Experimental Investigation on Cyclic Variation of Scavenging Flow across Cylinder and Its Emission in a Small Two-Stroke Engine

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ABSTRACT

The purpose of this study is to clarify the cyclic variation of scavenging flow in a part-loaded spark-ignited two-stroke engine. In this study, the relationship of cyclic variation among the flow behavior in the transfer port, the exhaust pipe and the upper part of the cylinder, the pressure variation, and the CO and CO_2 emissions at the exhaust exit of cylinder was experimentally investigated, focusing on the previous and following cycles of misfiring. The velocity variations of transfer-port flow, exhaust-pipe flow and in-cylinder flow from the boost port towards the exhaust port were measured by a fiber-optic LDV system. The flow field at the upper-part of combustion chamber showed quite different characteristics from the transfer-port or exhaust-pipe flow, which was not directly influenced by the pressure propagation in the engine, but formed by the transfer-port and exhaust-pipe flow.

INTRODUCTION

Misfiring detection and its control to reduce exhaust emissions from spark-ignited engines are recently main subjects in engine research fields. Developments of two-stroke engines for low-emission vehicles depend on the success of technologies in controlling the scavenging flow across the cylinder which influences the in-cylinder mixture-gas formation and combustion state(1-5). To control the scavenging flow requires accurate comprehension of relationship between pressure variation and gas flow behavior at each flow field in the engine.

Scavenging and exhaust flows in a conventional two-stroke engine are not controlled by mechanical gas pumping but greatly affected by pressure variation upstream and downstream of the cylinder(6-10). This causes short-circuit of fresh gas going to the exhaust port in scavenging process(11) and disagreeable cyclic variations of combustion states and misfiring at low engine speeds or part load conditions. Cyclic variation itself induces high level unburnt hydrocarbon (HC) emissions. In order to decrease HC emission, the flow behavior across the cylinder must be understood together with the pressure variations in the engine, from the inlet pipe through the cylinder to the exhaust pipe, in relation to combustion states, i.e., misfiring(9,11-13).

Misfiring could occur in early flame development near the spark plug or during flame propagation in the combustion chamber(1),which is called quenching. Both two processes are governed by the flow pattern and the constituent of the charged gas, that is, the ratio of fresh gas to residual burnt gas in the cylinder. Therefore, the time-series data of in-cylinder flow from transfer-port and exhaust-pipe flow in the scavenging process should be investigated with cyclic variation of combustion state and pressure. On the other hand, gas flow in the scavenging process is very complicated, and a lot of simulation studies on scavenging flow in cylinders have been reported(11). However, inlet and outlet conditions for the calculations and evaluation methods are not correctly made available within computational data by the researchers, because of lack of the data in firing conditions.

Our research on the actual flow behaviors in a fired two-stroke engine has been focusing on the pressure variation at each flow field due to the combustion pressure propagation through the engine in each cycle. Regarding the cyclic phenomena in the engine, data classifying has been applied for the data acquisition at each crankangle in the cycle instead of time-series data. By LDV measurements together with simultaneous pressure measurements, it has been made clear that the flow behaviors in the transfer port and the exhaust pipe are significantly dependent on the pressure variation(6-10,12). The discrepancy of scavenging flow behavior in the transfer port and the exhaust pipe and CO and CO_2 emissions between the previous cycle before misfiring and firing were shown in the author's latest paper(13).

The purpose of this study is to clarify the cyclic variation of scavenging flow across the cylinder. In this study, the source and influence of misfiring were investigated from the relationship among the gas flow in the transfer port, the exhaust pipe and the upper part of cylinder, the pressure variations, and the CO and CO_2 emissions by a fiber-optic LDV system and fast-response gas analyzer.

EXPERIMENTAL APPARATUS

Test Engine

The test engine used in the present experiment is the same as that in the previous reports(8-10,12,13). The engine had 98.2 cm^3 displacement capacity and was a conventional loop-scavenged two-stroke motorcycle engine(Suzuki Motor Corporation : AX100). The engine was operated at 1500 r/min and 10% throttle opening. This condition is the idle of the engine, in which emission reduction is compulsory. In this condition, the delivery ratio was 0.13, time-averaged indicated mean effective pressure (IMEP) was 0.071MPa, and average emission concentrations of the three constituents were 3.8% of CO, 4.8% of CO_2 and 1.05% of HC(C_6H_{14}). The present experiment was carried out in the practical condition such as using regular gasoline mixed with two-stroke engine motor oil in the ratio of 50:1.

Measurement System

The measurement system in this study is shown in Fig. 1. The flow velocities in the transfer port, the exhaust pipe and the cylinder were measured by a fiber-optic LDV(8), which was optimized for the actual velocity measurement in low signal-to-noise condition. The velocity measurement positions at the transfer port and the exhaust pipe are shown in Fig. 2(a) and (b). For the in-cylinder velocity measurements, seven positions were selected by taking optical access into account to observe the flow field in the upper-part of the cylinder, that is, in the clearance volume of the combustion chamber, as shown in Fig. 2(c). Thermal expansion due to combustion may have caused the cracking of the optical window on the cylinder head in the LDV measurements. In order to prevent the break-up of the window against the thermal expansion, the cylinder head with the quartz window had been warmed up before the experiments. The optical window was coated with thin oil film(10), which made the measurement duration long enough to obtain the data number for data classification for each combustion state in practical conditions.

The gas near the exhaust exit of the cylinder was sampled and its constituent concentrations were quantified using a fast-response exhaust-gas analyzer, non dispersive infrared(NDIR) type (Horiba, Ltd.:MEXA-1300FRI)(16). The orientation of gas-sampling probe with 2-mm inner diameter and 6-mm outer diameter in this study is shown in Fig. 3. This orientation was chosen so as not to disturb the exhaust flow but to immediately measure the blow-down gas before it was mixed with the residual gas in the exhaust port. The gas was drawn into the sampling probe at 1.5 l/min that corresponded to 1.0 cm^3/cycle at 1500 r/min engine speed. Such a small volume was approximately 3-4% of the bulk flow rate in the exhaust pipe, which could not affect the exhaust flow behavior. In this exhaust-analyzer application to the practical two-stroke engine, the time response was not enough to show the cycle-resolved variation of emission data but enough to show the cyclic variation, as empirically shown in the previous paper(16). Due to the gas-sampling method of the NDIR analyzer which make the gas chilled by cold water through the probe jacket, and condense H_2O vapor from the gas, high level in unburnt-mixture gas condensed and HC emission level did not show any variation(16). In this study, CO and CO_2 emission variations were considered to represent an opposite variation to HC.

RESULTS AND DISCUSSION

Data Classification by In-Cylinder Pressure

The LDV measurement data were simultaneously obtained with pressure data in order to classify the combustion states. In the previous reports(12,13), we had examined the data classification methods using the in-cylinder pressure. The flows in the scavenging ports and the exhaust ports were demonstrated and the results showed that the method was very useful in order to understand the flow characteristics whether firing or misfiring. In order to clarify the discrepancy of cyclic variations of the flow behavior in the scavenging process among different combustion cycles, the data classification were performed on the measurement data of velocities, pressures and emissions. The data classification, instead of IMEP, using

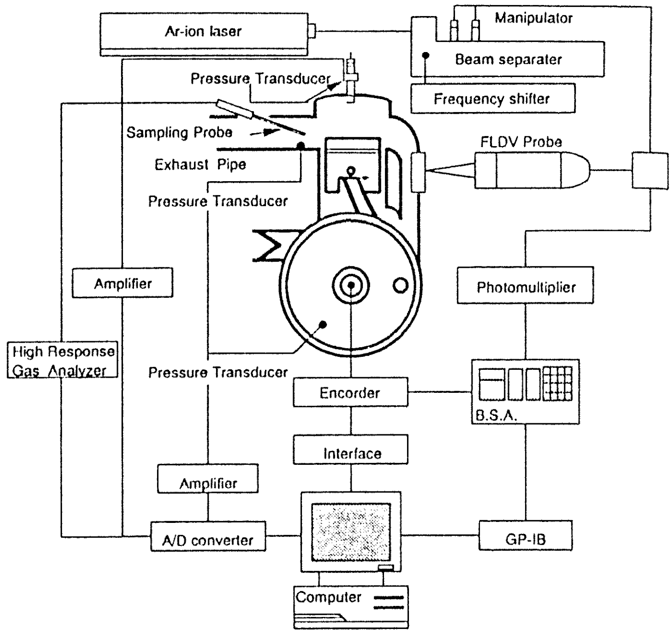
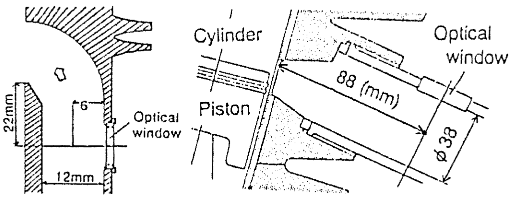
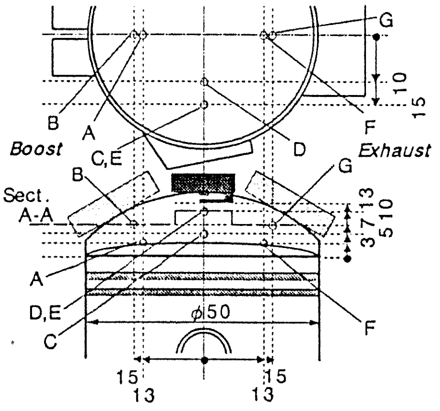


Fig. 1 Measurement system



(a) Transfer port (b) Exhaust pipe



(c) Combustion chamber

Fig. 2 Velocity measurement position

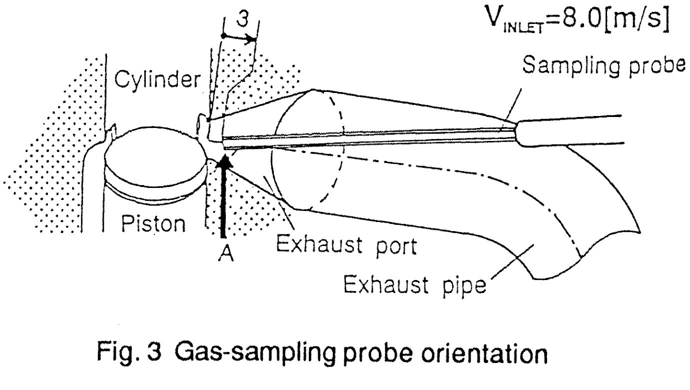


Fig. 3 Gas-sampling probe orientation

the in-cylinder pressures at TDC(*PTDC*) and the crankangle of maximum RMS variation(*PRMS*), and polytropic change equation, were useful for classifying the combustion state of each cycle into misfiring, incomplete firing or firing groups as follows;

$$P_{RMS} < P_{TDC}\left(\frac{V_{TDC}}{V_{RMS}}\right)^{n} \quad : \textit{Misfiring}$$

$$P_{TDC}\left(\frac{V_{TDC}}{V_{RMS}}\right)^{n} \leq P_{RMS} < P_{TDC} \quad : \textit{Incomplete Firing}$$

$$P_{RMS} \geq P_{TDC} \quad : \textit{Firing}$$

, where *VTDC* and *VRMS* are the in-cylinder volume at TDC and the crankangle of maximum RMS variation respectively, and n is the polytropic index, which was assumed to be 1.3 in this study.

Using this data classifying method, the classified and ensemble-averaged combustion states are shown as the heat-release fraction and its ratio against a crankangle in Fig. 4. Combustion started at TDC in incomplete firing and firing cycles, and combustion promoted in delay crankangle in an incomplete firing cycle compared with firing cycle. In a misfiring cycle, any increase of heat release did not detected, which means that the judgment in this study can correctly detect misfiring and classify combustion states.

Cyclic Variation of Scavenging Flow

In order to demonstrate the scavenging flow across the cylinder and the relationship between the transfer-port, the exhaust-pipe and the in-cylinder flow in cyclic variation condition, measurement data of velocity, pressure and emission respectively were classified into misfiring, incomplete firing and firing cycle, and are shown in Fig. 5. It has been clarified that the center points of the transfer port and the exhaust pipe (Fig. 2) are representative of the velocity variations on each cross section(8,10). Regarding the in-cylinder flow, the representative point of the flow field could not be determined, as described in the next section. The points B, D, E and G on the Sect. A-A (Fig. 2(c)) were selected for velocity measurement at the upper-part of the cylinder to observe the flow from the boost port to exhaust pipe.

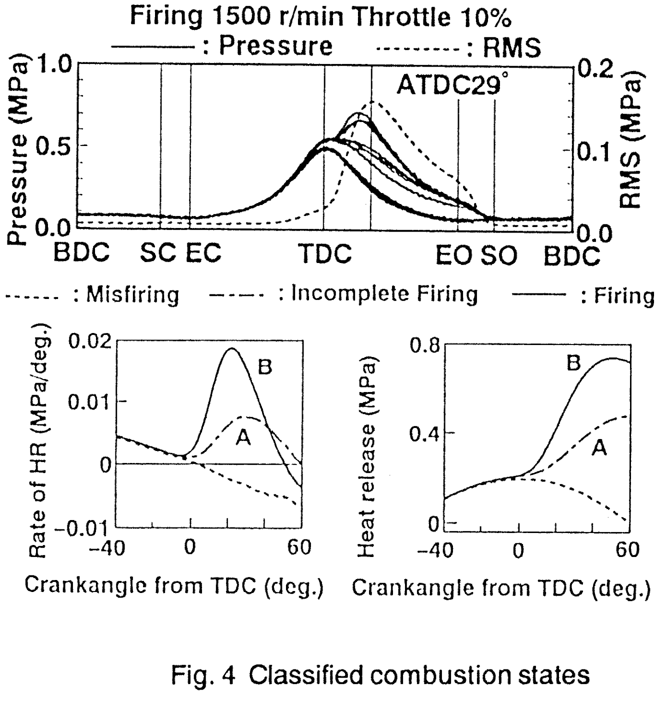


Fig. 4 Classified combustion states

In the misfiring cycle, any large pressure and velocity variation could not be seen, and interlinked velocity variation was observed between the transfer port and the exhaust pipe, which leads to short-circuit flow of fresh mixture gas. In the incomplete firing and the firing cycle, large pressure variation in the exhaust pipe generated by the combustion pressure caused large velocity variations at the transfer port and the exhaust pipe. These duct flows of the transfer port and the exhaust pipe, are significantly influenced by the pressure propagation in the engine(8-10). The in-cylinder flow at every measurement point, however, did not show any large effect of the pressure variation or corresponding flow with the transfer-port flow and the exhaust-pipe flow, and the velocity variations at the different points showed similar curves except at G point in the misfiring cycle. The velocity variation of reverse flow around SO at G point was influenced by the exhaust flow after EO in misfiring cycle. The velocity variation of in-cylinder showed large value from SO to almost ignition timing (BTDC 20 C.A.) in firing and incomplete firing cycles, compared with misfiring cycles. This may be due to the large momentum of the transfer-port and the exhaust flows related with large variations of pressure in the engine. The in-cylinder flow showed different characteristics from the transfer-port and the exhaust-pipe flows.

In-Cylinder Flow Characteristics

In order to fundamentally investigate the velocity variation of in-cylinder flow, RMS (root-mean-square) and PDF (probability density function) of sampled data number of the in-cylinder velocity are shown together with the ensemble mean velocity in Fig. 6.

First, from ATDC 20 C.A. to EO, sampling number showed almost zero, namely in firing cycle, and mean velocity also indicated zero. During this period, LDV data could not be obtained due to combustion effect on disappearance of scattered particles or some other reasons which cannot correctly be described here. The PDF of sampled number showed two peaks just before and after TDC in every cycle. This might be due to some optical noise as a result of reflection on the piston head, during this time, the velocity value indicated zero.

Comparing different combustion state, velocity and PDF variation were similar characteristics in every cycle, but, between the misfiring cycle and the firing or the incomplete firing cycle, the PDF variations were different. In the misfiring cycle, sampling number increased just after EO and large peak did not appear. The RMS variation also increased from EO in the misfiring cycle and from SO in the firing cycle. Such PDF variations were similar to the transfer-port velocity variation of the first peak in every cycle, which means that scattered particles were included in the fresh mixture gas from the transfer and boost ports or the residual gas in the exhaust port. The PDF of sampling number during scavenging process at B point which is located above the boost port showed early rising and early peak time by 11 degree of C.A. in firing cycle, compared to G point which was symmetry point of B point against the spark plug location.

The ensemble-mean velocity variation at B point also showed early second peak time, compared to G point. These time differences are similar characteristics of variation to PDF. The time difference of the second peak, which corresponds to

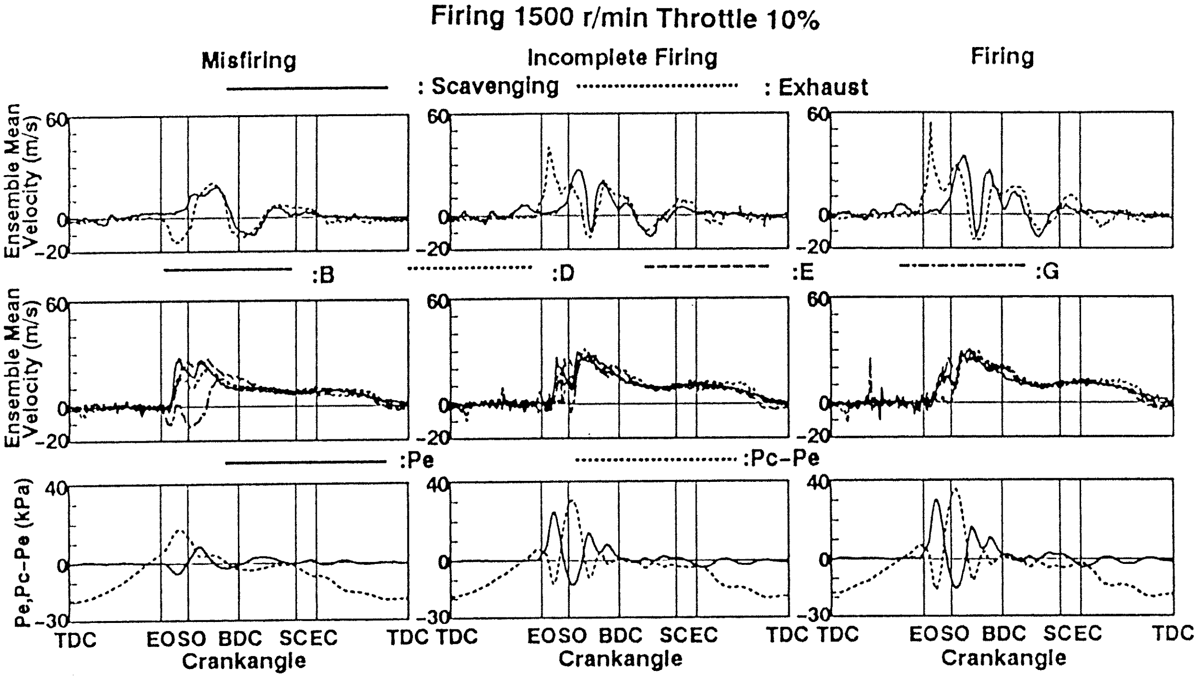


Fig. 5 Velocity variations of each classified cycle

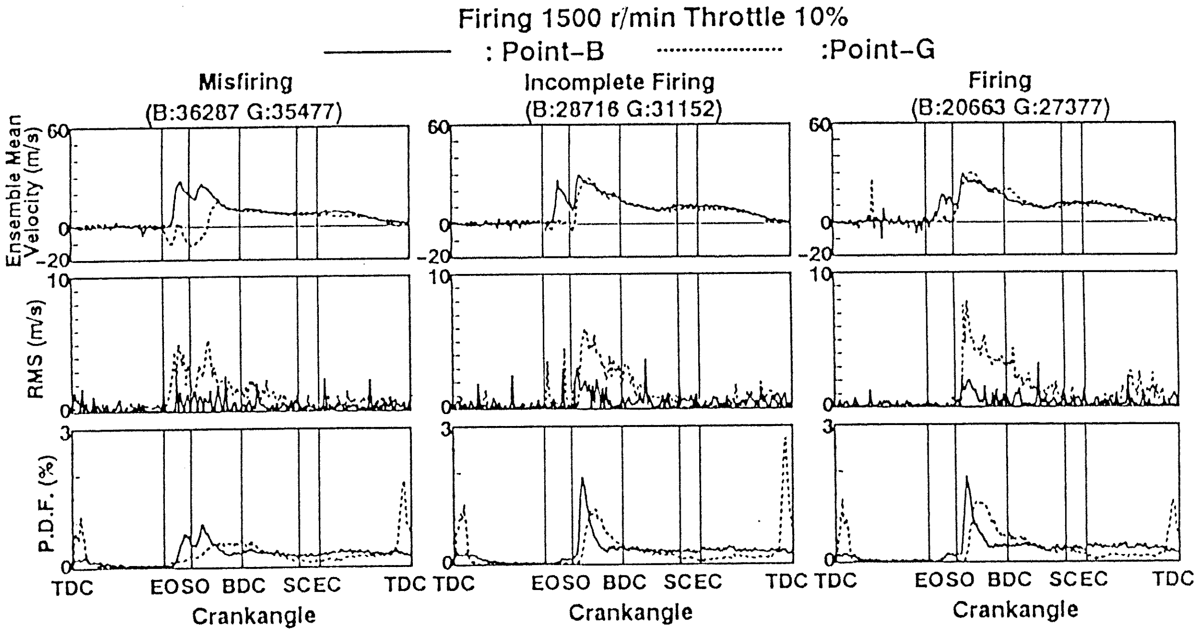


Fig. 6 In-cylinder LDV data

the velocity peak of scavenging flow, of the in-cylinder flow velocity between B and G point are shown in Table 1, together with the velocity values at the peaks. Propagation velocity of the second peak between the 30 mm distance of two points was calculated from crankangle difference between the two peaks. In the misfiring cycle, the propagation velocity of second peak velocity from point B to point G was 16.9 m/s, which was the middle velocity of the two peak velocities at B and G. Flows in the transfer port and the exhaust pipe are formed by the pressure propagation, for example, the velocity of pressure propagation showed approximately 500 m/s in the exhaust pipe$^{(10)}$. In the firing cycle and the incomplete firing cycle, the propagation velocities also indicated the middle values of the two peak velocities as shown in table 1. These results mean that the gas transfer was yielded not by the pressure propagation, but by bulk velocity of the flow in the upper-part of the cylinder. In the scavenging process, the in-cylinder flow in firing cycle showed large velocity peaks, compared with misfiring or incomplete firing cycle. This velocity increase may be in proportion to rise in temperature of the in-cylinder gas due to combustion. It has been found that the in-cylinder flow behavior was totally different from the other passage flows, e.g., transfer-port and exhaust-pipe flow.

Velocity Distribution of In-Cylinder Flow

One-dimensional velocity distributions consisting of the seven points (Fig. 2(c)) are shown in Fig. 7, at 6 timings of the crankangle in a cycle, in order to observe flow formation at the upper-part of the cylinder during scavenging and compression process in misfiring and firing cycle, respectively. Upper part of the figure shows the measurement direction of velocity distribution.

The in-cylinder velocity distributions at the exhaust side of the cylinder showed opposite flows against boost flows towards exhaust port till SO in misfiring cycle, which affected by the reverse flow of the exhaust flow from EO. In the initial stages of scavenging process, till BDC, larger velocities can be seen in the upper part of the measurement points (Sect.A-A), in both conditions. From BDC to 330 C.A. of 10 C.A. before ignition timing, flow towards the exhaust port at every measurement point remained. In the firing cycle, large velocity flows were observed during whole period, compared with misfiring cycle. These fast flows in the firing cycle were caused by high temperature gas due to combustion.

Scavenging Flow before Misfiring

In order to clarify the characteristics of scavenging flow before misfiring, velocity variations of the transfer-port, the exhaust-pipe and the in-cylinder at point B and G, as well as emission variations of CO and CO_2 in two consecutive cycles of incomplete firing to misfiring and incomplete firing to firing are comparatively shown in Fig. 8. In the cycle before misfiring, the velocity variations of the transfer-port and exhaust-pipe flows showed large fluctuation including the negative values during scavenging process. CO and CO_2 concentrations showed high level. Much burnt gas mixed with some flesh gas had become residual gas in the cylinder, which led the in-cylinder gas to high temperature and showed high velocity of the in-cylinder flow. This led to the in-cylinder velocities in the cycle before misfiring to remain high, compared with the cycle before firing. This in-cylinder flow may have consisted of much burnt residual gas which could cause misfiring.

Table 1 Time difference of in-cylinder velocity peak

	Point-B	Point-G	$\frac{dx}{dt}$
Misfiring	139deg. (25.7m/s)	155deg. (14.6m/s)	16.9m/s
Incomplete firing	135deg. (29.5m/s)	145deg. (27.8m/s)	27.0m/s
Firing	137deg. (29.0m/s)	146deg. (30.4m/s)	30.0m/s

CONCLUSIONS

The in-cylinder flow velocities in a part-loaded two-stroke engine were directly measured by the FLDV. The cyclic variation of scavenging flow across the cylinder formed by the transfer-port and exhaust-pipe flows was experimentally investigated together with that of CO and CO_2 emissions by the data classification into different combustion states. The knowledge clarified in this study are summarized as follows:

1. In the LDV measurements of in-cylinder flows, PDF of sampled data number increased when the scavenging process started, namely, and fresh gas flew into the cylinder.
2. In the scavenging process, the velocity variations of transfer-port and exhaust-pipe flow were synchronized, while that of in-cylinder flow showed quite different characteristics from the transfer-port and exhaust-pipe flows.
3. The in-cylinder flow field at the upper-part of combustion chamber was not directly influenced by the pressure propagation in the engine, but formed by the momentum of the transfer-port and exhaust-pipe flows. In order to control the in-cylinder flow, controlling the transfer-port and exhaust-pipe flow are required.

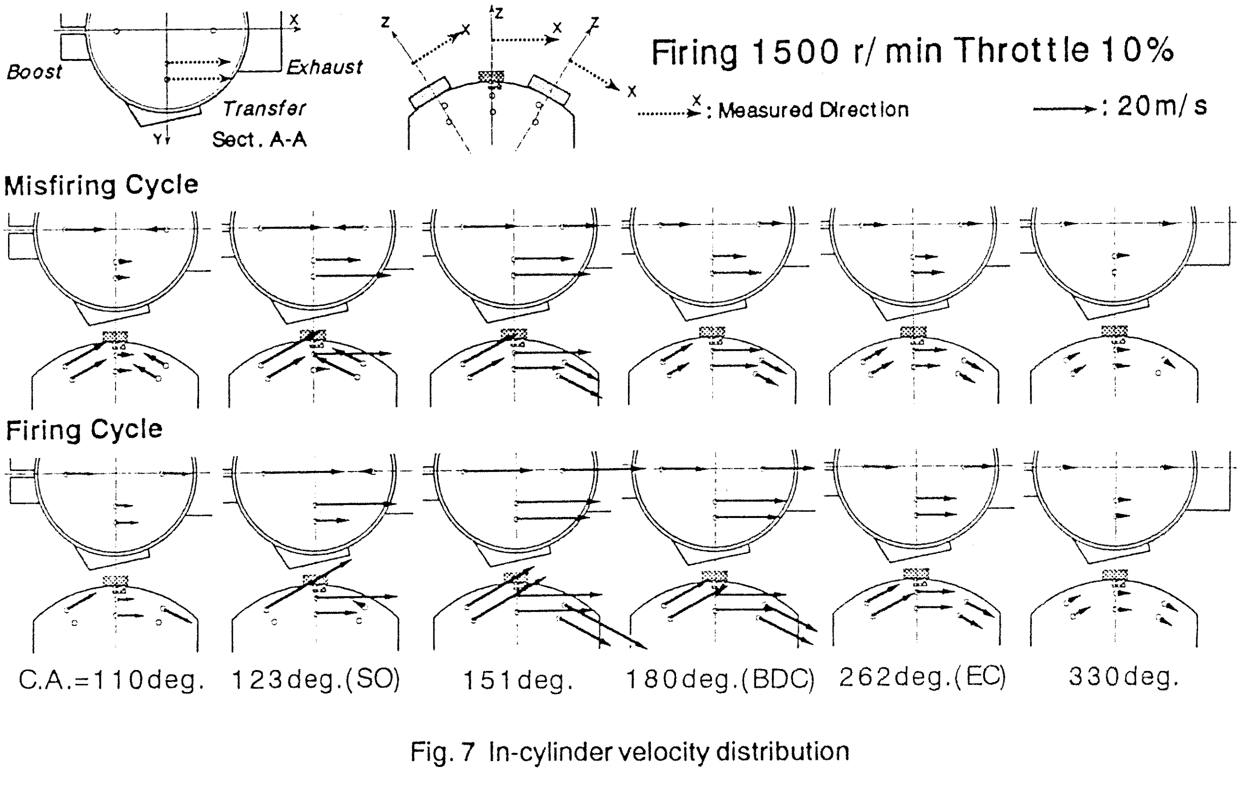


Fig. 7 In-cylinder velocity distribution

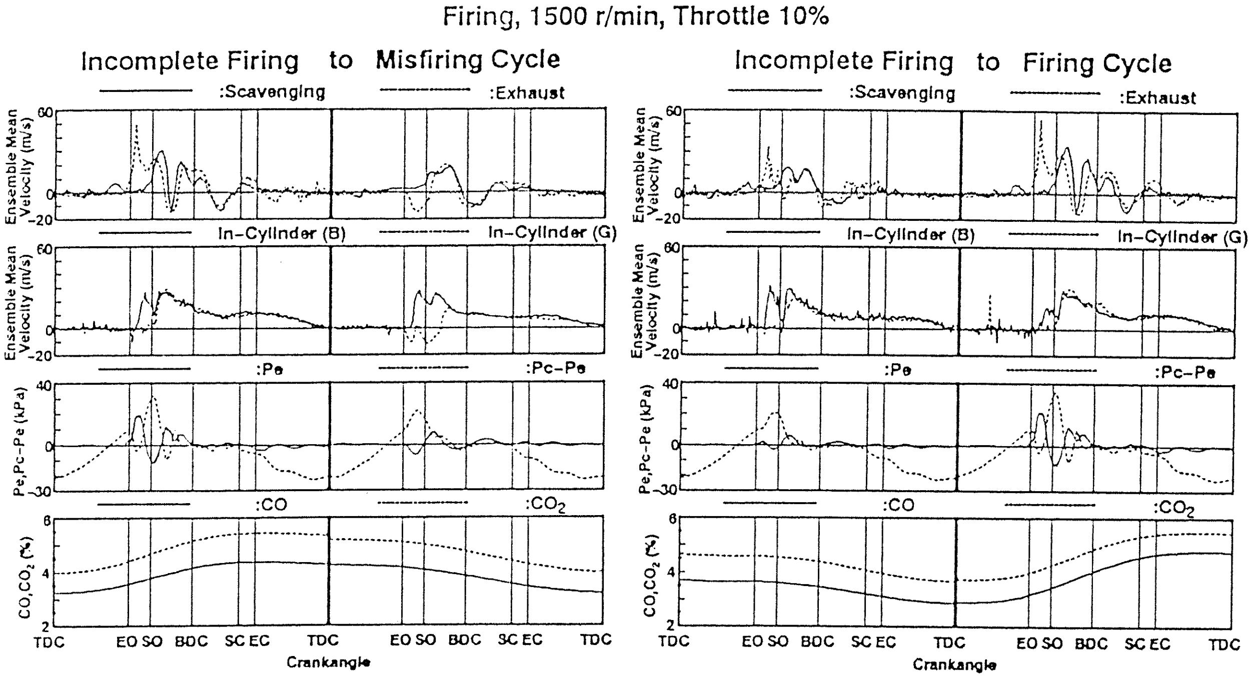


Fig. 8 Difference between misfiring and firing

4. In the initial stages of scavenging process around SO, the in-cylinder flows were yielded by the reverse flow from the exhaust pipe in misfiring cycles or intake flow from the transfer ports. From BDC to near the ignition timing, the in-cylinder velocity variation showed almost constant flow from the boost port towards the exhaust port.
5. During scavenging process before a misfiring cycle, the fast in-cylinder flow, the large variation of transfer-port and exhaust-pipe flow velocity and the high level emissions of CO and CO_2 were quantitatively measured. Such scavenging flow consists of much burnt gas could lead to misfiring.

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