技術論文

Analysis of Mixture Formation Process in a PFI Motorcycle Engine

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要旨

吸気管内燃料噴射システムを備える二輪車では、レイアウトの制約などによっては噴射した燃料の一部が管内壁面に付着し、レスポンスの低下等の問題を生じる場合がある。このため燃料液滴径や空間濃度分布といった噴霧の特性を理解することが重要となる。ポート内での噴霧形成を考慮する際、燃料液滴の分裂、蒸発、壁面衝突という３つの事象が不可欠となる。しかしそれらを同時に観測することは難しいため、著者らは個々の事象に分けて研究を行なってきた。これまでは液滴の分裂と壁面衝突について着目した計測を行っており、今回は液滴の蒸発に着目した。FID(Flame Ionization Detector) を用いた蒸発燃料の直接サンプル法を確立し、簡易ポート内での空間濃度分布を計測、解析した。結果、ポート内の空気流速が速くなるほど液滴がせん断力で分裂、微粒化することにより蒸発量が増加し、また流動の仕方や燃料の蒸留特性によっても容易に燃料蒸発が影響を受けることが分かった。

Abstract

PFI (Port Fuel Injection) gasoline engines for motorcycles have some problems such as slow transient response because of wall wet of fuel caused by the injector's layout. Hence, it is important to understand the characteristics of fuel sprays such as droplet size and distribution of fuel concentration. Considering the spray formation in a port, there are three kinds of the essential elements: breakup, evaporation and wall impingement. However, it is difficult to observe three of them at the same time. Therefore, the authors have made research step by step. In the authors' previous study, the authors focused on the wall collision, droplet sizes, droplet speeds and the space distribution of the droplets. In this study, the authors focused on evaporation. A direct sampling method using FID (Flame Ionization Detector) for evaporating fuel was established and the concentration distribution of evaporating fuel in the port was measured and analyzed. As a result, it was found that higher velocity in the port increases fuel concentration with enhanced atomization and that evaporating fuel is easier to be affected by the flow and fuel distillation characteristics.

1 INTRODUCTION

The fuel supply system of a gasoline engine for motorcycles is almost the port fuel injection system to meet the stringent regulation of exhaust gas emissions. This system is basically the same as of a passenger car, but due to the space restriction, the injected fuel does not necessary impinge on the intake valve as the injector is located at an upstream position. This difference may cause worse characteristics such as slow vaporization, slow time response and also fuel attachment on the intake pipe wall while it does good characteristics such as high degree of freedom in injector installation. The worse characteristics may be recovered by optimizing the injector settings. For this process, numerical simulations are useful, but the accuracy is not well evaluated and also detailed experimental study has been scarcely made [1, 2].

In the authors' previous study [3], the spray characteristics injected upstream the intake valves were investigated by using a transparent duct to allow optical access. An improved ILIDS (Interferometric Laser

Imaging for Droplet Sizing) method [4] that can measure the velocity and diameter of spherical droplets on a plane, PDA (Phase Doppler Analysis) method that can measure the velocity and diameter of a spherical droplet in a small measurement volume and also laser tomography on a plane were applied. Experiments with changing conditions such as flow speed and injection direction were carried out using these techniques. As a result, the effects of injection direction, ambient flow speed and wall roughness on the fuel-air mixture formation process were examined, considering the three conditions of cold start, light to medium load operation and high load operation.

In this study, the effect of evaporation is carefully examined. A technique to measure only the evaporated fuel (in gas phase) concentration was proposed. As the experimental parameters, fuel, flow velocity, gas temperature and measurement locations were changed. The variations of evaporated fuel concentration were examined and also used for the evaluation of spray model in a commercial code.

2 EXPERIMENTAL APPARATUS

2-1. MEASUREMENT DEVICES

Figure 1 shows the schematic of experimental apparatus. An acrylic passage with a square cross-section of 20 x 20 mm was used. To make a cross-flow to spray inside the passage, an electric blower was installed with a laminar flow meter. The exit of the passage was connected to a vacuum pump to adjust the pressure in the passage.

A port fuel injector with four holes, spray angle of 5 degrees and volume flow rate of 145 cc/min was employed using n-heptane or i-pentane as a fuel and injection pressure was set at 0.3 MPa as a standard condition. The injection direction was set at 30 degrees to the flow axis as shown in Fig. 1. Heaters were installed in the upstream to control the inlet gas temperature.

Figure 2 shows a gas sampling device of designed for only evaporated gaseous mixture. At the tip, a flange is attached to make a flow separation, removing liquid film or droplets into the probe. By taking high-speed video, it was confirmed that no liquid film or droplet was sucked into the probe. The inner diameter of probe is 0.41 mm. To avoid the condensation of fuel inside the probe, the probe was heated with rubber heaters.

The amount of sampled gas was controlled using a DI (Direct Injection) injector as shown in Fig. 3. The sampled gas was stored in a chamber of 1.93L. An electric fan was attached to the chamber to make homogeneous gas

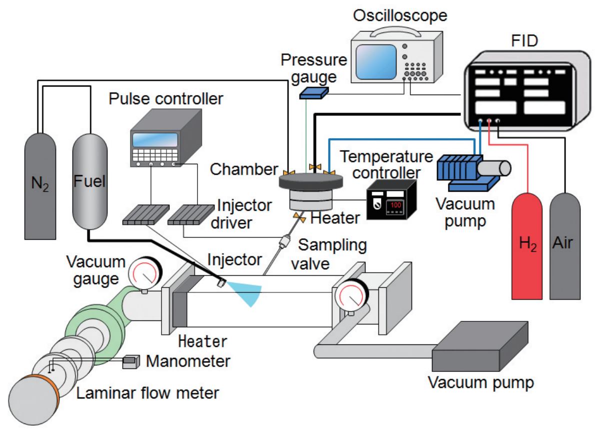


Fig.1 Experimental setup

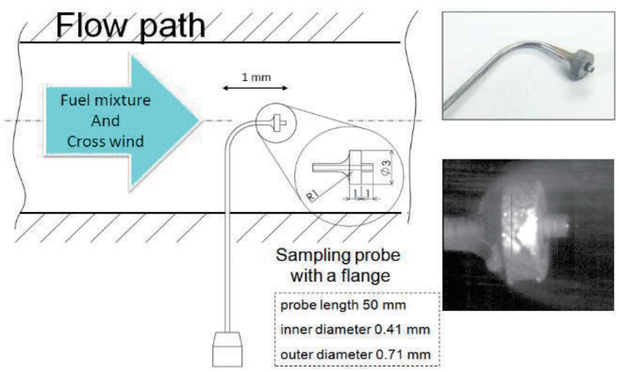


Fig.2 Gas sampling probe

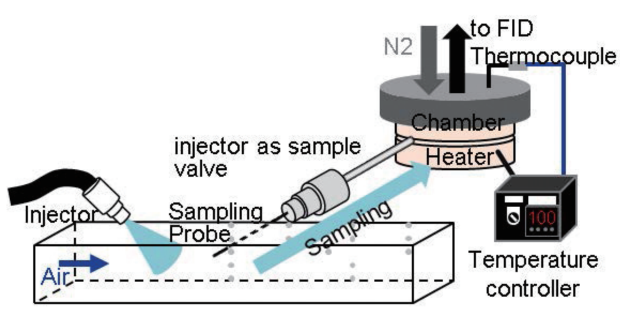


Fig.3 Schematics of gas sampling system

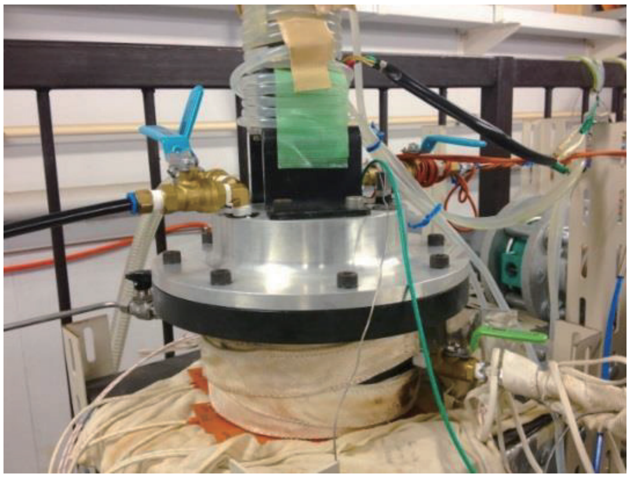
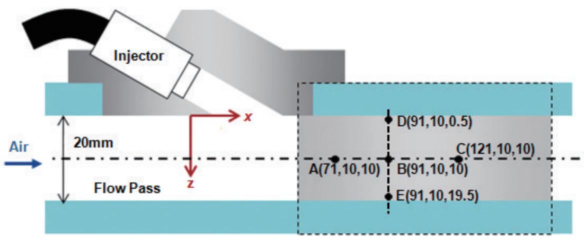
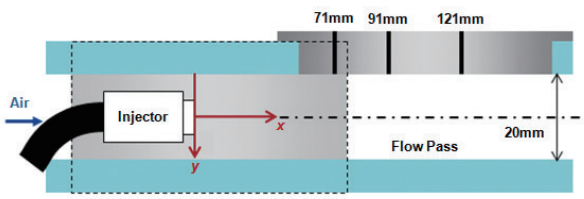


Fig.4 Picture of the sampled gas chamber



(a) side view



(b) top view

Fig.5 Measured points of gas sampling

inside. Also, the chamber was heated at over the boiling point of a fuel. Pressure sensor and thermocouples were installed to the chamber. The picture of the sampled gas chamber is indicated in Fig. 4.

Figure 5 shows the measured points of gas sampling. Points A~C are on the center-line of the passage while D, B, E are points on a vertical line.

2-2. EXPERIMENTAL PROCEDURE

The evaporated mixture's concentration was measured by the following procedure; (1) evacuate the chamber, (2) start injections of fuel from PFI injector and gas sampling, (3) charge N2 into the chamber to measure the mixture concentration using a FID.

Table 1 : Experimental conditions

Fuel (Boiling temperature [C])	i-pentane (28) n-heptane (98)
Cross wind velocity [m/s]	40, 60
Temperature of flow path [C]	25, 60, 90
Fuel pressure [MPa]	0.3
Injector	4-holes for PFI
Injection/Sampling frequency [Hz]	2
Injection duration [ms]	15
Sampling duration [ms]	3.3
Sample start time (ASOI) [ms]	0, 5, 7.5, 10, 15, 20, 40

Table 1 indicates experimental conditions. Two kinds of fuel with different boiling points were used.

3 EXPERIMENTAL RESULTS

3-1. SPATIAL DISTRIBUTION

Figures 6~11 show the temporal changes of local equivalence ratio with varying flow velocity, gas temperature or fuel. Figures 6, 8, 9 and 11 indicate that a richer mixture was found at closer position to the injector. A direct photograph of spray with n-heptane, velocity 60 m/s and gas temperature of 25 C at 7.5 ms after start of injection (ASOI) is shown at Fig. 12(a). The picture indicates liquid fuel in white and the area of liquid expands and the intensity becomes weak in the downstream because the injected fuel diffuses in the passage. As a result, the richer mixture was found at closer positions to the injector.

Comparing Figs. 7 and 10, the local equivalence ratio takes the maximum at point E in Fig. 7 while at point D in Fig. 10. Figures 12(b) and 12(c) indicate the direct pictures using n-heptane and i-pentane, respectively with flow velocity of 40 m/s and gas temperature at 60 C at 7.5 ms after start of injection. Figures 7 and 13 are results of n-heptane where the ambient gas temperature is under the boiling point of the fuel 98 C. When the gas temperature is less than the boiling point of fuel, much liquid fuel remains in the passage that are difficult to be affected by the ambient flow. Figure 12(b) also indicates that the injected fuel is not carried on by the flow, but impinges on the wall and flow along the lower wall. This causes fuel-enrichment near the lower wall.

Meanwhile, when i-pentane was used, most fuel is evaporated as its boiling point is 28 C. Figure 12(c) indicates less white area compared to Fig. 12(b) due to evaporation. As a result, much evaporated fuel are easy to follow the flow near the upper wall and the equivalence ratio at point D increased. This result means that an evaporated fuel concentration strongly depends on the evaporation characteristics of fuel.

3-2. EFFECT OF FLOW VELOCITY

Figures 13~15 show the effect of gas velocity. The larger the gas velocity is, the larger the local equivalence ratio is. Figure 16 indicates that most of injected fuel does not follow on the flow but impinges onto the bottom wall while Fig. 17 does that fuel spray follows on the flow and that more homogeneity of mixture was achieved. The reasons were found why the equivalence ratio increases with larger gas velocity; fuel atomization effect and fuel evaporation on the fuel path where fuel is carried on.

Here, let us consider the effect of fuel atomization. When fuel is injected into a field with high flow velocity, atomization of fuel is enhanced. The generated small droplets are easy to evaporate. When the fuel keeps liquid phase long, the path of gas and that of liquid fuel are different. Thereby, fuel enrichment near the bottom wall was found. However, when evaporation is enhanced, the paths of gas and fuel are similar to each other. As a result, more homogeneous mixture can be prepared.

3-3. EFFECT OF GAS TEMPERATURE

Figures 18, 19 and 21 show experimental results. Higher gas temperature causes higher equivalence ratio. The direct pictures with different gas temperatures of 25, 60, 90 C with n-heptane, with velocity 40 m/s at 7.5 ms ASOI are shown in Figs. 22, 23 and 24, respectively. Comparing these pictures, higher temperature causes less white area due to enhanced evaporation. The spray angle is affected by the gas temperature as decreasing the liquid fuel component brings about the less impingement of fuel onto the bottom wall.

Meanwhile, Fig. 21 indicates that the relationship between local equivalence ratio and temperature. Except point A, the relationship was not clearly shown. To examine this, observing Figs. 25 and 26, no liquid fuel (white area) was found at the measured points except A. Moreover, equivalence ratio at point C takes higher value than at B, closer to the injector with velocity 40 m/s. For this reason, most of fuel impinges and bounds as indicated in Fig. 27(a). Meanwhile, equivalence ratio increases as increasing the x distance with velocity 60 m/s. For this reason, most fuel follows on the strong flow with enhancing evaporation with x distance as indicated in Fig. 27(b).

Finally, in Fig. 10, equivalence ratio at point D takes exclusively higher value than at B or E. For this reason, evaporated fuel can follow on the gas flow as indicated in Fig. 20.

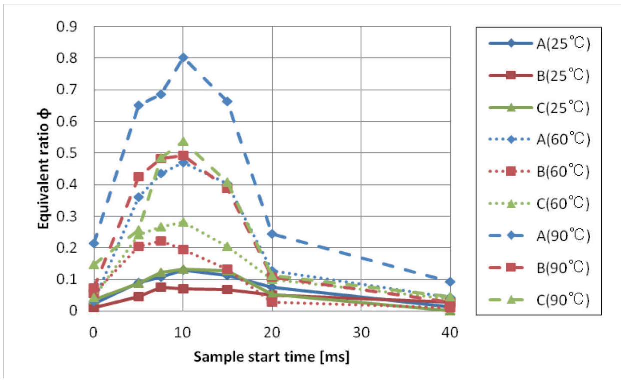


Fig.6 Equivalent ratio (n-heptane, 40 m/s)

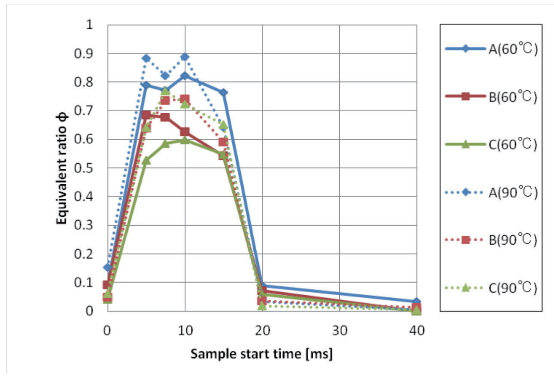


Fig.9 Equivalent ratio (i-pentane, 40 m/s)

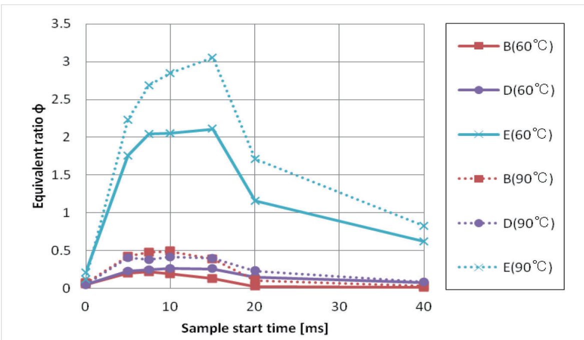


Fig.7 Equivalent ratio (n-heptane, 40 m/s)

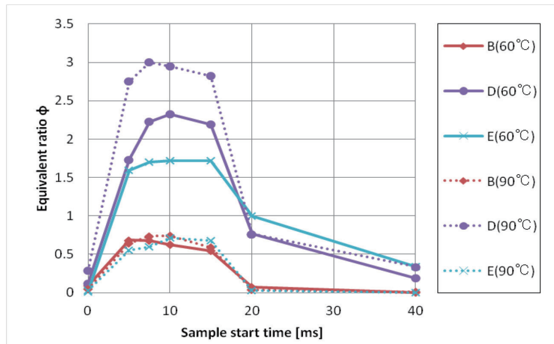


Fig.10 Equivalent ratio (i-pentane, 40 m/s)

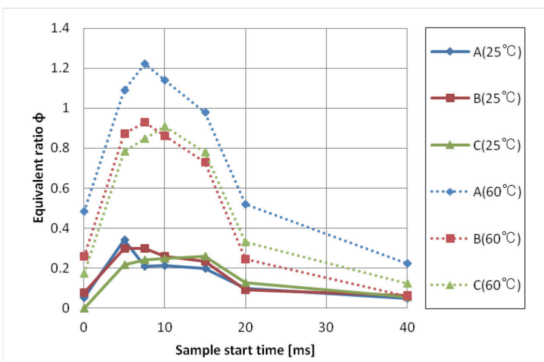


Fig.8 Equivalent ratio (n-heptane, 60 m/s)

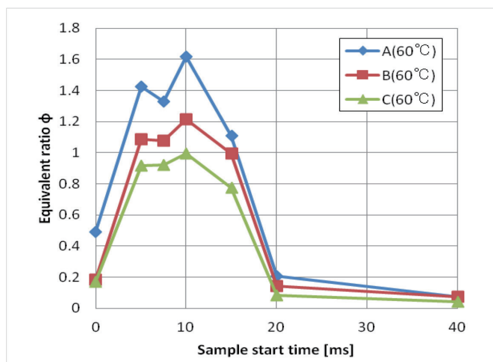
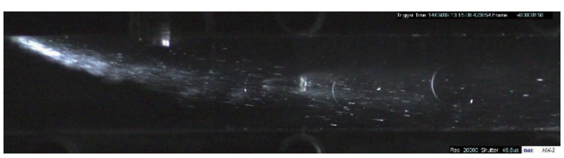
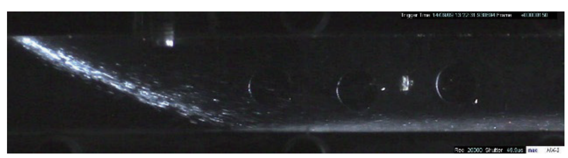


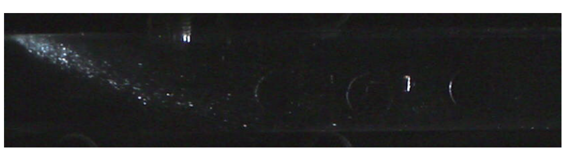
Fig.11 Equivalent ratio (i-pentane, 60 m/s)



(a): n-heptane, 60 m/s, 25 C, 7.5 ms



(b): n-heptane, 40 m/s, 60 C, 7.5 ms



(c): i-pentane, 40 m/s, 60 C, 7.5 ms

Fig.12 Pictures of spray

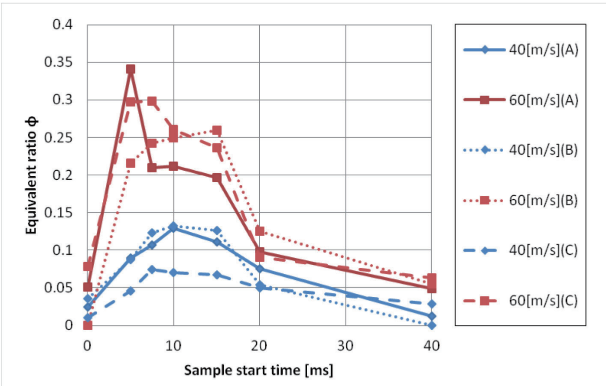


Fig.13 Equivalent ratio (n-heptane, 25 C)

Fig.16 Spray picture (n-heptane, 40 m/s, 60 C, 7.5 ms)

Fig.17 Spray picture (n-heptane, 60 m/s, 60 C, 7.5 ms)

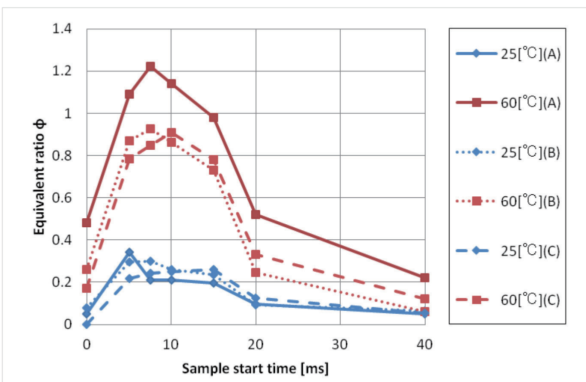


Fig.14 Equivalent ratio (n-heptane, 60 C)

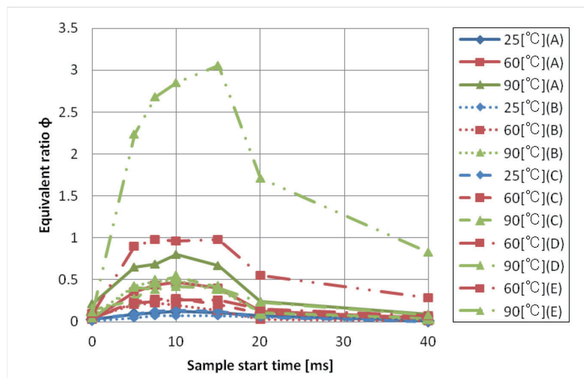


Fig.18 Equivalent ratio (n-heptane, 40 m/s)

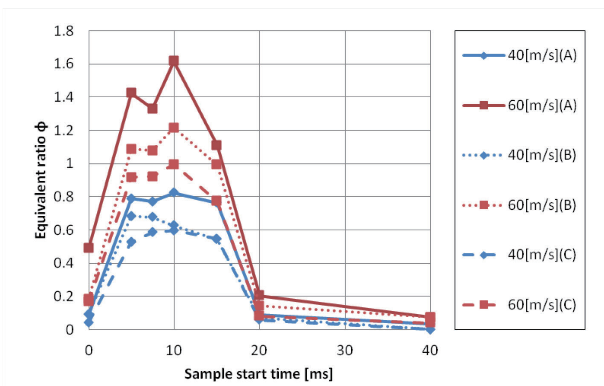


Fig.15 Equivalent ratio (i-pentane, 60 C)

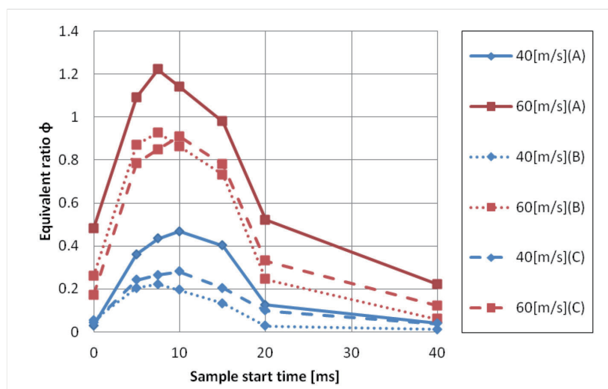


Fig.19 Equivalent ratio (n-heptane, 60 m/s)

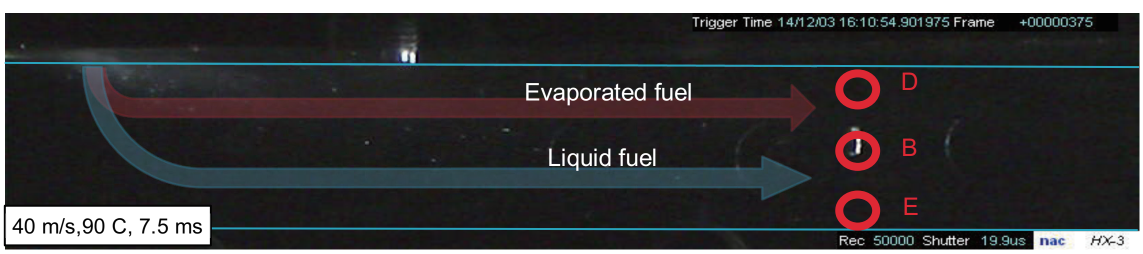


Fig.20 Passages of evaporated fuel and liquid fuel

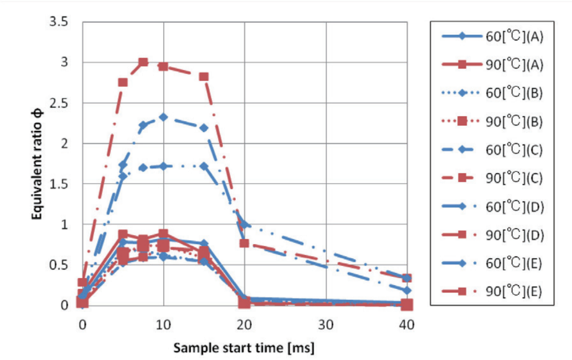


Fig.21 Equivalent ratio (i-pentane, 40 m/s)

Fig.22 Spray picture (n-heptane, 40 m/s, 25 C, 7.5 ms)

Fig.23 Spray picture (n-heptane, 40 m/s, 60 C, 7.5 ms)

Fig.24 Spray picture (n-heptane, 40 m/s, 90 C, 7.5 ms)

Fig.25 Spray picture (n-heptane, 40 m/s, 90 C, 7.5 ms)

Fig.26 Spray picture (i-pentane, 40 m/s, 90 C, 7.5 ms)

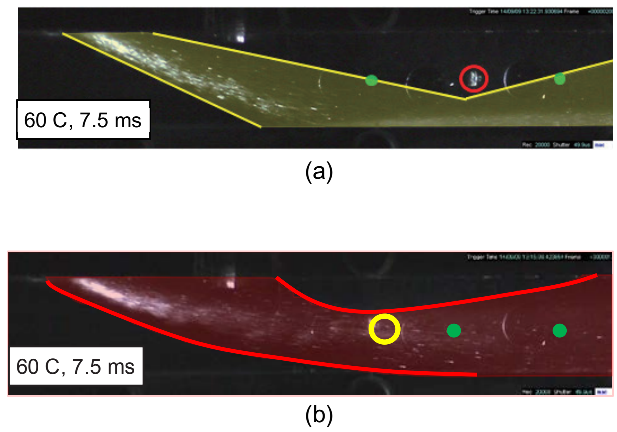


Fig.27 Picture of injected fuel with liquid fuel area presumed

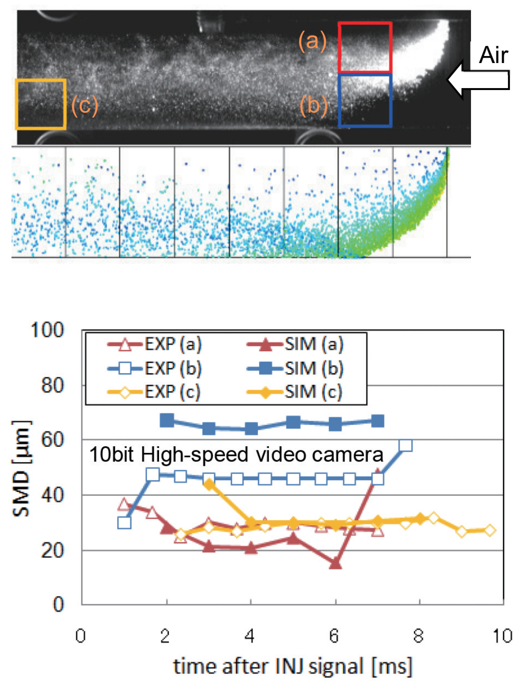


Fig.28 Comparison of SMD between calculation and measurement at three areas

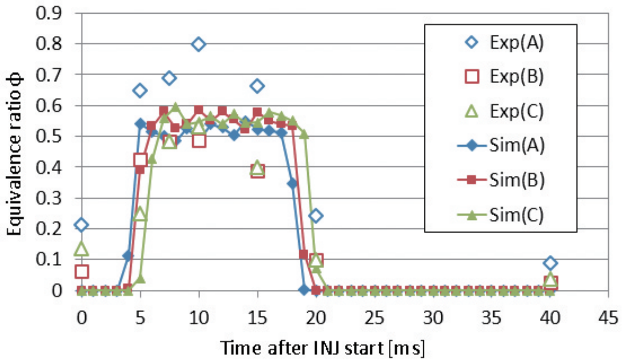


Fig.29 Comparison of equivalence ratio between calculation and measurement at three positions (n-heptane, 40 m/s, 90 C)

3-4. DISCUSSION

The mixture formation process was analyzed by using two techniques of the local vapor concentration measurement and the visualization. As a result, main three factors were found: the boiling point of fuel, the wall impingement of fuel and the cross-flow. As the evaporation is enhanced, the fuel easily follows on the gas flow. When the liquid fuel impinges on the wall, some scatters in droplets and some flows along the wall, leading to local rich mixture. The cross-flow may curve the spray and cause classification of size of droplets, leading to mixture stratification.

In the authors' previous study [2] where the effect of evaporation was not accounted for, the following conclusions were deduced; 1) When the ambient flow speed is high, most droplets of a spray do not impinge on the wall, but when the flow speed is low, some or most droplets impinge on the wall and then be convected by the flow. This difference causes different atomization characteristics at the intake port far downstream, 2) In the upstream region, due to the difference of the locally relative velocity between the ambient flow and the droplet, when the injection is made to the same direction of the flow, SMD (Sauter Mean Diameter) of droplets becomes small with high flow velocity compared to with low flow velocity, 3) In the downstream region, the droplet size shows smaller value when the flow velocity is low. This is probably due to that the effect of wall impingement is more dominant than of breakup by the ambient flow, 4) The effect of wall impingement was examined. When the flow is slow, a large difference in SMD was found at injection direction of -60 degrees (oncoming to gas flow).

In this study, not only the atomization effect examined in the previous study but also the evaporation effect was examined. As a result, the distillation characteristics of fuel, classification of droplets and follow-up of droplets to gas flow were found to enhance making homogeneous mixture.

4 EVALUATION OF SPRAY MODEL

4-1. MODELING OF SPRAY

Numerical simulations were carried out using RICARDO VECTIS code [5]. Figure 28 shows the comparison of SMD of droplets between calculation and measurement. The injection angle is 90 degrees to the flow using n-heptane and the wind velocity is 72 m/s in room temperature and pressure. In both areas (a) and (c), a good agreement was found. In area (b), calculated result indicated larger value due to the wall impinging model that is formulated on the basis of empirical study and mass, momentum and energy conservation constraints [6]. In this calculation, employing the revised drag force model of droplets that accounts for the vertical and horizontal distortion of droplet [7] caused better predictions.

In Fig. 29, the comparison of local equivalence ratio is shown. The calculation results indicate good agreements to each other at different positions except at point A.
The employed simulation models in VECTIS were found fine to use as a design and analysis tool.

5 CONCLUSIONS

In order to prepare a controlled fuel-air mixture for motorcycle gasoline engines, the numerical simulation is widely used for its design. As the mixture formation process is complicated, spray models such as breakup, drag force, evaporation and wall impingement are quite important to make accurate predictions. However, these models have not been evaluated with experimentally measured data. The authors tried to evaluate these models in the previous paper except the effect of evaporation. Thereby, in this study, the effect of evaporation is carefully examined to analyze the above effects and also to evaluate the simulation models used for the design of the fuel supply system of motorcycles. As a result, the following conclusions were deduced.

(1) A technique to measure the evaporated fuel (only gas phase) concentration was originally proposed. The accuracy of this method was confirmed by using different fuels with different boiling point.

(2) A fuel spray is diffused along its passage getting to a homogeneous mixture. The effects of fuel distillation characteristics, injection angle and wall impingement must be accounted for to make quantitative predictions.

(3) The larger the gas velocity is, the larger the evaporated fuel concentration becomes. Also, the enhancement in atomization and evaporation will enable the mixture control by controlling the gas motion. Meanwhile, the higher the gas temperature is, the higher the evaporated fuel concentration takes.

(4) Evaluation of spray models employed in a simulation code was carried out. As a result, the predictability of a commercial code was found good and appropriate for a design and analysis tool.

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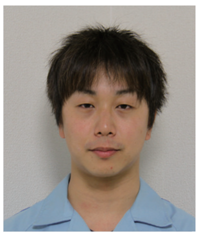

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