LDV Measurements of Axial Distributions of In-Cylinder Gas Velocities*

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Characteristics of in-cylinder gas flow in a two-cycle uniflow-type engine were investigated by using laser doppler velocimetry (LDV). Through swirl velocity measurements at several sections along the cylinder axis, it was found that in the early compression stroke, axial distribution of angular momentum is uneven and swirl velocity at each measuring section fluctuates periodically. Mean angular momentum in the whole of the combustion chamber, however, decays monotonously and analysis showed that its decaying process after a late compression stroke is similar to the swirl-decaying process in a cylindrical constant-volume bomb. A secondary airflow in the upper part of the combustion chamber is inferred from the measured radial and axial velocities in an early compression stroke.

Key Words: Internal Combustion Engine, In-cylinder Gas Flow, Flow Measurement, Laser Doppler Velocimetry, Swirl Velocity, Angular Momentum, Decaying Process

1. Introduction

The air-fuel mixing process in a direct injection diesel engine and a stratified charge (DISC) engine needs to be promoted by air motion in the combustion chamber. Therefore, the in-cylinder air motion, such as swirl or squish, is an important factor of fuel economy and emission characteristics of these engines. In recent years, various aspects of swirl flow have been revealed by numerous LDV measurements^{(1)~(4)}. Their main focus, however, is on the in-cylinder gas behavior near TDC which has dominant influences on the air-fuel mixing process. Measuring points and measured velocity components were too limited by the difficulty of laser beam access into the combustion chamber to understand the characteristics of the whole swirl flow from the beginning of the compression stroke. However, measurements of velocity distributions in several sections are necessary to check the validity of numerical models or to modify their

constants because the axial velocity distribution is considered to have a large influence on the subsequent variation process of in-cylinder flow. In this study, three velocity components of air motion near the cylinder head and swirl velocity distributions in several sections along the cylinder axis were measured in detail with the LDV system using a two-cycle uniflow-type engine under motoring conditions. Swirl velocities in all measuring sections were axially averaged and their decaying processes were analyzed using the experimental equation about the dissipation rate of kinetic energy in a combustion chamber^{(5)~(8)}. Complicated three-dimensional air motion in the early compression stroke was detected, and other useful information for in-cylinder gas flow was obtained.

2. Experimental Apparatus and Procedure

2.1 Test engine

A single-cylinder two-cycle uniflow-type engine was used in this study. The main specifications of this engine are shown in Table 1 and the schematic figure of the main part is shown in Fig. 1. The combustion chamber has a pancake shape with 21 mm top clearance. Swirl is generated by the guide vanes fitted

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around the scavenging ports. Swirl intensity can be adjusted by changing the direction of these vanes. Two exhaust valves opposed diametrically on the combustion chamber wall are actuated radially. This layout allows a transparent window of simple disc shape to be installed as the cylinder head. The piston crown is also transparent and is installed on an elongated aluminum piston body. In order to measure the axial velocity component in the upper part of a combustion chamber, two other small windows with the same diameter of 24 mm located equidistantly from the exhaust valves are installed on the circumferential combustion chamber wall.

2.2 Laser doppler velocimeter system

A dual-beam forward-scattering LDV system was used. The main specifications of this system are shown in Table 2 and its optical construction to measure tangential and radial velocity components is shown schematically in Fig. 2. A Bragg-cell frequency shift system was used for the detection of velocity direction. In the case of the axial velocity measurements, all equipment was set in line along the diameter connecting the centers of the small windows which were on opposite sides of the combustion chamber.

2.3 Seeding

Talc ($\text{SiO}_2\text{-MgO}$, mean diameter $2.3\text{ }\mu\text{m}$) was

used as the scattering particles. Compressed airflow from the blower was divided into two streams for seeding. One was seeded by a feeder with revolving spiral threads and flowed into a centrifugal separator which separates smaller particles. The other was made to by-pass the above process and was mixed with the seeded flow just downstream of the separator. The seeding level was able to be controlled by changing the ratio of the seeded airflow rate to the by-passed one, keeping the total airflow rate constant.

2.4 Data acquisition and processing

Doppler signals were converted into digital voltage inversely proportional to the input frequency by a counter-type processor unit. These voltage and validation signals for the frequency-counting procedure were transmitted to a computer system with crank angle pulses under 2 kHz sampling frequency. Then an ensemble-averaged velocity over about 30 cycles was calculated. The number of sampled cycles was increased up to 60 cycles according to the validation level and the uncertainty of the flow direction. Because of the rejection of unreasonable velocity fluctuations, which were caused by signal dropout or noise from the shifter system, the data rate was not always high enough to evaluate the turbulence; so, in this study, data analysis was bounded in calculating

Table 1 Engine specifications

Bore × Stroke	100 × 83 mm
Compression ratio	4.09
EVO / EVC	±60 deg. BBDC
SPO / SPC	±60 deg. BBDC

Fig. 1 Schematics of test engine

Table 2 LDV specifications

Laser wavelength	514.5	nm
Focal length of focusing lens	247, 500	mm
Angle of intersecting beams	10.97°, 5.59°	
Calibration factor	2.7, 5.3	m/s/MHz

(1) Ar ion laser	(2) Beam splitter
(3) Bragg cell	(4) Focusing lens
(5) Collecting lens	(6) Photomultiplier
(7) Frequency mixer	(8) Frequency counter

Fig. 2 Optical arrangement of LDV system

the ensemble-averaged velocity.

2.5 Experimental conditions

All measurements were made under the motoring condition at an engine speed of 600 rpm. Scavenging pressure was adjusted to 0.126 MPa. The direction of the guide vanes around the scavenging ports was set tangential to an imaginary circle with a diameter of 0.8 times the cylinder bore. Measuring positions in this study were chosen as shown in Fig. 3. A two-dimensional coordinate (r, z) system is adopted to specify the location of measuring points. It defines the cylinder axis as the z -axis and the position of the piston head at BDC as $z=0$ mm. Radial direction towards the engine front is defined as the positive direction of r . Radial position is expressed by a ratio of r to the cylinder radius R . The positive direction of swirl velocity is clockwise around the cylinder axis and coincident with the induced airflow direction. Measurements of swirl velocity were made along every diametrical line of $z=93, 84, 63, 42$ and 24 mm. The $z=93$ mm plane corresponds to the midplane in the clearance volume. The heights of other measuring planes were selected considering the piston positions at intervals of 30 degrees from TDC. The radial position was chosen at intervals of $0.10R$ (5 mm)

between $r/R=-0.80$ and $r/R=0.80$. On the diametrical line of $z=93$ mm between $r/R=-0.90$ and $r/R=0.90$, axial velocity and tangential velocity were measured. The radial velocity was measured only along the diametrical line of $z=99$ mm at $r/R=0.20, 0.50$ and 0.70 .

3. Results and Discussions

3.1 Swirl velocity

Measured results of swirl velocity are summarized in Figs. 4 to 7. Figure 4 shows the three-dimensional displays of measured swirl velocities against crank angle and radial distance in $z=93, 84$ and 63 mm, respectively. Scaling of these two axes is arranged to make the decaying process of swirl velocity easily perceived. The blank areas in the figures indicate the period when a piston surface is over or across the measuring volume and when the scattered light from the piston surface obstructs doppler signal acquisition. In all measuring planes, the velocity distribution is nearly axisymmetric and the profile of the velocity distribution has an image of solid-body rotation at an early stage of the compression stroke. Steeper decay in the region of larger radial distance, however, makes the profile flattened by a later expan-

Fig. 3 Measuring points

Fig. 4 Measured swirl velocities versus crank angle and radial positions at different measuring heights

sion stroke. Small velocity components exist on the cylinder axis in all cases, although their directions are not coincident with one another. The decaying process of swirl velocity is not monotonous, but oscillating especially in the early compression stroke. At some crank angles, swirl velocity increases during the decaying process, which can be seen also in the results of previous work^{(3),(4)}. Figure 5 shows swirl velocity profiles both during a compression and an expansion stroke in the negative side of the radial position on the planes of $z=93, 84$ and 63 mm, respectively. At the beginning of a compression stroke, a near-solid-body rotation profile prevails within the radial distance of $0.80R$. As the piston rises, the swirl velocity gradually decays except for the region within a radial distance of $0.20R$ to $0.30R$. Since the larger velocity at the outer radial distance decays more quickly, swirl velocity decays to a trapezoidal profile in an expansion stroke. The plane of $z=93$ mm shows smaller swirl velocities than the other planes, especially in an early

compression stroke. Figure 6 shows the decaying processes of swirl in $z=93, 84$ and 63 mm. Radial positions for this figure are selected as $r/R = -0.30, -0.50$ and -0.70 . It can be seen that a periodic oscillation of swirl velocity in an early compression stroke exists in all cases; and this oscillation becomes smaller as swirl velocity decays along the course of compression stroke. Figure 7 shows the variation of swirl velocities along the cylinder axis in the early compression stroke. Because the moments when swirl velocity increases or sharply decreases by the periodic oscillation change with measuring heights as shown in Fig. 6, it is found that the axial distribution of swirl velocities is not even and distribution pattern changes with crank angle. Although swirl velocities in the plane of $z=93$ mm tend to be lower than the other planes, axial distribution becomes uniform as compression advances. From these velocity measurements, it is revealed that the radial distribution of swirl changes its profile from a near-solid-body rotation pattern

Fig. 5 Swirl profiles at different measuring heights

Fig. 6 Swirl-decaying processes at different measuring heights

into a flat-top trapezoidal one along the course of compression and expansion strokes, and that the periodic oscillation of swirl velocity and its uneven axial distribution exist in an early compression stroke. The latter implies the necessity of velocity measurements along the cylinder axis to evaluate the decaying process of swirl.

3.2 Decaying process of angular momentum

The angular momentum in a cylinder is considered to be another measure of swirl decaying nature. It is also useful to check the validity of numerical models and to estimate the swirl intensity around TDC in practical engines. As mentioned in the previous section, temporary velocity increase detected in each measuring section and axially distribution of swirl intensity make it difficult to estimate the mean angular momentum in the whole of a cylinder from single section measurements. In this paper, the mean angular momentum in a cylinder volume was reckoned from swirl velocities at several sections. Swirl velocity is assumed to be constant from $0.80R$ to $0.95R$, which is inferred from the measurement in the $z=93$ mm plane, and to be at rest on the cylinder axis and the cylinder wall. At all the other radial positions, the averaged velocity between the positive and the negative sides of r is chosen in all cases. Figure 8 shows the angular momentums per unit mass calculated on the swirl velocity in each measuring section and on their average. The mean angular momentum shows monotonous decay while that of each measuring section fluctuates in some degree. The mean angular momentum at TDC decays to be about 65% of the initial value of the compression stroke. The monoto-

nous decay of the mean angular momentum is seductive to analyze the qualitative nature of its decaying process. In a cylindrical constant-volume bomb, it was reported that swirl and turbulence show the same way of decaying because both have no energy supply and decay monotonously by generating smaller eddies^{(5),(6)}. That is also expected for swirl in reciprocating engines⁽⁷⁾. The experimental decay-law of turbulence in a constant-volume bomb can be modified for swirl as follows⁽⁸⁾.

$$(2\varepsilon/\nu^3)^{1/4} = C_n(\bar{U}_\theta H/\nu)^m \quad (1)$$

$$\varepsilon \equiv -\frac{1}{2}d\bar{U}_\theta^2/dt \quad (2)$$

where ε is the rate of dissipation of swirling kinetic energy per unit mass (m^2/s^3); ν the kinetic viscosity (m^2/s); H the combustion chamber height (m); C_n the experimental constant; $\bar{U}_\theta$ the mean swirl velocity (m/s) and m the exponent of Reynolds number based on H . The effects of compression are considered through H and ν . For a swirl-decaying process in a cylindrical constant-volume bomb, 0.7 and about 0.72 are recommended as m and C_n respectively⁽⁶⁾. Figure 9 shows the results of calculations where m is set to 0.7 and 1.0 with proper variation of C_n . As shown in the figure, the calculation of $m=1.0$ and $C_n=0.034$ gives a good prediction in the early compression stroke, and the one of $m=0.7$ and $C_n=0.73$ can be successfully applied after a late compression stroke. Consequently, in-cylinder air motion in this test engine changes into a swirl flow similar to the one in a cylindrical constant-volume bomb as the piston approaches TDC. It is difficult to apply the decay-law of $m=0.7$ to the whole of the decaying process.

Fig. 7 Swirl velocity variations along the cylinder axis

Fig. 8 Angular momentum variations versus crank angle

Fig. 9 Comparison between the mean angular momentum and the calculated values

Moreover, a qualitative difference can be recognized between the calculation results and the measured decaying process. Existence of radial and axial flow remaining from the scavenging period, and a higher swirl velocity than in the constant-volume bomb case could be pointed out as reasons for that difference in the early compression stroke.

3.3 Axial and radial velocity

Figure 10 shows axial velocity changes versus crank angle in the $z=93$ mm section. The averaged velocity of the positive and negative sides of r is plotted in the figure. Upward velocity before TDC and slightly downward velocity after TDC are detected at the selected radial positions of $r/R=0.10$, 0.50 and 0.80 . Around 90 degrees BTDC, the axial velocity at $r/R=0.50$ shows a rapid increase while that at $r/R=0.80$ shows a rapid decrease. The latter so decreases as to change the flow direction. The axial velocity at $r/R=0.10$, however, shows a smooth decrease. This suggests that in the upper part of the combustion chamber, the secondary airflow seems to occur from the inner part towards the outer part of the cylinder and to be deeply related to the swirl velocity oscillation around that crank angle. The direction of the secondary flow is coincident with that expected from a circumferential layout of exhaust valves. Figure 11 shows the change of radial velocities with crank angle at $r/R=0.20$, 0.50 and 0.70 in $z=99$ mm. Velocity oscillations similar to the case of swirl or axial velocity are also detected in a compression stroke. Velocity direction at all measuring positions is clearly outward

Fig. 10 Axial velocity variations versus crank angle

Fig. 11 Radial velocity variations versus crank angle

around 90 degrees BTDC when a rapid drop in swirl velocity was observed in the plane of $z=93$ mm, which confirmed the existence of secondary airflow expected from the swirl and axial velocity measurements.

4. Conclusions

From the LDV measurements of in-cylinder air flow in a two-cycle uniflow-type engine, the following conclusions were obtained:

(1) Radial distribution of swirl velocity changes its profile from a near-solid-body rotation pattern into a flat-top trapezoidal one along the course of compression and expansion strokes. Periodic oscillation of swirl velocity exists in the early compression stroke.

(2) Axial distribution of swirl is not uniform, so that detailed measurements of axial distribution are necessary to evaluate the decaying process of swirl and angular momentum in the whole of the combus-

tion chamber.

(3) A secondary air flow from the inner part towards the outer part of the combustion chamber exists in the early compression stroke.

(4) In spite of the velocity fluctuation in each measuring section and the axial distribution of the swirl intensity, the angular momentum averaged over the cylinder volume shows monotonous decay which is similar to that of swirl in a cylindrical constant-volume bomb after the late compression stroke.

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