

Simultaneous Measurements of Flame Propagation Velocity and Unburned Mixture Velocity in a Spark-Ignition Engine

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Keywords: Flame image velocimetry, Particle image velocimetry, Simultaneous measurements, Spark-ignition engine

ABSTRACT

The purpose of this study is to evaluate the behavior of unburned mixture compressed by the propagating flame front in a spark-ignition engine. This study employs a compression-expansion machine (CEM) to achieve simultaneous visualization of in-cylinder unburned mixture flow and the propagating flame using a bottom-view approach, aiming to understand the structure of turbulent premixed flames and combustion phenomena. By using high-speed color camera, CW YAG laser and flame-resistant solid tracer particles, both in-cylinder unburned mixture flow and the propagating flames were visualized simultaneously. By utilizing the characteristic scattering light of laser-traced particles and the propagation of blue flames, green channel (G-channel) was extracted to detect unburned mixture flow within the cylinder, while blue Channel (B-channel) were extracted to detect propagating flames. Methods for detecting flames from the visualization images and evaluating techniques for simultaneously measuring flame propagation velocity and unburned mixture flow velocity were investigated. A comparison of the unburned mixture velocity and the flame propagation velocity revealed that the unburned mixture is compressed by the propagating flame. Regarding the vicinity of the flame front, the vorticity was calculated from the velocity distribution of the unburned mixture obtained through experiments and compared with the flame front shape. It was confirmed that the vortices in the unburned mixture were intensified in a manner that follows the shape of the elongated and protruding flame.

1. Introduction

In recent years, improving thermal efficiency and reducing emissions in spark-ignition engines has become an urgent priority from an environmental protection perspective. To meet these demands, research and development of high-dilution and lean-burn combustion technologies, such as high Exhaust Gas Recirculation (EGR) and ultra-lean burn, are actively underway. Lean combustion lowers the combustion gas temperature, enabling operation at higher compression ratios than conventional methods and offering the advantage of reducing harmful nitrogen oxide (NO_x) emissions. However, under high-dilution and leaner conditions, the reduced flame

propagation velocity causes slower combustion. To overcome this, efforts have focused on enhancing the propagation velocity by creating high-speed, highly turbulent flow fields within the cylinder. This approach, however, can also increase ignition and combustion instabilities, leading to problems such as reduced ignitability, partial combustion, and misfiring. Therefore, a detailed understanding of the relationship between in-cylinder unburned mixture flow and flame propagation is essential.

The purpose of this study is to evaluate the behavior of the unburned mixture compressed by the propagating flame front in an SI engine with methane (CH_4) as fuel. This study employs a compression-expansion machine (CEM) to achieve simultaneous visualization of in-cylinder unburned mixture flow and the propagating flame using a bottom-view approach, aiming to understand the structure of turbulent premixed flames and combustion phenomena. By utilizing a high-speed color camera, a CW YAG laser, and flame-resistant solid tracer particles, both the in-cylinder unburned mixture flow and the propagating flames were visualized simultaneously. Through the extraction of the green (G) and blue (B) channels from the RGB color channels of high-speed color camera, the unburned mixture with tracer particles and the propagating flames were independently characterized.

2. Experimental set-up

A general schematic of the spark-ignition (SI) engine used in this research is shown in Fig. 1a). The single-cylinder SI engine has a bore of 78 mm, a stroke of 67 mm, and a compression ratio of 6.8. The cylinder and mixture tank were initially charged with a homogeneous CH_4 -air mixture at an equivalence ratio (ϕ) of 1.0. The engine was driven by an electric motor at a constant speed of 600 rpm with the valve open. Air was initially introduced into the cylinder through the inlet valve at a pressure of 0.1 MPa and a temperature of 298 K. After a predetermined period, the valve was closed when the piston reached bottom dead center (BDC). The valve features a shroud to enhance swirl flow with anticlockwise rotation. The gas was then compressed and ignited by an electric spark at a selected crank angle of -15 deg. ATDC. In-cylinder pressure was recorded using a Kistler piezoelectric transducer, while the timing system supplied transistor-transistor logic (TTL) pulses from a Stanford Research System DG 635.

Figure 1b) shows the image obtained through the quartz window in the piston top. A CW YAG laser was used, shaped into a sheet via cylindrical lenses. Note that the laser sheet could not illuminate the center due to the side electrode of the spark plug. Tracer particles made of SiO_2 (mean diameter: $2.5 \mu\text{m}$) were premixed into the fuel-air mixture. The high-speed camera used was a Photron FASTCAM SA-Z, with a capture speed of 20,000 fps and an image size of

1024×1024 pixels. The capture period spanned from -15° to 12° deg. ATDC, acquiring a total of 150 images at 0.18° intervals per cycle. The spatial resolution of the obtained images is 0.052 mm/pixel .

High-speed images consist of three RGB color channels, which were utilized to decouple the combustion phenomena. By exploiting the characteristic scattering of laser-illuminated particles and the luminance of blue flames, the green (G) and blue (B) channels were extracted to characterize the unburned mixture flow and flame propagation, respectively (Fig. 2). First, the flame front is identified within the B-channel images through filtering techniques (Fig. 3); subsequently, the unburned mixture region is distinguished from the flame front using the G-channel. Particle Image Velocimetry (PIV) was implemented to resolve the velocity field of the unburned mixture; a laser sheet was projected onto the seeded particles, with displacement vectors ($\mathbf{u}$) determined via image correlation over a temporal interval (Δt). Concurrently, the flame propagation velocity was estimated via Flame Image Velocimetry (FIV) [1], which employs a similar correlation-based approach to track brightness pattern displacements. To evaluate the accuracy of the flame front velocity estimation, two different approaches were compared: a technique (Distance of Surface) utilizing cross-correlation between two consecutive flame front images and the FIV method. Figure 4 illustrates the velocity vectors derived from both approaches. While the image correlation technique resulted in a high density of erroneous vectors, the FIV method demonstrated superior robustness with negligible errors. Consequently, the FIV method was selected for calculating the flame propagation velocity. This methodology enables the simultaneous acquisition of both unburned mixture dynamics and flame propagation characteristics.

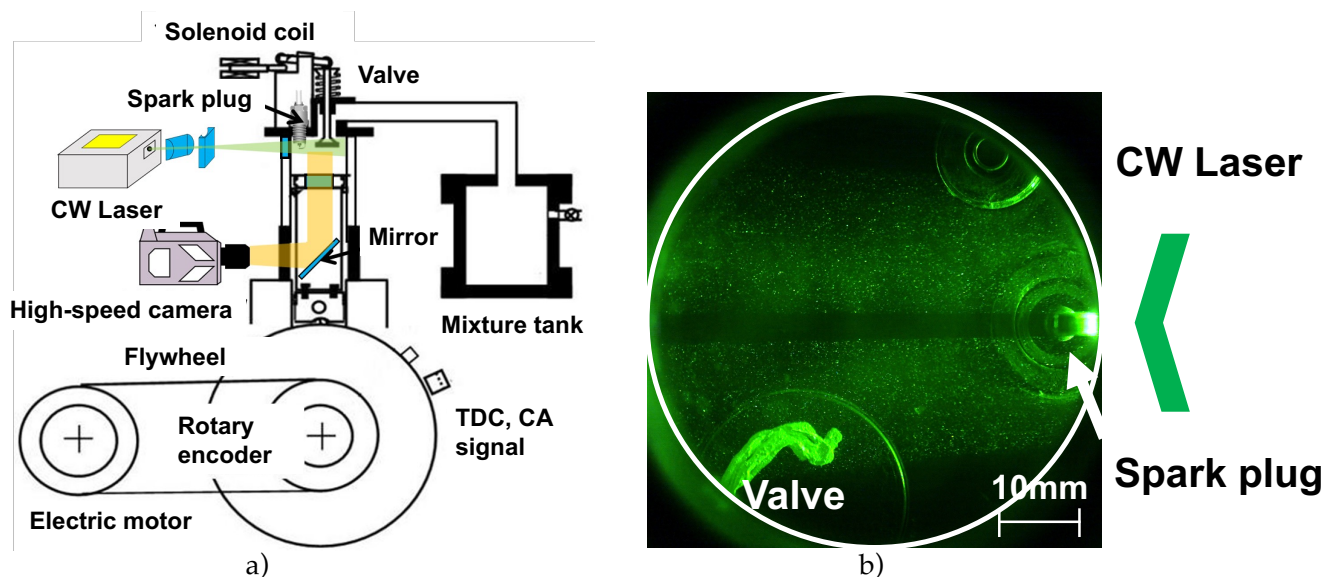


Figure. 1 Experimental set-up

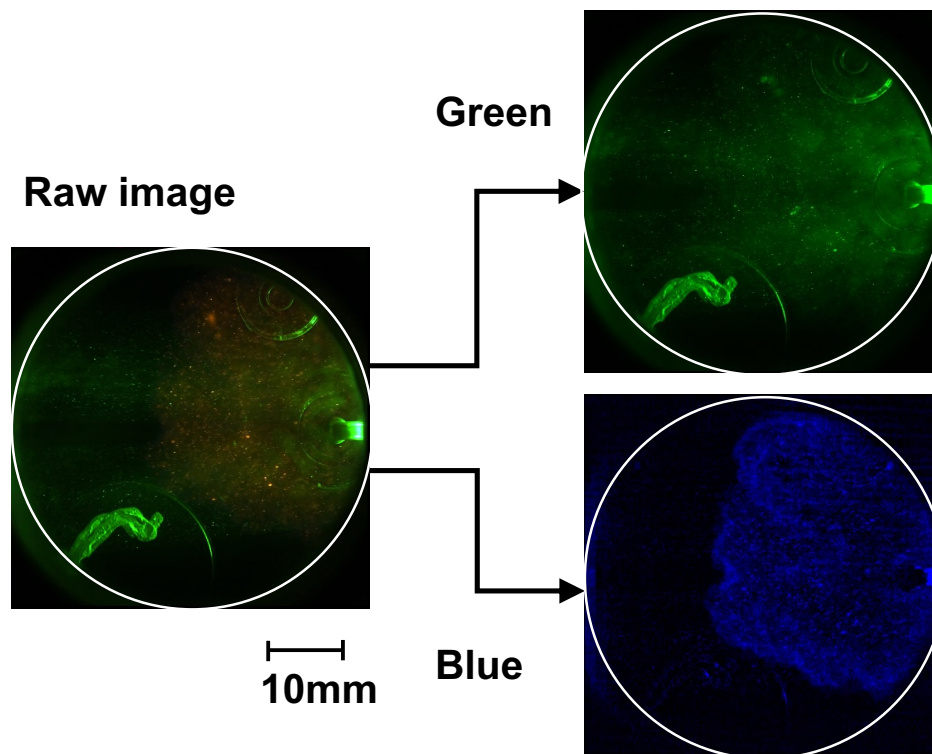


Figure. 2 Green and blue components of obatined image

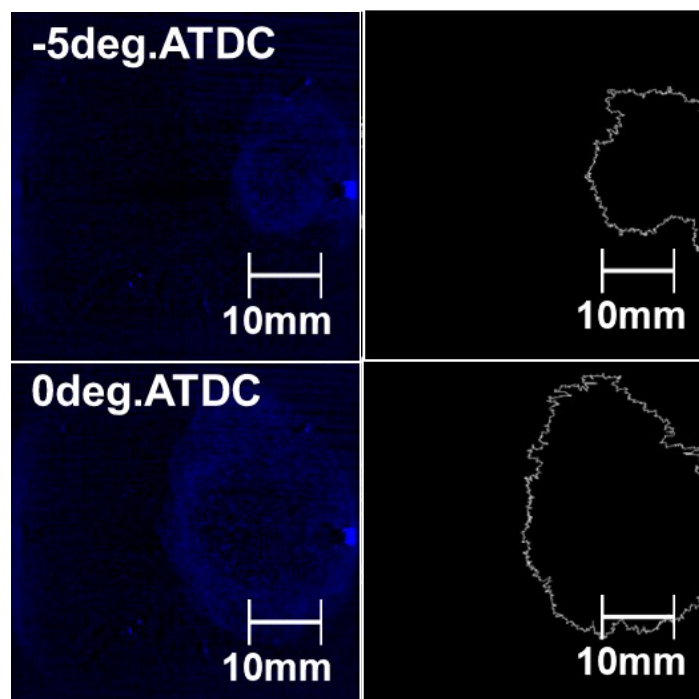


Figure. 3 Detection of flame surface using blue component of obatined image

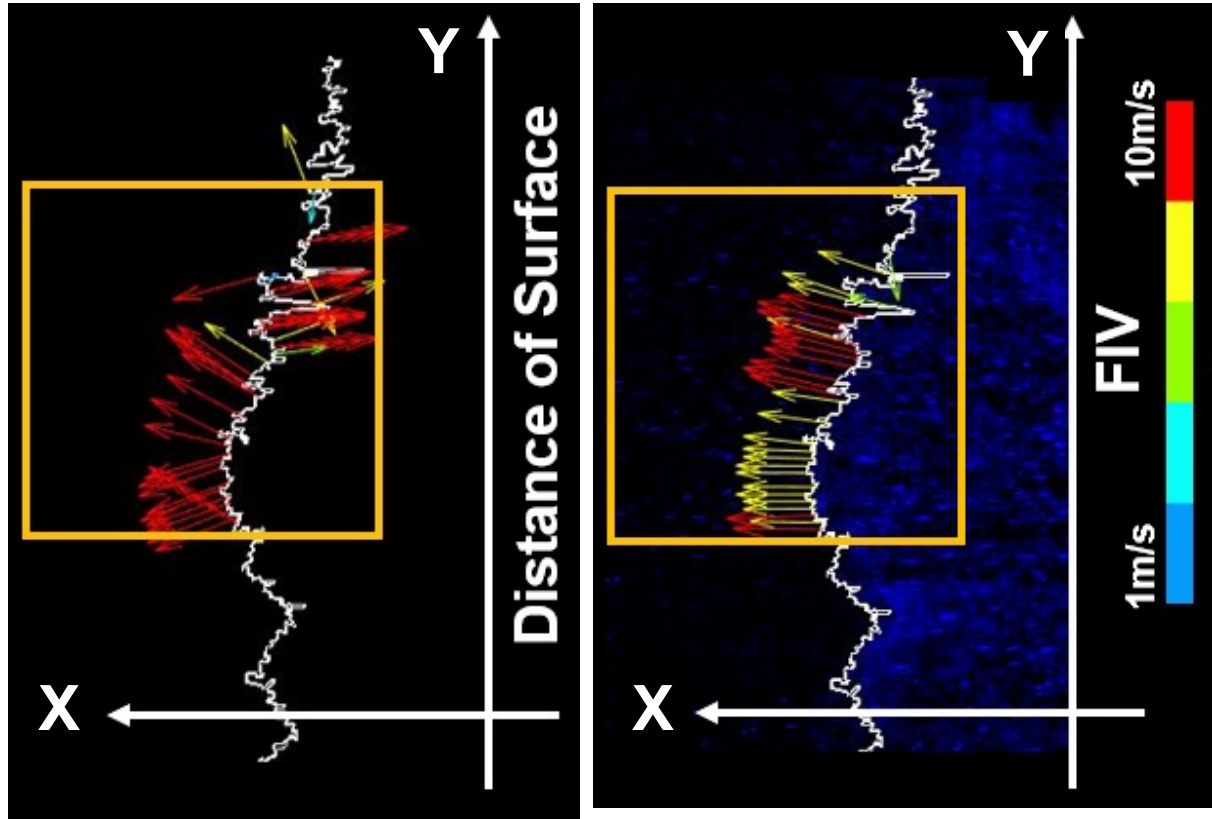


Figure 4. Detection of flame front velocity

3. Results and Discussion

Figure 5 shows the time-series results of the velocity distribution obtained via PIV and FIV analysis on the captured G-channel and B-channel images, representing the velocity distribution of the unburned mixture flow within the cylinder and the propagating flame. Regarding the visualization images: after spark ignition at -15 deg. ATDC, the flame gradually propagates. The flame moves diagonally upward and to the left from the spark plug, riding a counterclockwise swirl flow, and fills the visualization area by 10 deg. ATDC. Comparing the G-channel and B-channel results: at -15 deg. ATDC, tracer particles emitting scattered light are confirmed in the G-channel but not in the B-channel.

Shortly after spark ignition (at -10 deg. ATDC), the emission intensity was low, and the propagating flame could not be clearly confirmed. However, by -5 deg. ATDC, the presence of the propagating flame was confirmed in the B-channel; at this time, the flame front was not visible in the G-channel. From 0 deg. ATDC onwards, while the inner part of the propagating flame appears brighter in the G-channel, a distinct propagating flame front is not clearly visualized there. Conversely, in the B-channel, the propagating flame front is clearly captured without interference from tracer particles. The propagating flame fronts are indicated by red lines. By separating the

visualization images into G and B channels, the unburned mixture (with tracer particles) and the propagating flame can be observed independently.

The PIV and FIV analysis results were evaluated from these images. The velocity distribution of the unburned mixture flow was estimated using PIV from the G-channel, while the flame propagation velocity was estimated using FIV from the B-channel. At -15 deg. ATDC, an unburned mixture flow field of approximately 2–4 m/s in a counterclockwise direction (along the swirl flow) is obtained. From -5 deg. ATDC, unburned mixture velocities of approximately 5–7 m/s—higher than the surrounding flow—are measured at the leading edge of the propagating flame front, confirming that the unburned mixture is expelled by the propagating flame.

Regarding the FIV analysis results: velocity vectors were not yet detected at -10 deg. ATDC. However, from -5 deg. ATDC, a flame propagation velocity of 6–8 m/s can be observed near the flame front. To verify whether PIV and FIV results could be evaluated separately, a comparison of unburned mixture velocities near the propagating flame front was performed in "Region 2" (a 10 mm square area where the flame flows into the swirl flow), as shown in Fig. 6. PIV and FIV measurements were taken at 0.5 mm intervals, starting from 2 mm away from the flame front toward the unburned gas side. The results analyzed at -1.0 deg. ATDC are shown in Fig. 6. Between 2.0 and 1.0 mm, no FIV velocity vectors were detected; only PIV velocities were present. FIV velocity vectors were detected starting at 0.5 and 0.0 mm. At these same analysis points, FIV velocities were higher than PIV velocities, suggesting successful separation of the unburned mixture flow and flame propagation measurements. Regarding the PIV results, unburned mixture flow velocities at 2.0 mm were 4–6 m/s, increasing to 5–7 m/s closer to the flame front. Furthermore, in the region where Y is 6–9 mm, the flow velocity changes in a manner consistent with the flame propagation; specifically, the velocity at the 0.0 mm location is faster than the surrounding area. This confirms that the unburned mixture flow accelerates as it is compressed by the propagating flame.

Regarding the vicinity of the flame front, the vorticity was calculated from the velocity distribution of the unburned mixture obtained through experiments and compared with the flame front shape (Fig. 7). To capture the flow field and the flame front shape at a higher resolution, images near the flame front were captured by increasing the resolution from 0.052 mm/pixel to 0.025 mm/pixel. By focusing on areas where the propagating flame forms convex structures and utilizing magnified imaging with a high-speed color camera, the wrinkled structure of the propagating flame front was captured. Additionally, vortices were detected within the velocity distribution of the unburned mixture. It was confirmed that the vortices in the unburned mixture were intensified in a manner that follows the shape of the elongated and protruding flame.

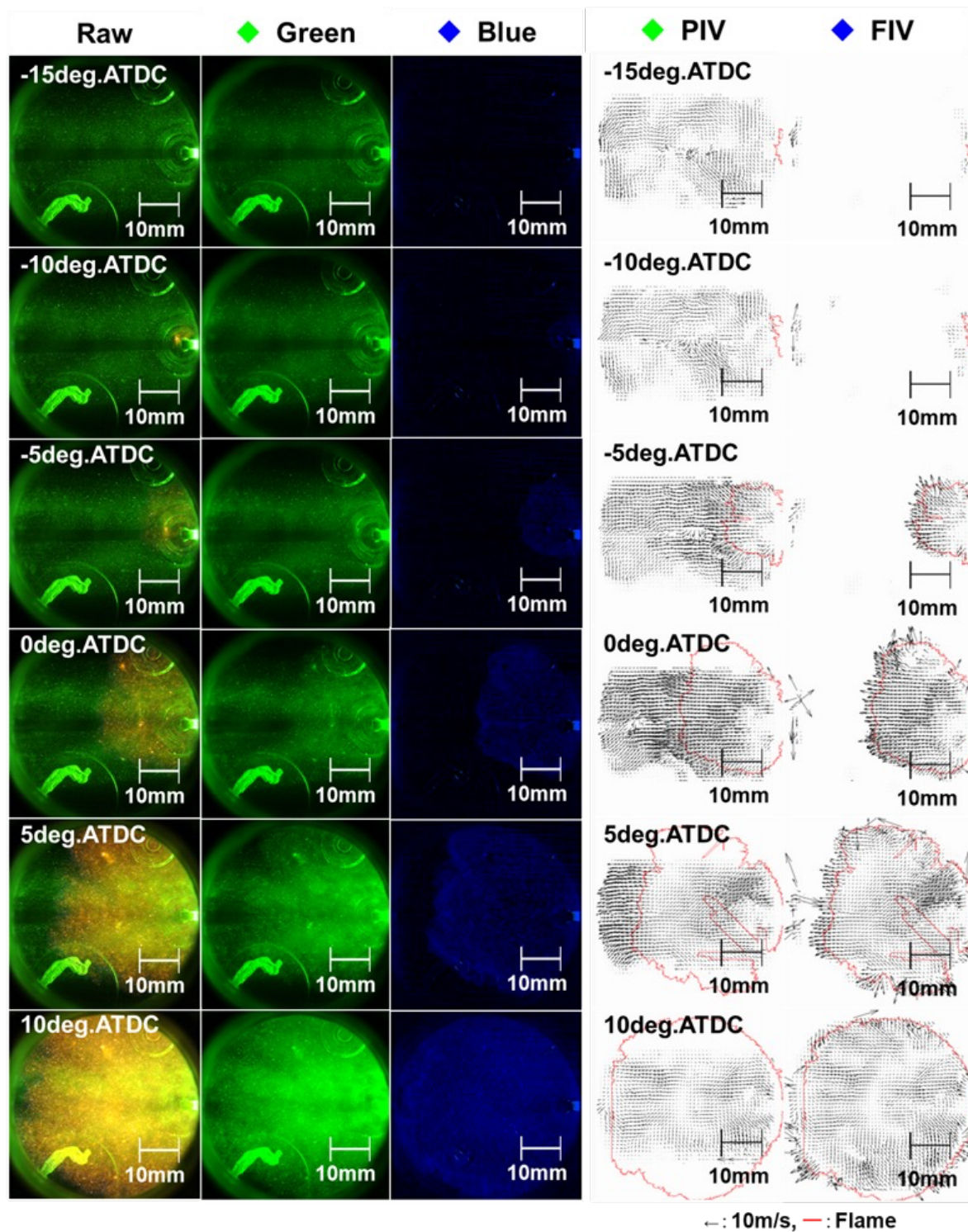


Figure. 5 Comparison of unburned mixture flow field with a propagating flame

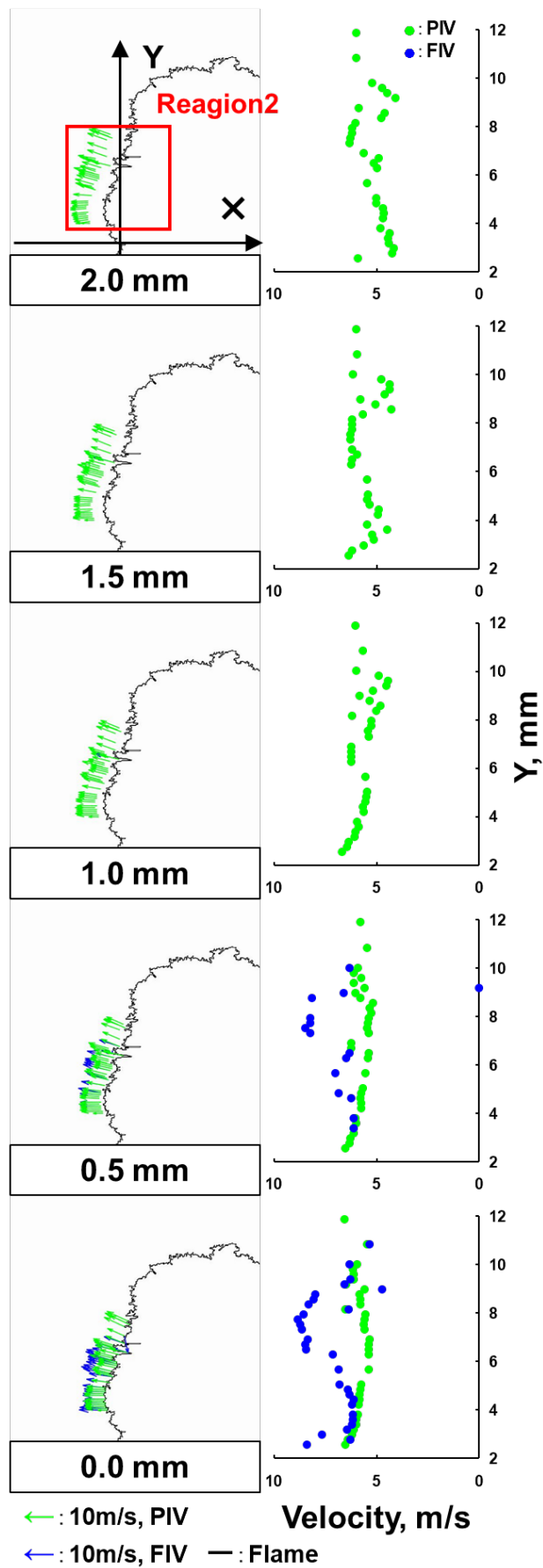


Figure. 6 Unburned mixture flow compressed by the propagating flame front

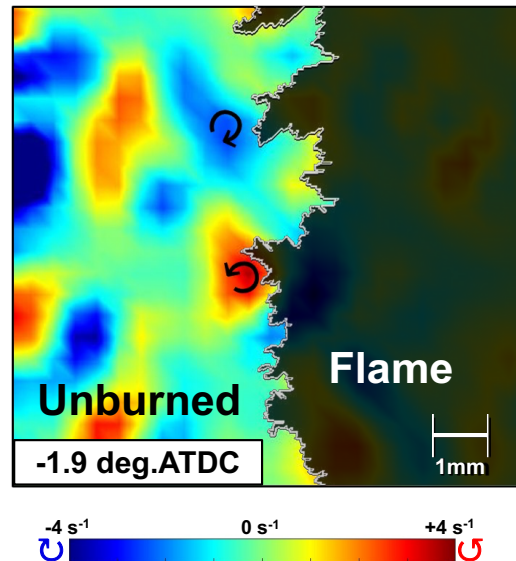


Figure. 7 Vorticity of unburned mixture flow compressed by the propagating flame front

4. Conclusions

In this study, simultaneous measurements of the unburned mixture flow and flame propagation within a cylinder were carried out using PIV and FIV with a high-speed color camera and a CW YAG laser. By extracting the G and B channels from the RGB color channels of high-speed color camera, it was possible to measure both the unburned mixture flow and the propagating flame simultaneously. A comparison of the unburned mixture velocity and the flame propagation velocity revealed that the unburned mixture is compressed by the propagating flame. Regarding the vicinity of the flame front, the vorticity was calculated from the velocity distribution of the unburned mixture obtained through experiments and compared with the flame front shape. It was confirmed that the vortices in the unburned mixture were intensified in a manner that follows the shape of the elongated and protruding flame.

References

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