

In-cylinder turbulence measurements with a spark plug-in fiber LDV

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ABSTRACT

Turbulence is generated at the end of an engine compression stroke by the breakdown of large-scale structures that persist during induction and compression. In a four-valve engine system with a pent-roof combustion chamber, placing a spark plug at the center of the chamber will shorten the duration of combustion, improve the flame-propagating speed, and increase turbulence as a result of the tumbling gas flow. It is necessary to study the gas flow characteristics inside the cylinder to investigate the effects of turbulence.

Most studies have used optical engines, which limited speeds to approximately 1500 rpm or less. However, a practical engine generally operates at over 5000 rpm. Direct measurements of the turbulence in the vicinity of the spark plug in a practical engine are required to obtain data at speeds that are typical of engine operation.

In this study, a fiber laser-Doppler velocimetry (LDV) system was developed and installed in a spark-plug port, with no structural modifications to the engine. The ensemble-averaged velocity, RMS, and turbulence intensity were measured in a spark-ignition (SI) engine at speeds of up to 5000 rpm. The ensemble-averaged velocity and RMS were normalized by the mean piston speed to explore the relationship between turbulence intensity and mean piston speed.



Fig.1 Developed LDV probe and casing

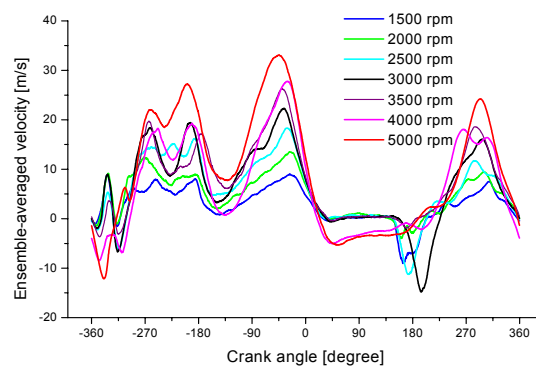


Fig.2 Variations of Ensemble-averaged velocity

1. INTRODUCTION

Many studies have examined the effect of the gas flow inside a cylinder on the combustion characteristics. It is desirable to control gas flow, since its characteristics determine engine performance and emissions. Intense turbulence in the flow near the spark plug ensures rapid and complete engine combustion. This turbulence also controls the flame that develops from the spark-generated kernel after the spark discharge, and contributes to both combustion stability and expansion of the lean limit. Turbulence is generated at the end of the compression stroke by the breakdown of large-scale structures that persist during induction and compression or by compression of the flow near top dead center (TDC) of the compression cycle in certain combustion chamber geometries. In a four-valve engine, however, there is little compressed flow, because of the limited area, and compressed flow has little effect on the turbulence characteristics. If such a system incorporates a pent-roof combustion chamber, the duration of combustion can be shortened and the flame-propagating speed improved, since the spark plug can be located at the center of the chamber; the tumbling gas flow causes high-intensity turbulence.

Many studies of the turbulence characteristics near a spark plug have been performed using LDV (Lorenz, et al., 1990, Ikeda, et al., 1990, Ikeda, et al., 1992, Itoh, et al., 1998, Urushihara, et al., 1996, Belmabrouk, et al., 2000, Liou, et al., 1985, Liou, et al., 1983 and Catania, et al., 1987) and PIV (Muniz, et al., 1996, Kaneko, et al., 2000 and Kaneko, et al., 2001) measurements to investigate flame propagation. These studies have mostly used optical rather than practical engines, which have limited experimental conditions to speeds below approximately 1500 rpm, whereas a practical engine generally operates at over 5000 rpm. Direct measurements are needed of the turbulence near spark plugs in practical engines at typical engine operating speeds.

In this study, a fiber LDV system (Fig. 1) was developed and installed in a spark plug, with no structural modifications to the engine. The ensemble-averaged velocity, RMS, and turbulence intensity were measured in an SI engine at speeds of up to 5000 rpm (Fig. 2). The ensemble-averaged velocity and RMS were normalized by the mean piston speed to understand the relationship between turbulence intensity and mean piston speed.

2. EXPERIMENTAL APPARATUS

The engine used in this experiment was a practical 1500 cc four-stroke engine [Subaru]. Its specifications are listed in Table 1. The measurement system is illustrated in Fig. 3. The test engine was operated at typical motoring conditions, with a direct current dynamometer.

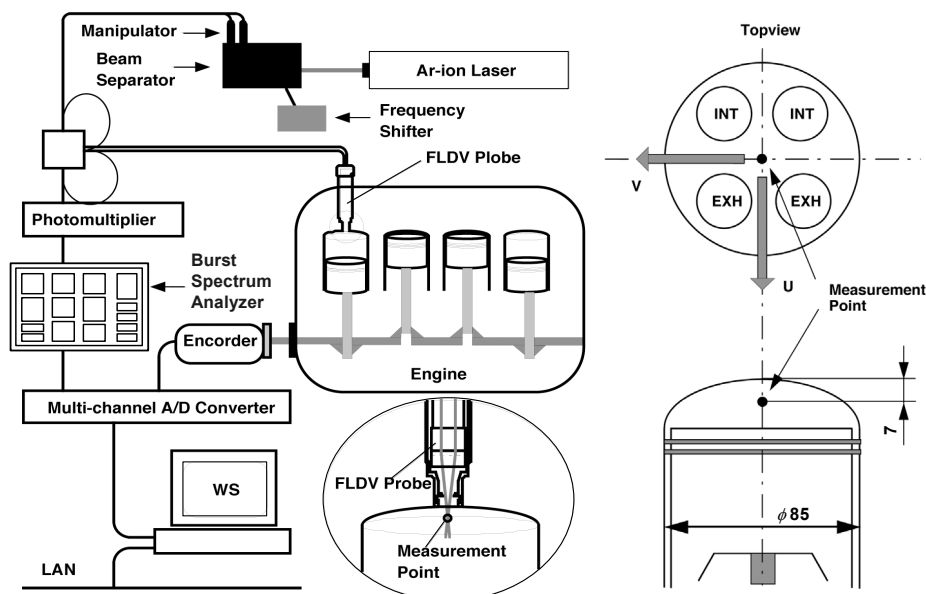


Fig. 3 Schematic diagram of experimental apparatus

The fiber LDV (FLDV) (Ikeda, et al., 2000) that we developed was installed in one of the cylinders instead of a standard spark plug, as shown in Fig. 4. LDV measurements were made at the center of the combustion chamber, where the spark plug is normally located. An Ar-ion laser was used as the laser source, and a burst spectrum analyzer (BSA) was used to collect and process the measured Doppler signals. Silicon oil was used to provide seeding particles, which were supplied to the cylinder through the intake port by compressed air. The engine speed was varied from 700 to 5000 rpm. Measurements were performed in all cylinders.

The optical components and specifications of the plug-in FLDV are shown in Fig. 5. The measurements were made 7 mm from the optical window. The measurement volume and other optical parameters were determined by considering several factors, including the band width of the signal processor [DANTEC57N10], measurable dynamic range, desired accuracy and data rate, ease of cleaning, apparatus set up, cylinder pressure, and engine vibration.

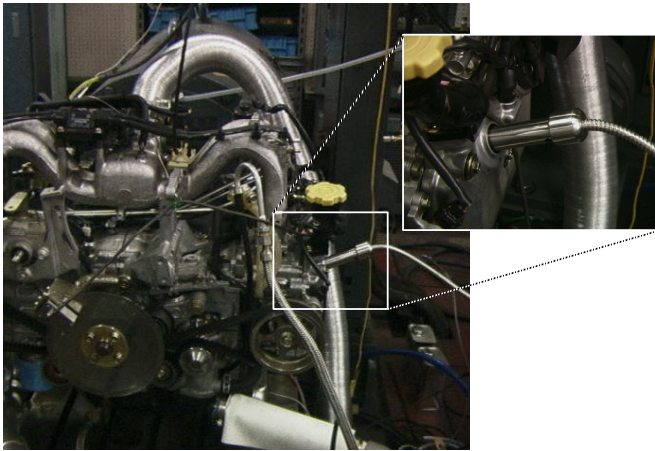
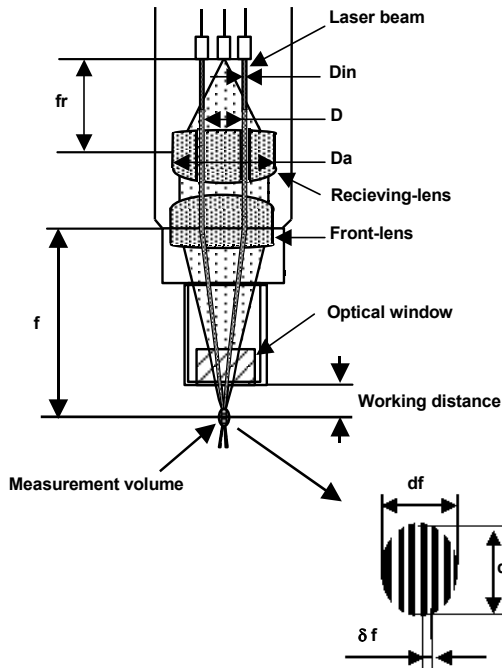


Fig. 4 Photograph of installed plug-in FLDV

Table 1 Specification of test engine

Type of Engine	4-cylinder, 4-stroke, Spark Ignition, 16-valve	
Cooling System	Water-cooled	
Displacement Volume	1493 cm ³	
Intake Valve	Open	BTDC 2° (C.A.)
	Close	ABDC 54° (C.A.)
Exhaust Valve	Open	BBDC 48° (C.A.)
	Close	ATDC 8° (C.A.)
Bore × Stroke	85 × 65.8 [mm]	
Compression Ratio	10.0	

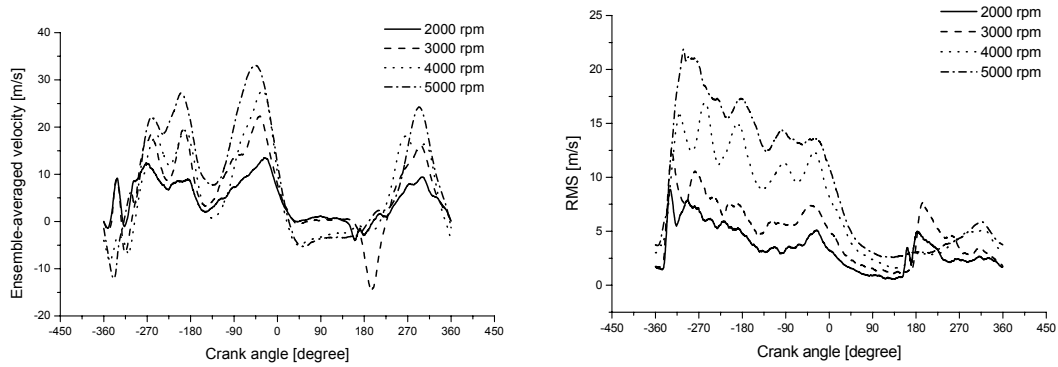


l [nm]	514.5
f [mm]	31
D_a [mm]	15.74
D [mm]	7.5
D_{in} [mm]	0.4037
D_f [mm]	50.3
D_z [mm]	415.8
D_f [mm]	2.142
Nf	23.65
SNRP	45.2×10^{-6}
WD [mm]	7.0
Laser Power [W]	1.0
Probe [mW]	60

Fig. 5 Specifications of plug-in FLDV

3. RESULTS AND DISCUSSION

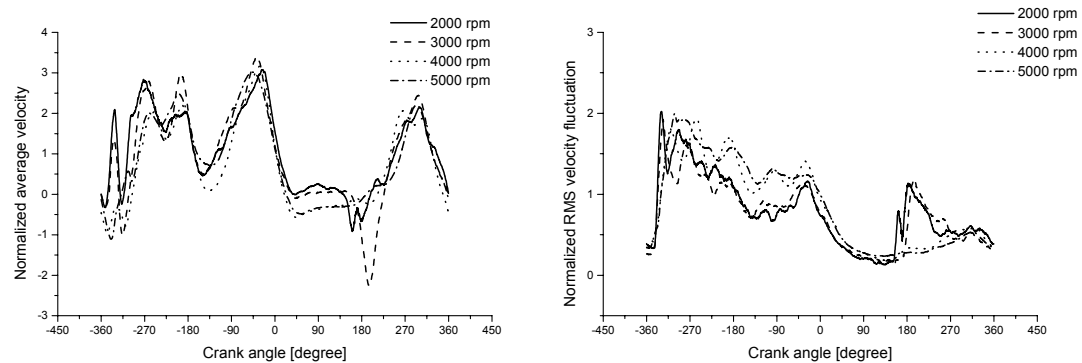
The ensemble-averaged velocity and RMS variations as a function of engine speed are shown in Fig. 6. The temporal and spatial characteristics of turbulence near TDC and the spark plug are generally used to analyze the gas flow characteristics that influence engine combustion. Therefore, the measurements focused on times when the piston was close to TDC, and on turbulence at the center of the combustion chamber. The data obtained near the intake and close to the exhaust stroke may be incorrect due to deviation from the measuring range. For this reason, the velocities shown during the intake and exhaust strokes are lower than those measured at TDC. The velocity and turbulence intensity, especially near TDC, are proportional to the engine speed. The flow through the intake valve or port is responsible for many features of the in-cylinder motion, and is proportional to the piston speed. Therefore, the in-cylinder flow velocities at different engine speeds are expected to scale with the mean piston speed. Consequently, we need to consider both the absolute gas flow velocity and the velocity normalized by the mean piston speed to investigate the influence of the mean piston speed on the gas flow characteristics. Figure 7 shows the ensemble-averaged mean and RMS velocity fluctuations normalized by the mean piston speed throughout the cycle at different engine speeds. All of the curves have approximately the same shape and magnitude, indicating the appropriateness of this velocity scaling. This result highlights the fact that the gas flow inside the cylinder is largely influenced by the mean piston speed and not by other factors.



(1) Ensemble-averaged velocity

(2) RMS

Fig. 6 Variations of Ensemble-averaged velocity and RMS velocity fluctuation with engine speed (U-direction)

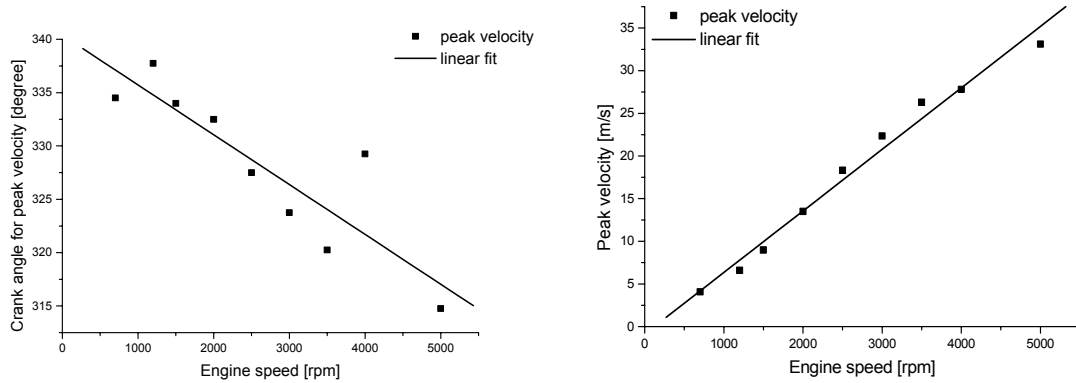


(1) Ensemble-averaged velocity

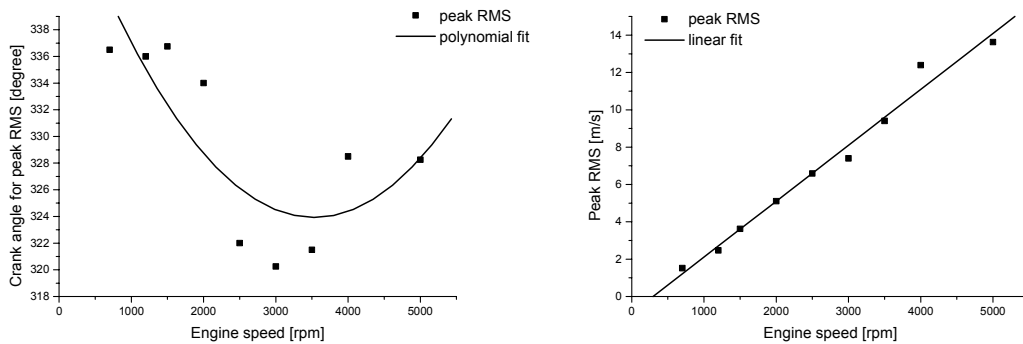
(2) RMS

Fig. 7 Variations of Ensemble-averaged velocity and RMS velocity fluctuation normalized by mean piston speed with engine speed (U-direction)

The peak average velocities, peak RMS values, and crank angle at these peak values were investigated to study their relationships with the engine speed. The variation in the peak velocity and crank angle is shown in Fig. 8. The peak velocity appeared at lower crank angles as the engine speed increased. This may influence the minimum spark advance for the best torque (MBT). Furthermore, the velocity increased linearly with the engine speed due to the increased mean piston speed (Heywood, et al., 1988). Figure 9 shows the variation in the peak RMS values with crank angle. The peak RMS value appeared at the lowest crank angles at engine speeds of approximately 3500 rpm. This phenomenon is affected by the intake port length, valve timing, valve lift, and engine speed (Heywood, et al., 1988). The turbulence intensity near TDC influences the ignition delay, flame propagation, and combustion duration. The MBT advances continuously with the engine speed to produce the most efficient cylinder pressure. Although the peak RMS fluctuation appeared earliest for engine speeds near 3500 rpm, its appearance was delayed at other engine speeds, as shown in Fig. 9(1). Therefore, matching the time at which the peak RMS value appears with the timing of the spark is very important for improving the pushing force of the piston during the expansion stroke. Normal engines have a maximum torque at 3000~3500 rpm. Therefore, the matching was optimal in the region at which the maximum torque was produced. The RMS magnitude increased continuously with engine speed.



(1) Crank angle for peak velocity (2) Peak velocity
 Fig.8 Variation of the peak velocity and the crank angle when it appears (U-direction)



(1) Crank angle of peak RMS (2) Peak velocity
 Fig.9 Variation of the peak velocity and the crank angle when it appears (U-direction)

The gas velocity increases with the mean piston speed. However, we did not expect the flow velocity to be proportional to the mean piston speed. There should be a maximum flow rate at a certain engine speed, which will be the engine's most efficient operating condition. Figure 10 shows the relationship between the peak ensemble-averaged velocity normalized by the mean piston speed and the engine speed. The maximum value appears near 3500 rpm, which also indicates that optimal operation of the test engine used in this study was near 3500 rpm.

Figure 11 shows the variation in the intensity of turbulence with mean engine speed at TDC of the compression stroke. There is substantial variation in the proportionality constant, in part because the ensemble-averaged RMS fluctuation was the quantity actually measured. This result indicates that the turbulence intensity at TDC has a maximum value equal to about half of the mean piston speed in the absence of swirl (Bopp, et al., 1986).

The variation in the gas flow characteristics of neighboring cylinders is shown in Fig. 12, which indicates that the gas flow characteristics are not identical in all the cylinders, due to differences in the curvature and length of the intake manifold.

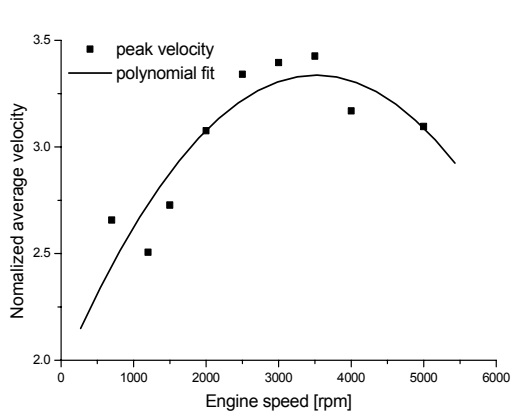


Fig.10 Variation of the peak velocity normalized by mean piston speed

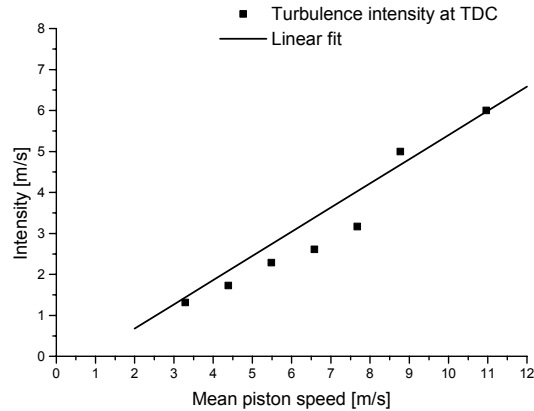
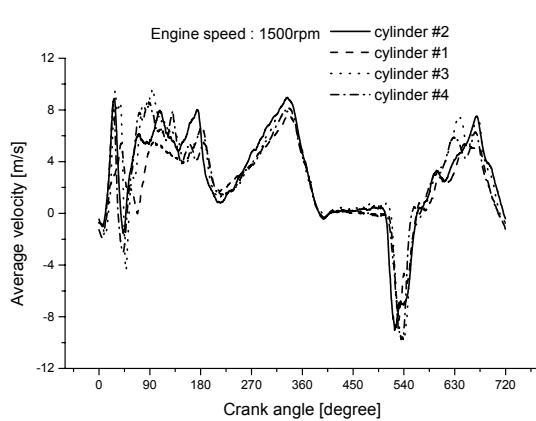
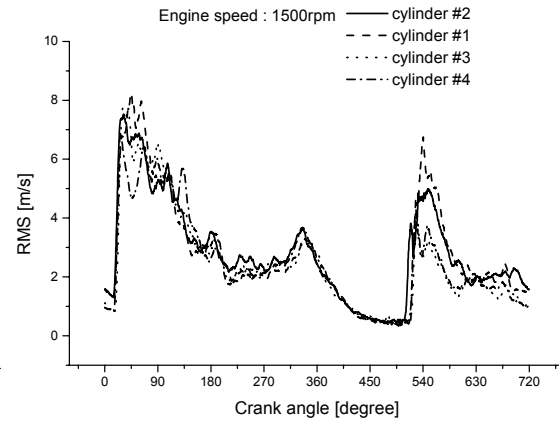


Fig.11 Variation of the turbulence intensity at TDC according to mean piston speed



(1) Average velocity



(2) RMS

Fig. 12 Variation of gas flow characteristics for neighbor cylinders (U-direction)

4. CONCLUSIONS

A fiber LDV was developed and installed in a standard spark plug port. The gas flow characteristics in the engine cylinder were investigated at speeds of up to 5000 rpm under typical motoring conditions. The average velocity and magnitude of the RMS values were proportional to the engine speed. The peak value of the RMS appeared at the lowest crank angle, and the average velocity normalized by the mean piston speed was highest at speeds near 3500 rpm in the engine studied. The turbulence intensity at TDC, in the absence of swirl, had a maximum value equal to about half the mean piston speed. The gas flow characteristics differed in each cylinder, due to differences in the curvature and length of the intake manifold. These results can be used in engine designs to improve the cylinder, intake port, and valve system.

5. REFERENCES

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