# In-Cylinder Air Flow Measurements and Turbulent Kinetic Energy Analyses

# 실린더 내 공기유동 측정 및 난류운동에너지 해석

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**Key Words** : In-cylinder Flow(실린더 내 유동), LDV(레이저 도플러 속도 측정장치), Tumble(텀블), Swirl(스월), Turbulent Kinetic Energy Iso-surface(난류운동에너지 등가면), SI Engine(불꽃점화 기관)

**요약** : 본 연구는 SI기관 실린더 내의 유동장 변이 과정을 3차원 LDV 측정 기술을 사용하여 흡입과 압축과정 동안 정량적으로 분석하였다. 실험은 헤드에 각각 2개의 흡입밸브와 배기밸브를 갖는 기관이 모터링되는 공회전 상태에서 실시하였다. 지난 30년 동안 텀블과 스월은 실린더 내의 평균 유동 정량화에, 난류운동에너지는 난류 측정에 많이 사용되어 왔다. 그러나 텀블은 solid body 회전 유동을 비교하는데 적절하며, 서로 다른 유동 패턴 비교에는 부적절 하다는 것이 보고되고 있는 실정이다. 3차원 LDV시스템의 우수한 공간 분석 능력은 순간적인 유동장 구조와 더불어 상대적으로 미세한 유동장의 구조 까지도 측정이 가능 하도록 하였다. 따라서 측정한 결과로 부터 유동장의 난류운동에너지 등가면을 계산할 수 있었다. 본 실험 결과는 실린더 내의 난류 유동장 특성을 난류운동에너지 등가면 정보를 이용하여 세심하게 관찰할 수 있음을 제시하고 있다.

## Nomenclature

| | |
|---|---|
| Tx | : x-tumble ratio |
| Tz | : z-tumble ratio |
| Ty | : swirl ratio |
| TKE | : turbulent kinetic energy [Joules/kg] |
| x, y, z | : cylinder coordinate |

## 1. Introduction

It has been known that the combustion process in SI engines is strongly affected by the turbulence and flow field present during combustion. It is also well accepted that this flow field very strongly results from the precursor flow pattern setup in the cylinder during the intake and compression strokes. In general, the intake and compression flow patterns are the result of the flow entering the cylinder through the intake valves and interacting with the combustion chamber and piston crown geometries.

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.[1-7] These studies have illustrated that the in-cylinder flow is highly complex and three dimensional(3-D), 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 turbulent kinetic energy(TKE) with the 2-D laser Doppler velocimetry(LDV) measurement data.[1] That study suggested that the turbulent intensity is mislead by the 2-D velocity vectors. Then, a 3-D LDV system was employed to quantify the in-cylinder flow by the 3-D velocity vectors. 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 the 3-D velocity vectors.

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In-cylinder flows in motored four-valve SI engine was quantified by a simultaneous 3-D LDV measurements. The head tested was a typical pent-roof head geometry with two intake and exhaust valves, and the engine operating point corresponded to an idle condition. 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 iso-surface, which indicates the local turbulent strength in the cylinder. For the detailed quantification of in-cylinder flow, velocity profiles were measured in the entire cylinder displacement volume. Approximately 2,000 points were measured to map the 3-D flow field of engine setup by the 3-D LDV system during the intake and compression strokes.

It is well documented that strongly organized tumble and swirl motions generally have a beneficial effect on combustion characteristics. This effect is mainly achieved through a better mixing of the air-fuel in the combustion chamber and a higher level of turbulence during the combustion. Hence, it is highly desirable to understand and optimize the in-cylinder flow pattern and its effect on turbulent kinetic energy and combustion. Thus, the objectives of this study are several fold: ( Ⅰ ) to quantify the turbulent kinetic energy in space with engine crank angles; (Ⅱ) to obtain the evolution of the turbulent kinetic energy iso-surface during the intake and compression strokes; and (Ⅲ) to gain a better understanding of intake generated flows and its effect on turbulent kinetic energy.

## 2. Experimental facility

A single-cylinder research engine was modified to adopt the test engine setup. The research engine provided the reciprocating piston and a driving crank for a cylinder of the test engine. Crankshaft was restored for the different engine stroke, while production connecting rod was installed. The test cylinder head, quartz cylinder, research engine and a driving DC motor were assembled on a heavy bedplate. The specifications of the engine studied is listed in Table 1.

A 10 mm thick quartz cylinder was used to allow optical access for LDV measurements. Production piston was modified to fit on the extension, which is installed on the top of the research engine piston.

Table 1 Research engine specification

| | |
|---|---|
| Bore | 90 mm |
| Stroke | 90 mm |
| Connecting rod length | 230.3 mm |
| Test throat condition | WOT |
| Compression ratio | 9.5 : 1 |
| Motoring engine speed | 600 rpm |

A simultaneous 3-D LDV system was employed to measure the velocity vectors of the in-cylinder flow fields in the test engine setup. 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.

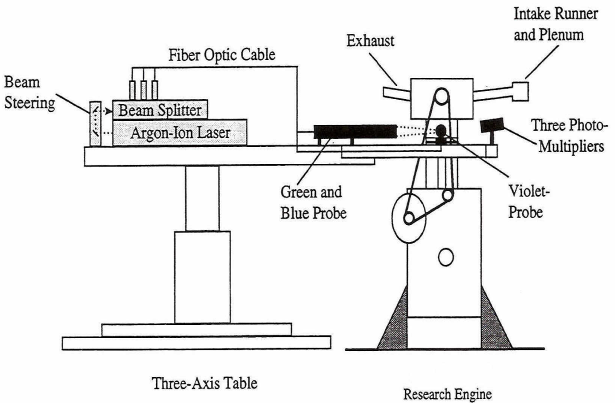


Fig. 1 3-D LDV system setup with test rig

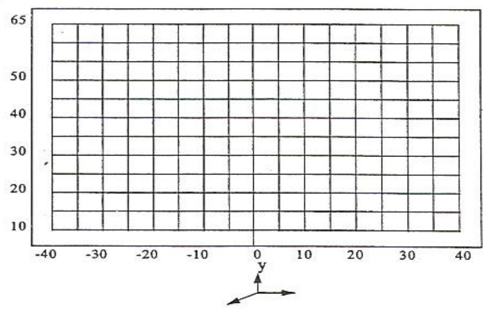


Fig. 2 Measurement grid

## 3. Velocity measurements and data processing

The three orthogonal components of velocity vector were collected, with data rate of 1,000 Hz, at each measured point. 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 (Fig. 2). 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) is located at the cylinder center perpendicular to the other planes. The locations of planes can be seen in Fig. 3.

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 is utilized to calculate the parameters such as velocity vector fields, tumble or swirl ratios, and TKE for each vertical plane, horizontal plane, or the whole cylinder volume. Sets of graphs and figures of these 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 were created for 3-D ensemble averaged-velocity profiles and TKE contour iso-surface for the whole cylinder volume with crank angles. The evolution of in-cylinder flow and TKE can be studied in any vertical plane, horizontal plane, and whole cylinder volume using these animations.

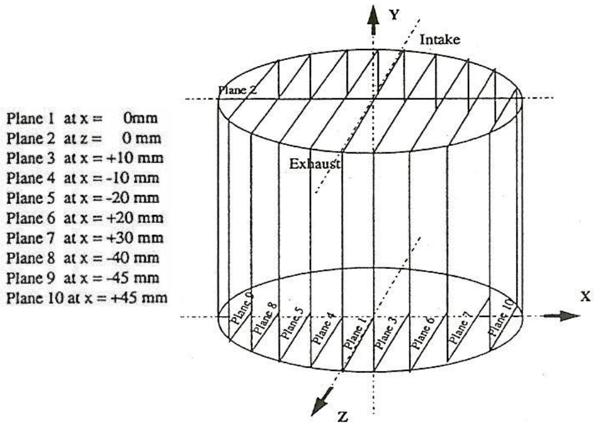


Fig. 3 Measurement vertical planes and cylinder coordinate system

## 4. Results and discussion

### 4.1 Ensemble averaged-velocity

The flow patterns were examined in vertical planes, horizontal planes, and the entire volume for the engine setup. The center planes (Plane 1, 3 and 4 in Fig. 3) experienced higher velocity profiles and stronger vortices. In general, intake flow generates two downward flows that form vortices in the cylinder. During the early intake, the downward velocity of intake side is faster than that of exhaust side.

As to be expected from a four-valve engine, the flows in center plane (Plane 2) and horizontal planes appear symmetrical throughout the measured crank angles. In plane 2, a downward flow along the cylinder liner and an upward flow within the center of the plane can be observed during early intake. During intake, two counter rotating vortices develop and prevail until BDC. During the compression, an upward directed velocity field develops in plane 2. The velocity vectors within the horizontal planes demonstrate overall symmetric flow patterns with the crank angles.

### 4.2 Tumble and swirl motion

The induction of air into the cylinder generates jet-like intake flows through the valve areas. Their velocities are highly turbulent and usually a multiple of the mean piston speed. The bulk air motion is of similar importance since the breakdown of large scale rotating flow patterns is considered to increase turbulence during the late compression stroke. Furthermore, bulk air motion around the two axes normal to the cylinder axis affects the combustion under stoichiometric conditions with high levels of exhaust gas recirculation.

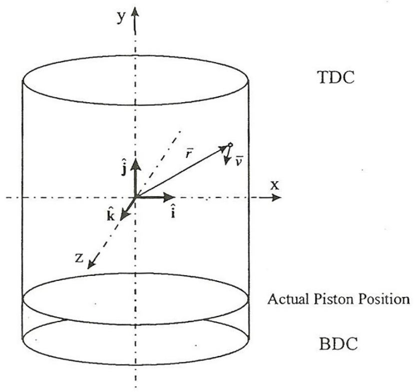


Fig. 4 Cylinder coordinate system with moving origin about the instantaneous center of the volume

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 axisymmetric cylinder axis. Tumble and swirl are created by bringing intake air flow into the cylinder with an initial angular momentum. Tumble ratios were calculated for the vertical planes and swirl ratios were calculated for horizontal planes. Also, tumble and swirl ratios were examined for the entire measured volumes.

The volumetric tumble ratios were calculated at every specific crank angle from all available ensemble averaged-velocity vectors. Details of the calculation can be found elsewhere.[4)] For this paper, the volumetric tumble ratios were calculated around moving origin that was the origin of coordinate at the center of the displaced cylinder volume at each crank angle (Fig. 4).

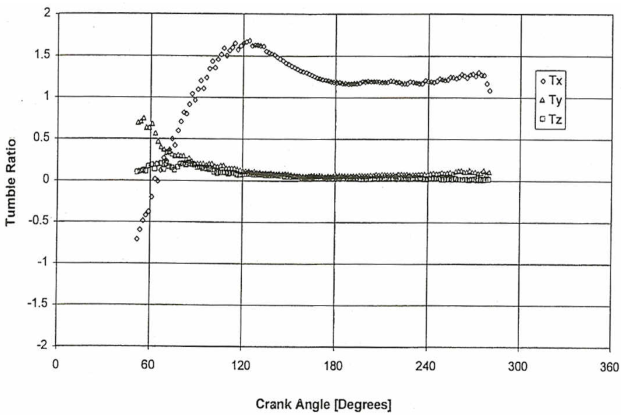


Fig. 5 Volumetric tumble ratios around the moving origin

Fig. 5 shows the volumetric tumble and swirl ratios around the moving origin for the engine setup. The x-tumble(Tx) has large tumble ratios for all measured crank angle range, while z-tumble(Tz) and swirl(Ty) ratios remain in small.

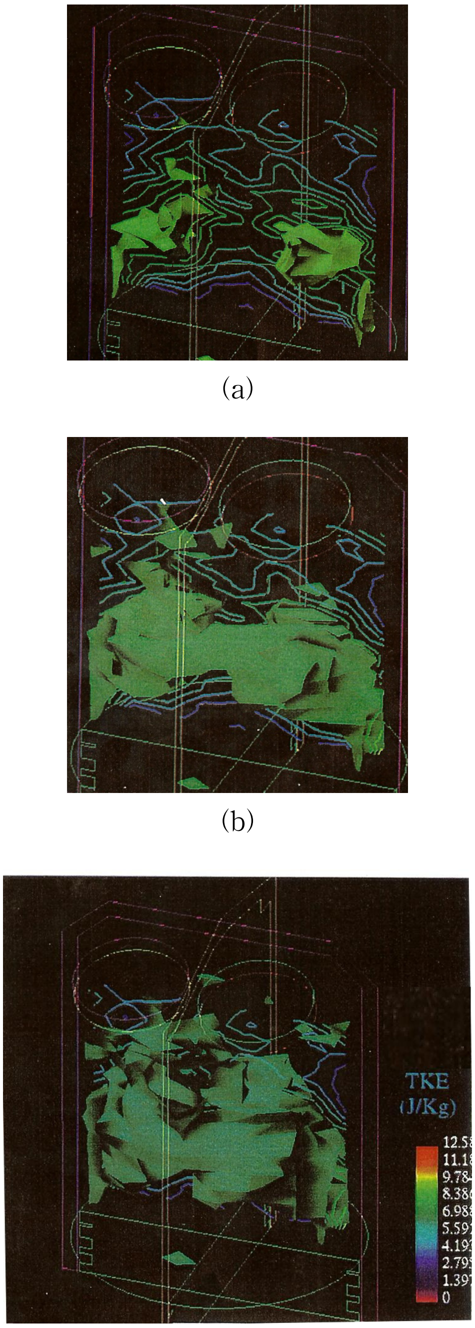
The x-tumble ratios have large values because the two main vortices rotate in same direction which is counter-clock wise view from the positive x-axis. On the other hand, the z-tumble ratios illustrate small. Two symmetry counter flow patterns reduce the z-tumble ratios. The overall swirl ratios remain low throughout the measured crank angles. Due to the symmetry of the four-valve engine, the calculated swirl ratios were relatively small. The results of the z-tumble and swirl calculations indicate that only small size of tumble and swirl motion exists within the cylinder through most of the intake and compression strokes, even though the two counter rotating vortex structures contribute to the flow field generating strong turbulence in the cylinder flow. This calculation result may not represent the flow field which occurred in the engine cylinder.

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 Iso-surfaces of TKE

This study investigated the turbulence in the cylinder. A better understanding of its evolution, which strongly influences a mixing of the air-fuel in the cylinder and a higher level of turbulence during the combustion, can help to improve engine efficiency and emissions. It is also important to understand the mechanism of TKE development and dissipation in conjunction with the in-cylinder flow structure. In this paper, turbulent kinetic energy stands for a quantity of energy calculated with the fluctuations including turbulence and cycle-to-cycle variation. Details of the calculation can be found elsewhere.[5] The TKE was examined without the change of mass, computing the specific TKE per unit mass (Joules/kg). The calculation of specific TKE exposes variations in turbulence from the fluctuating air motion. 3-D TKE contour map was constructed to examine the mechanism of TKE development and dissipation with crank angle throughout the cylinder volume during the intake and compression strokes. These iso-surfaces allow the user to view where and when pockets of higher turbulence exist in the measured volume.

During the early intake stroke, TKE is generated by the injected flows through the intake valves. Hence, higher TKE was observed in the area which the flows meet, and it was located between the intake valves and near the cylinder wall on the intake side. 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 the intake stroke. Late intake stroke shows donut shape of TKE contour iso-surface which is parallel to the Plane 2.



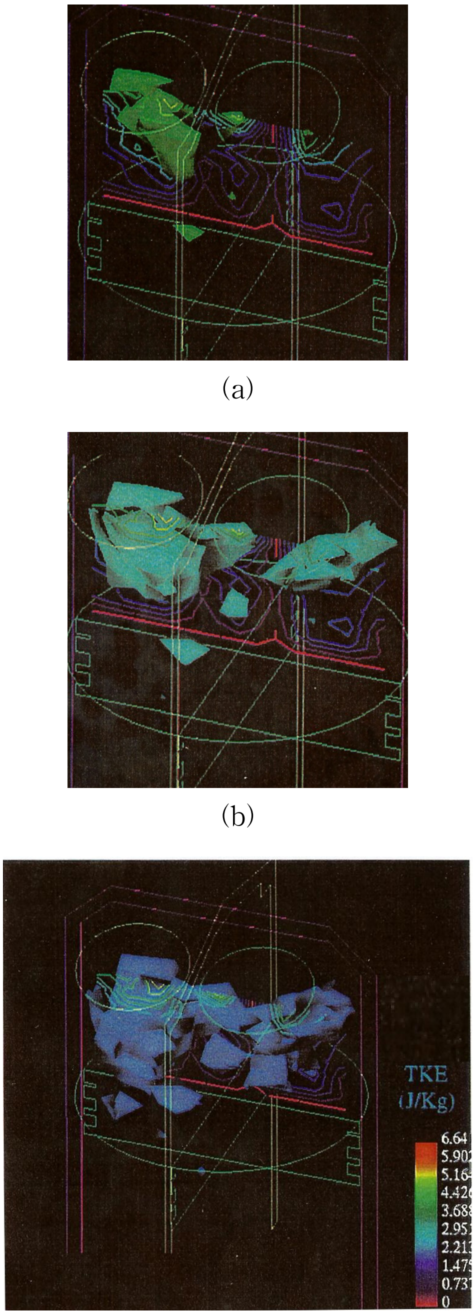
(a)

(b)

(c)

Fig. 6 TKE iso-surface mapping at 180 crank angle degree

Figures 6 and 7 show three different levels of TKE iso-surfaces at 180 and 290 crank angle degrees, respectively. A simple wire frame represents the piston, cylinder, combustion chamber, and two intake valves. The (a) figures show a high TKE area and the next levels of TKE iso-surfaces (b and c figures) envelop the higher level TKE iso-surfaces. At BDC, near the piston top, a 'horse shoe' shaped TKE



(a)

(b)

(c)

Fig. 7 TKE iso-surface mapping at 290 crank angle degree

iso-surface structure can clearly be seen in Fig. 6During the compression stroke, TKE broke down into small structure and was spread out in the combustion chamber. During the late compression stroke (after IVC), Fig. 7 depicts two higher TKE iso-surfaces near the intake valves. These figures also show that the TKE is higher on the intake side than on the exhaust side of the cylinder.

## 5. Conclusion

In-cylinder flow characteristics were quantified with the ensemble averaged- velocity, tumble and swirl ratios, and TKE iso-surfaces. From the careful study of these quantities, the results of this study support the following conclusions:

1) The volumetric flow patterns inside the investigated four-valve SI engine exhibit a large degree of symmetry about the y and z axes, which continues throughout the compression stroke.

2) Tumble and swirl ratios do not accurately represent the complex in-cylinder air motion during the intake stroke, due to the two symmetry counter flow patterns. The ratios without flow pattern study may not be useful as parameters for the characterization of in-cylinder flows.

3) During the early intake stroke, TKE in middle planes dissipates faster than in outer planes. This shows that more turbulence exists in middle area than outer area.

4) TKE obtained from one or two planes may mislead the characteristics of the turbulence in the cylinder.

5) TKE iso-surfaces can be used to display comparable regions of turbulence within the cylinder volume. Higher levels of TKE prevailed in zones of mean velocity collisions and regions where significant directional changes in the mean velocity patterns occurred.

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