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CORRELATION STUDY OF THE MEASURED TUMBLE RATIOS USING THREE DIFFERENT METHODS: STEADY FLOW RIG; 2-DIMENSIONAL PIV; AND 3-DIMENSIONAL PTV WATER FLOW RIG

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ABSTRACT–In-cylinder flows such as tumble and swirl play an important role on the engine combustion efficiencies and emission formations. The tumble flow, which is dominant in current high performance gasoline engines, is able to effect fuel consumptions and emissions under a partial load condition in addition to the volumetric efficiency under a wide open throttle condition. Therefore, it is important to optimize the tumble ratio of a gasoline engine for better fuel economy, lower emissions, and maximum volumetric efficiency. First step for optimizing a tumble ratio is to measure a tumble ratio accurately. For a tumble ratio measurement, many different methods have been developed and used such as steady flow rig, PIV, PTV, and LDV. However, it is not well known about the relations among the measured tumble ratios using different methods. The purpose of this research is to correlate the tumble ratios measured using three different methods and find out merits and demerits of each measurement method. In this research the tumble flow was measured, compared, and correlated using three different measurement methods at the same engine: steady flow rig; 2-dimensional PIV; and 3-dimensional PTV water flow rig.

KEY WORDS : Tumble flow, Steady flow rig, PIV, PTV, Water flow rig, Impulse torque meter

1. INTRODUCTION

Strict emission regulations and high gas price have demanded the development of new technologies to achieve high thermal efficiencies and low exhaust emissions. VVT (Variable Valve Timing), VVL (Variable Valve Lift). EMV (Electromagnetic Valve), cooled EGR (Exhaust Gas Recirculation), VCR (Variable Compression Ratio), etc are some examples of new technologies in automotive engines to meet the emission regulations and consumer's demand. Automotive engineers could control the air/fuel mixing, in-cylinder flow, residual gas fraction, etc, to reduce the exhaust emissions and fuel consumptions. In particular in-cylinder flow control is one of the most effective tools to affect combustion qualities in the internal combustion engine. Flame ignition, propagation, extinction, air/fuel mixing including stratification, and so on are influenced partially or dominantly by the in-cylinder flow such as swirl and tumble. Tumble flow is more dominant than swirl flow in current high performance gasoline engines because they have two intake valves to maximize volumetric efficiencies. Even if tumble flow is dominant in most of the gasoline engines, it is not actively used for combustion and emission control except in GDI (Gasoline Direct Injection), lean burn or high EGR engines. However, appropriate tumble flow in the gasoline engine is needed for obtaining an idle combustion stability, EGR susceptibility, high volumetric efficiencies, etc. It is generally known that the higher tumble ratio means faster combustion speed. However, the flow coefficient (C_f) of a cylinder head is also affected by a tumble ratio. A target tumble ratio and a flow coefficient (C_f) of the cylinder head are usually determined at the initial design stage of a new engine development process. In the prototype design and initial experiment stage, tumble ratio and flow coefficient of a new prototype engine are measured and compared with a target value. Therefore, it is important to measure the tumble ratio accurately and consistently in the engine development process. Quite a lot of different technologies have been developed and used to measure a tumble ratio. Automotive companies and research centers have their own specific rig for a tumble ratio measurement. Therefore, it is not easy to compare the tumble ratios measured by using different measurement methods under different operating conditions. Steady flow rig using an impulse torque meter is one of the widely used

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tumble measurement techniques (Xu, 2001; Stone and Ladommatos, 1992; Ricardo, 1993). 2-dimensional or 3-dimesional PIV (Particle Image Velocimetry) and PTV (Particle Tracking Velocimetry) techniques are also utilized to measure an in-cylinder flow (Trigui *et al.*, 1994; Denlinger *el al.*, 1998; Choi and Guezennec, 1999; Bevan and Ghandhi, 2004; Yang *el al.*, 1998; Lee *et al.*, 2005). LDV (Laser Doppler Velocimetry) is used to analyze an in-cylinder flow field and especially to find out the turbulent intensity and turbulent length scale (Marc *el al.*, 1997; Yoo *el al.*, 1995; Lee, 1997).

Tumble ratio measurement using a steady flow rig is the cheapest, easiest, and fastest method even though it also has a lot of limitations. First, the steady rig does not operate valve systems during tumble ratio measurements. It measures the tumble or swirl ratio at a fixed valve lift and calculates the overall tumble or swirl ratio using a valve profile. Therefore, the measured tumble ratio using a steady rig could be different from that of a real engine. Especially in-cylinder flow variations due to valve timing changes in a VVT engine cannot be anticipated from the steady rig measurement only. Second, in-cylinder flow has a 3-dimensional flow structure. Steady flow rig test is not able to reflect the 3-Dimensional flow characteristics of the in-cylinder flow. Third, steady flow rig calculates a tumble or swirl ratio based on the assumption of a rigid body rotation of the in-cylinder flow. However, real in-cylinder flow is much different from that of a rigid body bulk flow assumption. In spite of these limitations the steady rig tumble flow measurement method is still widely used in the automotive companies and research centers due to its convenience, low cost, and fastness.

2-Dimensional or 3-dimensional PIV, PTV, LDV techniques measure the in-cylinder flow directly using optical method under real engine operating conditions. The measured in-cylinder flow and flow numbers by using these techniques could be assumed as closest to the real flow field. In order to apply these optical measurement tools for tumble ratio measurement, test engine needs to be modified for an optical access. For example, quartz cylinder liner, specially designed piston, and other mirror systems are usually used for optical access. In addition to the engine modification, expensive equipments (lasers, high speed camera, lens, filters etc) are also needed. Therefore, in-cylinder flow measurements using optical methods need more time and costs than that of the steady flow rig.

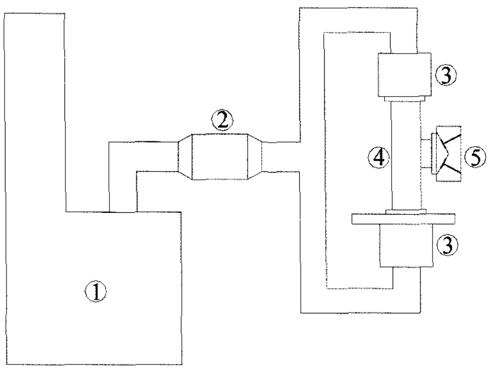
The main purpose of this research is to find out the correlations among the tumble ratios measured by using different measurement methods in the internal combustion engine. Since many different methods are used in measuring the tumble ratio and each method has its own characteristics, it is not easy to find out the relation between the measured tumble or swirl ratios using different measurement methods. Therefore, it is needed to compare the flow measurement results using different methods at a same engine and find out the correlation between those methods. The comparison would help understanding the characteristics and relations among these flow measurement techniques and the measured tumble ratios. In this research three different flow measurement methods (steady flow rig, 2-dimensional PIV, and 3-dimensional PTV water flow rig) are used to measure the tumble ratios of the four different engine cylinder configurations. The measured tumble ratios are compared and correlated with each other.

2. TEST METHODS

Three different measurement methods (steady rig, 2-dimensional PIV, and water flow rig) were used to measure the tumble ratio. For the steady rig tumble ratio measurement, impulse torque meter and specially designed T-type tumble adaptor were used to measure the angular momentum generated by an in-cylinder tumble flow. Optical engine with the quartz cylinder liner, Nd-Yag pulsed laser, and other optical systems were used for the 2-dimensional PIV measurement. Water flow rig can simulate the real engine operation through the dynamic and geometric analogy using the water. The tumble ratio in the water flow rig was measured using 3-D PTV technique. Since the water is used as an operating medium, the cylinder flow can be captured only during the induction stage. Equipment setup and measurement methods of each flow rig are discussed in the following subsections in more detail.

2.1. Steady Flow Rig

The steady flow rig is widely used to measure a flow coefficient, swirl ratio, and tumble ratio of a cylinder head. Tumble ratio in the steady rig is usually measured by using an impulse torque meter or a paddle wheel. The impulse torque meter measures an angular momentum of the intake flow and the tumble ratio is calculated using the measured angular momentum and flow rate. The paddle wheel measures the angular speed of the intake flow. The basic assumption involved in tumble ratio measurement using a paddle wheel meter is that in-cylinder flow has a linear velocity distribution across the cylinder bore. The impulse swirl meter (P7300, Cussons Inc.) was adopted for the steady rig measurement in this research since this method can measure the angular momentum directly without any assumptions. For the tumble ratio measurement L or T-type adaptor between a cylinder head and an impulse torque meter needs to be installed. T-type tumble adaptor was used in this steady rig. Figure 1 represents the overall configuration of the steady tumble rig.



① Superflow SF-600
② Laminar flow meter
③ Impulse torque meter
④ T-type tumble adaptor
⑤ Test cylinder head

Figure 1. System configuration for the tumble ratio measurement in the steady rig.

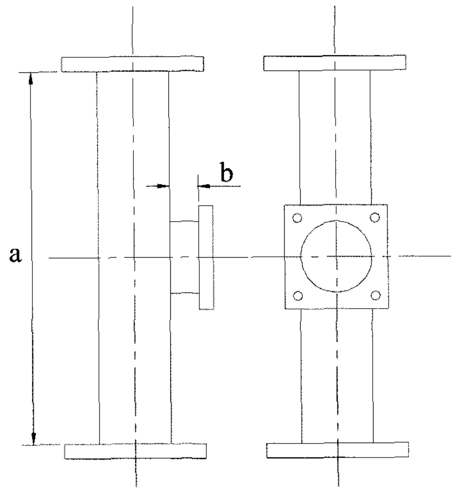


Figure 2. T-type adaptor.

In Figure 1, Superflow bench (Superflow SF-600, Cussons Inc.) is used for the suction of an air. During the tumble ratio measurement pressure difference between the tumble adaptor and the atmosphere was maintained as 25 inH_2O. The test pressure was changed from 20 inH_2O to 40 in H_2O. The flow coefficient and the tumble ratio were not changed a lot according to the test pressure. Therefore, test pressure was set to 25 inH_2O for preventing from overheating of an electric motor. The tumbling flow is transferred to the impulse torque meter via T-type tumble adaptor. For the symmetric structure of the tumble rig, two identical impulse torque meters were installed at each end of the T-type adaptor. Tumble ratio was calculated based on the average value of these two impulse torque meters. Air flow rate of the steady rig was measured using a laminar flow meter installed between the T-type adaptor and the Superflow SF-600. Air flow rate and impulse torque meter were measured from 1 mm valve lift to maximum valve lift via 1 mm increments.

Figure 2 shows the detailed configuration of a T-type adaptor. The diameter of this adaptor was same with that of an engine bore. The vertical length (a) was set to 1 m to avoid the interference between the cylinder head and the flange. The height (b) was minimized as 25 mm to increase the measured tumble torque.

2.2. 2-Dimensional PIV

The second method for measuring in-cylinder flow is 2-dimensional PIV. 2-D PIV takes two consecutive pictures of the in-cylinder flow at known time difference and rebuilds the in-cylinder flow data via statistical methods. The overall system configuration for a 2-dimensional PIV measurement is shown in Figure 3.

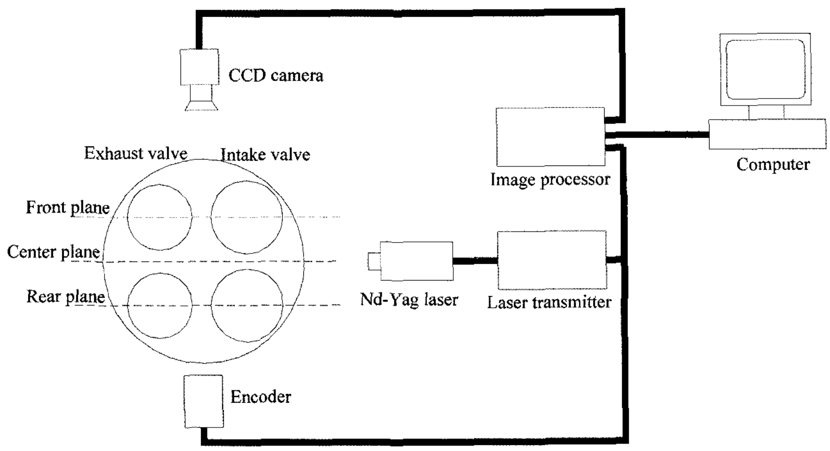


Figure 3. System configuration for 2-dimensional PIV measurement.

Nd-Yag pulsed laser (Spectra physics Inc.) was used as a light source. Two consecutive images with 10 micro-second time difference are captured by CCD (Charge Coupled Device) camera and transferred to the computer for data processing. The laser and CCD camera are controlled by an image processor (Dantec dynamics Inc.) and the synchronization between the PIV system and the engine is based on the optical encoder (720 pulses/cycle, AVL Inc.) installed in damper pulley. Three different cylinder cross sections (front plane, center plane, and real plane) were captured by CCD camera. The center plane is located on the cylinder center line. The front and rear planes are crossing the center lines between the intake valve and the exhaust valve. The 2-dimensional PIV measurements were conducted under three different engine operating conditions: 1200 rpm/50 kPa, 2000 rpm/40 kPa, and 2000 rpm/60 kPa. Pressures in the operating condition represent the intake manifold pressure and were measured by piezoresistive pressure transducer. Under these operating conditions, in-cylinder flows were measured at three different measurement planes and five different crank angles. The measured crank angles are ATDC (After Top Deadcenter) 60°, 120°, 180°, 240°, and 300°. At each test condition, 10 consecutive engine cycles were logged and averaged using 2-dimensional PIV system.

2.3. 3-Dimensional PTV Water Flow Rig

The basic principle of a water analog rig is to simulate the in-cylinder flow of a real engine by using dynamical and geometrical analogies. The water rig system in this research was made by FloCoTec Inc. This system is using 3-dimensional PTV technologies to get the in-cylinder flow information. At the BDC (Bottom Dead Center) piston position, five consecutive images were taken by two CCD cameras and in-cylinder flows were rebuilt 3-dimensionally by using PTV algorithms. In order to simulate the valve and piston operation of a real engine, three servo-motors are used for operating the in/ex valves and piston. A strobe light was used as a light source. Real engine data including bore, stroke, valve profile, etc are stored in the personal computer and used to control the correct timing for servo motors and strobe light. Figure 4 shows the overall system configuration for the 3-dimensional PTV water flow rig.

The water rig system used in this research can take the images only at BDC position. Five consecutive images were taken at BDC and 200 consecutive engine cycles were measured and averaged for a tumble ratio calculation.

3. TEST ENGINE

For the tumble ratio measurement, four different engine heads were tested using three different methods. As a baseline engine, HMC (Hyundai Motor Company) 2.0 L Beta engine was used. Detailed specifications of the baseline engine are shown in Table 1.

Table 1. Test engine specification.

Engine name		HMC Beta 2.0 L
Displacement (cc)		1975
Bore (mm)		82
Stroke (mm)		93.5
Valve timing	IVO	BTDC 9° CA
	IVC	ABDC 43° CA
	EVO	BBDC 50° CA
	EVC	ATDC 6° CA

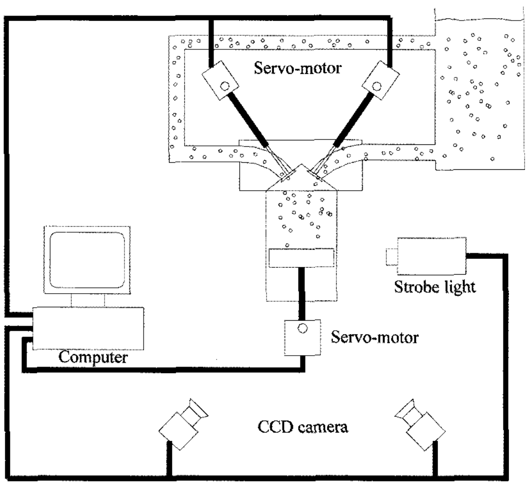


Figure 4. Water analog rig using 3-dimensional PTV.

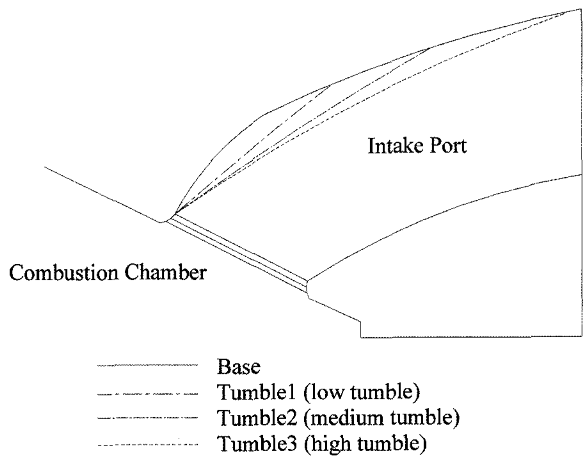


Figure 5. Intake port modification for the four different tumble ratios.

Four different engine heads were prepared by modifying the intake port of the baseline engine. Figure 5 indicates the intake port modifications to change the tumble ratio.

As shown in Figure 5, the upper parts of the intake port are modified to affect the tumble ratio.

4. RESULTS AND DISCUSSIONS

Table 2 shows the tumble ratios of four different intake ports measured using three different methods.

Steady rig tumble ratios were calculated based on the averaged values of two impulse torque meter readings. During steady rig measurements two impulse torque meters showed almost same values. Tumble ratios of the water flow rig were calculated based on the flow data at twenty cross sectional cylinder planes. Even though the cylinder flow is measured 3-dimensionally in the water flow rig, the tumble ratio calculation is based on the 2-dimensional plane flow data. The measured 3-dimensional cylinder flow is divided into twenty tumble planes and the tumble ratio is averaged tumble ratio of these tumble planes. The average tumble ratio is an ensemble averaged value of the measured 200 consecutive engine cycles.

In the 2-dimensional PIV measurements, the images were taken at three different sections and at six different crank angles. The tumble ratio of 2-dimensional PIV data shown in Table 2 is an ensemble averaged value of 10 consecutive engine cycles. The measured tumble ratios using three different measurement methods are discussed at the following subsections in more detail.

4.1. Steady Rig VS. Water Flow Rig

The main difference between the steady rig and the water flow rig is the valve operation during the measurements. Since the steady flow rig doesn't actuate the valve system, the tumble ratio is calculated based on the measured impulse torque data at each valve lift. The non-dimensional tumble ratio can be defined as Equation 1 (Ricardo 1993).

Table 2. Steady rig tumble measurement results.

		Baseline	Tumble1	Tumble2	Tumb3
Steady rig		0.6	0.83	0.97	1.08
Water flow rig		0.35	0.5	0.75	1.0
PIV	1200 rpm/ 50 kPa	0.12	0.54	0.72	0.86
	2000 rpm/ 40 kPa	0.3	0.79	1.06	1.32
	2000 rpm/ 60 kPa	0.13	0.78	1.17	1.38

$$N_r = \frac{8M}{\dot{m}VoB} \quad (1)$$

N_r : non-dimensional tumble ratio
M : measured torque in the impulse torque meter
$\dot{m}$: measured flow rate
V_o : theoretical intake flow velocity
B : cylinder bore

The non-dimensional tumble ratio in Equation 1 is defined as the linear ratio between the tangential swirl velocity and the fictitious ideal velocity. Since the angular momentum is measured using the impulse torque meter, the tangential velocity is calculated from the measured torque and the moment of inertia. In order to calculate the charge vortex rotational speed from the measured impulse torque values, the in-cylinder flow motion is assumed as a solid body rotation. Non-dimensional tumble ratio is measured at each valve lift. The engine tumble ratio is usually defined as shown in Equation 2.

$$R_t = \frac{\text{Charge votex rotation speed}}{\text{Engine speed}} \quad (2)$$

The swirl ratio is calculated by the integration of the non-dimensional swirl number and the flow rate during the intake valve opening period. That is, using the non-dimensional tumble ratio, the tumble ratio of the cylinder head was calculated using Equation 3 and 4 (Ricardo 1993). In Equation 3, and represent the intake valve opening and closing crank angle.

$$R_t = \frac{L_d \int_{\alpha_1}^{\alpha_2} C_f N_r d\alpha}{\left(\int_{\alpha_1}^{\alpha_2} C_f d\alpha\right)^2} \quad (3)$$

$$L_d = \frac{BS}{n_v D_v^2} \quad (4)$$

R_t : Tumble ratio
C_f : flow coefficient
L_d : shape factor
B : bore diameter
S : stroke length
n_v : number of intake valves
D_v : intake valve diameter

The tumble ratio in the water rig is defined as shown in Equation 5.

$$TR = \frac{\int_v \rho(\vec{r} \times \vec{V}) \cdot \vec{i}\, dv}{w \int_v \rho(\vec{r} \times \vec{r}) dv} \quad (5)$$

The definition of Equation 5 is basically same with Equation 2. That is, tumble ratio is defined as the ratio between the charge rotational speed and the engine

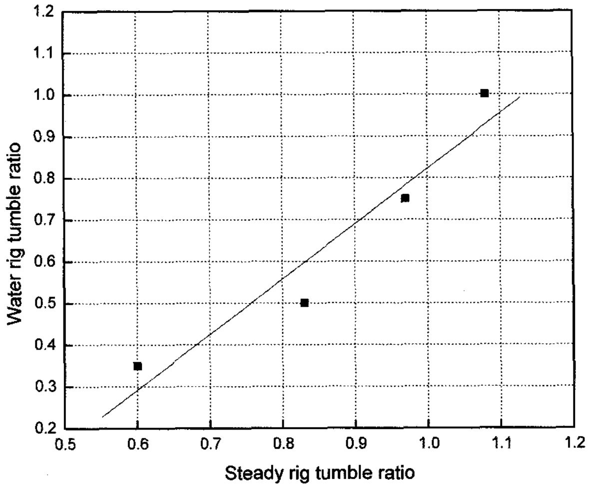


Figure 6. Tumble ratio correlation between the steady rig and the water analog rig.

rotational speed.

Figure 6 shows the correlation curve between the steady rig tumble ratio and the water rig tumble ratio. The linear regression ratio between these two tumble ratios is 0.97. Linear regression ratio 1 means a perfect correlation. Thus, Figure 6 means that the tumble ratio measured in the water rig can be correlated well with that of the steady rig.

4.2. Steady Rig VS. 2-D PIV

The definition of the tumble ratio in the 2-dimensional PIV is same with that of the water flow rig. The tumble ratio correlation between the steady rig and the 2-D PIV rig are shown in Figure 7. The reference position for the tumble ratio calculation was set to the center of the measured plane. Since 2-D PIV measurements were taken at different crank angles and different cross sections, the reference center position was changed as the piston moves. Figure 7 shows the correlation results between the steady rig and the 2-D PIV. As shown in Figure 7, tumble ratios measured in 2-D PIV are increasing as the engine speed increases from 1200 rpm to 2000 rpm. However, the tumble ratio didn't show much variation as the load was changed. Even if the tumble ratios in the 2-D PIV method are changed according to the engine operating conditions, the correlation between the steady rig and the 2-D PIV is almost perfect. The linear regression ratios between the steady rig and the 2-D PIV rig showed over 0.99 at all operating conditions.

The tumble ratio of the 2-D PIV shown in Figure 7 is an averaged value at three different planes and five different crank angles. The tumble ratios measured by 2-D PIV showed the variation according to the measurement plane and the crank angle. Figures 8–10 indicate the tumble ratio variations according to the measurement plane and the crank angle. The tumble ratios are varying as the piston moves in these figures. Especially at ATDC 60° the tumble ratio shows the negative values. This

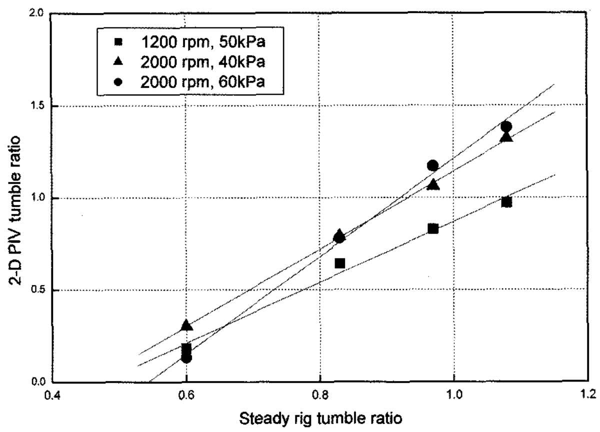


Figure 7. Tumble ratio correlation between the steady rig and the water flow rig.

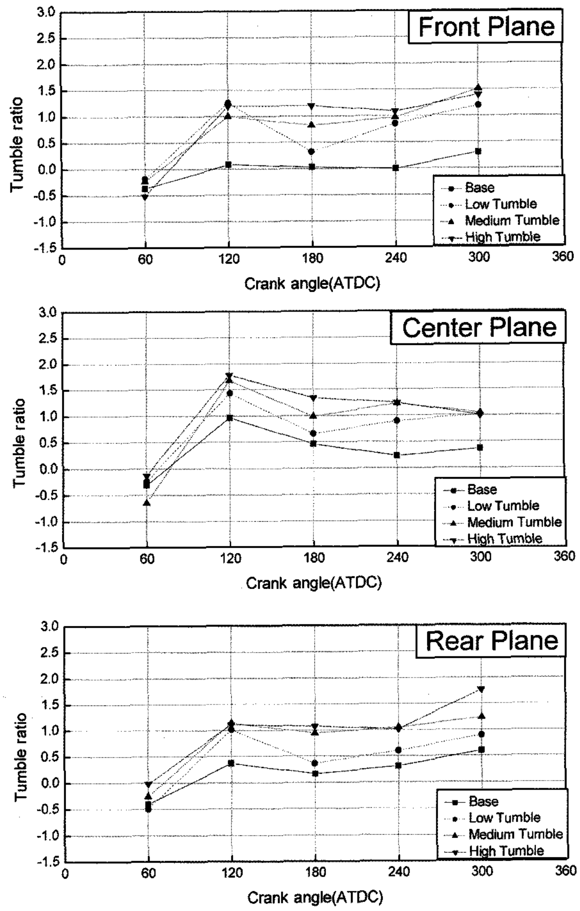


Figure 8. 2-D PIV tumble ratio at 1200 rpm, 50 kPa.

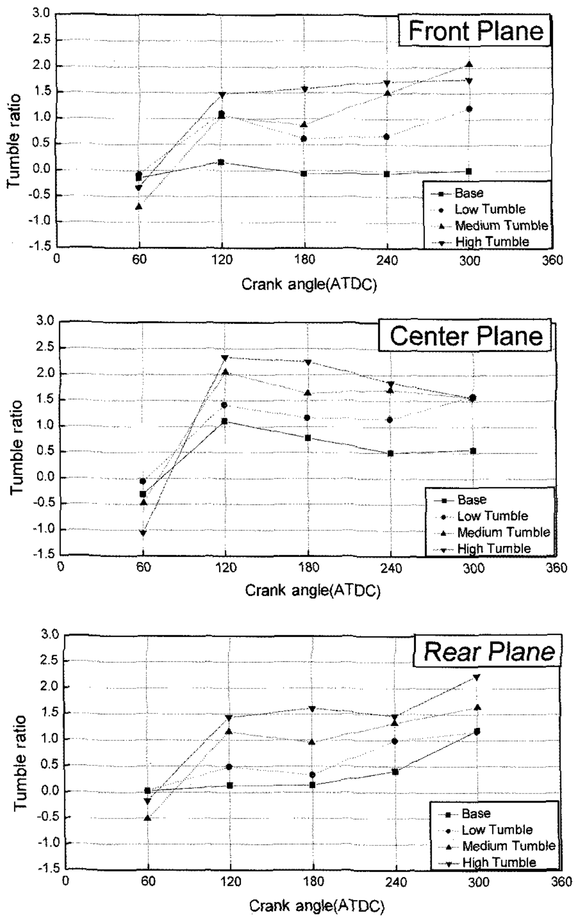


Figure 9. 2-D PIV tumble ratio at 2000 rpm, 40 kPa.

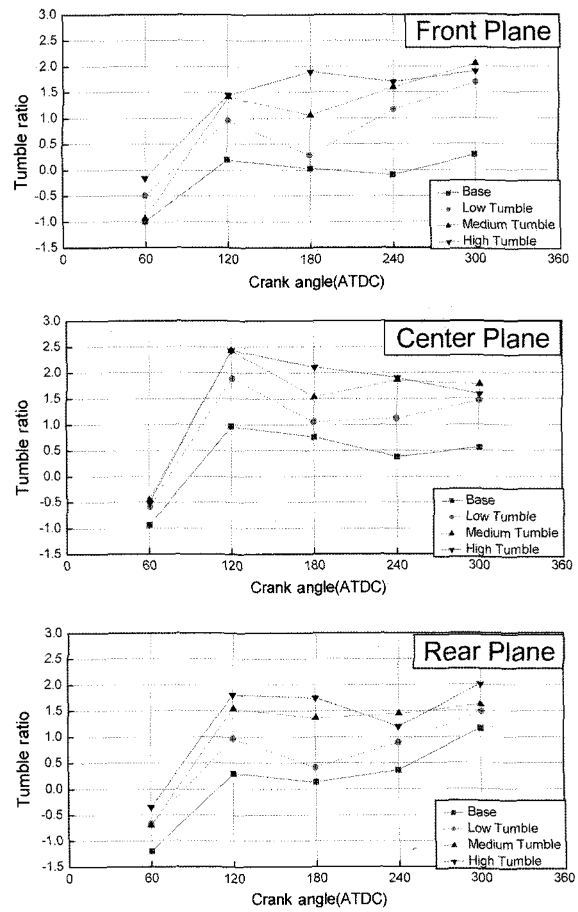


Figure 10. 2-D PIV tumble ratio at 2000 rpm, 60 kPa.

means that at the initial valve opening more intake flow is directing the reverse direction. That is, more intake flow is going downward along the cylinder wall. As the piston moves more downward, the tumble ratio turns into positive values. Tumble ratios increase until the piston reaches to ATDC 120°. The tumble ratio after ATDC 120° doesn't show the consistent trend. According to the measured cross sections and the operating conditions, measured tumble ratios are changing. At the center plane the tumble ratio declines after ATDC 120° irrespective of the operating conditions. The tumble ratios at front and rear planes also fluctuate as the piston moves further.

4.3. Water Flow Rig VS. 2-D PIV

The main difference between the water flow rig and the 2-Dimensional PIV is operating media. Water flow rig uses the water as a medium and so cannot simulate in-cylinder flow during the compression process. In addition to the compression stroke the cylinder flow variations during the valve overlap cannot be simulated by the water flow rig. 2-Dimensional PIV system is able to measure the in-cylinder flow at the same engine operating conditions including compression process. Figure 11 represents the tumble ratio correlation between the water flow rig and the 2-Dimensional PIV. Tumble ratios of these two measurement systems are well correlated. The linear regression factor between these methods showed over 0.99 irrespective

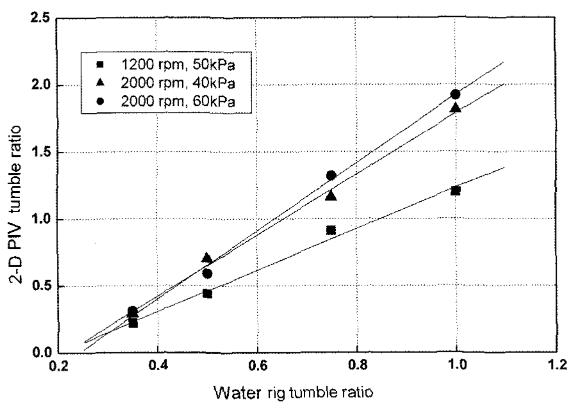


Figure 11. Tumble ratio correlation between the water flow rig and the 2-dimensional PIV.

of the engine operating conditions.

5. CONCLUSIONS

In-cylinder flow field such as swirl and tumble flow is one of the most important parameters which could affect the combustion speed and exhaust emissions. In-cylinder flow controls are actively used for obtaining the combustion stability in lean burn and high EGR engine operating regions. In the current gasoline engine, tumble flow is dominant in contrary to the diesel engine in which swirl flow is generated by specific intake port design and used for combustion control. Target tumble ratio is determined and tested at the initial stage of the engine design. In this research tumble ratios measured using three different methods were compared and correlated. Steady rig tumble ratio using the impulse torque meter and T-type adaptor was well correlated with those of the 2-dimensional PIV and the water flow even if it cannot simulate the dynamic operation of the real engine. 2-D PIV measurements show the variation of the measured tumble ratio under different engine operating conditions. As the engine speed was increasing, the tumble ratio of 2-D PIV was also increased. However, even though the tumble ratio of 2-D PIV was not constant under different operating conditions, the measured tumble ratio at each operating condition was correlated well with those of steady rig and water flow rig. Water flow rig tumble ratio showed a good correlation with the 2-dimensional PIV tumble ratio even if it simulated the real engine operation using static and dynamic similarities and couldn't simulate the compression stroke.

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