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

* 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)

ummarized in some papers (Brehob and Newnan 1992; Ozdor et al., 1994). Although the :auses of cycle-to-cycle variability are identifiible, there has been difficulty in quantitatively :stablishing the contributions of these phenom:na. Detailed investigation on this problem by :xperiment is difficult due to the difficulty of :ontrolling and measuring the changes in these nfluencing factors. Consequently it is not clear vhich factor is the most important in combustion 'ariations and hence how to reduce this variation Hinze, 1997; Han and Chung, 1998).

One way to examine this problem is using a :omputer simulation (Shen et al., 1994; 1996). These researchers investigated how the velocity ınd turbulence within different locations close to he spark plug influence combustion at individual :ycles in a spark ignition engine. Two-dimen:ional cycle-resolved Laser Doppler Velocimetry LDV) measurements have been done both inside he spark gap and around the spark tip to extract /elocity information (Wahiduzzam, Morelshow, ınd Sheard, 1993). And these researcher show a ;ignificant influence of both the mean velocity ınd turbulence during the early part of combus:ion when the velocity was measured close to the ;park plug tip. The velocity influence was less ;ignificant when measured at some distance from he electrodes for both a pancake and a high ;quish combustion chamber. The correlation ɔetween the velocity close to the spark plug and he early flame development showed no depen:lence on the air-fuel ratio and a modest depen:lence on ignition timing (Arcomumanics, Bae, ınd Hu, 1994; Johansson, 1994).

Therefore, it can be estimated that other factors ɔeside turbulence intensity have an influence :ombustion phenomena. Some researchers (Han :t al, 1995) related turbulent flow to the ignition, :lame propagation, and lean limit. The authors :onsidered that, the turbulent flow direction and :he variation rate of turbulent flow direction at :he spark plug location of gasoline engine have an important effect on the ignition process and the :arly 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

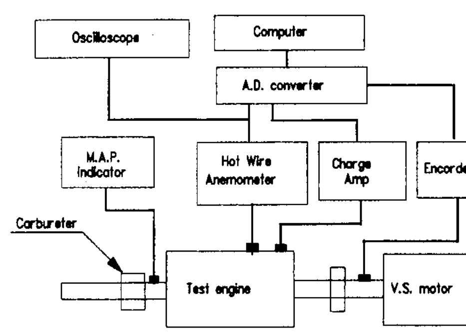

Fig. 1 Schematic diagram of air flow measurement system

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 platiniridium ($\Phi=12.7\mu$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 Channel 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.

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

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

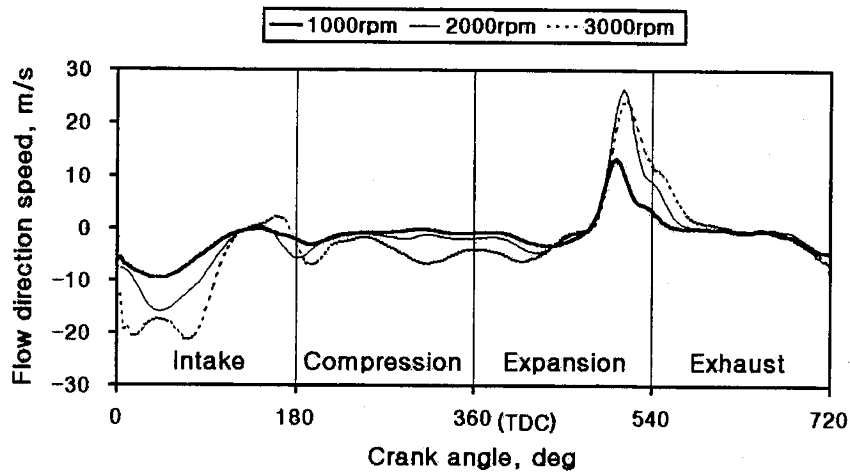

Fig. 2 Relation between the flow direction component and crank angle at each engine speed

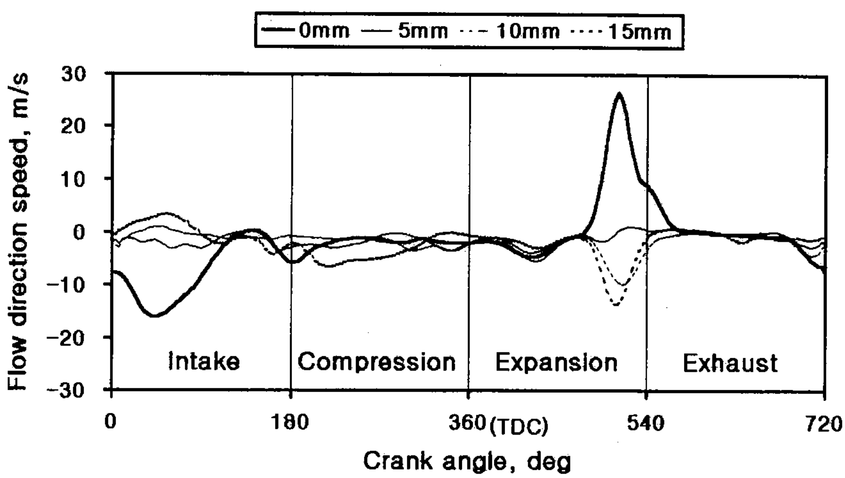

Fig. 3 Relation between the flow direction component and crank angle at each measuring point

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 ($\Delta\theta=45°$), from the end of compression BTDC 45 to TDC, with an increase in the engine speed, the flow speed increases from -0.72m/s to -5.16m/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. 36m/s. We know that the flow direction is appeared (+) component in process of opening exhaust

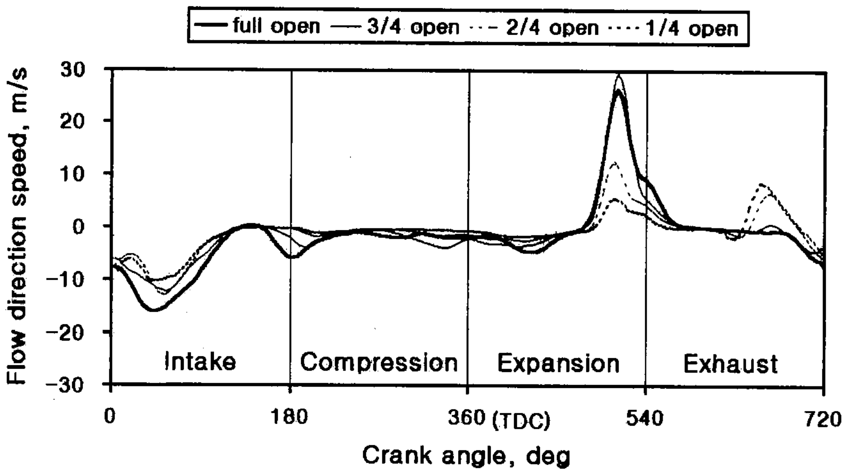

Fig. 4 Relation between the flow direction component and crank angle at each throttling opening

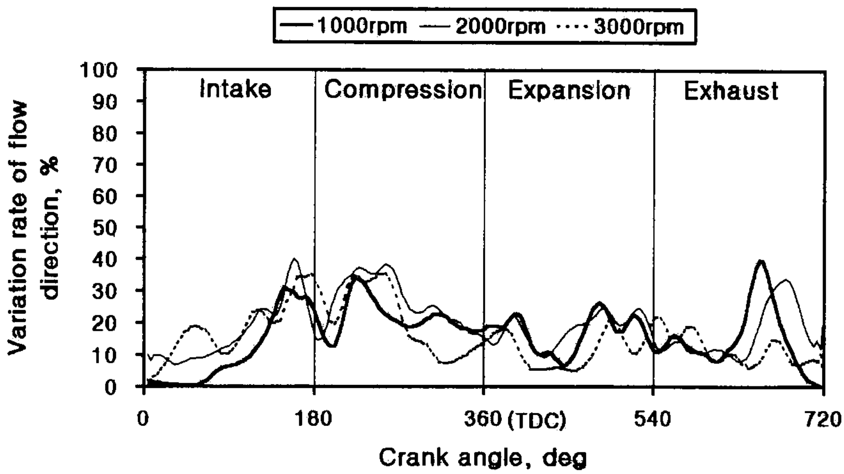

Fig. 5 Relation between the variation rate of flow direction and crank angle at each engine speed

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

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

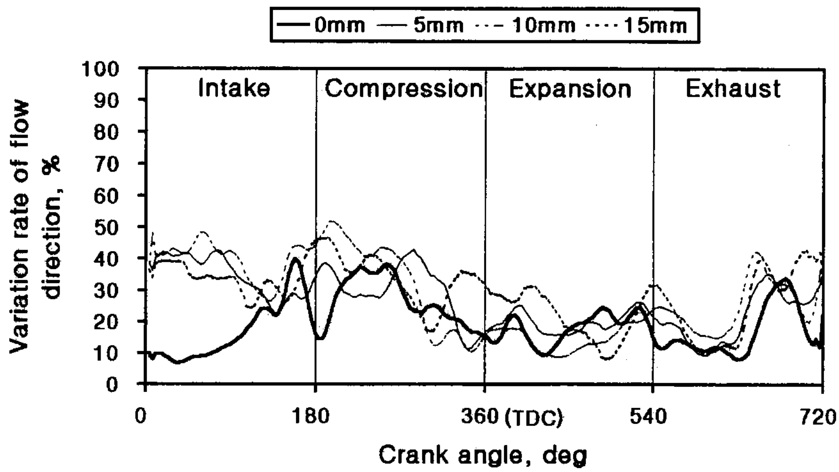

Fig. 6 Relation between the variation rate of flow direction and crank angle at each measuring point

irection is revealing a similar quantitative trend ithout regarding the throttle valve opening, the ırottle valve opened during opening the inlet rocess and exhaust valve accordingly, the flow irection component is greatly increased, the flow irection of (-) component that is, the flow direcon of a right direction with crank shaft is in'eased gradually in the inlet process, it is appearıg prevailing the flow direction shaft-the flow irection of crank shaft in process of opening the thaust valve, and then that volume, throttle ılve is opened as gradual accordingly, is in'eased gradually and highly. However, the openıg rate of throttle valve of the flow direction)mponent is increased in the compression and (pansion duration accordingly, even though it is ıcreased slightly, that change is small. And, ırottle opening rate is increased on spark plug uration ($\Delta\theta=45°$) accordingly, even though the ow direction component is increased slightly, ut that size is smaller, the averaged value is -1. 4m/s and the direction of flow is a right angle ith the crank shaft. In the case of the throttle ılve to be opened as much 1/4 after exhaust rocess, even though it have the flow direction)mponent of (+) component, in case of throttle ılve to be opened gradually, it is decreased and is appeared almost 0 value on duration of ırottle valve to be opened perfectly. In light of ıis, we know that the flow component in the ght 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-

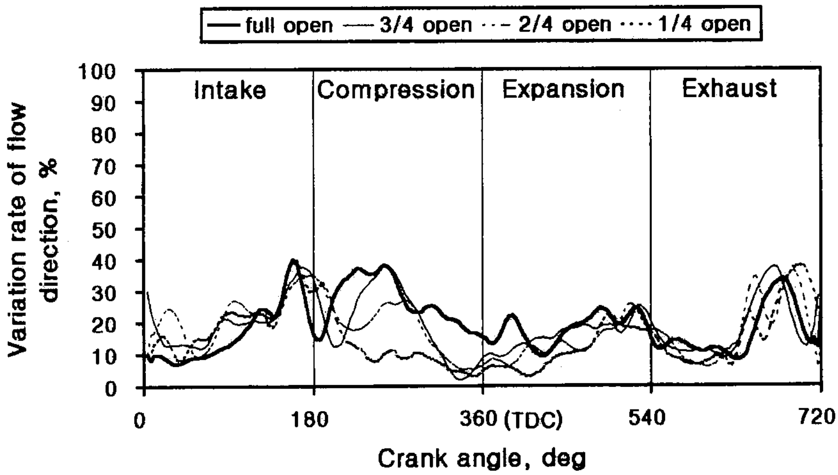

Fig. 7 Relation between the variation rate of flow direction and crank angle at each throttle opening

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

:ion is increasing engine speed from 1000rpm to 2000rpm, 3000rpm accordingly, it is showing the :urbulence flow component being increased to :rank shaft and a right-vertical direction, so that .t is estimated that the ignited initial flame at ;park 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 hat direction of ensemble averaged mean velocity s forming the flow shaft of a right-vertical direcion to the crank shaft in position of spark plug. And in accordance with engine speed being increased, as view of turbulence intensity to be ncreased gradually, the engine speed is increased accordingly, even though growth of initial flame would be given an effect with cause of the cooling oss 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 s the flow direction component being increased o crank shaft and a right-vertical direction gradually for a while, the flow direction component is hifted toward the crank shaft and a right-vertical direction at 15mm,and when the movement distance 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.

Acknowledgement

This study has been supported in part by Induk Institute of Technology in Seoul, Korea. The authors would like to thank Dr. Peter C. Hinze at Sandia National Laboratory, CA, U. S. A., for his helpful suggestion for the project.

References

Anderson, R. L., 1986, "In-Cylinder Measurement of Combustion Characteristics Using Ionization Sensors," *SAE* Paper 860485, pp. 3.295 ~3.306.

Arcomumanics, C., Bae, C. H., and Hu, Z, 1994, "Flow and Combustion in a Four-Valve.

Spark-Ignition Optical Engine," *SAE* paper 940475.

Brehob, D. D. and Newman, C. E., 1992, "Monte Carlo Simulation of Cycle by Cycle Variability," *SAE* Paper 922165.

Han, S. B., Chung, Y. J., and Lee, S. Y., 1995, "The Analysis of Turbulent Flow by Various Factors in the Engine Combustion Chamber," *Proceeding of International Conference on Power Engineering*, Shanghai, China, May 22-26, pp. 1167~1172.

Han, S. B., Chung, Y. J., and Lee, S. Y., 1995, "Effect of Engine Variables on the Turbulent Flow of a Spark Ignition Engine," *KSME International Journal*, Vol. 9, No. 4, pp. 492~501.

Han, S. B., and Chung, Y. J., 1998, "A Study on the Effect of Operating Conditions for the Stability at Idle," *KSME* International Journal, Vol. 12, No. 4, pp. 694~700.

Heywood, J. B., 1988, Internal Combustion Engine Fundamentals, McGRAW - HILL International Editions.

Hinze, P. C., 1997, "Cycle-to-Cycle Combustion Variations in a Spark-Ignition Engine Operating at Idle," MIT Ph. D. Thesis.

Johansson, B., 1993, "Influence of the Velocity Near the Spark Plug on Early Flame Development," *SAE* Paper 930481.

Keck, J. C., 1985, "Laminar Burning Speed Measurements of Indolene-Air-Diluent Mixture at High Pressure and Temperatures," *SAE* Paper 850047.

Ozdor, N., Dulger, M. and Sher, E., 1994, "Cyclic Variability in Spark Ignition Engines A Literature Survey," *SAE* Paper 940987.

Shen, H., Hinze, P. C. and Heywood, J. B., 1994, "A Model for Flame Initiation and Early Development in SI Engine and its Application to Cycle-to-Cycle Variations," *SAE* Paper 942049.

Shen, H., Hinze, P. C. and Heywood, J. B., 1996, "A Study of Cycle-to-Cycle Variations in SI Engines Using a Modified Quasi-Dimensional Model," *SAE* Paper 961187.

Wahiduzzam, S., Morel, T., and Sheard, S., 1993, "Comparison of Measured and Predicted Combustion Characteristics of a Four-Valve S. I. Engine," *SAE* Paper 930613.

Witze, P. O., 1986, "Direct Measurement of the Turbulent Burning Velocity in a Homogeneous Charge Engine," *SAE* Paper 861531, pp. 6.540 ~6.551.

Xu, Y., Dong, Y., and Tsao, K. C., 1991, "Application of Turbulent Combustion Model to a Spark Ignited L-Head Engine," *SAE* Paper 910056.