as this. An air-cooled borescope (SMETec) has 70 degree-view angle and 70 degree-view direction. Only visible light can be transmitted through this scope. A monochrome camera with C-MOS image sensor (Photron: FASTCAM-MAX) was used to record consecutive flame images at 20000fps without filter. An image intensifier (Hamamatsu photonics: C9548-03) was used to intensify weak emission of the initial flame. The image intensity was controlled according to the luminosity. A lens (Nikon: 50 mm, f=1.2), which transmits only visible light, was equipped.

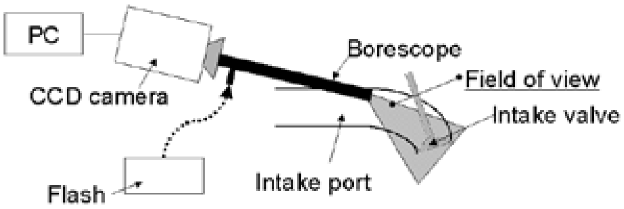


Figure 4 Pattern diagram of setting for observation in intake port.

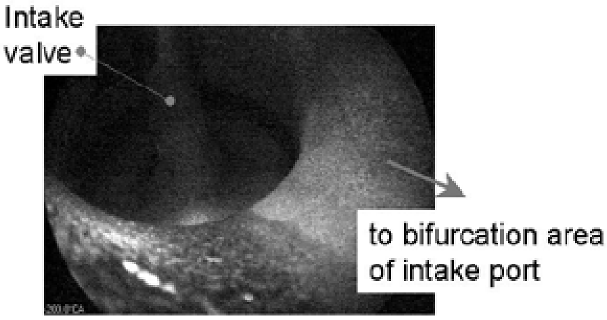


Figure 5 Actual field of view for intake port.

Table 3: Experimental condition

Injection System No.		1	2	3	4
Engine Speed [rpm]		4000			
Ignition timing		MBT			
IMEP [kPa]		400/450, 1200			
Throttle Angle [deg]		4.7, 76			
AFR		14.5			
Coolant Temperature [°C]		80			
Start of Injection BTDC [deg]	at IVC	240			150
	at IVO	390			300
	at IVO-40	430			340

<u>Visualization configuration of wall film</u>

Shown in Figure 4 is the layout of borescope on the intake port. A non-air-cooled borescope has 67 degree-view angle and 30 degree-view direction. Frame rate was limited by frequency of flash, about 15 Hz, to illuminate inside the intake port. Area of view of this system is shown in Figure 5. All images in the intake port near the valve in this paper were taken with the same direction as this.

<u>Measurement of fuel concentration in the intake port</u>

Fast Flame Ionization Detector (Fast-FID, CAMBUSTION: Fast-FID HFR400) was used to detect concentration of hydrocarbon in the intake port. The probe for measurement was equipped for two zones, nearby intake valve and bifurcation of the intake port. Cycle-averaged data were used in the investigation.

EXPERIMENTAL CONDITIONS

Experimental conditions, shown in Table 3, are under partial and wide open throttle range at 4000 rpm. Intake air quantity was controlled by the throttle valve installed between the air box and the intake port. In this paper, injection timing is called as the timing when fuel droplets reach valve area. For example, "injection timing of IVC" means that spray reaches intake valve at timing of intake valve close (IVC) and so on. The ignition timing was MBT for the respective operation condition.

3 RESULTS

In this section, results of measurement are described in the order by going upstream from the combustion chamber to injector: pressure in the combustion chamber, flame image, spray and wall film image, and fuel concentration in the intake port.

COMBUSTION PROPERTY AND EXHAUST POLLUTANTS

In this section, the result of combustion analysis based on the pressure in the combustion chamber is described under low load condition with various injection systems and injection timing.

CoV of NMEP shown in is very low and shows small difference by injection system with injection timing of IVC. Combustion stability of System 3 is the most sensitive to injection timing, followed by System 2. In terms of injection timing, condition of IVO+40 results in the worst combustion stability.

Shown in Figure 7 and Figure 8 are the results of MFB 10-90 % and MFB 0-10 %, respectively. MFB 10-90 % shows clear dependence on injection timing similar to CoV of NMEP. MFB 0-10 % does not show clear dependence on injection timing nor injection system.

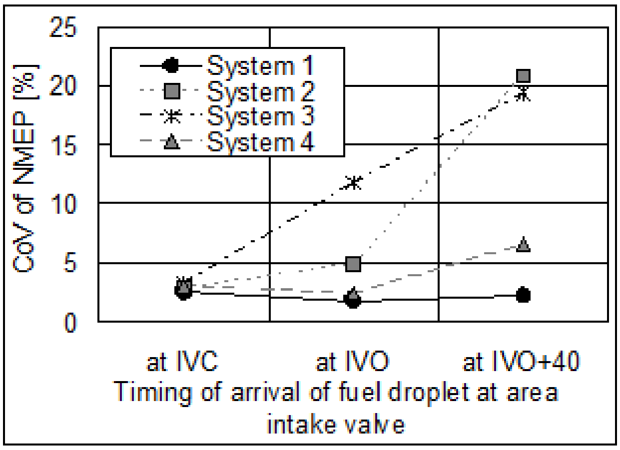


Figure 6 Influence of injection system and timing on combustion stability under low load condition.

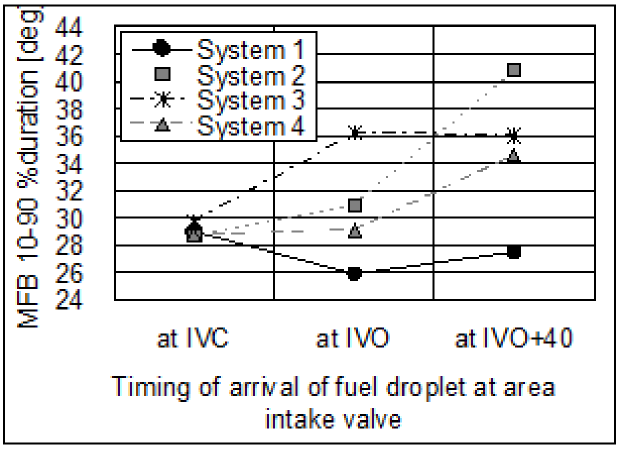


Figure 7 Influence of injection system and timing on MFB 10-90 % duration under low load condition.

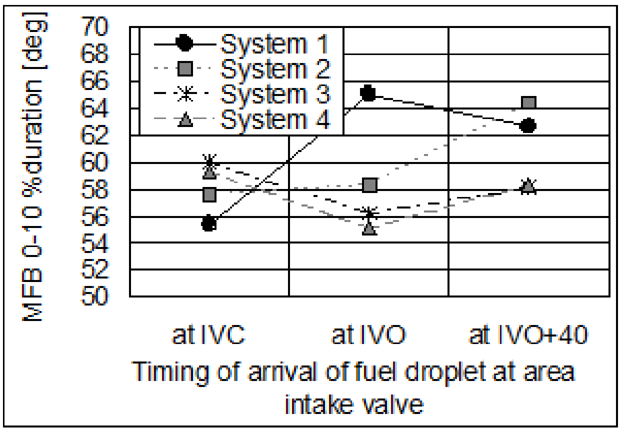


Figure 8 Influence of injection system and timing on MFB 0-10 % duration under low load condition.

Figure 9 shows the relation between CoV of NMEP and combustion duration (MFB 10-90 %). MFB10-90 % duration is longer when combustion stability is worse.

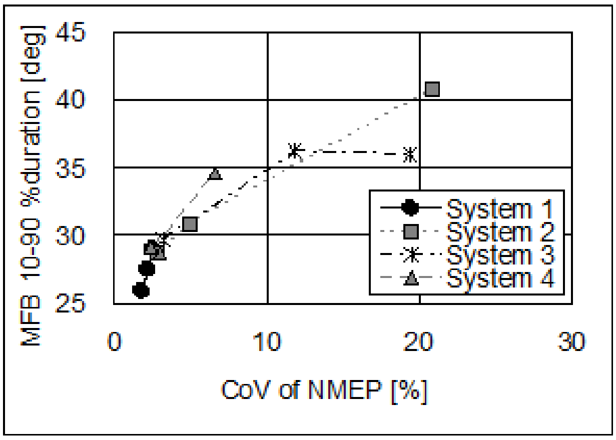


Figure 9 Relation between MFB 10-90 % duration and CoV of NMEP under low load condition.

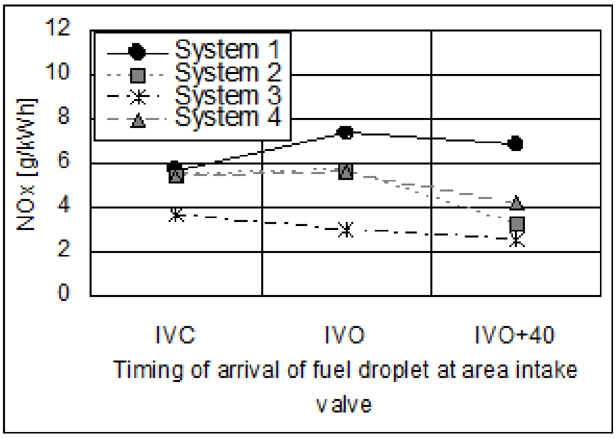


Figure10 Specific emission of NOx.

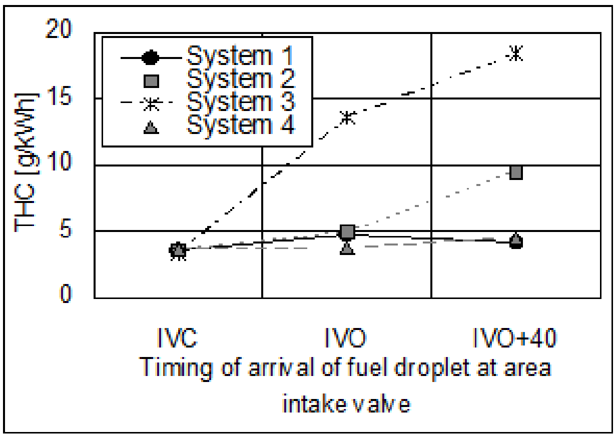


Figure 11 Specific emission of total hydrocarbon.

Specific emission of NOx and total hydrocarbon is shown in Figure10 and Figure 11. Specific emission of NOx is low in System 3 and System 2 with injection timing of IVO+40.

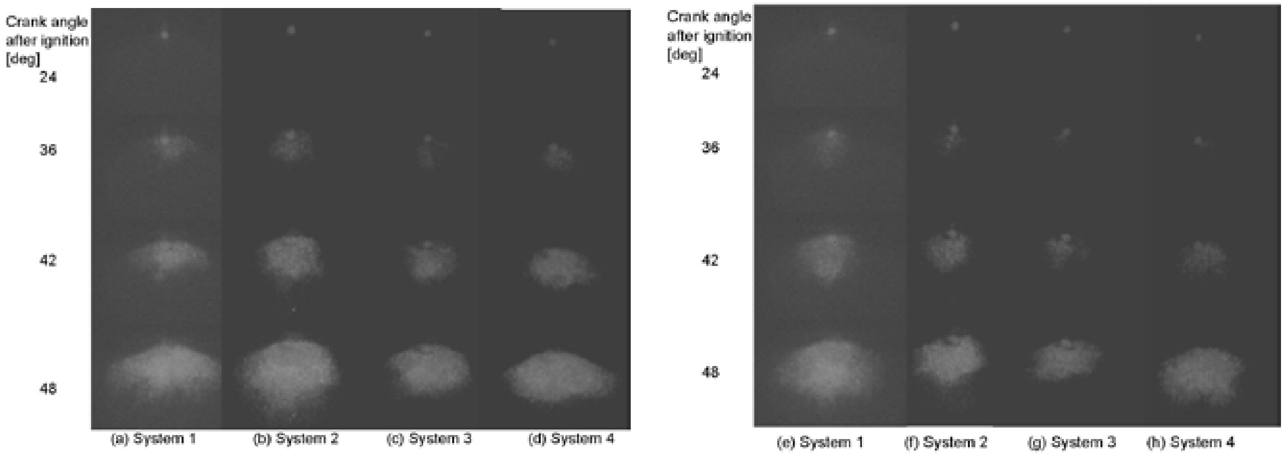


Figure 12 Images of initial flame propagation with injection timing of IVC. Peak pressure:(a)-(d); 2 MPa, (e)-(h); 1.6-1.8 MPa.

Specific emission of total hydrocarbon is large in System 3 and System 2 with injection timing of IVO+40. These are related with long combustion duration and large CoV of NMEP.

FLAME PROPAGATION IMAGE

Effect of injection system with IVC injection under low load condition

Shown in Figure 12 are images of flame propagation in all systems with injection timing of IVC. Figure 12 (a)-(d) are the images extracted from a cycle with the cycle-averaged peak pressure of 2 MPa, whereas Figure 12 (e)-(h) are from the cycle with the peak pressure of cycle average minus standard deviation among 500 observed cycles.

Compared among lines of (a)-(d), the flame images show small difference by injection system, whereas big in comparison among lines of (e)-(h). System 2, 3 and 4 show smaller flame at 36 degree after ignition than System 1. This means influence of injection system is not so big under this condition as far as peak pressure is the same. Peak pressure has strong relation with initial flame propagation. This conducts extension of MFB 0-10 % duration in System 2, 3 and 4 as shown in Figure 8.

Effect of injection timing with spray targeting wall under low load condition

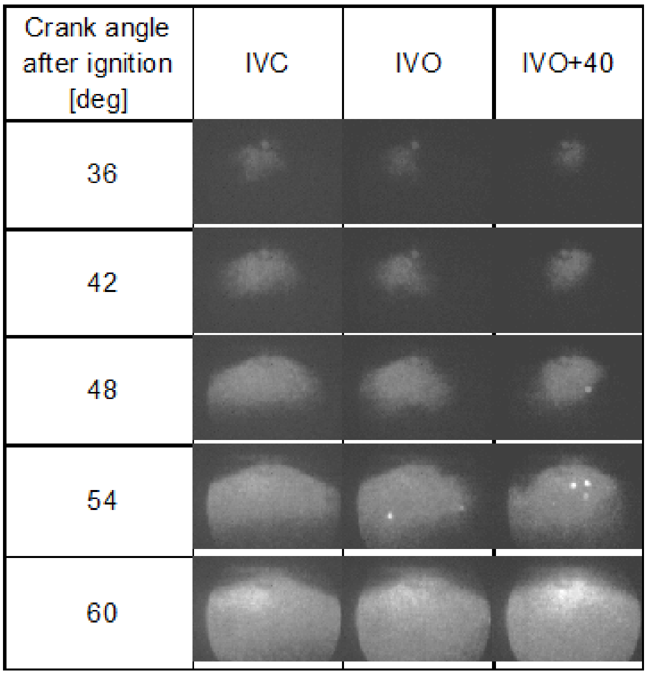


Figure 13 Flame propagation with different injection timings in System 1.

Here we try to see the effect of injection timing on flame image in System1 and 4 where Cov of NMEP is not sensitive to the injection timing. Shown in Figure 13 are typical images of flames in System 1 with different injection timings. These figures were extracted from the cycle with the cycle-averaged peak pressure among 500 observed cycles.

Small number of luminous emissions is observed with injection timing of IVO and IVO+40 in Figure 13. These emissions can be seen in almost all cycles with these injection timings. Here we define this word "luminous emission" as localized more luminous area than

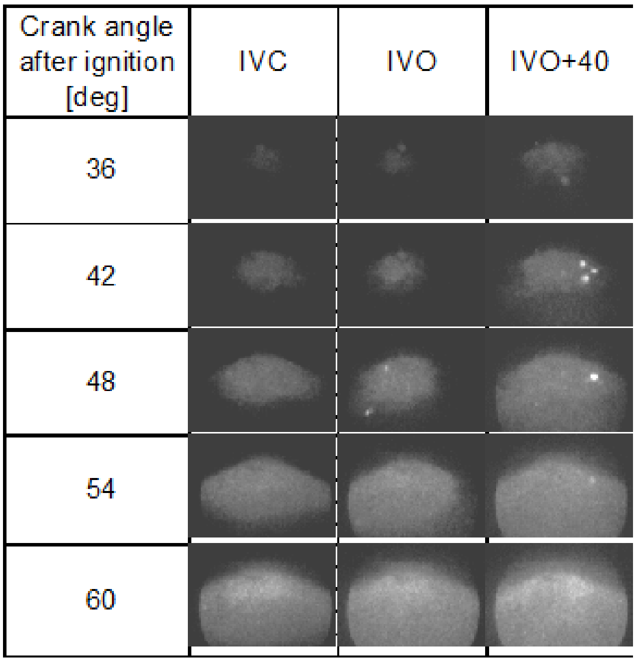


Figure 14 Flame propagation with different injection timings in System 4.

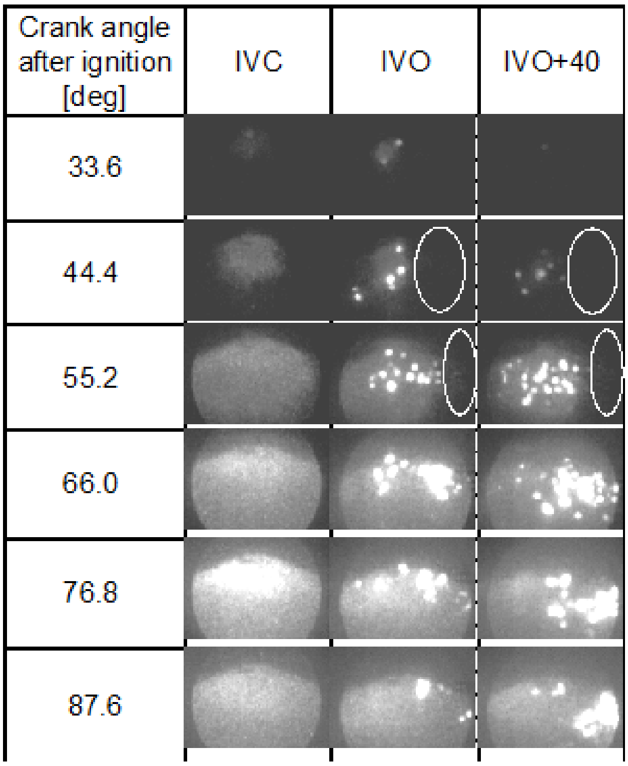


Figure 15 Flame propagation with different injection timing in System 2. Flame propagation is suppressed in the circles.

background flame with weak brightness. There is no luminous emission with injection timing of IVC.

Shown in Figure 14 are typical images of flames in System 4 at different injection timings. These figures are the images extracted from a cycle with the cycle-averaged peak pressure of 2 MPa among 500 observed cycles. Small number of luminous emissions is observed at IVO, IVO+40 in Figure 14. These emissions can be seen in almost all cycles with injection timing of IVO and IVO+40. There is no luminous emission at IVC. These results in System 4 are coincident with those of System 1.

<u>Effect of injection timing with spray targeting valve under low load condition</u>

Here we try to see the effect of injection timing on flame image in System 2 where Cov of NMEP is sensitive to the injection timing. Shown in Figure 15 are images of flame at different injection timing in System 2. Flame size is the smallest with injection timing of IVO+40 in the images at 33.6 degCA after ignition timing. Luminous emissions are observed with injection timing of IVO and IVO+40, but not IVC. Luminous emissions are observed under spark plug and exhaust side. Number of luminous emissions for

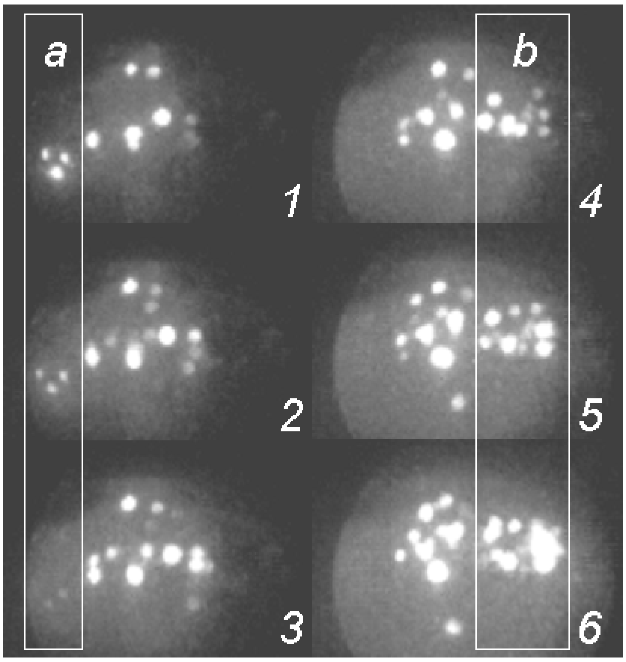


Figure 16 Luminous emissions at injection timing of IVO in System 2, captured at every 2.4 degree after 48 degrees of ignition timing. a; Luminous emission disappears, b; Luminous emission enlarges.

IVO and IVO+40 condition is greatly larger than that of System1 and 4.

Luminous emissions can be classified into two types. One is small and disappears relatively quickly. The other stays for a long time and has various sizes. Shown in Figure 16 is an example of series of flame images with injection timing of IVO, captured at every 2.4 degree from 48 degrees after ignition timing. Focusing on square “a” in Figure 16, smaller luminous emissions disappear finally, though other emissions stay longer. The emissions in square “b” grow larger, and even connect each other in this series. Let us notice that this does not necessarily mean physical coalescence due to the property of the borescope, very deep depth of field.

As to the relationship with flame propagation, emissions quickly disappeared seem to have no influence on flame propagation, considering the thin emission in the image, which represents flame propagation, passes without any interference with them. On the other hand, large block of emissions shows behavior related more to flame propagation. The initial flame propagation is more distorted and tends to besuppressed on the exhaust side with injection timing of IVO and IVO+40 as shown in the circles in Figure 15. After the flame passes, large block of luminous emissions are frequently found in the region.

Luminous emission under wide open throttle condition

Here we try to see the flame under high load condition. Combustion images are shown in Figure 17 in all injection systems with injection timing of IVC. Firstly, let us notice that the flame propagation depends on injection system and timing much less under high load condition than low load. Therefore, we will focus on the luminous emission.

Small luminous emissions are observed among all systems. These luminous emissions are observed in most of cycles in all tested injection systems with all injection timing. The size of the luminous emissions is similar to that seen under low load condition. Figure 18 shows the comparison of the flame image with injection timing of IVO+40. The number of the luminous points is smaller in System 4 than System 2.

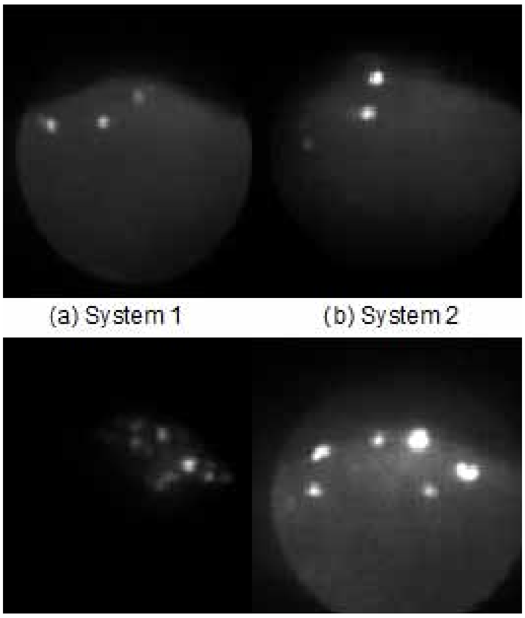
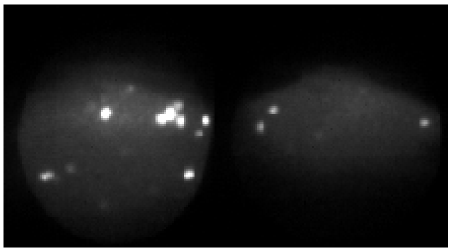
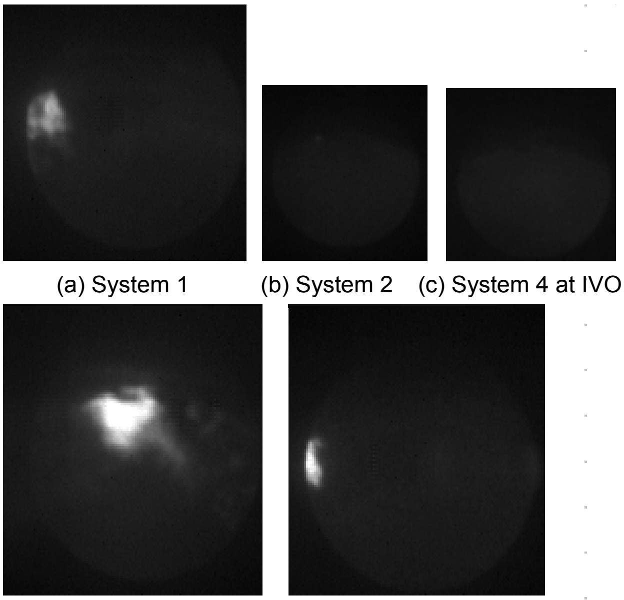


Figure 17 Images of flame at 32.4 deg aTDC under wide open throttle with injection timing of IVC.



(a) System 2 (b) System 4

Figure 18 Images of flame at 32.4 deg aTDC under wide open throttle with injection timing of IVO+40.



(d) System 3 (e) System 4

Figure 19 Flame images at 100.8 deg aTDC under wide open throttle with injection timing of IVC except (c).

Next, shown in Figure 19 are images in combustion chamber in all injection systems with injection timing of IVC, extracted at 100.8 deg aTDC. The bulky luminous emissions are still observed after heat release. This is found usually with injection timing of IVC. This is never found with injection timing of IVO (Figure 19 (c)), except in System 3 in which it is observed with all injection timings at all cycles. It is rarely observed in System 2, once every ten cycle. They are observed at intake (left) side at System 1 and 4 at IVC timing (Figure 19 (a), (e)), and center at System 3. The luminous emission area in System 3 is bigger than in other injection systems.

DROPLET BEHAVIOR AND MIXTURE DISTRIBUTION IN INTAKE PORT

Effect of injection system with IVC injection under low load condition

Behavior of fuel droplets is investigated in this paragraph using the visualization of intake port. Shown in Figure 20 is comparison of droplets near intake valve in different injection systems with the same injection timing of IVC. The field of view of these images is same in Figure 5. The timing extracting an image from the movie is when droplets start to be observed inside field of view. It was at IVC in System 2, whereas 40 CA after IVC in System 1 and 4, 15 CA after IVC in System 3.

Fuel droplets can be seen as white spots in the image. Difference between the images is due to the injection system, considering that the amount of injected fuel is almost the same among all specifications except System 3, which has twice as other cases.

Firstly, the size of fuel droplets is big in System 2 and System 3, while very small in System 4. Secondly, the number of the fuel droplets is the biggest in System 3, bigger in System 2. These facts can easily be explained by the layout of injection and SMD. Injection target area of System 2 and 3 allow fuel droplets to reach directly toward the area near the intake valve. In System 3, all fuel is supplied into one side of the intake port. Fewer and smaller droplets found in System 1 support an assumption that the most part of the spray sticks on the wall as wall film, and the number of the droplets, made by rebound or splash of the spray at the wall, is small. Considering still much fewer and smaller droplets in System 4, enhancement of evaporation and suppression of rebound or splash of the spray are caused by smaller SMD.

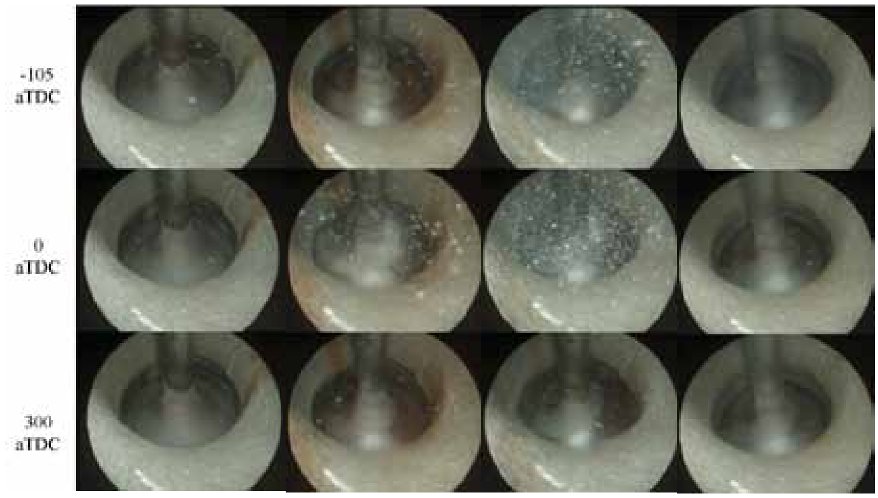
Shown in Figure 21 is behavior of droplets near the intake valve in all injection systems with injection timing of IVC. It is seen that these droplets finally disappear before IVO among all systems under this condition.

Shown in Figure 22 is comparison of droplets near bifurcation of the intake port in all injection systems with the same injection timing of IVC. The first timing extracting the image from the movie is when droplets start hitting on the wall or when droplets start to be seen inside frame. Other two images are after 20 degrees from the previous.

Impingement of the spray is observed at the lower right area in Figure 22 (a) and (j). According to Figure 22, the size of droplets in System 4 is the smallest out of all systems. The second smallest is in System 1. This infers that mixture in System 4 near zone of bifurcation is richer than that of System 1, considering smaller droplets tends to evaporate more easily.

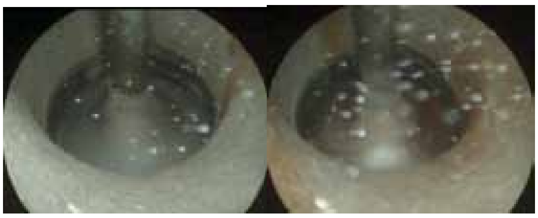
Effect of injection system with IVO injection under low load condition

Behavior of fuel droplets is compared with IVO injection in which condition CoV of NMEP shows significant difference by injection system. Shown in Figure 23 are images in all systems during intake valve open when droplets arrive near valve. As can be seen in this figure, many fuel droplets flow into the combustion chamber directly. The number of droplets near intake valve is in a row, System 3, System 2, System 1 and System 4. Droplets in System 1 and System 4 are much smaller than in System 2.

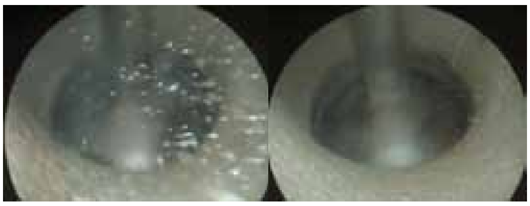


(a) System1 (b) System 2 (c) System 3 (d) System 4

Figure 21 Behavior of droplets near intake valve, IMEP; 400 kPa, injection timing of IVC.



(a) System 1 (b) System 2



(c) System 3 (d) System

Figure 20 Spray arrival at intake valve, IMEP= 400 kPa, injection timing at IVC. Timing extracted is (a) and (d): 40 deg after IVC, (b): at IVC, (c): at15deg. after IVC.

(a) -145 deg aTDC (b) -125 deg aTDC (c) -105 deg aTDC

System 1

(d) -165 deg aTDC (e) -145 deg aTDC (f) -125 deg aTDC

System 2

(g) -165 deg aTDC (h) -145 deg aTDC (i) -125 deg aTDC

System3

(j) -135 deg aTDC (k) -115 deg aTDC (l) -95 deg aTDC

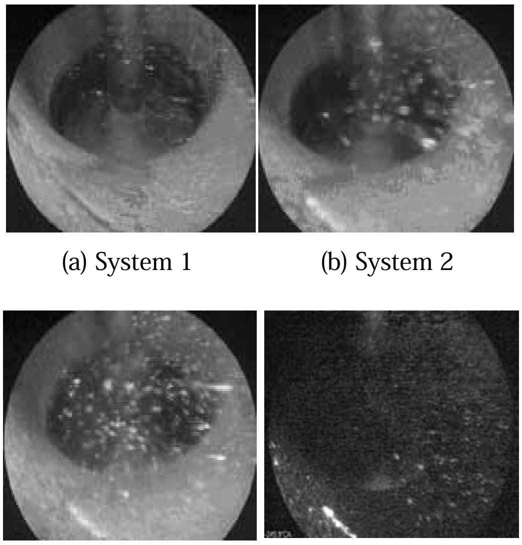
System 4

Figure 22 Spray behavior near bifurcation area in the intake port. IMEP; 400 kPa, injection timing of IVC.

Fuel droplets under wide open throttle condition

This paragraph describes the behavior of fuel droplets among systems under wide open throttle condition and compares with the results under low load condition.

Shown in Figure 24 is the comparison of images inside the intake port just before intake valve open with injection timing of IVC in all injection systems. Many fuel droplets stay even just before intake valve open with all injection systems. This is different from the result under low load in which fuel droplets almost evaporate fully at

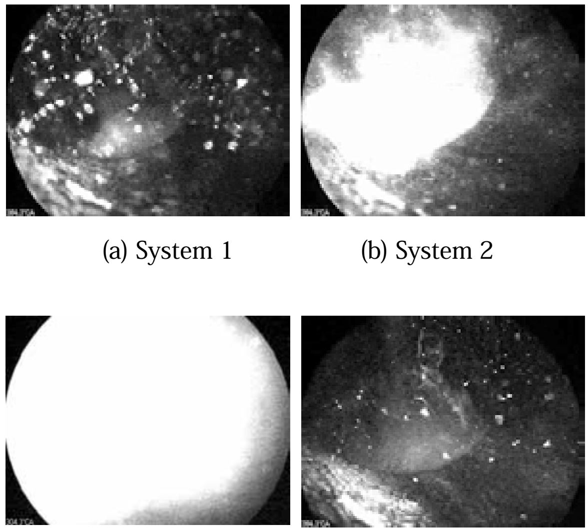


(a) System 1 (b) System 2

(c) System 3 (d) System

Figure 23 Droplet behavior with injection timing of IVO, IMEP; 400 kPa

the same timing with the same injection timing of IVC. This is because more amount of fuel is injected under wide open throttle condition than low load. The size of fuel droplets in System 4 is smaller than that of System 1 as expected. In System 2 and 3, the bright white area is seen instead of small particles in the other cases. This can be regarded as many droplets stayed near the valve. The bright area is larger in System 3 than in System 2, because the amount of fuel in System 3 is larger. These droplets hang over near valve till valve open with all injection timings in all injection systems.



(a) System 1 (b) System 2

(c) System 3 (d) System

Figure 24 Spray images of view inside intake port at timing just before intake valve open with injection timing of IVC.

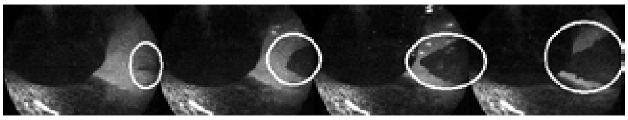


Figure 25 Wall film developments under wide open throttle at every 10 cycle with injection timing of IVO in System 2.

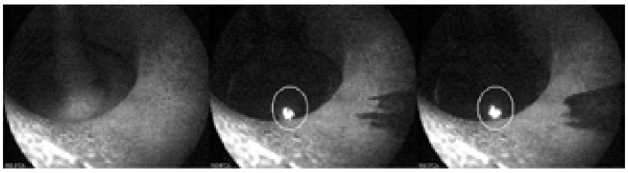


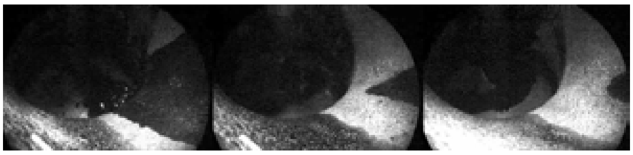
Figure 26 Wall film at intake valveis under wide open throttle at every 2cycle in System 3 at IVC. Circle: Flush light is visible in these images because of large wall film.

Wall film under wide open throttle condition

This paragraph describes the behavior of wall film under wide open throttle.

Figure 25 shows development of the wall film at every ten cycle after start of injection at a fixed crank angle. Certain amount of wall film exists with all injection systems, while it is rarely seen under low load. This wall film finally flows directly into combustion chamber in all systems.

The wall film is found usually at lower side of the intake port. In System 3, however, it is found also on the intake valve. Shown in Figure 26 are images in System 3 including the intake valve. The fact that a part of the valve circled in the figure shines confirms existence of wall film on the intake valve. This corresponds to the spray image in Figure 24 (c): intake port is fulfilled with spray in this case. On the other hand, wall film on the intake valve cannot be seen in System 2 as clearly as System 3 even with the same injection direction. It is because the amount of fuel supplied one side port in System 2 is the half of System 3. The wall film on the valve appeared only two cycles after injection starts both in System 3. It takes more cycles, and part of the intake valve is kept dry in System 1 and 4.



(a) IVC (b) IVO (c) IVO+40

Figure 27 Effect of injection timing on wall film in System 4.

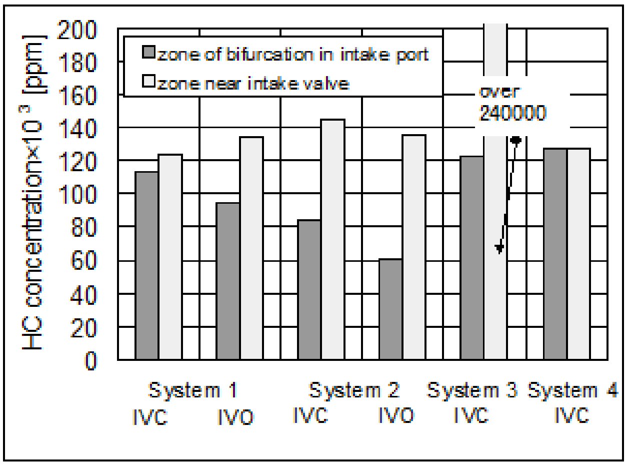


Figure 28 Hydrocarbon concentration, IMEP; 400 kPa.

With regards to wall film amount, it is difficult to estimate only by the images under steady operation. An index, instead, how fast the wall film moves, is used to evaluate the amount quantitatively. We define the number of cycles as the index between the cycle when the wall film on the lower side of intake port first appears inside view and the cycle when it finally reaches the valve.

The result is that the index is the same in System 1 and 4 with IVC, while it is eight times smaller than that of System 2 with IVC, and is three times smaller than that of System 3 with IVC. It is inferred that amount of wall film is the same level in System 1 and 4, while less in System 3, and much less in System 2. This is reasonable result considering the injection direction, while somewhat surprising that System 4, injection with smaller SMD, shows almost the same behavior as System 1. This indicates importance of the injection target even with small SMD.

The effect of injection timing is shown in Figure 27. These images show development of wall film at the different crank angle at the same cycle after start of injection in System 4. Images are extracted at different crank angle for each injection timing in order to show the image without spray. The area of wall film corresponds to amount of wall film. The wall film at lower wall is large in a row according to IVC, IVO, IVO+40. This order was common for all tested systems.

Summarizing these facts, wall films under wide open throttle condition existed with all tested injection systems. The amount of wall films along lower wall was large with injection direction to the wall and injection timing of IVC. The amount of wall films on intake valve was the largest in System 3.

Fuel concentration distribution in the intake port under low load condition

The distribution of mixture inside intake port is investigated under low load condition in this paragraph.

Shown in Figure 28 is hydrocarbon concentration at two zones, which is near the intake valve and near the bifurcation in the intake port, close to the injection target area of System 1 and 4. Hydrocarbon concentration near intake valve is too high (above 240 000 ppm) to measure in System 3.

Hydrocarbon concentration near intake valve is higher than the other zone except System 4. The difference between two zones is the biggest in System 2. This is well related to the fact that more and larger droplets is seen in System 2, as shown in Figure 20 Spray arrival at intake valve, IMEP= 400 kPa, injection timing at IVC. Timing extracted is (a) and (d): 40 deg after IVC, (b): at IVC, (c): at15deg. after IVC.20 and Figure 23. System 1 and 4, however, show only small difference between two zones. Hydrocarbon concentration at bifurcation in System 4 is higher than that of System 1 in Figure 28. These results are brought from better-atomized droplets as shown in Figure 22 (j)-(l).

4 DISCUSSION

EFFECT OF INJECTION TIMING ON COMBUSTION STABILITY UNDER LOW LOAD CONDITION

In this section, we are trying to explain how the combustion stability under low load condition is determined based on the results shown in the previous section. Generally, combustion stability is related to conditions such as instability of flame kernel growth, inhomogeneous mixture by poor mixing or incomplete evaporation, residual gas fraction and its distribution, and flow field in the cylinder. Among them, effect of residual gas and flow field can be excluded in this study, because influence of spray on it is small.

CoV of NMEP under low load condition was:

- very low and little affected by injection system with injection timing of IVC.
- sensitive to injection timing with injection targeting valve.
- high with long MFB10-90 % duration, but less related to MFB 0-10 duration.
- related with low specific emission of NOx and large specific emission of total hydrocarbon.

Firstly, let us see the relation between the flame size with constant period after ignition and CoV of NMEP. Injection with timing of IVC gives almost same CoV of NMEP regardless of injection system, and the flame shows only small difference by injection system. Even though the flame is influenced by pressure, COV of NMEP is almost same in injection system with spray targeting wall. On the other hand, in injection system with spray targeting valve, the difference of the flame is much larger than in spray targeting wall: conditions with injection timing of IVO and IVO+40 shows slow expansion of flame followed by luminous emission, and COV of NMEP is higher than the case with injection timing of IVC.

As for injection timing, luminous emission in the flame with injection timing of IVO+40 tend to continue longest, and that of IVO is the next, and that of IVC does not continue long. Considering that the large block of emissions which survives long seems to suppress flame propagation, these facts result in a good explanation of combustion instability of this condition.

Secondly, let us see the relation between the spray image in the intake port and the facts discussed above. Injection with timing of IVO and IVO+40 targeting one side of the intake port and timing of IVO+40 targeting both ports shows higher CoV of NMEP than 10%. Many large droplets have been seen at the timing of arrival at intake valve open and even at the timing of full lift of the intake valve in these conditions. These results imply that direct induction of large droplets into combustion chamber relates to combustion instability. Large droplets are hardly ever seen under other conditions when CoV of NMEP is below 10 %, however, injection with timing of IVO with spray targeting both ports shows large droplets near valves in spite of below 10 % of CoV of NMEP. This means combustion instability is not necessarily caused by direct introduction of large droplets into the combustion chamber.

Difference of mixture distribution in the intake port is well related to the droplet behavior. For example, plenty of fuel droplets reach area near the intake valve with spray targeting valve, and mixture near intake valve is richer than at upstream. This can cause the greatest inhomogeneity of mixture in the intake port. With spray targeting wall, smaller and fewer droplets near the intake valve has been seen and mixture near the intake valve is leaner than with spray targeting valve.

Combustion stability is worse when difference of hydrocarbon concentration between zone near intake valve and zone of bifurcation in the intake port is large, in case with spray targeting both valves at IVO timing.

Combining all these results together, derived conclusion is that one of the most important reasons of combustion instability is inhomogeneous mixture. This conclusion is also supported by CFD results that very rich region which cause luminous emission has been found at the exhaust side in the combustion chamber with spray targeting valves with injection timing of IVO [9]. Direct induction of larger droplets into combustion chamber is one of the important reasons to make mixture inhomogeneous. But other factors, such as mixture homogeneity in the intake port, must be considered.

Large CoV of NMEP because of inhomogeneous mixture based on injection timing and injection systems makes specific emission of total hydrocarbon high. For instance, these conditions are under at IVO and IVO+40 injection timings in System 3 and at IVO+40 in System 2. In the same way, long combustion duration (MFB 10-90 %) makes specific emission of NOx low.

Let us notice that the homogeneity of the mixture in the combustion chamber depends on not only the distribution in the intake port and direct induction of the droplets, but also gas velocity and turbulent field in the combustion chamber. CFD analysis gives quantitative information combining all of the factors above, as far as the physical models included in the code work well enough. Diagnostics may not give us quantitative information, while overall phenomena can be grasped with less supposition than in CFD. In short, both of them are necessary for efficient development of modern IC engines.

LUMINOUS EMISSION UNDER WIDE OPEN THROTTLE CONDITION

This section indicates the relation between luminous emission in combustion chamber and fuel droplets and wall film in intake port under wide open throttle condition.

As for influence on injection systems, no bulky luminous emission exists with spray targeting both valves, when wall film is smaller. On the other hand, in case with plenty of wall film at lower wall of intake port with spray targeting wall, bulky luminous emissions have been found below intake valve. And in case with plenty of wall film on the intake valve with spray targeting one side of the intake port, bulky luminous emissions have been found around center of cylinder.

As for influence on injection timing, bulky luminous emissions have been found in all injection systems except with spray targeting valve, in case with plenty of wall films at lower wall of intake port with IVC. They have not been found below intake valve with other injection timings, and the wall film is small in these cases. In case with plenty of wall film on the intake valve, they have been found only with spray targeting one side of the intake port. They have been found with all injection timings in this injection system.

Considering these relations, we can conclude bulky luminous emissions found under wide open throttle condition occurred in very rich region made by direct induction of wall film into combustion chamber. The fact that they survived after heat release in some cases implies that the wall film makes not only transient behavior slow, but also the efficiency low. Therefore, the generation of wall film must be minimized from both point of view.

POSSIBILITY OF WELL ATOMIZED INJECTOR

Finally, we would like to discuss possibility of highly atomized spray to improve both combustion stability and transient behavior within our results. Starting from the wall film generation, injection timing is very important: judging from the occurrence of luminous emission in the flame under wide open throttle, injection timing of IVC must be prevented. With injection timing of IVO, the number of the luminous points in flame images is smaller with smaller SMD. This indicates advantage of injection with small SMD: more homogeneous mixture has been formed even with direct induction into combustion chamber. The combustion stability with injection timing of IVO was kept as the same level as with injection timing of IVC under low load. Combining these results, we can conclude this system has great potential to improve combustion stability and fuel efficiency by operating engine under stoichiometry without sacrifice of transient behavior. Let us reconfirm that the injection direction is not optimized in our test: injection target is the wall. We think there must be better layout of injector, as well as the properties of the injector itself, such as spray angle. More extensive work to prove it is necessary to realize it into market.

5 SUMMARY AND CONCLUSIONS

Relation of mixture formation to combustion in spark ignition engine for motorcycle has been investigated by visualization of initial flame, wall film, fuel droplets and fuel distribution in the intake port. We have obtained conclusions as below:

- Combustion stability and combustion duration under low load condition are greatly influenced by mixture inhomogeneity in the combustion chamber.
- Mixture inhomogeneity makes high specific emission of total hydrocarbon and low specific emission of NOx.
- Mixture inhomogeneity is due to direct induction of considerable amount of liquid fuel with large size into combustion chamber and mixture inhomogeneity in the intake port.
- Combustion stability under low load condition is not influenced even with direct induction of fuel droplets into combustion chamber if they are not too many and well atomized, such as the case of System 1 and 4 with injection timing of IVO and IVO+40.
- A large quantity of fuel droplets inducted directly into combustion chamber cause luminous emission during combustion.
- Wall film is generated on the intake port wall under wide open throttle condition. Injection timing of IVC results in the largest in all tested injection systems.
- Wall film flowing directly into combustion chamber under wide open throttle causes bulky luminous emission in the flame. The area it is found depends on injection direction as below:
  - Below intake valve with spray targeting wall.
  - Around center of cylinder with spray targeting one side valve.
- Spray with small SMD of 30 μm has shown great potential to attain both good combustion stability under low load and good response due to small wall film with injection timing IVO.

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ABBREVIATIONS

AFR: Air Fuel Ratio
CA: Crank Angle
CFD: Computational fluid dynamics
CoV: Coefficient of Variation
FID: Flame Ionization Detector
IMEP: Indicated Mean Effective Pressure
IVC: Intake Valve Close
IVO: Intake Valve Open
NMEP: Net Mean Effective Pressure
NOx: Nitrogen Oxide
MBT: Minimum spark advance for Best Torque
MFB: Mass Friction Burned
SMD: Sauter Mean Diameter

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