

# Flow Direction Characteristics in the Vicinity of the Spark Plug in an S. I. Engine

Sung Bin Han\*, Yong Hoon Chang

*Department of Mechanical Engineering, Induk Institute of Technology*

Yon Jong Chung

*Department of Automotive Engineering, Taegu Future College*

The flame speed may be decomposed into the burning speed and the flame transport speed. The flame transport speed is affected considerably by the flow direction, variation rate of flow direction, and flow speed in the combustion chamber. Especially, the flow direction and the variation rate of flow direction at the spark plug location during the ignition period have an important effect on the ignition process and the early flame propagation process. We measured the flow direction component and the variation rate of flow direction with a hot wire probe at the spark plug location. It was shown that the representative flow direction of ignition period is the right-vertical direction of crank shaft and it was used to investigate the variation rate of flow direction.

**Key Words :** Flow Direction, Variation Rate of Flow Direction, Turbulence Intensity, Ensemble Averaged Mean Velocity

## 1. Introduction

A theoretically calculated burned gas fraction in engines is significantly affected by the flame front radius, spark location, and squish area. The basic concept of a spherical flame kernel was employed in the early stage of flame development and later super-imposed with the in-cylinder gas motion to define the flame front radius (Witze, 1986; Anderson, 1986). In addition, there are shape and flow factors which affect combustion phenomena in the combustion chamber of gasoline engine. The shape factors are decided by the combustion chamber shape, location of spark plug, and so on, but restricted to geometric problems (Xu, Dong, and Tsao, 1991). The flow factors are controlled more easily than shape factors.

And the effects for the turbulent flows in the combustion chamber show a large range of fluctuation per cycle even in the steady state condition. In order to study the in-cylinder flow direction characteristics in a spark ignition engine, the data of 250 cycles are collected and analyzed with ensemble average techniques.

The output of constant temperature hot wire anemometer is changed according to the temperature and pressure change of surroundings of the measured position as well as measured fluid velocity. Therefore it needs compensation. Researchers (Keck 1985; Heywood 1988) have made a study of combustion performance and flow phenomena in a cylinder. According to them intensive turbulence can realize the fast burn easily, and combustion velocity is affected by turbulence intensity. Both the turbulence intensity and bulk flame affect combustion phenomena, with varying degrees. Cycle-to-cycle combustion variability in spark-ignition engines limits the use of lean mixtures and lower idle speeds because of increased emissions and poor engine stability. The causes of the cycle-to-cycle variations are

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\* Corresponding Author,

E-mail : sungbinhan@mail.induk.ac.kr

TEL : +82-2-901-7635 : FAX : +82-2-901-7630

Department of Mechanical Engineering, Induk Institute of Technology, San 76, Wolgye-dong, Nowon-gu, Seoul 139-749, Korea.(Manuscript Received January 10, 2000; Revised May 9, 2000)

summarized in some papers (Brehob and Newman 1992; Ozdor et al., 1994). Although the causes of cycle-to-cycle variability are identifiable, there has been difficulty in quantitatively establishing the contributions of these phenomena. Detailed investigation on this problem by experiment is difficult due to the difficulty of controlling and measuring the changes in these influencing factors. Consequently it is not clear which factor is the most important in combustion variations and hence how to reduce this variation (Hinze, 1997; Han and Chung, 1998).

One way to examine this problem is using a computer simulation (Shen et al., 1994; 1996). These researchers investigated how the velocity and turbulence within different locations close to the spark plug influence combustion at individual cycles in a spark ignition engine. Two-dimensional cycle-resolved Laser Doppler Velocimetry (LDV) measurements have been done both inside the spark gap and around the spark tip to extract velocity information (Wahiduzzam, Morelshaw, and Sheard, 1993). And these researcher show a significant influence of both the mean velocity and turbulence during the early part of combustion when the velocity was measured close to the spark plug tip. The velocity influence was less significant when measured at some distance from the electrodes for both a pancake and a high squish combustion chamber. The correlation between the velocity close to the spark plug and the early flame development showed no dependence on the air-fuel ratio and a modest dependence on ignition timing (Arcomumanics, Bae, and Hu, 1994; Johansson, 1994).

Therefore, it can be estimated that other factors beside turbulence intensity have an influence combustion phenomena. Some researchers (Han et al, 1995) related turbulent flow to the ignition, flame propagation, and lean limit. The authors considered that, the turbulent flow direction and the variation rate of turbulent flow direction at the spark plug location of gasoline engine have an important effect on the ignition process and the early flame propagation process. Therefore, the author studied flow direction characteristics in the vicinity of the spark plug in a spark ignition.

## 2. Experiment

### 2.1 Experimental apparatus and method

Table 1 shows the specification an experimental engine. The test engine is a 4 stroke cycle, single cylinder, air cooling gasoline engine with a squish area of about 30% of Ricardo combustion chamber shape.

Figure 1 shows a block diagram of the experimental apparatus. To operate the engine at the motoring operation, the test engine is connected to a 5kW variable speed motor. To maintain turbulent flow conditions in the combustion chamber on motoring operation as during actual firing operation condition, carburetor was retained. The combustion chamber is a side valve type, so that the air through the carburetor flows into combustion chamber with rotating in 90 degree without swirl.

For flow measurement, a 2 channel, constant temperature hot wire anemometer was used. In addition, the spark plug was eliminated to study the ignitability of mixture and the characteristics

Table 1 Specification of engine used

Engine Type	4-cylinder, air cooling, overhead cam shaft
Displacement	267 cc
Bore × Stroke	74 × 62mm
Number of Cylinder	1
Compression Ratio	6.3

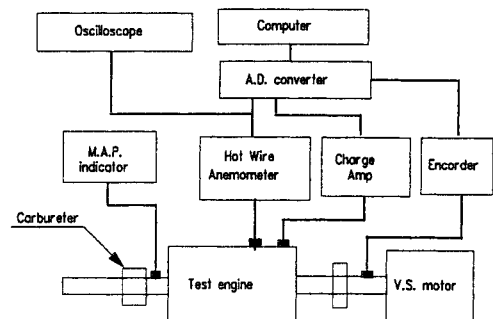


Fig. 1 Schematic diagram of air flow measurement system

of turbulent flow direction during the initial combustion period. The hot wire probe was inserted by using an adapter manufactured on that spark plug position. The X type hot wire probe (0250R-PI5) of alloy platinumiridium ( $\Phi=12.7\mu\text{m}$ ) for high temperatures to analyze the characteristics of the variation rate of flow direction in combustion chamber. The hot wire probes cross each other at 90 degrees; therefore the direction error with average velocity of main direction averages about 22%. The motoring pressure in combustion chamber is measured by a pressure transducer (Kistler, 6051A) for pressure compensation of hot wire anemometer. The outputs of the hot wire anemometer and pressure sensor are measured at every crank angle. This was input into the A/D converter (DT 2831G) of 250kHz and the data were analyzed by a computer. The engine speed was set to 1000, 2000, and 3000rpm respectively to study flow direction characteristics effects, and analyze the flow characteristics at the spark plug location. To estimate the effect of the flow direction while propagating the initial flame, the hot wire probe was inserted at 0mm, 5mm, 10mm, and 15mm from the spark plug location. The throttle valve was controlled, 1/4, 2/4, 3/4, and 4/4 of throttle valve opening, to study the effect of throttle valve opening.

## 2.2 Analysis method

Turbulent flows in the combustion chamber show large fluctuations per cycle even in the steady state condition. Therefore, to reduce standard deviation to less than 10%, data from 250 cycles were selected and analyzed with an ensemble averaging technique. A hot wire temperature compensation apparatus was used for temperature compensation and the pressure compensation equation on the basis of thermal equilibrium of hot wire is used for pressure compensation.

The authors had studied factors which influence turbulence intensity in combustion chamber at the spark plug location, and analyzed turbulent flows in the engine combustion chamber. In this study, Channel 1 is in the right-vertical direction to the crank shaft, and Channel 2 is in parallel with the crank shaft. In case the output of Chan-

nel 1 is bigger than that of Channel 2, the flow direction at the hot wire probe position is in the crank shaft direction. In contrast, when the output of Channel 2 is bigger than that of Channel 1, the flow is in the right-vertical direction to crank shaft. The flow direction component is defined as

$$U_d(\theta) = U_{ch_1}(\theta) - U_{ch_2}(\theta)$$

where,  $U_d(\theta)$  is the flow direction component. In case  $U_d(\theta) > 0$ : crank shaft direction,  $U_d(\theta) < 0$ : right-vertical direction to crank shaft. If the variation of flow direction would show that "(the output of Channel 1 > the output of Channel 2)" was changed to "(the output of Channel 1 < the output of Channel 2)" or "(the output of Channel 1 < the output of Channel 2)" was changed to "(the output of Channel 2 > the output of Channel 1)" according to crank angle, and then it was estimated the flow direction was changed. And then the variation rate of flow direction in a crank angle is defined as followings.

$$R_d(\theta) = \frac{n_d(\theta)}{N} \times 100$$

if,  $U_{ch_1}(\theta) > U_{ch_2}(\theta)$  and  $U_{ch_1}(\theta+1) < U_{ch_2}(\theta+1)$  then  $n_d(\theta+1) = n_d(\theta) + 1$ , if  $U_{ch_1}(\theta) < U_{ch_2}(\theta)$  and  $U_{ch_1}(\theta+1) > U_{ch_2}(\theta+1)$  then  $n_d(\theta+1) = n_d(\theta) + 1$ .

## 3. Results and Discussion

### 3.1 Analysis of characteristics of flow direction

Figure 2 shows the changes in flow with changes of engine speed at the spark plug location. In this figure, the sequence of strokes are intake, compression, expansion, and exhaust, where 360° is the top dead center at the end of compression. The (+) component in this figure means that the flow is in the direction of the crank shaft at the spark plug position, the (-) component means that the flow is in the right-vertical direction at the spark plug. As shown in the figure, the flow tends to the direction of the crank shaft in the inlet process as the engine speed increasing from 1000rpm to 3000rpm. Thus, we know that the average flow velocity is increased gradually in the direction of the crank shaft from

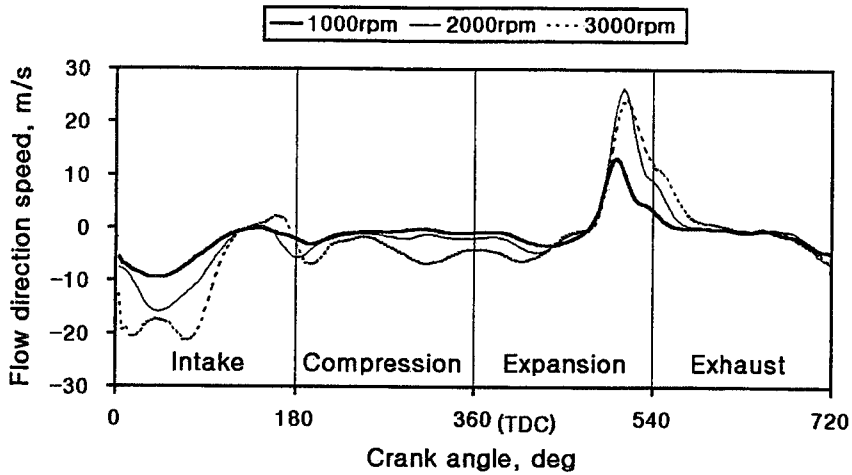


Fig. 2 Relation between the flow direction component and crank angle at each engine speed

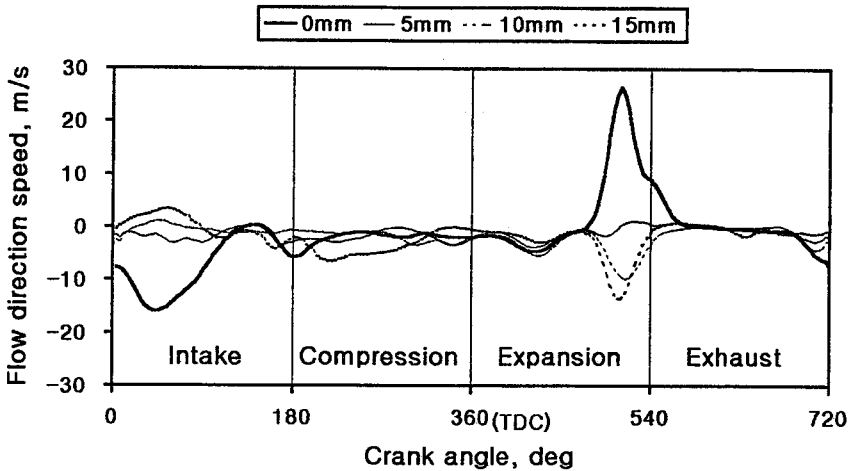


Fig. 3 Relation between the flow direction component and crank angle at each measuring point

4.43m/s, to 10.47m/s. As the engine speed is increased, at the time of the opening of the exhaust valve before bottom the dead center in the exhaust process, the flow direction is in the right angle to the crank shaft. During the spark duration ( $\Delta\theta=45^\circ$ ), from the end of compression BTDC 45 to TDC, with an increase in the engine speed, the flow speed increases from  $-0.72\text{m/s}$  to  $-5.16\text{m/s}$ . Thus the gas flow during the spark duration at the center of the spark position is consisted of the flow shaft with crank shaft direction and the right angle direction.

Figure 3 shows the flow direction component measured near the center position of the spark plug while the hot wire probe was moved to shaft

of spark plug direction gradually. If this would be ignited at spark plug, while the initial flame is propagating with spherical shape as for a center of spark plug to forward, and so that it would be pre-estimated that received influence of the turbulence flow, this measurement was experimented while inserting the hot wire probe with 4 steps of 0mm, 5mm, 10mm, and 15mm. As shown in the figure, with cause of that direction of gas flow being measured in the position of the spark plug is the flow direction of component in the inlet process evidently, it appears that the direction of flow is directed to crank shaft is averaged as  $7.36\text{m/s}$ . We know that the flow direction is appeared (+) component in process of opening exhaust

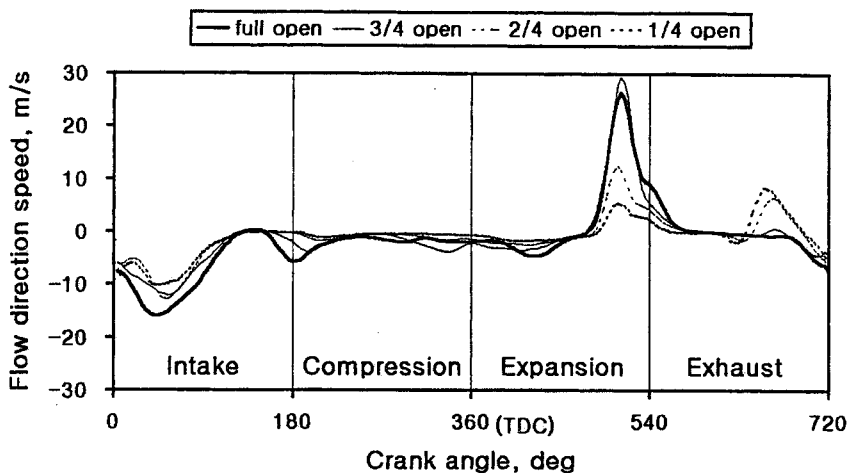


Fig. 4 Relation between the flow direction component and crank angle at each throttling opening

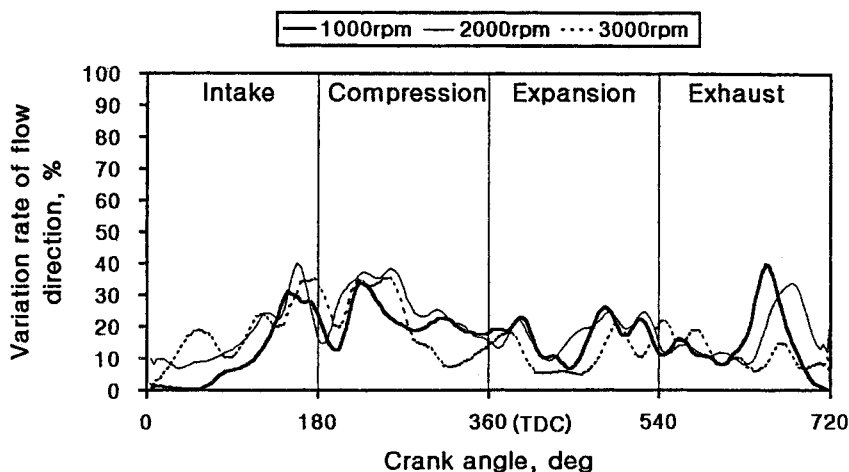


Fig. 5 Relation between the variation rate of flow direction and crank angle at each engine speed

valve before BDC, being positioned in the end of expansion process. At this time, the flow is in the same direction as the crank shaft direction; however, the measured result of moving the hot wire probe to 0mm, 5mm, 10mm, and 15mm to the inserted shaft of spark plug, while it is smallest in the initial process gradually, and then it is appearing 0 direction component with almost no direction at 10mm, if when it is advancing to 15mm, this flow direction is appearing the turbulence flow of (+) component. In view of this, we know that the flow direction during the inlet process is intersected the flow direction component at 0mm and 15mm positioned in spark plug. And if it is moving the hot wire probe as much 5mm at the

opening the exhaust valve, it is appearing almost 0 direction component and moving 10mm and 15mm, it is appearing (-) component evidently. As view of this, we can know that the turbulence flow direction in spark plug to be positioned at 0mm and in opening exhaust valve is a right angle to each other; in the light of this, we can estimate that with cause of that spark plug position of combustion chamber being inserted at about 10mm.

Figure 4 is showing the change of the flow direction component with changes in throttle valve opening. While the throttle valve opening such as steps of 1/4, 2/4, 3/4, 4/4, we used to measure variation rate of flow direction, the flow

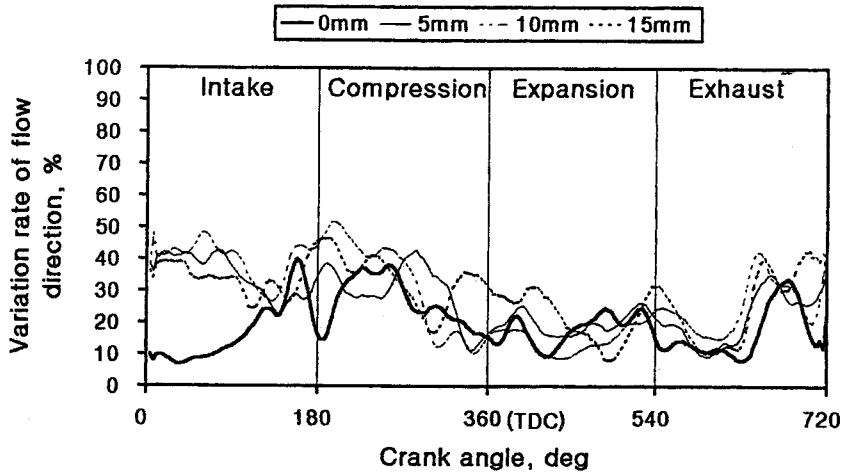


Fig. 6 Relation between the variation rate of flow direction and crank angle at each measuring point

direction is revealing a similar quantitative trend without regarding the throttle valve opening, the throttle valve opened during opening the inlet process and exhaust valve accordingly, the flow direction component is greatly increased, the flow direction of (-) component that is, the flow direction of a right direction with crank shaft is increased gradually in the inlet process, it is appearing prevailing the flow direction shaft—the flow direction of crank shaft in process of opening the exhaust valve, and then that volume, throttle valve is opened as gradual accordingly, is increased gradually and highly. However, the opening rate of throttle valve of the flow direction component is increased in the compression and expansion duration accordingly, even though it is increased slightly, that change is small. And, throttle opening rate is increased on spark plug duration ( $\Delta\theta=45^\circ$ ) accordingly, even though the flow direction component is increased slightly, but that size is smaller, the averaged value is -1.74m/s and the direction of flow is a right angle with the crank shaft. In the case of the throttle valve to be opened as much 1/4 after exhaust process, even though it have the flow direction component of (+) component, in case of throttle valve to be opened gradually, it is decreased and it is appeared almost 0 value on duration of throttle valve to be opened perfectly. In light of this, we know that the flow component in the right angle direction with crank shaft about the

opening variation of throttle valve has disappeared in this part.

### 3.2 Analysis characteristics of variation rate of flow direction

In Fig. 5 the flow variation is shown. In light of this figure, the entire variation of the flow direction is largely during inlet and initial compression, expansion end, exhaust end processed, except for exhaust end being opened valve duration, when piston is located at BDC in process of closing inlet and exhaust valves totally, variation rate of flow direction is appeared the approximately 30% above largely. Although the turbulence speed is appeared with maximum in the initial part of inlet process generally, variation of the flow direction is appeared less among the entire cycles because characteristics of direction of the inlet flow being inhaled through the inlet port. In case of increasing engine speed with 1000rpm and 2000rpm, 3000rpm, the whole cycle average with each 16% and 19%, 15% is appeared it to be increased slightly and then decreased at 2000rpm. However, with view of the averaged inlet process, engine speed is increased such as 11% and 16%, 18% accordingly, so that variation rate of flow direction is increased gradually. Engine speed is increased an ignition duration being influenced to ignition at spark plug accordingly, variation rate of flow direction is decreased gradually such as 18% and 17%, 10%, this engine speed of combus-

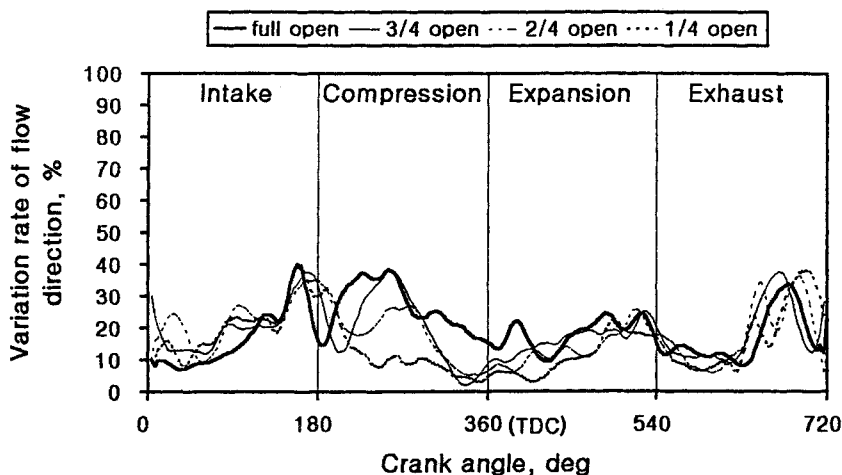


Fig. 7 Relation between the variation rate of flow direction and crank angle at each throttle opening

tion chamber's turbulence flow is increased accordingly, so piston speed is increased, this decrease variation of flow direction, it is understood that increase flow direction component of Fig. 2.

Figure 6 shows, when the hot wire probe is moved to inserted shaft of spark plug, variation rate of flow direction. As shown in the figure, in according to movement of hot wire probe, variation rate of flow direction shows the same trends; with view of the entire cycle average, it is appears that variations of flow direction are increased slightly and decreased such as at 0mm -19% and at 5mm -26%, at 10mm -28%, at 15mm -26%, at the time of 0mm in intake process on 17%, it is moving accordingly as 35% and 39%, 34%, though the entire cycle average is increased and thus again decreased of which is same trend, variation rate of flow direction in 0mm compared with other position, it is appeared less relatively. With view of this, we can know that, though intake process is variation rate of flow direction less in position of spark plug, big flow shaft is formed too right-vertical direction of crank shaft as the same result of Fig. 4.

Figure 7 shows the variation rate of flow direction about the opening variation of throttle valve in of spark plug position. As shown in this figure, it is appeared at least on inlet process in case of throttle valve to be opened perfectly, it is appeared at maximum on compression duration

Table 2 Summary of flow characteristics in the vicinity of the spark plug

	1000 rpm	2000 rpm	3000 rpm
Turbulence intensity, m/s	1.95	2.91	3.02
Ensemble averaged mean velocity, m/s	7.58	10.01	9.17
Flow direction component, m/s	-0.72	-1.77	-5.16
Rate of flow direction variation, %	18.5	17.7	9.9

and expansion in case of throttle valve to be opened perfectly. And variation rate of flow direction is increased from 4% to 18% in ignition duration gradually according to throttle valve being opened gradually. And as shown in figure, we can estimate that the exhaust duration can seldom be influenced by throttle valve to be opened in variation rate of flow direction. By these results as mentioned above, if we would herewith rearrange flow direction component and variation rate of flow direction, ensemble averaged mean velocity, turbulence intensity about variation of engine speed in the ignition duration of spark plug position influenced to ignition and the initial combustion duration, it is the same of the followings Table 2. In view of this table, the flow direction component in ignition duration being influenced to the initial combustion dura-

**Table 3** Summary of flow characteristics at 0mm, 5mm, 10mm, and 15mm

	0mm	5mm	10mm	15mm
Flow direction component, m/s	-1.77	-2.67	-2.81	+0.30
Rate of flow direction variation, %	17.7	17.6	14.0	34.2

tion is increasing engine speed from 1000rpm to 2000rpm, 3000rpm accordingly, it is showing the turbulence flow component being increased to crank shaft and a right-vertical direction, so that it is estimated that the ignited initial flame at spark plug would be influenced in moving toward piston.

And according to engine speed being increased, variation rate of flow direction is decreased from 18% to 10% down gradually, this is meaning that consistency of turbulence flow direction in combustion chamber is increased about 50% according to engine speed to be increased. And it is appearing that the ensemble averaged mean velocity is increased from 7.58m/s to 9.19m/s, as view of the flow direction component, we can know that direction of ensemble averaged mean velocity is forming the flow shaft of a right-vertical direction to the crank shaft in position of spark plug. And in accordance with engine speed being increased, as view of turbulence intensity to be increased gradually, the engine speed is increased accordingly, even though growth of initial flame would be given an effect with cause of the cooling loss and others to the flame growth, it is considered that increase of turbulence intensity would give an effect to combustion in following of growth as the initial flame once.

As shown in Table 3, in case of hot wire probe being moved to shaft direction of spark plug as gap of 5mm from 0mm to 15mm in the ignition duration, the flow direction component with -1.77m/s, -2.67m/s, -2.81m/s, 0.30m/s until 10mm is the flow direction component being increased to crank shaft and a right-vertical direction gradually for a while, the flow direction component is shifted toward the crank shaft and a right-vertical direction at 15mm, and when the movement dis-

tance of the variation rate of flow direction would be shifted to crank shaft and a right-vertical direction at 17.7% and 17.6%, 14.0%, it is increase quickly to 34.2%. This means that there are a large amount of flow variations between 10mm and 15mm, so that we know that the flow variation is highly by this phenomena of combustion chamber with cause that position of spark plug in combustion being distanced about 10mm at a spot to be dug from combustion chamber.

#### 4. Conclusions

The flow field in the combustion chamber was decided; the flow direction during the ignition duration is in the right-vertical direction to the crank shaft. According to the variation rate of flow direction, it was known the possibility to change the flow direction in a crank angle and the variation rate of flow direction in ignition duration.

With an increase in the engine speed, the variation rate of flow direction during the ignition duration is decreased from 18% to 10%. The flow direction component with the change in throttle valve opening during ignition is on the order of the variation rate of flow direction. About the depth of inserting hot wire in the ignition duration, the flow direction component is nearly right-vertical to the crank shaft.

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