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Quantification of Volumetric In-Cylinder Flow of SI Engine Using 3-D Laser Doppler Velocimetry (Ⅱ)

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Key Words : In-cylinder flow, LDV, Ensemble averaged-velocity, Tumble, Swirl, Turbulent kinetic energy

ABSTRACT

Simultaneous 3-D LDV measurements of the in-cylinder flows of three different engine setups were summarized for the quantification of the flow characteristics in each vertical or horizontal plane, and in entire cylinder volume. The ensemble averaged-velocity, tumble and swirl motions, and turbulent kinetic energy during the intake and compression strokes were examined from the measured velocity data (approximately 2,000 points for each engine setup). The better spatial resolution of the 3-D LDV allows measurements of the instantaneous flow structures, yielding more valuable information about the smaller flow structures and the cycle-to-cycle variation of these flow patterns. Tumble and swirl ratios, and turbulent kinetic energy were quantified as planar and volumetric quantities. The measurements and calculation results were animated for the visualization of the flow, and hence ease to analysis.

1. Introduction

The flow inside of an internal combustion engine is highly complex and varies greatly among different engine setup. For a long time IC-engine researchers have tried to classify the major mean flow patterns and turbulence characteristics using different measurement techniques. During the last three decades tumble and swirl numbers have gained increasing popularity in mean flow quantification while turbulent kinetic energy has been used for the measurement of turbulence in the cylinder.

In-cylinder flows in motored four-valve SI engines were quantified by simultaneous three component laser Doppler velocimetry (3-D LDV) measurements. The purpose of this study is to develop better physical understanding of in-cylinder flows regardless of the specific engine setup. Special attention is paid to swirl and tumble formation process, and three-dimensional turbulent kinetic energy (TKE).

The influences of the induction system, including runners, ports and valves, combustion chamber geometry, and piston crown geometry on in-cylinder flow have been studied for the last few years[(1)~(8)]. These studies have illustrated that the in-cylinder flow is highly complex and three-dimensional, and quantification is extremely difficult due to its 3-D complexity, turbulence nature and cycle-to-cycle variability. An early study established the importance of investigation of the tumble motion and TKE with the 2-component LDV measurement data[(1)]. That study suggested that the turbulence intensity could be

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mislead by the 2-D velocity vectors. Then, a 3-D LDV system was employed to quantify the in-cylinder flow. Two experimental studies had conducted to measure 3-D velocity vectors on two main vertical planes[(2),(3)]. Those studies revealed that the quantification could not be completed by examining only two vertical planes even measured by 3-component velocity vectors.

For the detailed quantification of in-cylinder flow, velocity profiles were measured in the entire cylinder displacement volume of three different engine setups by the 3-D LDV system[(4)~(6)]. Approximately 2,000 points were measured to map the 3-D flow field of each engine setup, during intake and compression strokes. Quantification of the flow field has been investigated by calculating tumble and swirl ratios, which are to characterize in-cylinder air bulk motion, and TKE, which indicates the local turbulence strength in the cylinder.

2. Experimental facility

In the current work, an AVL research engine, type 520, was modified to adapt to the three different engine setups. Crankshafts were restored for the different engine strokes, while production connecting rods were installed. The piston rings used were made of Rulon-LD which can withstand high temperature and compressive loads. The Rulon-LD rings allow for better optical access since they require no lubrication. Standard piston rings are unsuitable. They are hard enough to scratch the quartz cylinder wall easily. The test research engine and a driving DC motor were assembled on a heavy bed plate. The specifications of the engines studied are listed in Table 1.

Table 1 Engine specifications

Engines	A	B	C
Bore (mm)	96	90	90
Stroke (mm)	80	90	105
C/R	10.0	9.5	9.5
Speed (rpm)	600	600	600

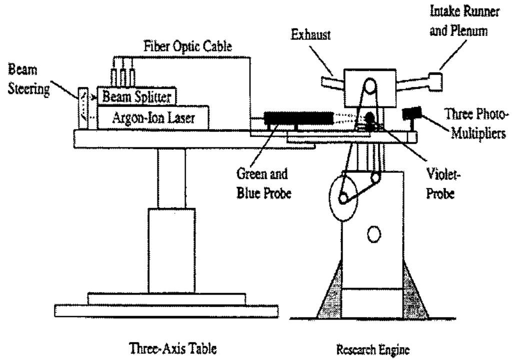


Fig. 1 3-D LDV system setup with test rig

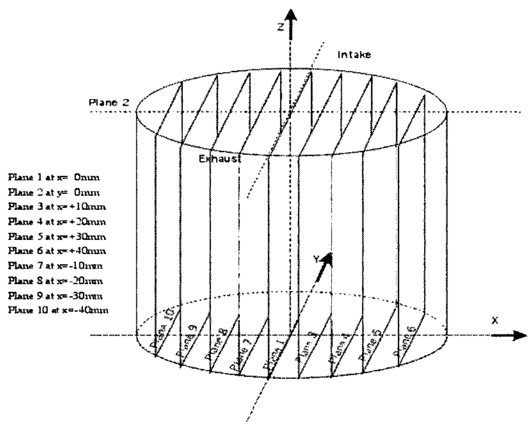


Fig. 2 Measurement vertical planes and cylinder coordinate system

Two quartz cylinders (96 mm and 90 mm bore diameters with 10 mm thick) were used for engine setups A, B and C to allow optical access for LDV measurements. Production pistons were modified to fit on the extension, which is installed on the top of the research engine piston.

A simultaneous 3-D LDV was employed to measure the velocity vectors of the in-cylinder flow field in three different engine setups. The 3-D velocity measurements were accomplished by placing three sets of orthogonal fringe patterns at a measurement volume. The LDV system was mounted on a traverse table, which is capable of transitional movement in the three Cartesian directions within 1 micrometer. The 3-D LDV system with the test rig is shown in Fig. 1.

3. Velocity measurements and data processing

The three orthogonal components of velocity vector were collected at each measured point over large number of cycles (Data rate : 1,000 Hz). The 3-D ensemble averaged-velocity was obtained based on the collected data set in 1.8° crank angle-degree steps. The location of each LDV measurement was spaced in a grid 5 mm apart within the 10 measurement planes. Each of the 9 measurement planes was aligned to be parallel to the center plane between the intake valves (or exhaust valves, Plane 1), and spaced 10 mm apart. One orthogonal plane (Plane 2) was located at the cylinder center perpendicular to the other planes. The locations of planes can be seen in Fig. 2.

A set of data and coordinates of each measurement case were combined to generate a data array bank to convert data sets based on the engine crank angle and measured location. The data array bank was utilized to calculate the parameters such as velocity vector fields, tumble or swirl ratios, and TKE for each vertical plane, horizontal slice, or the whole cylinder volume. Sets of graphs and figures of theses calculated parameters are generated to study the flow patterns, tumble and swirl developing processes, and TKE with engine crank angles.

For the effective analysis of this large LDV measurement data set, animations are created for 3-D ensemble averaged-velocity profiles and TKE contour iso-surface for the whole cylinder volume with crank angles. The developing process of in-cylinder flow and TKE can be studied in any vertical plane, horizontal slice, and whole cylinder volume using these animations. In addition, the velocity field can be compared with the predicted velocity vector field by CFD code side by side at each crank angle.

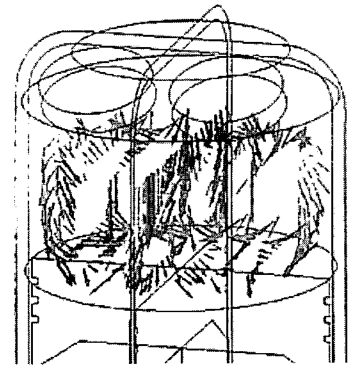
4. Results and discussion

4.1 Ensemble averaged-velocity

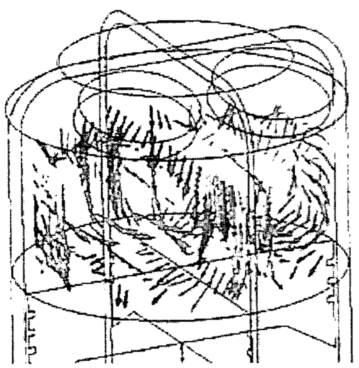
The major flow patterns of in-cylinder flow in the IC-engines can be examined in two different ways: the instantaneous flow field and the ensemble averaged flow field. The LDV data can provide the time history of the velocity at a measured point. Since measurements were conducted total approximately 2,000 points for each engine setup, the cycle-to-cycle variability can be studied by a specific point in the cylinder. To study the flow patterns in the entire volume or in a certain plane, the ensemble averaged-velocity profiles were calculated with crank angle 1.8° steps during intake and compression strokes. Details of the calculation can be found elsewhere(4)~(6).

The flow patterns were examined in vertical plane, horizontal slice, and the entire volume for the three different engine setups. As expected, the center planes (Plane 1, 3 and 7 in Fig. 2) experienced high velocity patterns and strong vortices. The four-valve design dominates the intake and compression flows. In particular, symmetric flow patterns were observed about the z-axis. During the intake stroke, the net fluid motion was observed to exist in both a downward and upward fashion. In general, intake flow generates two downward flows that form two or three vortices in the cylinder. During the early intake, the downward velocity of intake side is faster than that of exhaust side. Both flows created a collision region right above the piston surface, deflecting the downward flow between the exhaust valves diagonally upward towards the intake valves.

For the engine setup A, the flow rates of intake side and exhaust side are comparable. As a result, the strong induction flows eventually create two counter rotating vortical structures within the measurement planes. In Fig. 3 we can see large symmetric tendencies exhibited by in-cylinder fluid motion. The flow seems to be accelerating onto the descending piston surface. The counter rotation of the structures drives the flow in between them, resulting in a

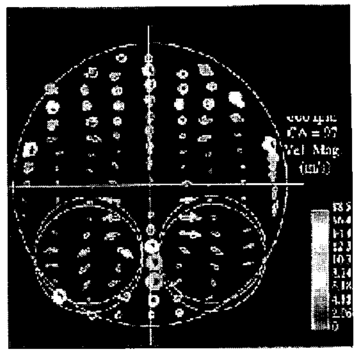


(a) View from -x axis intake valve

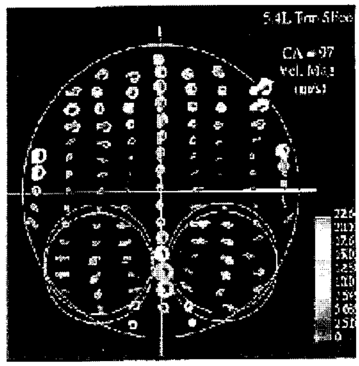


(b) View from +x axis intake valve

Fig. 3 Flow patterns in engine setup A at crank angle 94 ° (the wire frame model displaying the images of the flow fields only includes the two intake valves)



(a) Engine setup B at crank angle 97°



(b) Engine setup C at crank angle 97°

Fig. 4 Mean velocities in the top slice for the B and C engine setups (the wire frame only includes the two intake valves)

diagonally upward crossflow toward the intake valve side of the combustion chamber. Additionally, upward motion is found to occur almost symmetrically beneath both intake valves. This is the result of the first vortical structure whose geometry extends to these regions. The other vortical structure rotates in the opposite direction of the first one positioned above it. Its ends seem to be tilted slightly upward as well, but they point toward the exhaust valve side of the cylinder opposite to that of the first structure. Furthermore, these structures were observed to migrate. The migration of the structures is dependent on the intake flows as seen by the shifting of the regions of large upward and downward velocities.

The flow patterns in the B and C engine setups are very similar except the vortex shape. Vortex of intake side of C case is longer than that in B case. Fig. 4 shows the velocity vectors during early intake within the top-most slice for the B and the C engine setups. The flow rate of exhaust side region is larger than that of intake side region, while both flow rates are comparable for the engine setup A. Hence, during the intake stroke this 'exhaust side region' flow becomes more dominating, which is also reflected in tumble motion for both engine setups. The figures demonstrate overall symmetric flow patterns with higher velocity amplitudes for the C engine setup. After the crank angles shown, the velocity vectors are reduced in amplitude and point into the downward direction.

The vortices expanded throughout the evaluated cylinder volume, until they dissipated shortly after BDC. During the compression stroke, the highest velocities were measured right above the surface of the upward moving piston. This flow pattern exhibited low-level rotational velocities, which showed here referred to as resemblance to a tumble motion of low amplitude. The flow patterns show that the vortex shapes and horizontal component of velocity vectors are affected by the aspect ratio of the cylinder, which is the ratio of stroke to bore of the cylinder. The aspect ratios of these three engines are 0.83, 1.0, and 1.17.

4.2 Tumble and swirl motion

Tumble and swirl are defined as organized rotations of the charge air motion around specific cylinder axis. Tumble corresponds to rotational motion around either of the two axes in vertical planes (Plane 1 and 2), while swirl is the rotation around the symmetric axis of the cylinder. Tumble and swirl ratios were developed to express the bulk air motion inside a cylinder by a normalized number. Their values are intended to quantify the air motion as a solid body rotation. Tumble ratios were calculated for vertical planes and swirl ratios were calculated for horizontal slices. Also, tumble and swirl ratios were examined for the entire measured volumes. For this paper, the volumetric tumble ratios were calculated around moving origin that is the origin of coordinate at the center of the displaced cylinder volume at each crank angle (Fig. 5). The

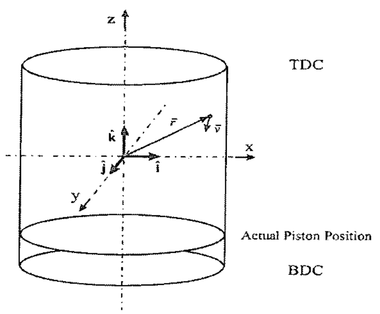
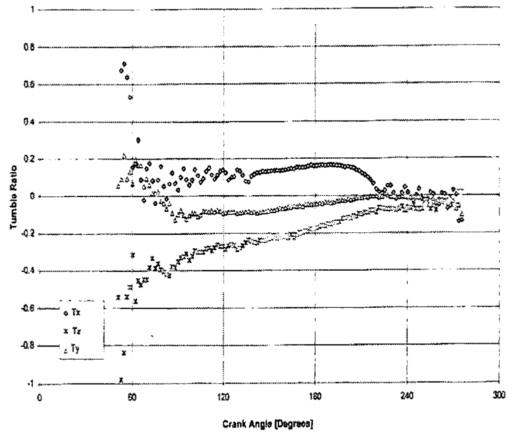
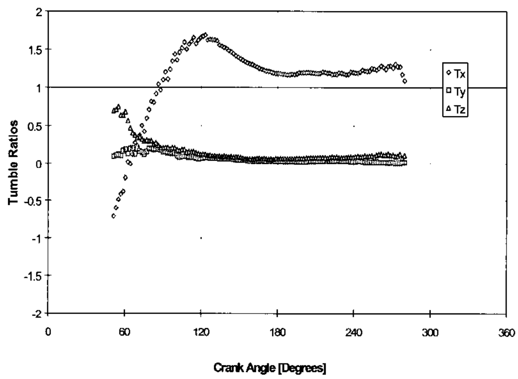


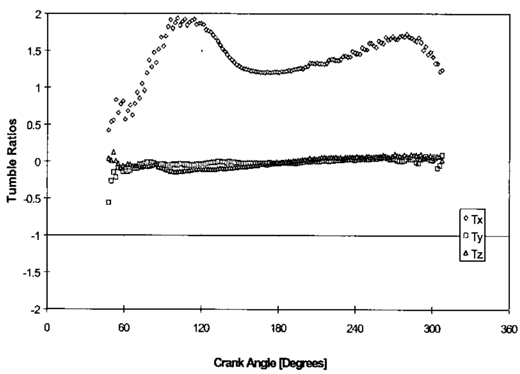
Fig. 5 Cylinder coordinate system with moving origin about the instantaneous center of the volume



(a) Engine setup A



(b) Engine setup B



(c) Engine setup C

Fig. 6 Volumetric tumble ratios around the moving origin for engine setups A, B and C volumetric tumble ratios around the moving origin are shown in Fig. 6.

One tumble ratio for each of the three directions was calculated from all measured velocities inside their planes. Engine setup A (Fig. 6(a)) shows that x-tumble (T_x), y-tumble (T_y) and swirl (T_z) ratios are small over the entire measured crank angles and an almost linear decreasing swirl ratio, here referred to as T_z. Fig. 6(b) and Fig. 6(c) show the tumble ratios for engine setup B and C. The x-tumble ratios show overall positive numbers throughout the measured crank angle range, while y-tumble and swirl ratios remain in small. After about crank angle 200° the x-tumble ratios have similar amplitudes for the engine setup B, while this phenomena occurs at about crank angle 150° for the engine setup C.

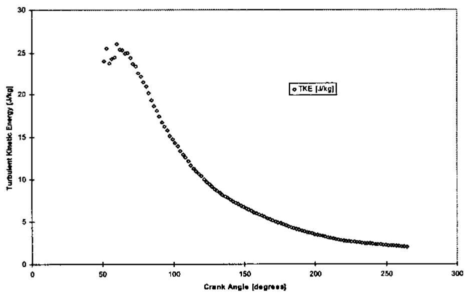
The x-tumble ratios of engine setups B and C have large values because the two main vortices rotate in the same direction, which is counter-clock wise view from the positive x-axis. On the other hand, for the engine setup A, two main vortices in Plane 1 have almost same size and rotate opposite direction. These two vortices rotate opposite direction canceled the effect of the x-tumble ratio. The y-tumble and swirl ratios for all three engine setups illustrate similar to the x-tumble in engine setup A. Two symmetric counter flow patterns reduce the y-tumble and swirl ratios. These results show that tumble and swirl ratios can be used for the comparisons of the flow characteristics only if the flow patterns are similar. The tumble and swirl ratios without flow pattern study may not be useful as parameters for the characterization of in-cylinder flows.

4.3 Turbulent kinetic energy

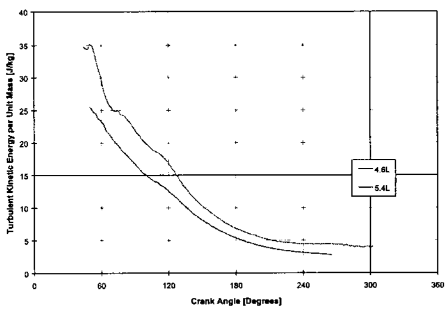
TKE stands for a quantity of energy calculated with the fluctuations including turbulence and cycle-to-cycle variation. TKE was examined in three different ways: per vertical plane, per horizontal slice, and per entire cylinder volume. TKE per vertical plane shows the development process and distribution of TKE in the cylinder with crank angle. TKE per horizontal slice indicates the turbulence intensity in each disk portion of the cylinder at a crank angle. Volumetric TKE can reveal the process of turbulence developing and decaying in the cylinder with crank angles. The volumetric TKE was examined in two different ways: total TKE and specific TKE.

Total TKE was calculated with total mass of the air at the crank angle, while specific TKE was obtained per unit mass so that the mass effect can be eliminated from the total TKE calculation. The specific TKE results are shown in Fig. 7. In general, after increasing in the early intake stroke, the specific TKE decreases over the remaining crank angles until late compression stroke. The dissipation of the specific TKE was observed to follow the exponential function.

Specific TKE in engine setup A decays smoothly while those in engine setups B and C show the slight delay in the middle of intake stroke. The TKE's in



(a) Engine setup A



(b) Engine setups B (4.6L) and C (5.4L)

Fig. 7 Specific TKE for measured volume of the engine setups A, B, and C engine setups A and B developed up to approximately 25 J/kg during early intake stroke, while in engine setup C developed TKE approximately 35 J/kg. Decay processes in engine setups A and B are very similar except the delaying at crank angle 110°. Turbulence dissipation in engine setup C generally follows the exponential function. At crank angle 70° and 110°, retarding of turbulence dissipation can be observed.

It is important to understand the mechanism of TKE development and dissipation in conjunction with the in-cylinder flow structure. 3-D TKE contour map was constructed to examine the mechanism of TKE development and dissipation with crank angle throughout the cylinder volume during intake and compression strokes. Using this 3-D TKE contour map, TKE contour iso-surfaces were animated with crank angle. During the early intake stroke, TKE is generated by the injected flows through the intake valves. The high TKE was observed in the area of the flows meet. Then the higher TKE region extended to the cylinder wall on intake side. The high TKE moved down with the piston until strong vortex tube appears in the middle of intake stroke. Late intake stroke shows donut shape of TKE contour iso-surface which is parallel to the Plane 2. During the compression stroke, TKE breakdown into small structure and was spread out in the combustion chamber.

5. Conclusion

In summary, several points can be made to the major mean flow patterns and turbulence characteristics issues in IC-engines.

1) In general, intake flow generates two downward flows that form two or three vortices in the cylinder and the center planes (Plane 1, 3 and 7 in Fig. 2) experienced high velocity patterns and strong vortices.
2) Tumble ratios do not accurately represent the complex in-cylinder air charge motion during the intake and compression strokes. The ratios are influenced by the direction of the vortices created by intake air flows.
3) The gradient of the volumetric TKE can be utilized to indicate and predict turbulence intensity of in-cylinder flows.
4) In this study high TKE regions were observed in the high shear areas where intake flows meet.

Comparison of this experimental result with the predicted result from CFD will be a good tool to design for the combustion engines.

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