High-Speed PIV, Spray, Combustion Luminosity, and Infrared Fuel-Vapor Imaging for Probing Tumble-Flow-Induced Asymmetry of Gasoline Distribution in a Spray-Guided Stratified-Charge DISI Engine

Wei Zeng^a, Magnus Sjöberg^a, David L. Reuss^{a,b}, Zongjie Hu^c

Abstract: In this study, the influence of intake-generated swirl and tumble flow on fuel-air mixing and combustion is investigated in a spray-guided stratified-charge direct-injection spark-ignited engine. Previously, it was demonstrated that the introduction of a combined swirl-tumble flow recovered combustion stability, which was otherwise lost when increasing the engine speed from 1000 to 2000 rpm. However the improved combustion came at the expense of elevated engine-out soot emissions. Here, high-speed combustion luminosity and PIV measurements at 2000 rpm confirm that soot incandescence is more prevalent with high swirl and tumble. The application of high-speed infrared (IR) gasoline-vapor imaging introduced here provides unique insights, revealing that operation with a combination of swirl and tumble generates an asymmetric fuel distribution that spatially correlates with highly luminous sooting combustion. The IR fuel-vapor imaging technique collects line-of-sight mid-infrared thermal emission from the C-H stretch band of the heated fuel near a wavelength of 3.4 μm . The IR images resolve the penetrating vapor plumes distinctly, demonstrating that the 3.4 μm band is suitable for quantitative measurements of vapor penetration during injection. After injection, the IR images provide a qualitative description of fuel-vapor spread *without* combustion. It is found that the no-swirl case has a symmetric fuel-vapor development during the latter part of the compression stroke. In contrast, for operation with strong swirl and tumble, vapor rotation and the development of an asymmetric and non-uniform fuel-vapor distribution is observed. PIV measurements reveal that the swirl flow dominates the vapor rotation, while the tumble flow appears to be a major reason for the asymmetric fuel-vapor distribution.

Key words: *Stratified DISI Engine, asymmetric vapor distribution and flame propagation, intake-generated swirl and tumble flow, soot emissions, PIV and Infrared fuel-vapor imaging*

1. Introduction

High thermal efficiency is achievable in direct-injection spark-ignited (DISI) engines using unthrottled stratified-charge (SC) combustion [1]. However, practical implementation of SC DISI engines has been inhibited by combustion instability; in particular the occurrence of misfire and partial-burn cycles [2]. Specifically, unfavorable flow direction and fuel distribution during early kernel growth can cause complete misfires or partial burns [3,4]. Hence, there is a need for managing flow and fuel-air mixing to reduce cycle-to-cycle variation of the main combustion. Intake-generated swirl flow has been incorporated in SC DISI engines to reduce flow variability during the early flame growth period and subsequent flame propagation [4,5]. However, strong swirl can have deleterious effects on stratified combustion with asymmetric flame propagation and increased rich burning [6]. The evolution of in-cylinder swirl and tumble structures, and their interaction with the fuel spray in an SC DISI engine have been studied previously [5]. However, their impact on the distribution of gas-phase fuel has not been addressed. The work here aims at revealing the role of swirl and tumble on fuel-air mixing and combustion in a spray-guided (SG) SC DISI engine using measurements of velocity fields, liquid and gas-phase fuel distribution, and flame propagation. High-speed mid-infrared (IR) thermography of C-H stretch band provides fuel-vapor visualization, while allowing an assessment of this technique's applicability for gasoline sprays. Swirl- and tumble-flow measurements provide a basis for understanding differences in fuel-air mixing for operation with and without swirl.

2. Single-cylinder engine and operating conditions

This single-cylinder four-valve research engine was operated either with an all-metal configuration for continuously fired performance testing, or with a geometrically identical optical configuration for skip-fired imaging studies. Engine specifications and operating conditions are given in Table 1. Figure 1 shows a cross section of the combustion chamber at top-dead-center (TDC) as setup for optical measurements. The piston has a moderately deep piston bowl to aid fuel stratification. For optical operation, the engine was equipped with a piston-bowl window (Fig. 1C) and a quartz window in the end of the pent-roof section (Fig. 1D). The piston-bowl rim has a cut-out (right side of Fig. 1A) for better optical access into the bowl via the pent-roof side window (Fig. 1D). Both quartz windows are flat on the combustion-chamber side. The piston window is flat on the crank-case side for PIV experiments but concave for flame, spray, and fuel-vapor measurements, thereby creating a negative lens for a larger field of view. The presented averaged image results are based on 20 cycles for IR, and 50 cycles for flame and PIV. With both intake valves active, no in-cylinder swirl is generated and the tumble index is low, see Table 1. To induce in-cylinder swirl, the intake valve closest to the pent-roof window (the lower-right valve in Fig. 1L) is deactivated, and this also raises the tumble level. In the following, one-valve operation is labeled “strong swirl & tumble”, while two-valve operation is labeled “no swirl & weak tumble”.

The engine has a centrally located 8-hole fuel injector with a nominal included angle of 60°. A single injection during the latter part of the compression stroke delivers 12.6 mg of certification gasoline per cycle [4,5], producing a gross indicated mean effective pressure (IMEP_g) of 380 kPa. The spark-plug gap is located 13 mm away from the injector tip. Similar to Ref. [5], the injector is oriented such that two of the liquid spray plumes straddle the spark-plug gap. The intake temperature and pressure were kept constant, and nitrogen addition without gas preheating was used to simulate the dilution effect of cooled EGR. Here, crank angles are given relative to TDC combustion, *i.e.* with negative numbers during the compression stroke. Exhaust soot was measured with an AVL-415S smoke meter. A complete description of the engine hardware is provided in Ref. [7,8].

Fig. 1 Cross-section of combustion chamber at TDC (A – F); PIV measurement plane for tumble flow (H) and swirl flow (I); camera location (J & K) and camera view (L & M) for measurement through piston-bowl window (PIV for swirl, IR imaging, liquid spray and flame imaging) and through pent-roof window (PIV for tumble).

Table 1 Engine specifications and operating conditions

Bore/Stroke/ Displacement	86.0mm/95.1mm /0.55 liter
Compression ratio / Engine speed	12:1/ 2000 rpm
Ignition Energy / Duration	106 mJ / 1.0 ms
Fuel injector	Bosch 8-hole w/ 60° included angle
Injection-duration/Fuel-mass	0.95 ms /12.6 mg
Intake / coolant temperatures	25-28°C / 90°C
Injection pressure/Fuel	17 MPa / gasoline
Intake pressure (abs.) / Intake [O ₂]	95 kPa / 19%
1. One-valve operation	Swirl/tumble index=2.7/0.6
2. Two-valve operation	Swirl/tumble index=0/0.2

3. Combustion stability vs. soot generation

Based on a previous comprehensive combustion study [7], all-metal engine tests were conducted to quantify the effect of the swirl and tumble on combustion variability and soot emissions. An engine speed of 2000 rpm was selected because it is

sufficiently high that a change of the intake flow affects the combustion strongly [5,7]. At 2000 rpm, start of injection (SOI) = -49°CA provides the most stable operation for operation both with and without swirl and spark-timing (ST) needs to coincide with the end of injection (EOI) [8]. Without swirl and with intake $[O_2]=19\%$, the coefficient of variation (COV) of $IMEP_g$ is 2.7%. In contrast, COV of $IMEP_g$ is reduced to 1.4% for operation with swirl. At these operating points with $[O_2]=19\%$, the smoke level is low. Nonetheless, it is 23% higher for operation with swirl, as indicated at the left of Fig. 2. This is consistent with larger soot-containing region for the swirl case, as shown in Fig. 2. To suppress NO_x formation, it is desirable to operate with substantially lower $[O_2]$. However, this is impossible for no-swirl operation due to onset of partial burns. For operation with swirl, stable combustion can be maintained even for $[O_2]=16.5\%$, achieving 4.5g NO_x per kilogram of gasoline. Unfortunately, the smoke level becomes very high (0.89 filter smoke number) for such low- NO_x operation with swirl. This motivates an optical investigation to determine the source of the high soot emissions.

Fig. 2 Ensemble-averaged RGB images of combustion luminosity at successive mass fraction burned (MFB), for no-swirl and strong-swirl cases.

Broadband flame luminosity was acquired every 0.5°CA (24 kHz) through the piston-bowl window (Fig. 1C) by a color CMOS camera (Phantom v6.11), with 416x416 pixel resolution. A default white-balance setting (RGB=1,1,1) is used in this study to emphasize natural soot luminosity. The images reveal that the distribution of soot luminosity is different for the two cases. Differences in both fuel distribution and flame spread can potentially explain this. Based on recent results in Ref. [4], flame-spread differences are discussed first. The different directions of the early flame convection is indicated by blue dashed arrows for each case in Fig. 2, as determined from averaged images of successive crank angles (not shown here). For the no-swirl case, the regions containing strong soot luminosity are located in the 12 o'clock direction, coinciding with the dominant early flame-spread direction. For the swirl case, the rotating flow drives the majority of the early flame counterclockwise. Thus, the flame quickly reaches the piston-bowl area in the 3-6 o'clock direction, again coinciding with areas of strong soot

luminosity. The spatial coincidence of soot luminosity and early flame arrival for either flow case is consistent with the fundamental role of continuous fuel-air mixing for stratified-charge operation. Generally speaking, gas volumes that are reached quickly by the developing flame are given less time for fuel-air mixing, thereby increasing the propensity for rich soot-producing combustion. However, Fig. 2 shows that the size of the highly luminous area is substantially greater for the swirl case, and this cannot be fully explained by the observed flame-spread differences.

4. High-speed flow, spray, and IR fuel-vapor measurements

The high smoke level for operation with low $[O_2]$ together with the asymmetric soot-luminosity distribution observed for the swirl case in Fig. 2 motivate an optical examination of differences in fuel distribution caused by changes to the intake-generated flow. Flow, fuel-vapor, and liquid spray were measured. High-speed planar PIV measurements with a CMOS camera (Phantom v7.10) provide an instantaneous vector field every $2^\circ CA$, both in a horizontal swirl-plane near the spark-plug gap (Fig. 1I) and in a vertical tumble-plane between the spark-plug electrode and the fuel-injector tip (Fig. 1H). These measurements were conducted without ignition, since the flow cannot be measured when the PIV oil seed is consumed by combustion. Details of the PIV measurement and uncertainty analysis are provided in [5, 9]. High-speed liquid-spray measurements were conducted simultaneously with the flame imaging discussed above. The spray was illuminated using a high-intensity green LED with a pulse duration of $4\ \mu s$ via the pent-roof window (Fig. 1D). The optical setup of spray and flame imaging is also detailed in Ref. [9].

Mid-infrared imaging was applied to investigate the effect of in-cylinder gas flow on fuel-vapor distribution. It has been previously verified that thermal emission (thermal-vibrational radiation) from the C-H stretch band near a wavelength of $3.4\ \mu m$ indicates the presence of hot hydrocarbon fuel, which has been heated by mixing with compressed ambient gases, typically at 700 K or higher [10,11]. Thus, the IR technique is potentially suitable for this study to visualize gasoline-vapor distribution in the late compression stroke where the gas temperature is well above 700 K. The IR images were recorded with a science-grade mid-wave infrared (MWIR) camera (FLIR SC6800) through the piston-bowl window (Fig. 1C), representing a line-of-sight integration of IR emission from the fuel. The IR camera houses a 640×512 InSb focal plane array with a $1.5\text{--}5\ \mu m$ detection range. Here, 128×128 pixel IR images were acquired at 2 kHz, providing one image per $6^\circ CA$ at 2000 rpm. A 50mm f/2.4 IR lens resolves the entire cylinder bowl at a resolution of 2 pix/mm. The camera was operated with an exposure duration of 0.1 ms ($1.2^\circ CA$). The camera lens was equipped with a ‘hot’ (*i.e.* without active cooling) $0.6\ \mu m$ wide band-pass filter centered at $3.2\ \mu m$. This provides the band gap through the piston-bowl window where silica transmits, allowing imaging of emissions from the expected $3.4\ \mu m$ asymmetric stretch from CH_2 groups. This $2.9\text{--}3.5\ \mu m$ band is well

isolated from most other emitting species, including the interference from CO_2 . However H_2O bands centered at $3\text{ }\mu\text{m}$ may contribute to emission from combustion products and intermediates. Hence, the IR imaging was conducted without combustion, just like the PIV measurements. The ‘hot’ filter and black-body IR radiation from in-cylinder surfaces combine with the noise of the detector to create a noise floor ranging from 900 to 1050 image counts depending on crank angle. This indicates that the background is not perfectly uniform. However, the signal from the hot fuel vapor dominates such that the peak intensity is much higher than the noise level, as shown in IR images of Figs. 3 and 6 at various crank angles. Therefore, the variation of noise level has a negligible effect on the presented results. For the presentation of the IR images, the noise level (at -28°CA ATDC) of 950 counts is chosen for consistency and 950 counts have been subtracted from the raw data. Additionally, the IR emission from fuel vapor increases during the compression stroke due to compression heating of the gases. To compensate for this, the upper limit of the false color scale is adjusted for each crank angle to facilitate a side-by-side comparison of flow effects on the vapor distribution (see Fig. 6.).

Fig. 3 (a) Ensemble-averaged IR image and (b) spray scattered-light image with swirl. Green and blue contours correspond to dilute and dense liquid boundaries, respectively. Red arrows define radial-penetration shown in Fig. 5. (c)&(d) IR images with detected liquid contours. The dashed orange arrows in (c)&(d) indicate the expected jet trajectories.

Fig. 4 Image intensity along the line highlighted in Figs. 3a&3b

Fig. 3a presents ensemble-averaged IR images at -43°CA , 0.581 ms after SOI (aSOI), for operation with strong swirl and tumble. Figure 3b shows the corresponding ensemble-averaged liquid-spray image. The two contours in Fig. 3b correspond

to 20% (blue contour) and 3% (green contour) of maximum intensity to demarcate the dense liquid region and the more dilute liquid boundary, respectively. These two contours, and those of the no-swirl case, are superimposed on the images in Figs. 3c&3d to indicate the liquid location without obscuring the hot vapor regions revealed by the IR image intensity (discussed in section 5). The six spray plumes appear asymmetric from this view both because the injector is angled and off axis (cf. Fig. 1), and because the in-cylinder gas flow momentum influences the liquid spray at this high speed [9]. Figure 4 plots the intensity distribution for both IR and Mie-scattering images along a line across two spray plumes, as indicated in Figs. 3a&3b. It demonstrates that in the dilute region, the light intensity of the liquid decreases in the penetrating direction of each spray plume, while the IR intensity increases and reaches peak values beyond the head of the liquid (green contour). Further away from the liquid sprays, the IR intensity demonstrates sharp gradients demarcating the border of vapor phase for both spray plumes. Figures 3a, 3b and 4 provide evidence that the IR imaging is capable of detecting the penetrating gasoline vapor, and does so without interference from the background thermal emission from the cylinder head. For reference, the surface temperature between the intake valves was measured to be 365 K, and the compressed-air temperature $\approx 655\text{K}$ at -43°CA .

5. Swirl effect on liquid and vapor penetrations

Figures 3c and 3d show the liquid and vapor distributions with and without swirl, respectively. The dashed orange arrows indicate the injection direction of each spray plume. These liquid trajectories were obtained previously at an engine speed of 300 rpm, where it was demonstrated that the gas flow had a minimal effect on the liquid structure [9]. A comparison of Figs. 3c and 3d reveals that operation with swirl at 2000 rpm results in a deflection in the direction of the swirl flow for most of the eight vapor plumes. In contrast, without swirl there is no systematic deflection of either liquid or vapor, and the vapor plumes have longer radial penetrations. This is quantified in Fig. 5, which shows the averaged radial penetrations of the 11 o'clock plume (solid arrows in Figs. 3a&b) for both liquid and vapor phases. As proposed by Siebers [12], the 3% threshold is used to demarcate the liquid penetration, while the “vapor border” threshold shown in Fig. 4 is used to demarcate the vapor penetration. Figure 5 shows that the radial penetration of the liquid and vapor overlap at the beginning of injection until 0.25 ms aSOI, then separate due to vaporization of the droplets in the head of the spray [13]. Before the separation, both liquid and vapor penetrations are independent of the intake-generated flow strength. After 0.25 ms, the vapor penetrates until it reaches the bowl edge, but it is noteworthy that the swirl case has a lower penetration rate. Meanwhile, no significant difference in liquid penetration is seen between swirl and no-swirl operation. Lastly, the liquid recedes quickly after the end of injection (EOI ≈ 1 ms), due to full evaporation of the fuel droplets. Therefore, shortly after EOI, the IR emission can be attributed entirely to vapor-phase fuel.

Fig. 5 Ensemble-averaged radial penetration of 11 o'clock jet swirl and no-swirl cases, liquid penetration profiles are shown until the appearance of plasma and/or early flame-kernel.

6. Post-injection vapor distributions

Figure 6 shows the post-injection evolution of ensemble-average and single-cycle vapor distributions with and without swirl. First, it can be observed that the large-scale features of single-cycle images generally resemble the averaged images; for example, the low-intensity center and high-intensity periphery of 6a & b. This indicates a relatively repeatable fuel distribution from cycle-to-cycle, regardless of the flow conditions. For either flow case, at -28°CA (9° aEOI) the vapor that was associated with leading portions of the fuel jets is now located along the bowl edge, while vapor associated with latter portions of the injection remains near the center of the piston bowl, surrounding the spark plug. In the -22° to -16°CA range, the no-swirl case maintains symmetry of the vapor distribution. By -4°CA , the fuel vapor is relatively evenly distributed within the bowl. In contrast, the swirl case develops a pronounced asymmetry which remains at 2°CA . It is noteworthy that highest IR signal is coming from the right-hand side of the bowl area, consistent with the location of the highly luminous areas in Fig. 2. Hence, it is possible that the observed fuel-vapor asymmetry contributes to the high smoke level observed for operation with low $[\text{O}_2]$, as discussed in conjunction with Fig. 2. This observation motivates further examination of the data to identify reasons for differences of fuel-vapor distribution between the two flow cases.

First, it is appropriate to make some notes about the interpretation of the IR images. Based on the data presented in Figs. 3-5 and in Ref. [11], the IR images can be trusted for tracking the penetration of fuel vapor into air. However, after well-defined fuel-vapor plumes vanish and a substantial IR signal exists throughout the view, the interpretation can become ambiguous. Specifically, a locally higher IR signal does not necessarily mean that a richer mixture is present. A higher IR signal can also result from a vertically thicker fuel vapor volume with a fuel concentration that is equal to surrounding fuel-containing volumes. Conversely, the interpretation of areas with very low IR signal is less ambiguous and these are believed to mark areas where nearly no fuel is present. As indicated by the blue markers in Fig. 6, such low-signal areas have IR intensities near the background noise level.

(a) No swirl & weak tumble single-cycle IR (b) No swirl & weak tumble averaged IR and flow (c) Strong swirl & tumble averaged IR and flow (d) Strong swirl & tumble single-cycle IR

Fig. 6 Effect of swirl flow on vapor distribution (intake and exhaust valves highlighted in the bottom-left image)

To guide further interpretation of Fig. 6, ensemble-averaged velocity distributions in the swirl plane are overlaid on the averaged IR images. It has been demonstrated that the interaction of fuel spray and intake-generated swirl flow creates a very strong vortex near the center of the piston bowl [5]. This leads to an asymmetric fuel-vapor distribution, see Figs. 6c&d. In particular, images at -28° & -22° CA show that the vortex drives the fuel that remains in the bowl center so that it merges with the fuel located in 6 o'clock direction, causing a low-signal area between the tail of the spray and the fuel located in 9-2 o'clock direction. Images at -22° & -16° CA demonstrate a vapor rotation that transports the merged fuel vapor towards the intake side and moves fuel from the intake side towards the bowl center. These swirl-driven processes contribute to the creation of an asymmetric fuel-vapor distribution. However, since the tumble index for the swirl case is three times larger than that of the no-swirl case, the role of tumble-spray interaction for the creation of an asymmetric fuel-vapor distribution needs to be discussed as well.

Figure 7a shows that the intake-generated tumble motion is counterclockwise at -13° CA after EOI (aEOI). At the EOI, the surrounding air is being entrained into the fuel spray. The flow on the (right) intake side accelerates into the spray, but the flow on the (left) exhaust side has to reverse direction and therefore shows much smaller vectors. Shortly after injection, the flow on the exhaust side reverses again so that at 24° CA aEOI the overall flow still follows the tumble direction.

Fig. 7 Comparison of tumble flow, swirl flow and fuel vapor, after the end of injection, aEOI.

Figure 7b shows a schematic of the combustion chamber and the directions of tumble and liquid spray are indicated. The tumble-flow direction in the measurement plane is overlaid on the IR images in Fig. 7b to show how tumble contributes to the creation of an asymmetric fuel-vapor distribution. Three fuel-containing regions are selected for discussion, as indicated

in Fig. 7b at 2°CA aEOI. Regions 1 & 3 represent the fuel vapor associated with the leading portions of the fuel jets in the 3 and 9 o'clock directions, respectively. Region 2 corresponds to the tail of the spray. The schematic and image demonstrate that the enhanced tumble flow on the intake side transports fuel vapor from region 1 towards the bowl center. In contrast, the fuel vapor in region 3 cannot travel towards the bowl center, since the flow direction in the tumble-plane is dominated by the counterclockwise flow from the intake side shortly after injection. Instead, the entrained fuel in region 3 is primarily driven by the vortex, traveling along the bowl edge. In this way, the combination of swirl and tumble causes the low-signal area between regions 2&3 at 2°CA aEOI. Moreover, the strong vortex drives the tail of the spray (region 2) away from the bowl center, leading to a larger low-signal area on the exhaust side at 24°CA aEOI.

7. Conclusions

High-speed IR fuel-vapor imaging with detection in the 2.9-3.5 μ m range allows effective diagnostics of gasoline fuel-jet penetration and subsequent interactions between fuel-vapor and intake-generated flow in a spray-guided stratified-charge DISI engine. It is found that intake-generated swirl flow is effective at suppressing combustion variability, but leads to higher soot emissions. Combined high-speed measurements of velocity fields, fuel-vapor distributions and soot luminosity allow identifying a potential source of the elevated soot emissions. With swirl, the IR fuel-vapor imaging shows a vapor rotation within the piston bowl and reveals an asymmetric and non-uniform fuel-vapor distribution during the latter part of the compression stroke. Furthermore, regions with stronger IR fuel-vapor signal correlate spatially with regions that exhibits strong soot luminosity. PIV measurements reveal that the swirl flow dominates the vapor rotation which contributes to the asymmetric vapor distribution, while the tumble flow is also a major reason for the asymmetry of vapor distribution. In contrast, a more symmetric and uniform fuel-vapor distribution is observed for the no-swirl case.

Acknowledgements

This research was conducted as part of the Co-Optimization of Fuels & Engines (Co-Optima) project sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies and Vehicle Technologies Offices. Sandia is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Reference

1. C. Schwarz, E. Schünemann, B. Durst, J. Fischer, SAE Technical Paper 2006-01-1265 (2006).
2. T.D. Fansler, D.L. Reuss, V. Sick, R. Dahms, Int. J. Engine Res. 16 (2015) 260-305.
3. B. Peterson, D.L. Reuss, V. Sick, Combust. Flame. 161 (2014) 240-255.
4. W. Zeng, M. Sjöberg, D.L. Reuss, Z. Hu, Combust. Flame., 168 (2016) 166-185.
5. W. Zeng, M. Sjöberg, D.L. Reuss, Int. J. Engine Res. 16 (2015) 306-322.
6. M.C. Drake, T.D. Fansler, A.M. Lippert, Proc. Combust. Inst., 30 (2005) 2683-2691.
7. M. Sjöberg, W. Zeng, D. Reuss, SAE Int. J. Engines 7 (2014) 642-655.
8. M. Sjöberg, D. Reuss, SAE Int. J. Fuels Lubr. 5 (2012) 1096-1113.
9. W. Zeng, M. Sjöberg, D. Reuss, SAE Int. J. Engines 7 (2014) 615-632.
10. E. Tomita, K Nobuyuki, N. Atsushi, Mea. Sci. Tech. 14 (2003) 1357-1363.
11. W.E. Eagle, L. Malbec, M.P.B. Musculus, 9th U.S. National Combustion Meeting (2015).
12. D.L. Siebers, SAE Transactions, 107 (1998) 1205-1227.
13. J. Manin, Y. Jung, S.A. Skeen, L.M. Pickett, S.E. Parrish, L.E. Markle, SAE Technical Paper 2015-01-1894 (2015).

Fig.1. Cross-section of combustion chamber at TDC (A – F); PIV measurement plane for tumble flow (H) and swirl flow (I); camera location (J & K) and camera view (L & M) for measurement through piston-bowl window (PIV for swirl, IR imaging, liquid spray and flame imaging) and through pent-roof window (PIV for tumble).

Fig.2. Fig. 2 Ensemble-averaged RGB images of high-speed flame combustion luminosity at successive mass fraction burned, (MFB), imaging for no-swirl and strong-swirl cases.

Fig.3. (a) Ensemble-averaged IR image and (b) spray scattered-light image with swirl. Green and blue contours correspond to dilute and dense liquid boundaries, respectively. Red arrows define radial-penetration shown in Fig. 5. (c)&(d) IR images with detected liquid contours. The dashed orange arrows in (c)&(d) indicate the expected jet trajectories.

Fig.4. Image intensity along the line highlighted in Figs. 3a&3b

Fig.5. Ensemble-averaged radial penetration of 11 o'clock jet swirl and no-swirl cases, liquid penetration profiles are shown until the appearance of plasma and/or early flame-kernel.

Fig.6. Effect of swirl flow on vapor distribution (intake and exhaust valves highlighted in the bottom-left image)

Fig.7. Comparison of tumble flow, swirl flow and fuel vapor, after the end of injection, aEOI.