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Effect of Engine Variables on the Turbulent Flow of a Spark Ignition Engine

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The turbulent flow in a spark ignition engine plays an important role in determining its combustion characteristics and thermal efficiency. In order to analyse the combustion process, the turbulent flow and its turbulence intensity must be studied. To study the turbulent flow as varying various factors in a combustion chamber of a spark ignition engine, the L-head with or without squish area are selected. The turbulent as varying flow on the piston speed, inlet flow velocity, and squish velocity are measured by using hot wire anemometer. To examine the characteristics of turbulent flow, the ensemble averaged mean velocity, turbulence intensity, turbulence intensity decrease ratio, production rate of turbulence intensity, production coefficient of turbulence intensity are analysied.

Key Words: Ensemble Averaged Mean Velocity, Turbulence Intensity, Turbulence Intensity Decrease Ratio, Production Rate of Turbulence Intensity, Production Coefficient of Turbulence Intensity

1. Introduction

The combustion process in a spark ignition engine forms by flame propagation and the flame propagation forms by turbulent flow in combustion chamber. The turbulent flow field in a spark ignition engine plays an important role in determining its combustion characteristics and thermal efficiency (Pope and Annand, 1986). To analyse about the combustion process, it must be studied the turbulent flow and its turbulent intensity (Fraser and et al. 1986).

In an effort to shorten development times, researchers (Borgnakke, 1981) have developed analytical techniques to predict the performance and emissions of spark ignition engines. These techniques (Tabaczynski, 1976, 1977) show promise for evaluating new design concepts and as research tools for understanding more about engine experiments. The importance of the turbulence structure in an engine has been recognized since the early experiments of Witze (1977), in which the intake event was eliminated and the rate of flame propagation decreased. However, the lack of an adequate measuring instrument has made measurements of turbulence quantities in an engine difficult at best.

Later, Heywood (1987) studied the fluid motion within the cylinder of internal combustion engines. Hall and Braco (1987) studied velocities and turbulence intensities measured in firing and motored engines. And the turbulent flow in combustion chamber is affected by the piston speed, inlet flow velocity, squish velocity and others. As a result, relatively few investigators have been active in this field and turbulence characteristics have been developed.

This paper investigates the features of turbulent flow in a spark ignition engine and the analysis of turbulent flow by various factors in the engine combustion chamber.

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2. Experimental Apparatus and Procedures

2.1 Experimental apparatus

To analyze the turbulent flow by using hot wire anemometer, hot wire probe was inserted in the combustion chamber and measure it with motoring operation. It is difficult to measure the turbulent flow because of the leakage of lubricant with reciprocation of piston. It is made the non-lubrication engine to solve this problem that the leakage of lubricant (see Fig. 1).

The L-head combustion chamber with squish area is used in order to study on the effects of squish velocity. And the L-head combustion chamber without squish area is used in order to study on the effects of piston speed and inlet flow velocity. The used hot wire probe is I type and the direction of measurement is vertical toward piston movement. The ensemble averaged velocity and the turbulent intensity is measured and analysed about experimental parameters. The measured ensemble averaged velocity and the turbulent intensity is analysed in the process of inlet, compression, expansion and exhaust.

Figure 1 shows schematic diagram of modified engine, hot wire probe removal device, and experimental apparatus. Combustion chamber without squish area and with squish area are used. The removal device for hot wire probe can be controlled accurate position for measurement.

The combustion chamber with squish area and without squish area are shown in Fig. 2. The volume of the combustion chamber with squish area is equal to the volume with squish area. Combustion chamber without squish area is used in order to study on the effects of piston speed and inlet flow velocity. Combustion chamber with squish area is used in order to study on the effects of squish velocity.

Figure 3 shows the schematic diagram of air flow measurement system. Figure 4 represents the measured points at stated intervals through the

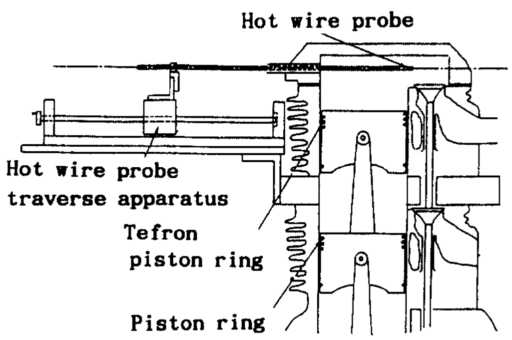

Fig. 1 Schematic diagram of modified engine

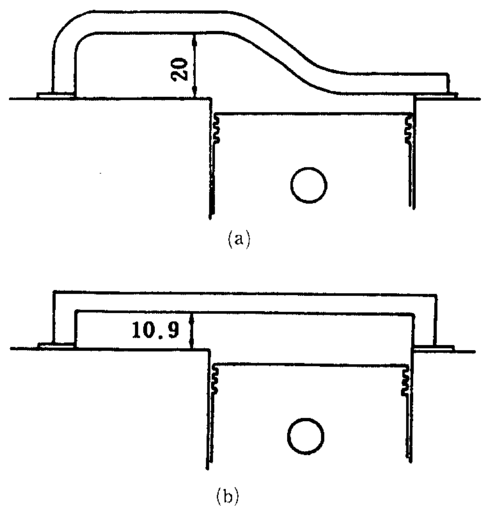

Fig. 2 Combustion chamber with squish area (a) and without squish area (b)

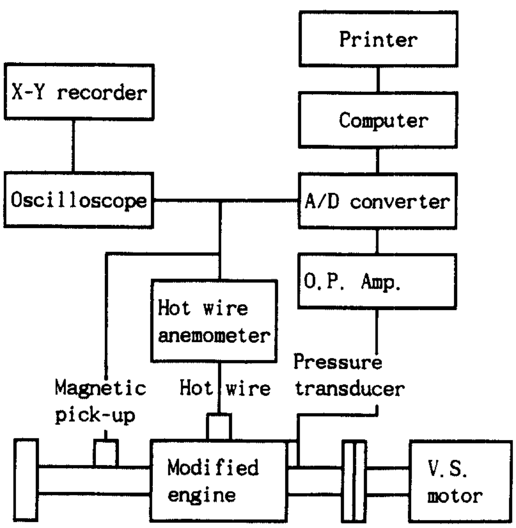

Fig. 3 Schematic diagram of air flow measurement system

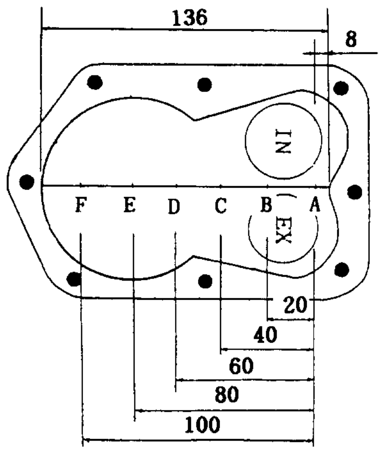

Fig. 4 Configuration of combustion chamber and measurement points

central line of combustion chamber.

2.2 Experimental procedures

2.2.1 Piston speed

The combustion process in a spark ignition engine forms with turbulent flow in combustion chamber. And the turbulent flow in combustion chamber is affected by the piston speed, inlet flow velocity, and squish velocity. The L-head combustion chamber without squish area is used in order to study on the effect of piston speed and to eliminate the effect of squish velocity. And in order to eliminate the effect of inlet flow velocity, it is affected in closed inlet and exhaust valves. The engine speed is operated from 1000 rpm to 2000 rpm by the variable motor. In this case, the turbulent flow in the combustion chamber will be affected by the piston speed.

2.2.2 Inlet flow velocity

The L-head combustion chamber without squish area is used in order to study on the effect of inlet flow velocity. The engine is operated from 1000 rpm to 2000 rpm by the variable motor in condition of full throttle valve. In this case, the turbulent flow in the combustion chamber is affected by the piston speed and inlet flow velocity. To analyze the turbulent flow by the effect of inlet flow velocity, it must be subtracted the effects of piston speed from turbulent flow.

2.2.3 Squish velocity

The L-head combustion chamber with squish area is used in order to study on the effect of squish velocity. The volume of the L-head combustion chamber with squish area is equal to the volume of the L-head combustion chamber without squish area. The turbulent flow characteristics in L-head combustion chamber with squish area can be analyzed by effects of piston speed, inlet flow velocity, and squish velocity.

3. The Turbulence Analysis on Turbulent Flow Field in Engine

3.1 Ensemble averaged mean velocity and turbulence intensity

The flow pattern in the engine combustion chamber is unsteady flow and changes into the instantaneous flow velocity with crank angle. With variation of flow per cycle, the analysis method might as well ensemble averaged technique as time averaged technique. Because the ensemble averaged mean velocity and turbulence intensity are large variation per cycle, it is treated instantaneous flow velocity with measured datum of 20 cycles.

The ensemble averaged mean velocity $U(\theta)$ in the cylinder at any crank angle is expressed as;

$$U(\theta)=\frac{1}{N}\sum_{i=1}^{N}U'(\theta+in\pi) \tag{1}$$

where n is the number of strokes in an engine cycle, and N the number of cycle and $U'(\theta)$ the instantaneous velocity.

And the turbulence intensity $u'(\theta)$ can be determined by

$$u'(\theta)=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[U'^2(\theta+in\pi)-U^2(\theta)\right]} \tag{2}$$

Figure 5 shows the ensemble averaged mean velocity and the turbulence intensity as a function of crank angle without valve operation. This figure indicates piston speed 2.33 m/s and 4.67 m/s respectively, and the measured position is the point D of Fig. 4. The turbulence intensity in the

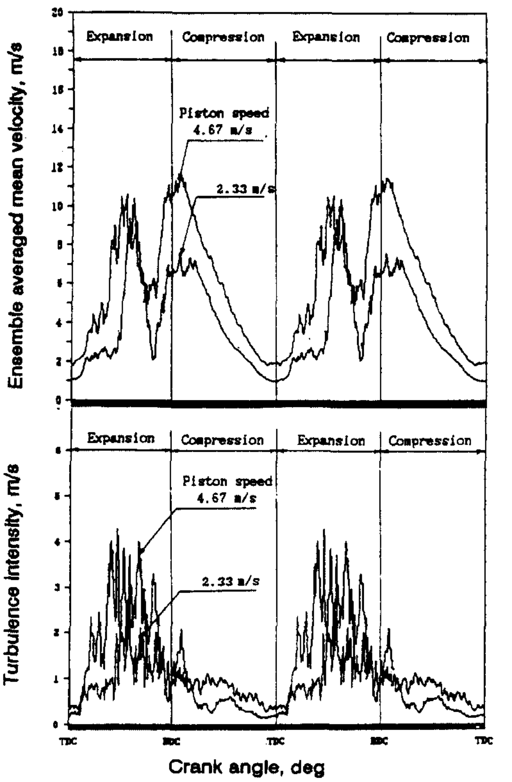

Fig. 5 Ensemble averaged mean velocity and turbulence intensity as a function of crank angle without valve operation

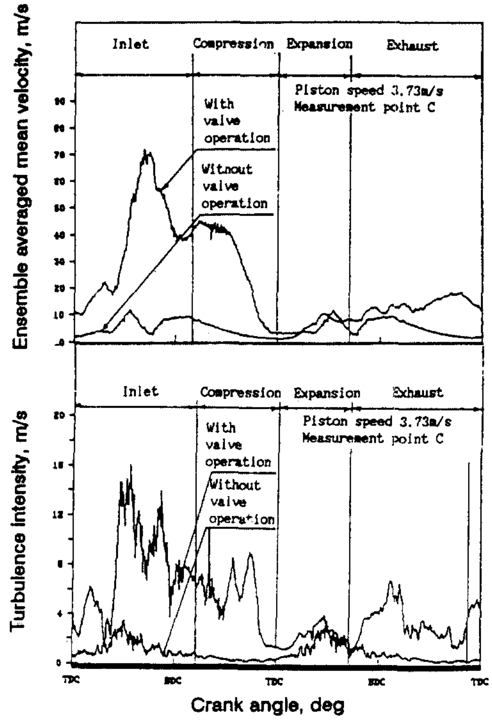

Fig. 6 Ensemble averaged mean velocity and turbulence intensity as a function of crank angle with valve operation and without valve operation

expansion process is similar to the ensemble averaged mean velocity. The turbulence intensity in the expansion process may be produced in proportion to the ensemble averaged mean velocity. The turbulence intensity in the compression process is not similar to the ensemble averaged mean velocity. According to compression of air in combustion chamber, the temperature and pressure of air increase and the density of air increases, and the turbulence intensity decreases according to the increase of kinematic viscosity.

Figure 6 shows the ensemble averaged mean velocity and the turbulence intensity as a function of crank angle without valve operation. The piston speed is 3.73 m/s, and the measured position is point D of Fig. 4. The effect of inlet flow velocity is maximum in around the middle point of the intake process and decreases gradually after that. The ensemble average mean velocity with inlet flow is large considerably than with only piston speed. But in the expansion stroke, the effect of inlet flow velocity decreases largely. The turbulence intensity in the intake process is similar to the ensemble averaged mean velocity generally. But in near TDC of the compression stroke, the turbulence intensity does not largely indicate the effect of inlet flow velocity.

3.2 Effect of piston speed

To estimate the turbulent flow for the effect of piston speed, we selected the end (TDC) of compression stroke, and the measured positions are 6 points at stated intervals as shown in Fig.4.

Figure 7 shows the ensemble average mean velocity with piston speed. The turbulent intensity with piston speed is shown in Fig. 8. And Figure 9 represents maximum ensemble averaged mean velocity in the compression stroke and ensemble averaged mean velocity near TDC of the compression stroke as a function of mean

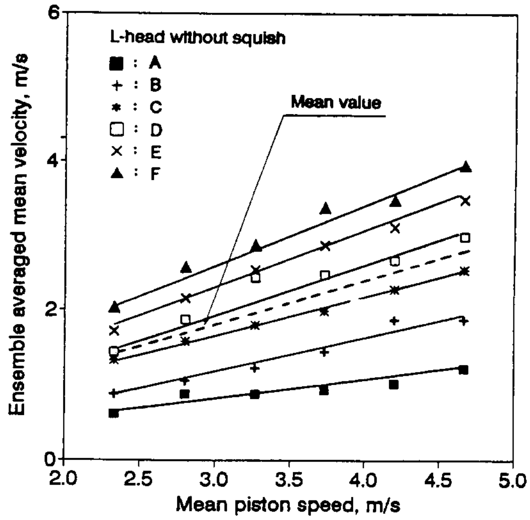

Fig. 7 Ensemble averaged mean velocity at the end of compression stroke as a function of mean piston speed without valve operation

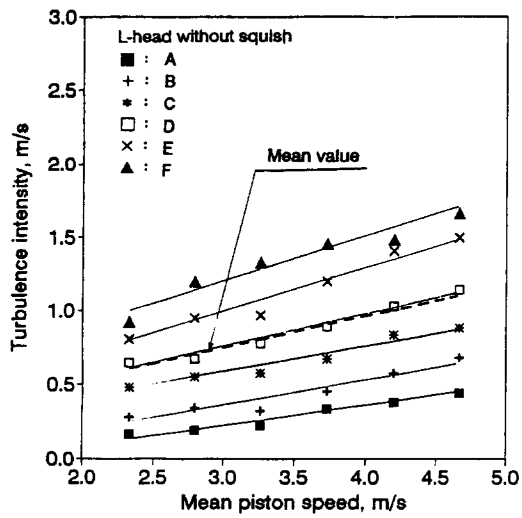

Fig. 8 Turbulence intensity at the end of compression stroke as a function of mean piston speed without valve operation

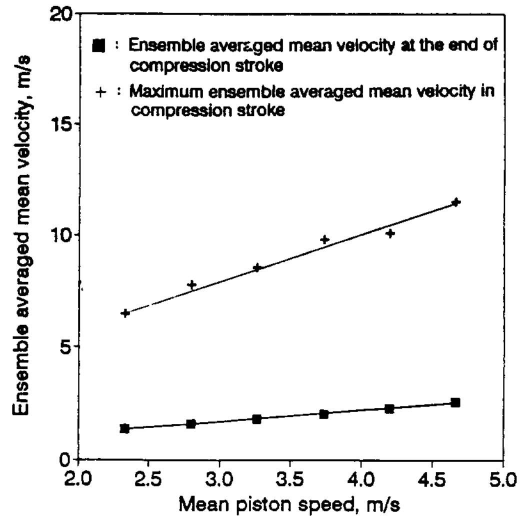

Fig. 9 Maximum ensemble averaged mean velocity in compression stroke and ensemble averaged mean velocity at the end of compression stroke as a function of mean piston speed without valve operation

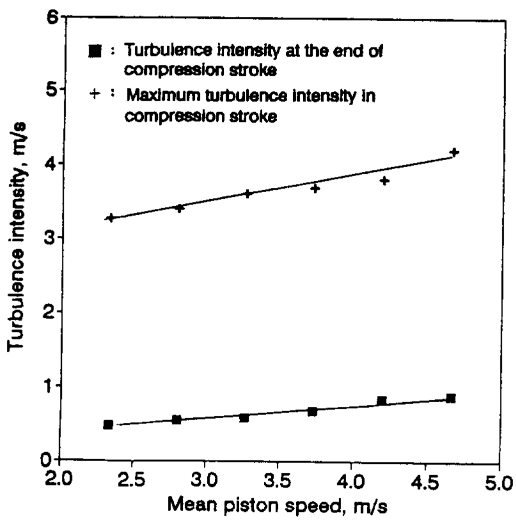

Fig. 10 Maximum turbulence intensity in compression stroke and turbulence intensity at the end of compression stroke as a function of mean piston speed without valve operation

piston speed without valve operation.

To understand maximum ensemble averaged mean velocity with piston speed near the end of compression stroke, we defined the decrease ratio of ensemble averaged mean velocity as Eq. (3);

$$\delta = (U(\theta)_{max} - U(\theta)_{min}) / U(\theta)_{max} \qquad (3)$$

$U(\theta)$max : maximum ensemble averaged mean velocity

$U(\theta)$min : minimum ensemble averaged mean velocity near the end of compression stroke

According to that piston speed is from 2.33 m/s to

4.67 m/s, the decrease ratio of ensemble averaged mean velocity is approximately 0.78 as shown in Fig. 11. This indicates that ensemble averaged mean velocity with piston speed decreases 78 % and remains approximately 22 % near the end of the compression stroke.

Figure 10 represents the maximum turbulent intensity in the compression stroke and turbulence intensity near the end of the compression stroke as a function of mean piston speed without valve operation.

The maximum turbulence intensity with piston speed decreases near the end of the compression stroke, and the remaining minimum turbulence intensity is defined the decrease ratio of turbulence intensity as Eq. (4);

$$\delta u' = (u'_{max} - u'_{min})/u'_{max} \tag{4}$$

u'_{max} : maximum turbulence intensity
u'_{min} : minimum turbulence intensity at the end of compression stroke

According to that piston speed is from 2.33 m/s to 4.67 m/s, the decrease ratio of turbulence intensity is approximately 0.82 as shown in Fig. 11. It means that maximum turbulence intensity with piston speed decreases 78 % and remains approximately 18 % near the the end of the compression stroke.

To understand increasement of turbulence intensity with piston speed near the end of the compression stroke, we defined the production coefficient of turbulence intensity as Eq. (5);

$$a_p = du'_p/dV_p \tag{5}$$

du'_p : variation of turbulence intensity with piston speed
dV_p : variation of piston speed

The production coefficient of turbulence intensity with piston speed near the end of the compression stroke is 0.17, a_p that evaluated from Eq. (5). It means that turbulence intensity with piston speed is 0.17, gradient of turbulence intensity near the end of the compression stroke.(see the Fig. 12)

And we defined the production rate of turbulence intensity with piston speed near the end of the compression stroke as Eq. (6).

$$\beta_p = a_p/a_{total} \tag{6}$$

a_p : production rate of turbulence intensity with piston speed
a_{total} : production rate of total turbulence intensity

The production rate of turbulence intensity with piston speed is 0.31, β_p that calculated from Eq.

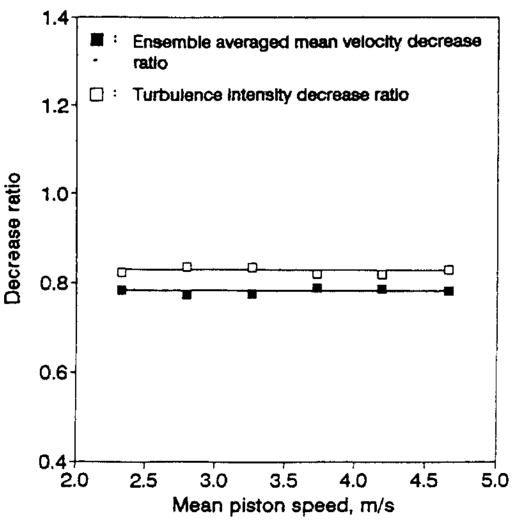

Fig. 11 Ensemble averaged mean velocity decrease ratio and turbulence intensity decrease ratio as a function of mean piston speed without valve operation

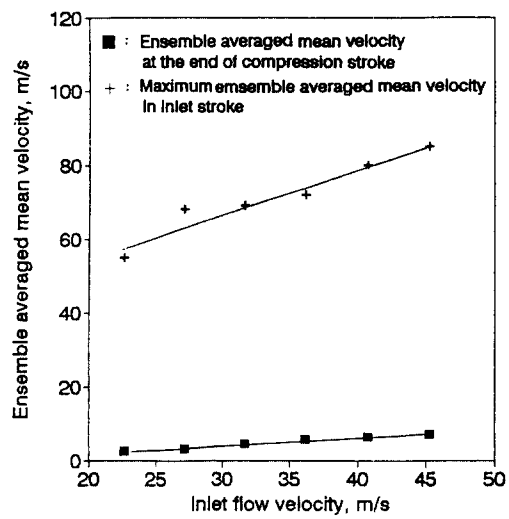

Fig. 12 Maximum ensemble averaged mean velocity in inlet stroke and ensemble averaged mean velocity at the end of compression stroke as a function of inlet flow velocity with valve operation

(6). It means that turbulence intensity with piston speed in total turbulence intensity is 31 %.

3.3 Effect of inlet flow velocity

In order to study on the effect of inlet flow velocity, we measured the turbulent flow in the L-head combustion chamber without squish, with valve operation. Figure 13 represents the maximum turbulence intensity in inlet stroke and turbulence intensity at the end of compression stroke as a function of inlet flow velocity with valve operation. By the decrease ratio of ensemble averaged mean velocity as Eq. (3), it is approximately 0.93 with inlet flow velocity from 22 m/s to 45 m/s.

Figure 14 shows the ensemble averaged mean velocity at the end of compression stroke as a function of mean piston speed with valve operation and without valve operation. By the decrease ratio of turbulence intensity as Eq. (4), it is 0.90 with inlet flow velocity from 22 m/s to 45 m/s. The ensemble averaged mean velocity and turbulence intensity are affected by not only inlet flow velocity but also piston speed. Therefore to estimate the ensemble averaged mean velocity and turbulence intensity by effect of net inlet flow velocity, it must be subtracted ensemble averaged mean velocity and turbulence intensity by effect of piston speed from ensemble averaged mean velocity and turbulence intensity in L-head combustion chamber without squish area, with valve operation.

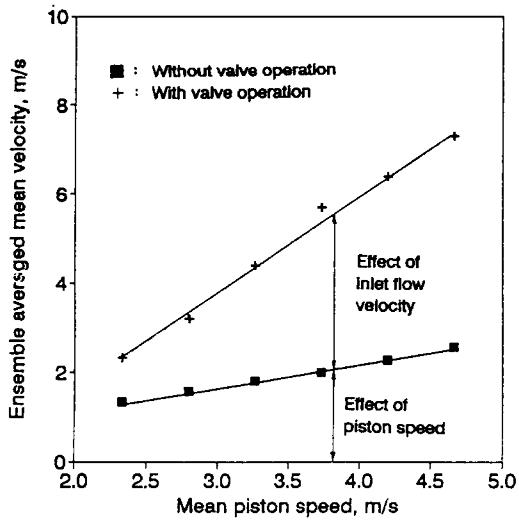

Fig. 14 Ensemble averaged mean velocity at the end of compression stroke as a function of mean piston speed with valve operation and without valve operation

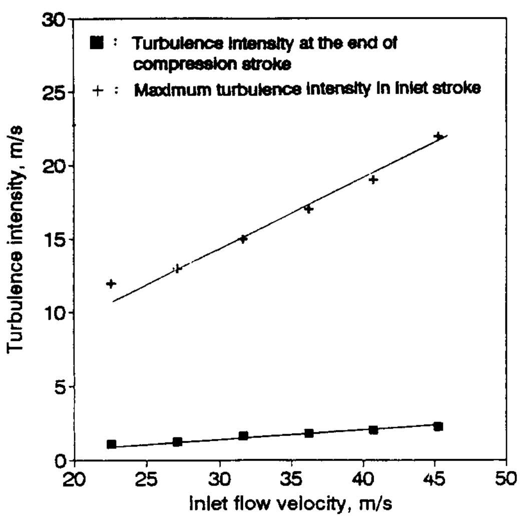

Fig. 13 Maximum turbulence intensity in inlet stroke and turbulence intensity at the end of compression stroke as a function of inlet flow velocity with valve operation

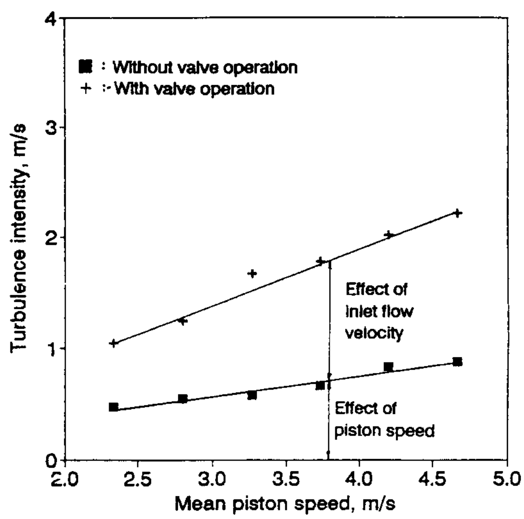

Fig. 15 Turbulence intensity at the end of compression stroke as a function of mean piston speed with valve operation and without valve operation

The turbulence intensity at the end of compression stroke as a function of mean piston speed with valve operation and without valve operation is shown in Fig. 15. And we defined α_i the production coefficient of turbulence intensity of inlet flow velocity as Eq. (7), and α_i is 0.03 at the end of compression stroke.

$$\alpha_i = du'_i/dV_i \tag{7}$$

du'_i : variation of turbulence intensity with inlet flow velocity

dV_i : variation of inlet flow velocity

And the production rate of turbulence intensity near the end of the compression stroke, β_i is defined as Eq. (8).

$$\beta_i = \alpha_i / \alpha_{total} \tag{8}$$

α_i : production rate of turbulence intensity with inlet flow velocity

α_{total} : total turbulence intensity

The production rate of turbulence intensity with inlet flow velocity is 0.46, β_i that obtained from Eq. (8). It means that turbulence intensity with inlet flow velocity in total turbulence intensity is 46 %.

3.4 Effect of squish velocity

Figure 16 shows the turbulence intensity as a function of crank angle in L-head combustion chamber with squish and L-head combustion chamber without squish. Here, the turbulence intensity is affected by squish area at the end of compression stroke.

In Fig. 17, the ensemble averaged mean velocity at the end of compression stroke as a function of mean piston speed in L-head combustion chamber with or L-head without squish are shown. And, the increasement of ensemble mean velocity by squish effect must be subtracted the ensemble mean velocity in L-head combustion chamber without squish area from the ensemble mean velocity in L-head combustion chamber with squish area. Therefore, the ensemble mean velocity by squish effect is 1.3 m/s to 2.5 m/s according to piston speed 2.33 m/s to 4.67 m/s.

The turbulence intensity at the end of compression stroke as a function of mean piston speed in L-head with squish or without squish are shown in Fig. 18. The turbulence intensity by squish effect must be subtracted the turbulence intensity in L-head combustion chamber without squish area from the turbulence intensity in L-head combustion chamber with squish area. Here, the turbulence intensity is 0.28 m/s to 0.56 m/s

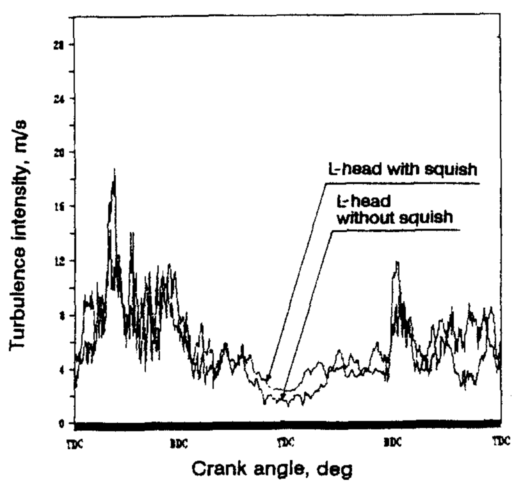

Fig. 16 Turbulence intensity as a function of crank angle in L-head with squish and L-head without squish

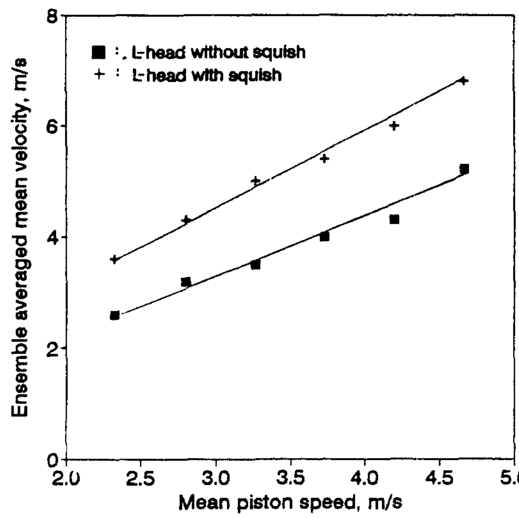

Fig. 17 Ensemble averaged mean velocity at the end of compression stroke as a function of mean piston speed in L-head with squish and L-head without squish

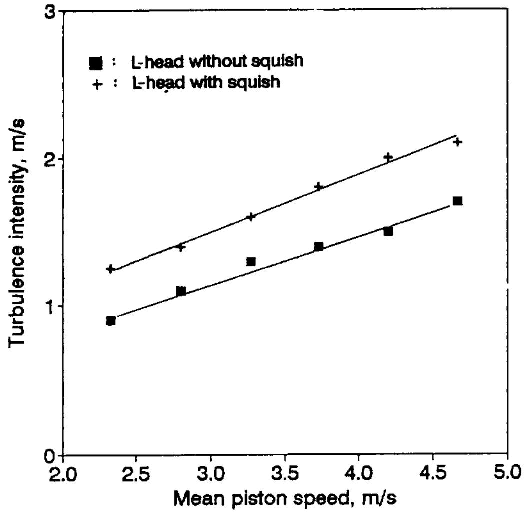

Fig. 18 Turbulence intensity at the end of compression stroke as a function of mean piston speed in L-head wi h squish and L-head without squish

according to piston speed 2.33 m/s to 4.67 m/s.

The production coefficient a_s, by squish effect is 0.12 that obtained from Eq. (9), and we knew that the squish area affects to improve the turbulence intensity in combustion chamber.

$$a_s = du_s'/dV_p \tag{9}$$

du_s' : variation of turbulence intensity with squish area

dV_p : variation of piston speed

It means that the gradient of turbulence intensity on turbulence intensity with squish velocity is 0. 17 at the end of compression stroke.

And the production rate of turbulence intensity with squish velocity is defined by Eq. (10) at the end of compression stroke.

$$\beta_s = a_s / a_{total} \tag{10}$$

a_s : production coefficient of turbulence intensity with squish velocity

a_{total} : total turbulence intensity

The production rate of turbulence intensity with squish velocity is 0.23, β_s that obtained from Eq. (10). It means that turbulence intensity with squish velocity in total turbulence intensity is 23 %.

4. Conclusions

As a result, following conclusions obtained through this study.

(1) The turbulence intensity increases linearly with piston speed. The decrease ratio of ensemble averaged mean velocity with piston speed is 0.78 and the decrease ratio of turbulence intensity is 0. 82. In addition to the decrease ratio of ensemble averaged mean velocity with inlet flow velocity is 0.93 and the decrease ratio of turbulence intensity is 0.90.

(2) From this engine combustion chamber, the production coefficient of turbulence intensity to study on the analysis of turbulent flow by various factors is 0.17 with piston speed, 0.03 with inlet flow velocity, and 0.12 with squish velocity respectively.

(3) The production rate of turbulence intensity to study on effects of turbulence intensity in the engine combustion chamber is 31 % with piston speed, 46 % with inlet flow velocity, and 23 % with squish velocity respectively.

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