The Interaction between In-Cylinder Turbulent Flow and Flame Front Propagation in an Optical SI Engine Measured by High-Speed PIV

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Abstract: The relationship between the flow field and flame propagation is essential in determining the dynamics and effects of turbulent flow in an optical SI engine. In this study, high turbulence flow at stable operations was achieved using 12,000 rpm engine speed, 60 kPa absolute intake pressure, 14.7 A/F, and 15 deg. BTDC spark timing. The turbulent flow field and flame propagation interplay were analyzed through the simultaneous high-speed PIV measurements of the in-cylinder flow and flame front propagation under firing conditions. The intensity of the seeder used was optimized by changing the crank angle. Successful simultaneous detection of the flame front and turbulent flow was demonstrated. Strong turbulence was produced at the flame front simultaneously with the flame movement. After ignition timing, the flame accelerated in the unburned region, and a vital turbulence region occurred.

Keywords: high-speed PIV; in-cylinder flow; flame front; ignition

1. Introduction

High thermal efficiency, reduced fuel consumption, and low exhaust emissions are vital goals in automotive powertrain development concerning gasoline engines [1–3]. The dilution of the air-fuel mixture and high EGR rate have long been considered effective methods, but the cyclic variation in combustion increases for ultra-lean and high EGR rate conditions. The increase in cyclic variations is due to the instability increase in the ignition and initial combustion and the decrease in the flame propagation speed. To achieve stable ignition and initial combustion even in ultra-lean conditions, many developers are continuously innovating ignition technologies such as pre-chamber ignition, corona ignition, and microwave ignition [4–8]. These types of ignition systems are called space ignition, which is characterized by more extensive volumetric combustion in contrast to point ignition systems [9]. Using the space ignition systems, high tumble flow and squish flow are effective methods to cause higher turbulence and improve the flame propagation speed. The turbulence and vortices of the in-cylinder flow enhance the flame surface area, and this leads to increasing the flame propagation speed and burning velocity. In optimization of the turbulence, the interaction between in-cylinder flow and flame front propagation needs to be understood.

Advancements in flow measurement and turbulence measurement in the combustion chamber are making significant progress in both simulations and experiments. The predictive computational fluid dynamics (CFD) approach of large eddy simulation (LES), which was initially proposed for simulating atmospheric flows in the 1960s, has become a practical method for simulating turbulent combustion [10]. The LES model of unsteady premixed flame propagation of hydrogen-enriched methane/air has been developed and validated by di Sarli et al. [11–14]. They were able to quantify the link between the increase in laminar burning velocity and the increase in maximum pressure and maximum rate of
pressure rise for hydrogen mole fraction in the fuel. During the validation of the simulations, actual experiments using laser doppler anemometry (LDA/LDV) and particle image velocimetry (PIV) are extensively used [15–23]. We previously reported the comparison of the LDV and PIV of cylinder optical engines in the past [24–28]. In PIV, it is possible to measure instantaneously for each crank angle, which led to a discussion of the structure of instantaneous turbulence. This is in contrast with the time-averaging acquisition used by LDV to measure the turbulent intensity. Since it has become possible to measure flame front surface turbulence by PIV at the combustion field, it has become possible to discuss the flame surface and turbulence structure. We have also discussed the error reduction method during PIV measurement [29–31]. Disturbances in the flow occur during combustion and non-combustion, where flame formation and flame spread, along with interference between the flame surface and the turbulence.

Many successful approaches for measuring the flow and turbulence in internal combustion engines have been reported [32–38]. We applied the high-speed PIV technique to measure and evaluate the in-cylinder flow under firing conditions to discuss not only the flow field during intake and compression stroke but also their effect on flame propagation under firing conditions [24–31]. The results of the measurement techniques also enable the analysis of many more aspects regarding in-cylinder flow and flame front phenomena, some of which are shown in Figure 1. The residual gas remained in the firing conditions, which influenced the flow, turbulence intensity, and cyclic variation. The flow field also affects the flame propagation speed, heat release, and combustion. The large bulk flow stretches the discharge and promotes the movement of the propagating flame, while the small-scale flow impacts the flame configuration and reaction zone thickness. The correlation between bulk flow and flame front propagation in the same cycle can provide a clear indication of the optimum velocity and turbulence distribution in-cylinder to realize faster flame propagation for rapid and complete combustion.

![Figure 1. Discussion items from simultaneous measurement of the flow field and flame propagation by high-speed PIV under firing conditions.](image)

We have successfully used a visualization engine to perform PIV measurements [29–31]. This time, we will focus on the vicinity of the spark plug and discuss the relationship
between the movement of the flame front and the turbulence induced by the flame surface from the measurement of instantaneous flow results. When the flame propagates due to ignition in the combustion chamber, the flame surface movement is shifted [29–31]. The formation of turbulence accelerates before and after the flame surface, and the turbulence strength increases. The intensity of the turbulent flow where the flame surface moves increases and the flame is seen flowing into it.

This study investigated the interaction between flow field and flame propagation in detail by using high-speed PIV under firing conditions. The effects of large and small flow structures on flame propagation and configuration were discussed. The flame front detection scheme was examined, and a detailed flame front structure was demonstrated in a cycle. Cyclic variation in the flame front movement was also discussed. We focused on the relationship between the movement of the flame surface and the turbulent spots formed after that by instantaneous PIV measurement. High-level attention to the relationship between the movement of the flame surface and the turbulent spots formed was analyzed.

2. Measurement Methods

The PIV measurement setup is shown in Figure 2. The laser light sheet of 2.0 mm thickness is illuminated from the laser source (Nano L 200-15 PIV, Litron, Dantec), which is guided to the vicinity of the optical engine through the optical guide arm. The single-cylinder engine uses conventional gasoline fuel delivery through a commercial port-fuel injection (PFI) system. Solid particles composed of SiO$_2$ (diameter: 4.0 µm) coming from the seeder are injected into the chamber [32]. The scattering of light is captured by a high-resolution double frame camera (HiSense MKII, Dantec) with a resolution of 1280 × 800 pixels per frame and a 12-bit dynamic. The synchronization and settings of the system are controlled by the PC.

![Figure 2. The PIV measurement setup.](image)
windows on the top of the piston (54 mm diameter) and in the pent roof. The measurement area was focused on the region near the spark plug in the bore center section [32]. The flow distribution and initial flame were measured before and after the compressed TDC. The laser beam at the tip of the guide arm is formed into a sheet of 2 mm thickness. The laser sheet is irradiated into the cylinder from the bottom via a mirror placed under the extended piston. To visualize the flow and flame in the vicinity of the spark plug, we took images from the window of the pent roof. The maximum frame speed of a high-speed camera was 16,600 fps with a full-frame of 1280 × 800 pixels².

A solid particle with burning resistance was used as the seeding particle because of exposure to high temperature at the combustion gas. The traceability of this article is enough for the kHz order and has been proven by LDV measurement previously under similar engine operating conditions [29–31].

To evaluate the interaction between the flame front and bulk flow with high resolution, we set the interrogation area to 16 × 16 pixels². This corresponds to 0.75 × 0.75 mm². The spatial filter of 6 mm was used to separate the instantaneous local flow velocity into a low-frequency component and a high-frequency component. The flame surface was detected from the high-speed PIV images by distinguishing the burned and unburned areas. Signal intensity from the particles in the burned area was lower than that of the unburned area because the density in the burned area was low. Therefore, the flame surface can be detected by the tomography technique [29–31]. Compared to other simultaneous measurements such as LIF [39–47], it is possible to eliminate errors caused by time and space mismatching during data integration because the flow distribution and the flame surface can be detected simultaneously from the same image. The experiments were conducted under firing conditions. The engine speed was 1200 rpm, and the absolute intake pressure was 60 kPa. The equivalence ratio was a stoichiometry condition.
ignition timing was set to 19 deg. BTDC; these conditions were determined to be conducive to stable combustion and less uncertainty, as in the previous report [29–31].

3. Results and Discussions

Seeding particles inside the combustion chamber burn and disappear on the flame surface. However, since these particles do not burn out completely, the scattered light intensities of the particles are varied, and the location of the largest concentration change is defined as the flame surface [29–31]. Figure 4 shows the seeding particle density measurements in a cycle to evaluate the error source for the flame front detection scheme. The seeding image was measured by the camera, and its intensity information was used for detection.

![Figure 4. Seeding particle density variation in a cycle.](image1)

Figure 4. Seeding particle density variation in a cycle.

Figure 5 shows the techniques used to eliminate the flame emissions and optimize the visualization of the scattered particles. The flame emission is eliminated using a 20 nm width bandpass filter with a 527 m center wavelength and 93% transmittance. The particles cannot be detected if the scattering light is too dark or the number of particles is saturated. The optimum condition is adjusted based on the concentration of scattered particles.

![Figure 5. Seeding particle images in combustion flow.](image2)

Figure 5. Seeding particle images in combustion flow.

The PIV image was image-processed by dividing it into a turbulent flow component and a bulk flow component using two filters of frequencies. The high-frequency range has a cut-off frequency of 0.3 kHz. Figure 6 shows acquired maps of the velocity vector and
the corresponding turbulent energy using PIV analysis. Each image was also subjected to flame front detection by subtracting the background, inverting the image, optimizing the range, and employing binarization and boundary detection.

![PIV analysis](image1)

**Figure 6.** Image processing of the flow and turbulence detection with flame front detection.

In our approach, the flame is assumed to be traveling in a normal direction to each point along the flame boundary. The intercept between the normal line and the second frame flame boundary is calculated as shown in Figure 7. The local displacement of the flame front is then defined as the distance between the first frame flame boundary and this intercept. This process is repeated for each point along the flame boundary. The flame front thickness and flame front propagation direction were determined with this method.

![Flame front detection](image2)

**Figure 7.** Vector maps show the intercept between the normal line and the second frame flame boundary.

The flame front was detected every two consecutive laser pulses of PIV. Using this, we visualized the movement of the flame surface of the two actual operation cycles, as shown in Figure 8. Combustion pressure fluctuations were significantly different in these two different operating cycles; thus, the bulk flow was not constant and was influenced by the different intakes and exhausts. The left side of Figure 8 shows a flame propagation
velocity of about 4–5 m/s, and the flame spreads in a symmetric semi-circle. When it reaches the piston, the flame grows sideways. Under the same operating conditions, the flame propagation velocity in the piston direction points in the downward direction for both cycles. The values are also almost the same at 3.7 m/s.

Figure 8. Flame front movement for different operating cycles.
Under conditions of −12 deg. ATDC, the instantaneous velocity vector in the cylinder, the bulk flow using the low-frequency filter, the turbulent flow component using the high-frequency filter, and the vorticity are shown together in Figure 9. In the figure on the right of Figure 8, three pieces of information, velocity vector, turbulent energy, and flame plane, overlap. The flame spreads from the spark plug to the bottom in a semicircular shape. The state of the flame surface is diffused by the turbulent vortex. A large amount of turbulence is generated in the traveling direction of the flame surface. It is considered that this is compressing the unburned mixer on the flame surface, which causes turbulence. The effect of enhancing this turbulence reaches the lower left. Disturbances are also generated in the direction in which the flame points clockwise. The second graph from the right shows the flame plane and low-frequency components, that is, the bulk flow. After the flame has passed, the low-frequency component shows a low value. The bulk flow shows a large value in the flame surface squadron and points toward the lower left. This looks different in the horizontal high-frequency components. High-frequency components, that is, flame-induced turbulence, are generated at the tip of the flame surface. Vorticity shows a large bulk flow.

![Instantaneous velocity](image1)

![Low frequency velocity](image2)

![Vorticity of velocity](image3)

![High frequency velocity](image4)

**Figure 9.** Interaction of flame front and bulk flow with turbulence component as well as vorticity.

Similarly, Figure 10 shows the information on different cycles under the same operating conditions. Under conditions of −12 deg. ATDC, the instantaneous velocity vector in the cylinder, the bulk flow using the low-frequency filter, the turbulent flow component using the high-frequency filter, and the vorticity are shown together. In the figure on the right of Figure 10, three pieces of information, velocity vector, turbulent energy, and flame plane, overlap.
The shape of the flame propagation from the spark plug is very different from the previous one. First, it propagates downward. However, the features are similar. The flow is accelerated at the tip of the flame, and the turbulence increases around the flame surface where the turbulence is occurring. It turns out that the vorticity rotates greatly from side to side.

Under these two conditions, the mechanisms of acceleration of the flow by the flame and the generation of forwarding turbulence with the movement of the flame surface were clarified.

Figures 11 and 12 show the movement of a series of flames under each operating condition. Both figures also show the flame development with the overlaid vectors of instantaneous flow and turbulence flow (high-frequency component). Here, the characteristic cycles in the same test condition were extracted. Figure 11 shows a cycle (cycle A) in which the flame propagates symmetrically. On the other hand, Figure 12 shows a cycle (cycle B) in which the flame propagates with bias. In Figure 11, there is no strong flow near the spark plug at the ignition timing, and strong turbulence regions are scattered and distributed in the cylinder. After the ignition timing, the flame front propagated symmetrically across the cylinder chamber, almost like a spherical flame front structure, because of the less strong flow across the spark plug. The flame front propagates by enhancing the large-scale existing tumble bulk flow that remained in earlier crank angle locations. The high flow velocity region induced where the propagating flame front joins the existing flow also results in a high frequency, that is, turbulent flow.
In Figure 12, the center of the large-scale tumble bulk flow from the intake and compression process is much closer to the spark plug. Therefore, the initial flame kernel generated following the flow enhances the flow on the front of the flame when the flame coincides with the tumble flow. In this case, it can also be observed that when the flow moves toward the flame front, the flame front propagation and increment are restricted where the flow is moving toward the flame front. The restrictions on flame front movement lasted for quite a long period until the counter flow disappeared. In this cycle, the region of the flame front that experiences the counter flow from the tumble has a very high turbulence level that remains even when the flame front is convoluted, and the strong bulk flow goes away.

As described above, the distribution of the bulk flow having a scale as large as the size of the combustion chamber influences the overall shape of the flame propagation, and the state of the flame propagation greatly fluctuates from cycle to cycle.
The motion of the flame, as shown in Figures 11 and 12, results in an increase in the bulk flow speed and turbulence. A maximum value is formed in the traveling direction of the flame. The high-frequency component becomes large around the flame surface, and the flame surface and the unburned mixture are agitated.

Figure 13 shows the high-frequency component of flow velocity and the flame front shape near the spark location of cycle A and cycle B. Figure 13a shows the velocity distribution of the high-frequency component at −9 deg. BTDC. In this cycle, the overall flame propagation is almost symmetrical, but the local flame shape is not smooth, with several peaks and valleys. Here, the area of 7 mm × 14 mm surrounded by the white dotted line is the target area to be enlarged and investigated. Figure 13b,c show the flame shape and velocity distribution in the target area of cycle A at −9 and −8 deg. BTDC, respectively. In Figure 13b, the high-frequency velocity component was strong near the local flame peak and weak near the local flame valley. The flame at the local peak region propagates while pulling the valley region in Figure 13c.
Figure 13. The interaction between in-cylinder flow and flame propagation in the cycle. (a) The high turbulence area is highlighted and enlarged at (b) −9 deg. ATDC and (c) −8 deg. ATDC.

Figure 14 shows the high-frequency component of flow velocity and the flame shape near the spark location of cycle B. In this cycle, the flame front propagates with bias under the influence of the tumble flow. Here, the target area is 7.2 mm × 13.5 mm² in the vicinity of the spark plug, indicated by a white dashed line in Figure 14a. The local flame shape was not smooth, and there were several small peaks and valleys. Figure 14b,c show the flame shape and velocity distribution in the target area of cycle B at −9 and −8 deg. BTDC, respectively. In Figure 14b, the high-frequency velocity component was strong near the local flame peak and weak near the local flame valley, as in Figure 14b. In the lower half of Figure 14c, the flame at the local peak region propagated while pulling the valley region and the local valley region disappeared. In the upper half of Figure 14c, near the spark plug, the flame surface was pushed back to the unburned portion under the influence of the flow opposite to the propagation direction. The turbulence level of the unburned area is enhanced in these existing bulk flow streams as the flame propagates through them. Small scale eddies have a strong effect on flame curvatures and are wrinkleless, which can also help to push the flame propagation through difficult bulk-flow conditions.
Figure 14. The interaction between in-cylinder flow and flame propagation in cycle B. (a) The high turbulence area is highlighted and enlarged at (b) −9 deg. ATDC and (c) −8 deg. ATDC.

Figure 15 shows the bulk flow in the cylinder, turbulence, and flame surface in another cycle. There is the movement of the flame surface with the movement of the piston. It can be seen that the size of the turbulence scale is larger than the thickness of the flame surface.

The flame surface advances to the bottom of the cylinder. However, the magnitude of the vortex on the flame surface is almost the same. Furthermore, a peak appears in which the energy is disturbed, and the turbulent energy increases in the direction in which the flame advances. Looking at the distribution of turbulence energy, we found that turbulence on the flame surface of the unburned part was generated with the movement of the flame. The same can be seen in the previous figure. The size of the vortex that can be seen from the turbulence distribution is indicated by the colored arrow.
Furthermore, a large amount of turbulent energy is generated along with the movement of this turbulent scale. It can be seen that the value of the turbulence energy of the unburned portion is larger than the turbulence scale of the burned portion.

4. Conclusions

In this study, the interaction between in-cylinder bulk flow and flame front propagation was investigated. The in-cylinder flow field and flame front propagation in an optical engine were measured simultaneously by high-speed PIV under firing conditions. The smart flame detection method can demonstrate a detailed flame front structure and its movement over a cycle. The interaction of the flame front and the turbulent structure was successfully demonstrated over a cycle. Detailed flame front structures with unburnt and burnt regions demonstrate different characteristics. As the flame moves forward downstream, the turbulent energy is increased by the flame front movement in every cycle. The bulk flow with a scale as large as the size of the combustion chamber influences the overall shape of the flame propagation, and the state of the flame front propagation greatly fluctuates from cycle to cycle. The flame propagates by enhancing the large-scale existing tumble flow that exists in earlier crank angle locations. If we focus on the local flame front structure, the high-frequency velocity component was strong near the local flame peak and weak near the local flame valley. The flame front at the local peak region propagates while pulling the valley region. The simultaneous measurement of in-cylinder flow and flame front propagation was demonstrated under firing conditions. After ignition timing, the flame front speed increased the velocity in the unburned region, and a strong turbulence region occurred.

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