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Measurement and simulation of wall-wetted fuel film thickness

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ABSTRACT

In gasoline engines, the quality of fuel mixture preparation in the intake has a strong influence on the performance and exhaust emission. This paper deals with the basic research on the fuel mixture preparation process, and reports the experimental and numerical investigations on characteristics of the wall-wetted fuel film. In the experiments, iso-octane mixed with 3-pentanone was injected against a flat wall. The film thickness on the wall was measured by using laser induced fluorescence (LIF) technique. The film area was measured with CCD camera. Influences of the injection duration, the impingement distance, and the impingement angle on the film thickness, film length, and film area are discussed. In the numerical simulation, the commercial computational fluid dynamics (CFD) software FLUENT was used. The results show that, in the radial direction, the film thickness increases to a peak around the impingement center and then decreases eventually reaching zero at the external edge. Enlarging the injection duration could expand the film area and make the fuel film thicker. As the impingement distance gets farther, the fuel film becomes thinner, and the film area becomes smaller. Minishing the impingement angle could expand the area of the thick part of the fuel film and meanwhile make the maximum film thickness smaller.

1. Introduction

In port fuel injected (PFI) gasoline engines, liquid fuel enters the intake and atomizes into droplets. Some of the droplets vaporize and mix with air, but a fraction of them settle on the wall of the intake manifold and the backside of the inlet valves. These impinged droplets on the wall surface seem to form the wetted wall film. The fuel in the film evaporates and is transported according to the physical properties of the fuel and the engine running conditions. The fuel film acts as a fuel sink or source which may cause a loss of control of the A/F ratio in the cylinder during transient conditions. On the other hand, the wall-wetted fuel film flow provides the heterogeneous mixture formation inside the combustion chamber. As a result, it leads to the emission of high concentration unburned hydrocarbon.

The control of A/F ratio during transient conditions and the hydrocarbon emission may be improved by optimization of the mixture formation in the intake manifold. Therefore studies of the fuel mixture preparation process including the spray–wall interaction inside the intake port are very substantial. Some researchers have studied the fuel mixture preparation process inside the intake port. For example, Johnen and Haug [1] observed the fuel film development process considering the effect of air flow in the intake of a model engine. Almkvist et al. [2] measured the fuel film thickness directly on the port wall surface.

As a fundamental research on studying the fuel mixture preparation process inside the intake port, studying the interaction process as a spray impinges on a flat wall is also of great importance. There are some works relating this basic research. Park and Lee [3] performed an experimental study to investigate the macroscopic behavior and atomization characteristics of a high-speed diesel spray impinged on the wall at various injection and impinging conditions. Senda et al. [4] examined the two-dimensional distribution in wall-wetted fuel film thickness by planar laser induced fluorescence technique (PLIF). Stanton and Rutland [5,6] developed a fuel film model incorporating spray–wall interaction and spray–film interaction to simulate fuel film flow on solid wall. Stanton and Rutland [5,6] found that, the film thickness increases to a peak and eventually reaches zero at the external edge along radial direction. The film thickness peak is located near the impingement center and far away from the external edge. Bai & Gosman [7] and Han & Xu [8] have also presented mathematical models for liquid film resulting from fuel spray impinging on a wall surface. However, the computational results of Bai & Gosman [7] and Han & Xu [8] indicate that there is an accumulation of liquid along the periphery

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Nomenclature

AEOI	after end of injection
ASOI	after start of injection
C	molar concentration
CFD	computational fluid dynamics
F	fluorescent intensity
k	rate coefficient
L	film thickness
LIF	laser induced fluorescence
I_0	laser intensity
PFI	port fuel injected
PLIF	planar laser induced fluorescence
t	measurement time
t_{ASOI}	the time after start of injection
t_{inj}	injection duration
$t_{ASOI} - t_{inj}$	the time after the end of injection
TAB	Taylor Analogy Breakup

Greek symbols

α	impingement angle
ε	molar absorption coefficient

of the film. Moreover, the measurement results of Han & Xu [8] also show that the film thickness peak is located near the external edge of the film. Therefore, there are various viewpoints about the film profile after the spray impinged on a flat wall in the reported literatures.

The film thickness distribution after the fuel spray impinged on a flat wall is very important. The known film thickness distribution enables the means, such as heating the intake port wall where the thick film locates, to reduce the wall-wetted fuel film thickness.

This paper presents the study of the film profile after spray–wall interaction. The study also goes into the influence of the injection duration, the impingement distance, and the impingement angle on the two-dimensional distribution of the wall-wetted fuel film with laser induced fluorescence (LIF) technique, which enables the optimization of the injection process by modifying the injection timing and parameters.

2. Experimental setup and procedure

According to Senda et al. [4], the emitted intensity F from a fluorescent substance (tracer) is given by the following equation.

$$F = kI_0\{1 - \exp(-\varepsilon CL)\} \quad (1)$$

Where I_0 is the incident laser light intensity. k is the rate coefficient for the excited transition. ε is the molar absorption coefficient for the wavelength of the incident light. C is the molar concentration of the substance. L is the thickness of the liquid film.

Consequently, when coefficient k is determined by calibration experiments, the liquid film thickness could be worked out from the relation shown in equation (1), in the case that fluorescent tracer distributes homogeneously in the liquid film and molar concentration of the tracer C are known in advance.

The experimental setup for fuel film thickness measurement on a flat wall is illustrated in Fig. 1. Fig. 1 also shows the definition sketch of the impingement angle and the impingement distance. The light was generated by a Nd:YAG laser (Continuum), and frequency doubled to generate the fourth harmonic, 266 nm. The energy of each laser pulse was in the order of 10 mJ, and with a duration of approx. 6 ns. The diameter of the laser light beam was diminished from the original about 6 mm to the final 2 mm by a baffle for the point measurement.

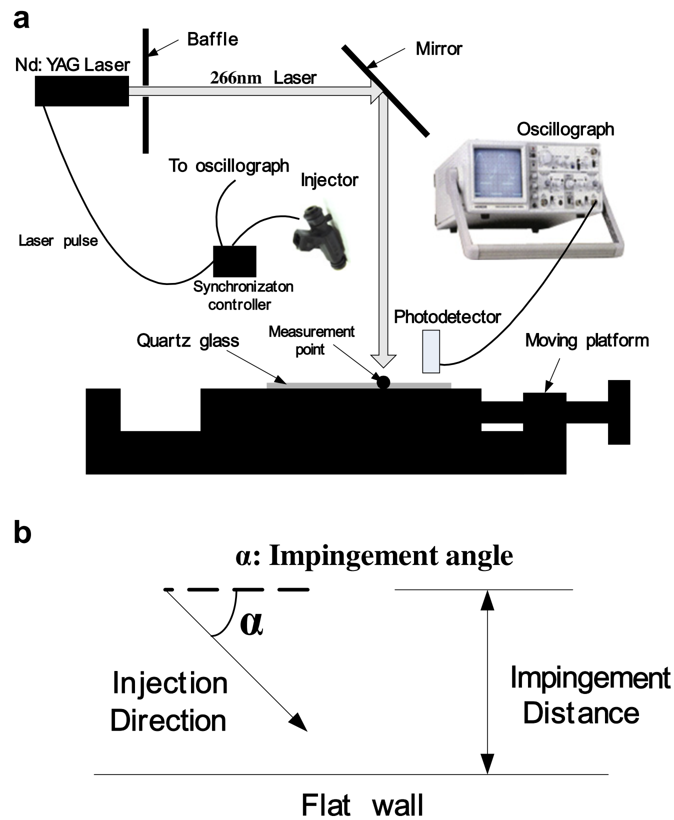

Fig. 1. Schematic diagram of experimental setup for film thickness measurement.

The fuel was iso-octane (base fuel) with 3-pentanone as a fluorescing additive. Iso-octane is a pure substance, similar in its physical properties to gasoline. And 3-pentanone is a suitable additive for the study of iso-octane. The evaporation pressures at different temperatures for 3-pentanone and iso-octane are very similar. The fluorescence emitted from 3-pentanone is near 420 nm in wavelength. The fluorescent emission from the mixtures was spectrally separated by a bandpass filter, centered at 427.5 nm with a full width of half maximum of 16.8 nm. Thereafter, the emission was detected by a photodetector and observed from an oscilloscope which could differentiate the low level signal from the much lower noise.

Mixed fuel of iso-octane with 3-pentanone of a fixed concentration 5% in volume fraction was injected through a hole type injector (Type BOSCH Y 280 K40 964-388, single hole, 0.3 mm in hole diameter) with 300 kPa in injection pressure into the quiescent environment with ambient temperature and atmosphere pressure. The spray impinged on a flat glass wall (quartz). The flat quartz glass and the injector were set on a platform which could move along the two dimensions. The minimum displacement of the platform in one dimension was 0.01 mm. The laser was fixed. The measurement position defined by the laser relative to the injector changed while shifting the platform.

For the oblique impingement case, the laser was vertical. For the normal impingement case, the mirror should be adjusted slightly so that the nearly vertical laser could detect the fluorescence emitted from the fuel film.

In equation (1), molar concentration of the tracer C and the film thickness L appear as their product $C{\cdot}L$. The influence of the product of a big C and a small L is the same as the influence of the product of a small C and a big L on the fluorescent intensity F, if the product of $C \cdot L$ keeps the same. In the calibration experiment of this paper, the film thickness L was fixed at 5.0 mm by a cuvette, while the concentration of the tracer C was changed from 0.05% to 0.025%, 0.0125% and 0.0% in volume fraction. Relation between the fluorescent intensity F and the concentration of the tracer C with fixed liquid film thickness L could be obtained. According to equation (1), the relation between the fluorescent intensity F and the concentration of the tracer C with fixed liquid film thickness L can be transferred to the relation between the fluorescent intensity F and the liquid film thickness L with fixed concentration of the tracer C. The coefficient k in equation (1) can be determined with such calibration procedure.

Fig. 2 shows the calibration curve for fluorescent intensity as a function of fuel film thickness with 3-pentatone concentration fixed at 5% in volume fraction. From the result, it can be derived that the fluorescent intensity increases nearly linearly with an increase in the film thickness. Accordingly, the fuel film thickness distribution on a flat wall could be determined with this calibration curve.

3. Results and discussions

3.1. Effect of injection duration

Experiments were conducted with the variation of injection duration t_{inj} from 4 ms, 6 ms, 8 ms to 10 ms under the conditions of 30 mm in impingement distance and to normal impingement case. In the normal impingement case, distribution of the fuel film on the flat wall should be axi-symmetric in theory. The one-dimensional distribution of the film thickness from the impingement center to one point on the external edge of the fuel film was measured. The length of the radius on the fuel film for measurement was 10 mm. The measurement points were evenly distributed every 2 mm on the radius. For one fuel injection, the film thickness for one location at a specified moment could be measured. However, if the measurement moment changed, the fuel film thickness could be determined by a repeated fuel injection. If the measurement location changed, the fuel film thickness could be acquired by a repeated fuel injection while shifting the platform.

Fig. 3 shows the film thickness distribution with the variation of injection duration. The measurement time t was equal to $t_{inj} + 10$ ms after the start of injection (ASOI). From the result, it can be seen that, the thickness summit of the fuel film was not at the impingement center but at the point where the radial distance measured from the impingement center was 2 mm. In radial direction, the film thickness increased from the impingement center to a summit, then decreased eventually reaching zero at the external edge. The reason of such result is that, at the region near the impingement center, the film experienced spray–film interaction which resulted in splashing of secondary droplets, thus the fuel film sank at the impingement center.

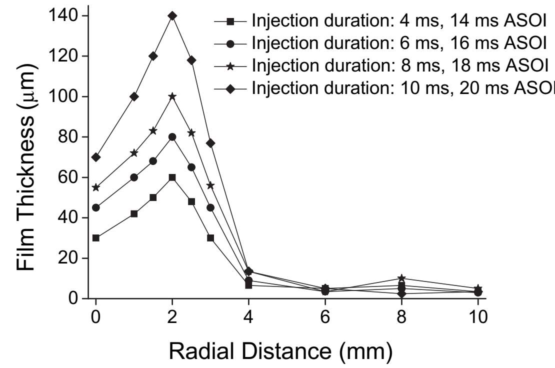

Fig. 3. Film thickness distribution with the variation of injection duration.

Fig. 3 also shows that the larger the injection duration is, the thicker the fuel film is. Because the larger the injection duration is, the more the injection fuel quantity is for 10 ms after the end of injection (AEOI).

Fig. 4 shows the film image for injection duration 8 ms. The film image was captured by a FASTCAM-APX 120KC type CCD camera. The record rate was 1000 fps, and the shutter speed was 1/1000 s. The figure shows that the fuel film seems to be a circle.

Fig. 5 shows the film area at different time with the variation of injection duration. The film area was captured from the CCD image. The time for comparing is $t_{ASOI} - t_{inj}$. t_{ASOI} is the time after start of injection and t_{inj} is the injection duration. $t_{ASOI} - t_{inj}$ denotes the time after the end of injection (AEOI). It can be concluded from Fig. 5 that, the fuel film expands till a certain time, and then the fuel film shrinks. For the 4 ms t_{inj} case, the fuel film expands till 8 ms AEOI, after then the film shrinks. For the 6 ms t_{inj} case, the fuel film expands till 9 ms AEOI. For the 8 ms t_{inj} case, such time is 10 ms. However, the fuel film continues to expand after 11 ms AEOI for the

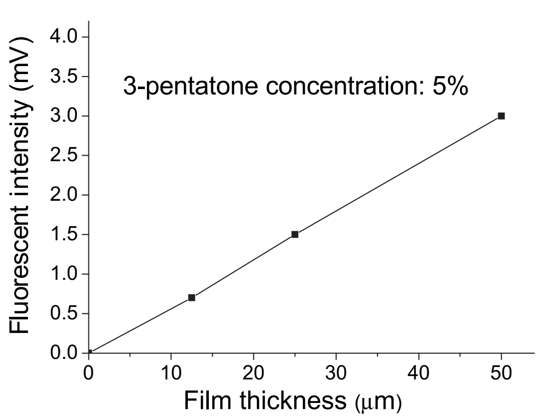

Fig. 2. Calibration curve for fluorescent intensity as a function of fuel film thickness.

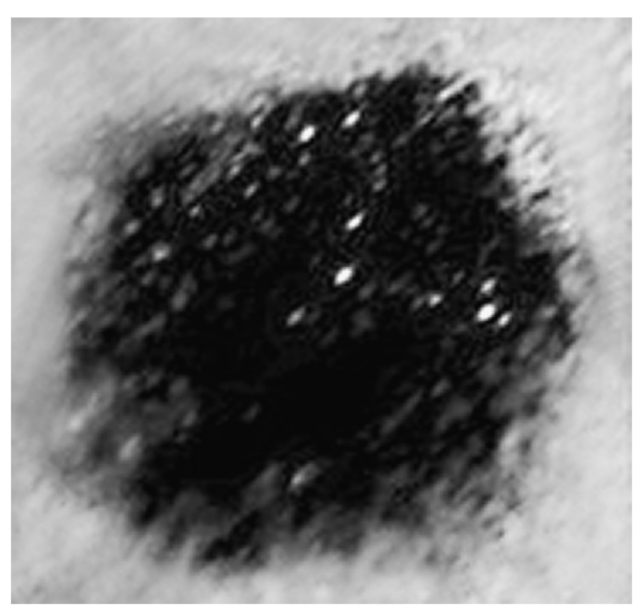

Fig. 4. Film image for injection duration 8 ms.

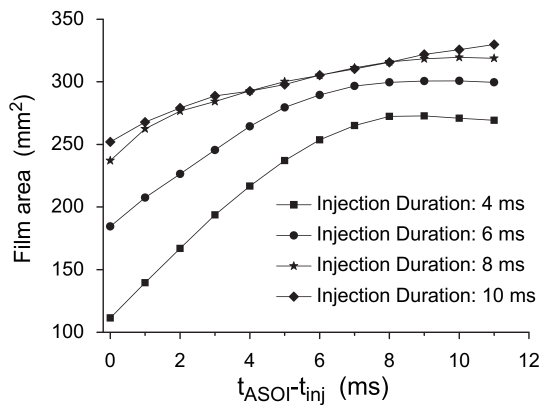

Fig. 5. Film area at different time with the variation of injection duration.

10 ms t_{inj} case. It could be deduced from the results that, as the injection duration increases, the time for the fuel film to expand after the end of injection lasts longer. The reason is that, the longer the injection duration is, the larger the momentum of the impinging fuel spray is, thus the longer the time is for the wall-wetted fuel film to expand.

Fig. 5 also shows that the film area is larger as the injection duration t_{inj} gets longer. However, the difference of the film area between different t_{inj} cases is less as the injection lasts more time. The reason is that, as the injection duration increases, the quantity of the impinging fuel spray is more, which would cause the film area expand. However the expanded film area will lead to better evaporation of the wall-wetted fuel film which would make the film area shrink. Under these two contrary effects, the difference of the film area decreases as t_{inj} increases.

Figs. 3 and 5 show that the longer the injection duration is, the thicker the fuel film is and the bigger the film area is. Therefore, it can be inferred that more and more fuel accumulates on the flat wall as the injection duration gets longer.

3.2. Effect of impingement distance

Experiments were performed varying the impingement distance from 30 mm, 40 mm, and 50 mm to 60 mm under the case of 4.0 ms in injection duration and 90° in impingement angle. The change in film thickness at the point where the radial distance is 2 mm and the impingement center with impingement distance is shown in Fig. 6. From the result, it can be concluded that, as the impingement distance increases, the film thickness decreases.

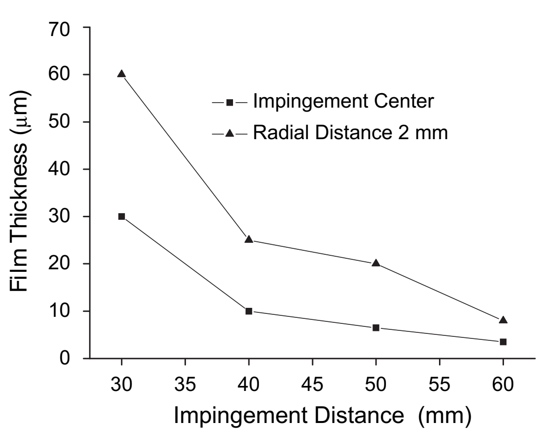

Fig. 6. Change in film thickness at the impingement center and the point where radial distance is 2 mm with impingement distance.

Fig. 7 shows the film area at different time with the variation of impingement distance. The film area decreases slightly with the increase of impingement distance. From Figs. 6 and 7, it can be deduced that, as the impingement distance decreases, both the film thickness and the film area increase, more fuel adhered on the flat wall to form the fuel film. It is because, as the impingement distance increases, it takes more time for the fuel spray to reach the flat wall. There are more fuel spray droplets entrained by the ambient air, and the evaporation of the fuel spray is better.

3.3. Effect of impingement angle

Experiments were carried out with the variation of impingement angle from 90°, 60°, 45° to 30° under the case of 4.0 ms in injection duration, 30 mm in normal impingement distance. The measurement time *t* was 14 ms ASOI.

The radius of the fuel film was 10 mm, which was measured from the impingement center. The measurement points were located every 2 mm on each radius. There were totally 12 radii evenly distributed for measurement. For one injection, the thickness of one point at a specified moment could be measured by the point measurement laser induced fluorescence technique. However, the thickness of another point or at another moment should be determined by a repeated injection.

Fig. 8 shows the two-dimensional distribution of film thickness on the wall measured by point LIF technique with the variation of the impingement angle. The coordinates of the *x* axis denote the horizontal distance to the impingement center of the measurement points located in front of or behind the impingement center along the injection direction. If the measurement points were in front of the impingement center, the coordinates are positive, vice versa negative. The coordinates of the *y* axis denote the horizontal distance to the impingement center of the measurement points in the direction perpendicular to the injection direction in the horizontal plane. The unit of the values of the contour lines which show the film thickness distribution on the flat wall is micron. As shown in Fig. 8(a), for the normal impingement case, the two-dimensional distribution of the film thickness is the same as that of the 4 ms t_{inj} case shown in Fig. 3 which was measured as an axi-symmetric case.

From Fig. 8, it can be seen that, for the normal impingement case, the thick part of the fuel film is located near the impingement center. As the impingement angle decreases, the thick part of the fuel film moves much far away from the impingement center along the injection direction due to the increasing horizontal momentum, meanwhile the area of the thick part of the fuel film increases and the maximum film thickness decreases. The maximum film thickness for the impingement angles varied from 90°, 60°, and 45° to

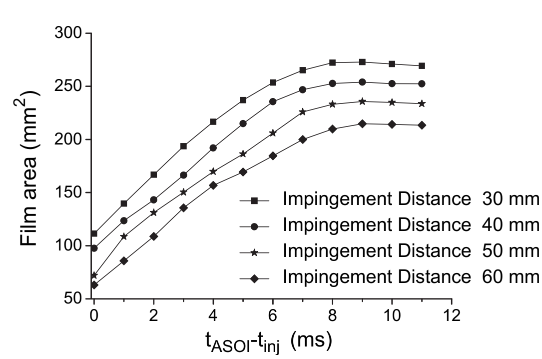

Fig. 7. Film area at different time with the variation of impingement distance.

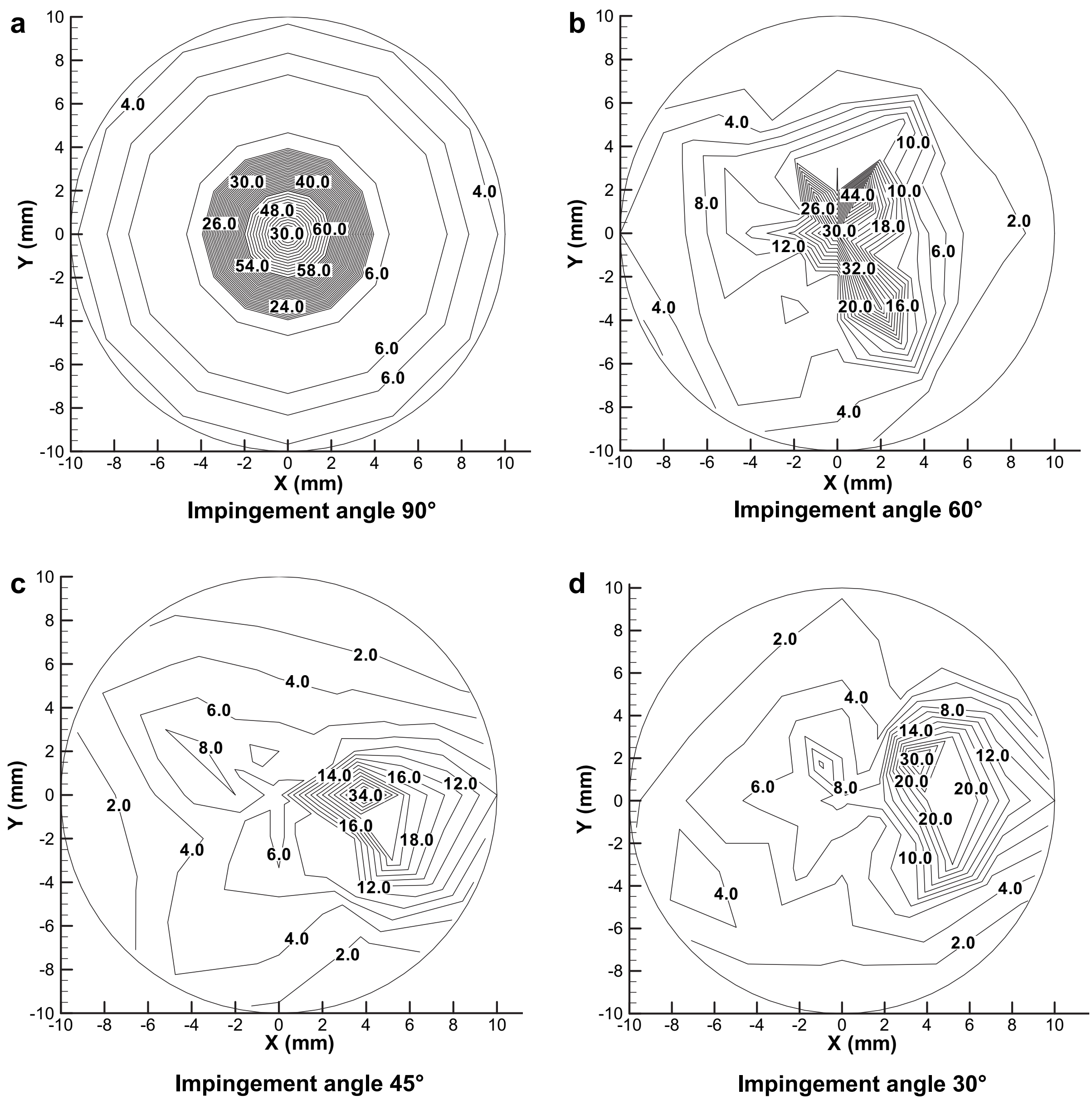

Fig. 8. Two-dimensional distribution of film thickness on the wall with the variation of impingement angle. (a) Impingement angle 90°. (b) Impingement angle 60°. (c) Impingement angle 45°. (d) Impingement angle 30°.

30° is 60 μm, 45 μm, 35 μm to 30 μm respectively. The relation between the maximum film thickness and the impingement angle is shown in Fig. 9. The results indicate that, as the impingement angle decreases, the film area increases due to the increasing horizontal momentum, thus the wall-wetted fuel film evaporates better leading to the thinner of the maximum film thickness.

Fig. 10 shows the film length at different time with the variation of impingement angle. It can be seen that, for a certain period of time after the end of injection, as the impingement angle decreases, the film length in the injection direction increases, while the film length in the direction perpendicular to the injection direction decreases. The reason for the increasing of the film length in the injection direction as the decreasing of the impingement angle is the increasing of the horizontal momentum of the fuel spray in the injection direction while decreasing the impingement angle. However the vertical impingement momentum of the fuel spray will decrease as the impingement angle decreases. This will lead to the decreasing of the film length in the direction perpendicular to the injection direction after impingement.

4. Simulation of wall-wetted fuel film thickness

Fig. 11 shows the experimental and numerical simulation results of the wall-wetted fuel film thickness distribution along the radial distance. The numerical simulation results were obtained by CFD software FLUENT. The impingement distance is 30 mm with 4.0 ms in injection duration and 90° in impingement angle. The measurement time is 14.0 ms ASOI. Discrete Phase Model was employed in the calculation. Droplet collision and the Taylor Analogy Breakup (TAB) droplet breakup model were employed in the spray model. The injection type was plain-orifice-atomizer. The inner diameter of the injector was 0.3 mm. The particle type was droplet. According to the characteristic data of the injector, the operating pressure was 300 kPa and the flow rate was 0.00125 kg/s. Temperature was 300 K.

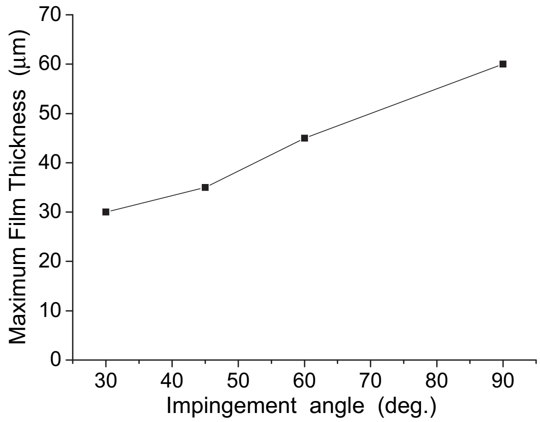

Fig. 9. Change in maximum film thickness with impingement angles.

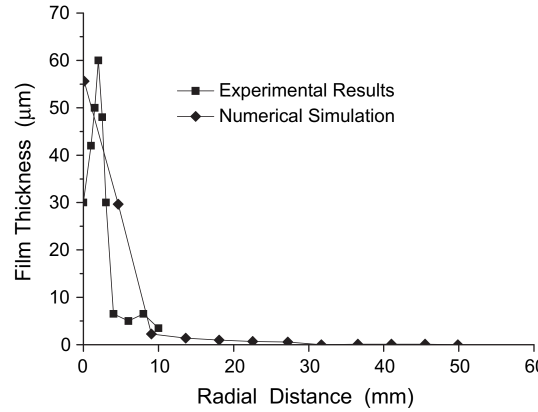

Fig. 11. Film thickness distribution with the radial distance.

The Discrete Phase Model condition for the boundary condition of the flat wall was wall film. The initial condition of the droplet size was 1 micron and the droplet velocity was about 21.32 m/s.

Fig. 11 shows that the wall-wetted fuel film mainly distributes in the area with radius 10 mm, and that the peak of the fuel film thickness is at the impingement center, rather than at the point with radial distance 2 mm, shown in the experimental results. The reason is that the Fluent code ignores the spray–film interaction in the region near the impingement center. The maximum fuel film thickness at 14.0 ms ASOI in numerical simulation results is 56.0 mm, which is a little different from the experimental results, 60.0 mm.

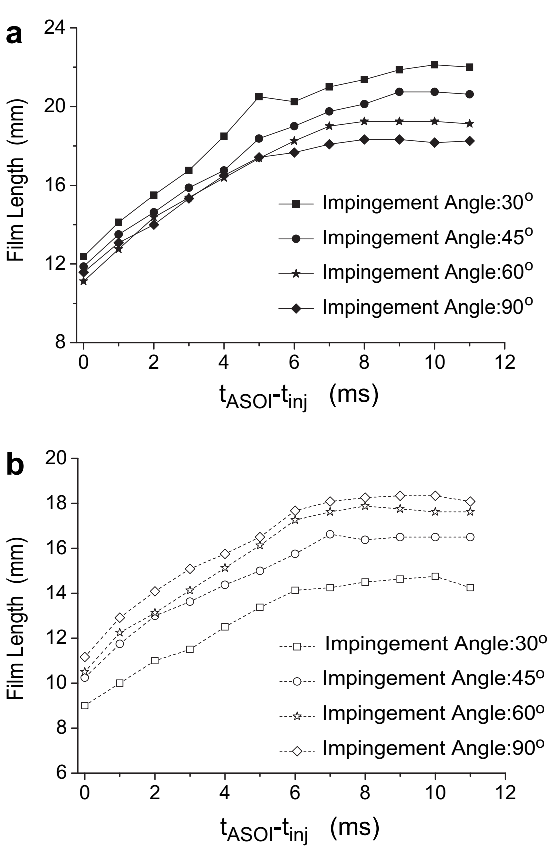

Fig. 10. Film length at different time with the variation of impingement angle. (a) Film length in the injection direction. (b) Film length in the direction perpendicular to the injection direction.

Fig. 12 shows the wall film ratio with the variation of impingement angle. The wall film ration is defined as the ratio of the mass of the wall-wetted fuel film to the mass of the injected fuel. The mass of the wall-wetted fuel film is calculated with FLUENT. As the time after the start of injection is less than the injection duration, the mass of the injected fuel is the product of the time after the start of injection and the flow rate, 0.00125 kg/s. As the time after the start of injection is greater than the injection duration, the mass of the injected fuel is the injection duration times the flow rate, 0.00125 kg/s.

Fig. 12 shows that for the impingement angle 45° case, it took 1.0 ms for the fuel to get to the flat wall. The wall film ratio increased to the maximum film ratio 44% at 5 ms ASOI, and then decreases. The time for the fuel to accumulate on the wall was from 1 ms ASOI to 1 ms AEOI, which was equal to the injection duration, 4.0 ms. After 1 ms AEOI the wall-wetted fuel decreases with time due to the evaporation of the fuel.

Fig. 12 also shows that, for the impingement angle 30° case, it took 2.0 ms for the fuel to get to the flat wall. The wall film ratio increased to the maximum film ratio 51.3% at 6 ms ASOI, and then decreased. From the result, it can be derived that, the smaller the impingement angle is, the more time it takes for the fuel to get to the wall and the more time it takes for the wall film ratio to get to its

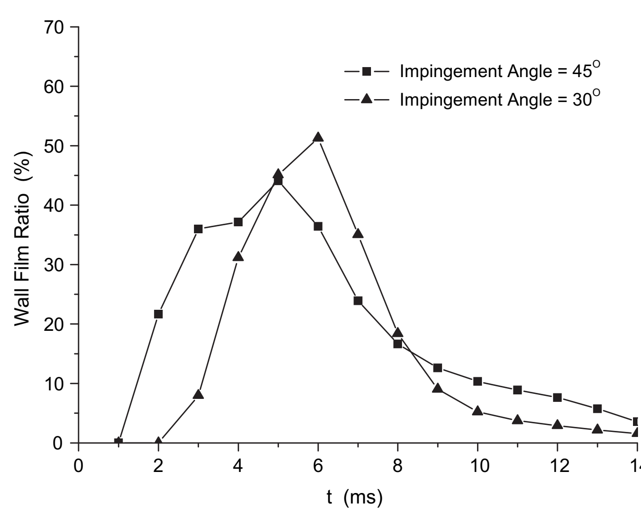

Fig. 12. Wall film ratio with the variation of impingement angle.

maximum value. For the two impingement angle 30° and 45° cases, about half of the injected fuel failed to settle on the flat wall.

From Figs. 12 and 8, it can be seen that as the impingement angle gets smaller, the maximum film thickness becomes smaller, and the maximum wall film ratio becomes bigger. This indicates that, as impingement angle gets smaller, the film area becomes bigger. Fig. 12 also shows that as the impingement angle gets smaller, the wall film ratio decreases faster. The reason is that, for the smaller impingement angle case, the fuel evaporates faster, due to the bigger film area. The results also show that, after 9 ms ASOI, as impingement angle gets smaller, wall film ratio becomes smaller. This implies that decrease the impingement angle could reduce the wall-wetted fuel film quantity.

5. Conclusions

An experimental method to measure the two-dimensional distribution of the wall-wetted film thickness by laser induced fluorescence with point measurement and numerical simulation of the wall-wetted fuel film thickness distribution have been reported. In the experiments, quantitative results could be obtained using a calibration procedure. The variables were the fuel injection duration, the impingement distance and the impingement angle. The following conclusions are drawn from the experiments and the simulation.

1. The thickness summit of the fuel film was not at the impingement center but at the point where the radial distance measured from the impingement center was 2 mm. In radial direction, the film thickness increased from the impingement center to a summit, then decreased eventually reaching zero at the external edge. At the region near the impingement center, the film experienced spray–film interaction which resulted in splashing of secondary droplets, thus the fuel film sank at the impingement center.
2. The fuel film expands after the end of injection till a certain time AEOI, after then the fuel film shrinks. As the injection duration increases, the time for the fuel film to expand after the end of injection lasts longer, due to the more momentum of the impinging fuel spray.
3. Shortening of the injection duration could reduce the film area, the film thickness and the wall-wetted fuel quantity.
4. The farther the impingement distance is, the thinner the fuel film is, meanwhile the smaller the film area is. Less fuel adhered on the flat wall due to the better evaporation of the fuel spray. Enlarging of the impingement distance could reduce the film thickness and the film area.
5. As the impingement angle decreases, the thick part of the fuel film moves from the central region to the downstream region along the injection direction, meanwhile the area of the thick part of the film increases while the maximum film thickness decreases. The film expands along the injection direction and shrinks in the direction perpendicular to the injection direction.
6. The smaller the impingement angle is, the more time it takes for the fuel to get to the wall and the more time for the wall film ratio to get to its maximum value. For the two impingement angle 30° and 45° cases, about half of the injected fuel did not settle on the flat wall. The more oblique the impingement is, the smaller the wall-wetted fuel quantity is.

Acknowledgements

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