Cycle-to-Cycle Flow Rate Measurement on Reciprocating HCCI Engine Using Fast-Response Laminar Flow Meter*

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Abstract

In recent years, higher thermal efficiency and lower emissions are required on a reciprocating engine development and therefore cycle-to-cycle combustion control is necessary. Especially it is a key factor to control HCCI combustion engine. In HCCI engine, one of the most promising combustion methods to achieve high thermal efficiency, the ignition timing strongly depends on the mass-averaged temperature of charged gas and residual gas and very precise combustion phase control is required. Therefore it is important to detect the changes of cycle-to-cycle intake air flow rate, EGR gas flow rate and as well as residual gas in each cycle. The traditional laminar flow meter has too low responsivity to measure cycle-to-cycle flow rate. In this study, the fast-response laminar flow meter was developed in order to measure cycle-to-cycle dynamical flow rate. The availability of the fast-response laminar flow meter for cycle-to-cycle intake air flow rate measurement of the HCCI engine is shown in this paper.

Key words: HCCI Combustion Engine, Dynamic Measurement, Intake Air Flow Rate, Laminar Flow Meter

1. Introduction

Against the backdrop of global warming and environmental concerns, higher thermal efficiency and lower emissions are being required on a reciprocating engine development. In order to realize them, cycle-to-cycle combustion control is necessary in the engine development and cycle-to-cycle combustion stabilization is required for higher thermal efficiency and output and also lower emissions. Moreover it is important to measure an intake air flow rate by cycle-to-cycle since an intermittent firing is done in the reciprocating engine. Especially in Homogeneous Charge Compression Ignition (HCCI) combustion engine, a stable combustion without cyclic combustion dispersion is necessary. In HCCI engine, the ignition timing strongly depends on the mass-averaged temperature of charged gas and residual gas and very precious combustion phase control is required. Therefore it is important to detect the changes of cycle-to-cycle intake air flow rate, EGR gas flow rate and as well as residual gas in each cycle.⁽¹⁾

In reciprocating engine development, a laminar flow meter is widely used for intake air flow rate measurement, since it is possible to measure with high accuracy, high linearity and

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low pressure loss. In order to measure the volumetric charge per 1 cycle, it is necessary to measure the flow rate and calculate its time integration during 1 cycle. However traditional laminar flow meter lacks responsivity and does not suit for cycle-to-cycle flow measurement. There are many researches regarding an instantaneous flow rate measurement.⁽²⁾⁽³⁾ However it was difficult to measure the flow rate with high responsivity and accuracy on the reciprocating engine.

In this study, in order to measure the cyclic flow rate into the cylinder with high responsivity and high accuracy, the fast-response laminar flow meter is developed. This laminar flow meter is equipped with the laminar flow element optimized for a pulsating flow in the induction system, the differential pressure sensor and the pressure conduit line. This system is applied to the single cylinder HCCI engine and its performance is confirmed. The availability of the fast-response laminar flow meter on cycle-to-cycle flow rate measurement is shown in this paper.

2. Fast response air flow measurement system and engine setup

2.1 Principal of laminar flow meter

In order to measure flow rate with the laminar flow meter, the flow should be laminar. Therefore mesh elements (Fig.1) are located in order to create thin passes where the air flows. In each of these small pipes, the flow is laminar.

A pressure drop is created as the gas goes through the meter's inlet. The gas is forced to form thin laminar streams that flow paralleling in the capillary tubes. The pressure differential is created by the gas drag; then it is measured by a differential pressure sensor connected to the top plate as shown in Fig.2. The differential pressure from one end of the laminar flow plates to the other end is linear and proportional to the flow rate of the gas.

The principal of a laminar flow meter is based on the Poiseuille's law. This law gives that the pressure drop in an incompressible fluid flowing through a long cylindrical pipe is proportional to the flow rate. The relation of the pressure drop (ΔP) and the flow rate (Q) are expressed in the following equation.

Fig. 1 Mesh pipes

Fig. 2 Schematic view of laminar flow meter

$$Q = \frac{n\pi d^4 \Delta P}{128 \mu l} \quad (1)$$

n	:	number of cylindrical pipe
d	:	diameter of cylindrical pipe
μ	:	coefficient of viscosity
l	:	length of cylindrical pipe

This relation excels in the linearity and it is possible to convert the differential pressure into the dynamic flow rate with high accuracy.

2.2 Fast-response laminar flow measurement system

The laminar flow meter consists of a laminar flow element, a pressure conduit line and a differential pressure sensor. The laminar flow element produces a differential pressure from a flow. The pressure conduit line transfers the differential pressure to a sensor. The differential pressure sensor detects the differential pressure.

In order to measure cycle-to-cycle dynamic flow rate, high frequent characteristics are necessary. In general, about twentieth-order harmonics is involved in intake flow. Consequently, frequent characteristic 250 Hz is necessary at $Ne=1500$ rpm. However each part of the traditional laminar flow meter does not have enough high responsivity and its frequent characteristic is 3 Hz in our setup. Therefore the fast-response laminar flow measurement system is developed. Figure 3 is the system configuration for the fast-response laminar flow meter.

a) Laminar flow element: Though a surge tank is normally equipped as in Fig.4 to dampen a pulsating flow and measure an averaged intake flow rate, it is necessary for cycle-to-cycle dynamic flow rate measurement to reduce a “dead volume” of an induction system in order not to average the intake flow. The dead volume of the induction system is reduced in this system as in Fig.5. Since the peak value of an instantaneous flow rate is larger than the average flow rate, 50L/s laminar flow element is adopted. With this laminar flow element, the pressure loss is about 0.9kPa at 50L/s.

b) Differential pressure sensor: In a view of dynamic responsivity, a magneto resistive type differential pressure transducer was selected at first. However, since it is necessary to shorten the pressure conduit line and since it was installed near the engine, a drift problem occurred at zero point temperature characteristics due to a wide temperature change. Therefore a nonadherent type of strain gauge transducer, the Stham PM283TC is selected. This transducer excels in zero point drift characteristic and in sensitive detections, 1kPa FS,

Fig. 3 System configuration of fast-response laminar flow meter

is possible. Since zero balance is kept through 4-bridge full gauge, the temperature characteristics are good. Moreover the line pressure is 200kPa in an absolute pressure and the diaphragm eigen frequency is $F_n=2\text{kHz}$. These values are high as a small pressure sensor. Therefore this transducer suits to dynamic high accuracy measurements.

The relation of a diaphragm eigen frequency F_n and a flat response frequency F_t is expressed by equation (2).

$$F_t = F_n/5 \quad (2)$$

From this equation, the flat response frequency F_t is almost 400Hz.

Fig. 4 Conventional air flow measurement system with a surge tank in the intake flow line, dead volume 57500cc

Fig. 5 Fast response air flow measurement system without a surge tank, dead volume 96cc

Fig. 6 Frequent response characteristics of pressure conduit lines, upper: variable lengths, lower: variable diameters

c) Pressure conduit line: The choice of the pressure conduit line is also important. The roll of the pressure conduit line is to conduct energy from the laminar flow element to the differential pressure transducer. An air column vibration or a phase lag makes the dynamic measurement impossible. Therefore it is necessary to optimize the length (L) and the diameter (D) of the pressure conduit line in Fig.2. Figure 6 shows the simulation results of the frequency response characteristics of P_0/P_i [dB]. P_0 is the pressure of the differential pressure transducer and P_i is the pressure of the laminar flow element. The variety of the combination of the length and the diameter are simulated.⁽⁴⁾ As a result, the combination of the diameter 0.7mm and the length 50mm is the optimal value in this system. According to the simulation, frequent characteristics of the pressure conduit line is almost 200Hz under the temperature of 50 degrees. Since the flat response frequency F_t is almost 400Hz, frequent characteristics of the pressure conduit line is dominant.

2.3 Engine under test

The engine used under this study is a modified HONDA GX340K1, which is an air-cooling, single cylinder and four-stroke engine. This is modified for HCCI engine. The two-stage exhaust cam is used to introduce hot EGR gas. The exhaust cam lifts the exhaust valve during both the exhaust stroke and the intake stroke. Both the inlet valve and the exhaust valve are open during the intake stroke. Therefore the hot EGR gas, which has once been exhausted, is re-breathed again. Moreover in order to control the ratio of stoichiometric pre-mixture, the hot EGR gas and the cold EGR gas, the 4 throttles: the Air throttle A, the Inlet throttle B, the Exhaust throttle C and the Cold EGR throttle D are located in the inlet port, the exhaust port and the EGR passage. DME (Di-methyl Ether) is used as a fuel and injected into the inlet port.

Fig. 7 Schematic view of test engine

3. Results and discussions

3.1 Experimental conditions

In a 4 stroke reciprocating engine, the inlet valve opens in the intake stroke and the piston descends from the top of the cylinder to the bottom, reducing the in-cylinder pressure. Air-fuel mixture is charged into the cylinder by a negative pressure. Since the inlet valve is closed, it is not charged into the cylinder during the compression, the expansion and the exhaust stroke. Therefore it is charged only in the intake stroke of 1 cycle. However since the traditional laminar flow meter pursuits linearity and accuracy and responsivity is not enough, the measurement result of the traditional laminar flow meter is a constant averaged flow rate during all strokes.

Therefore the fast-response laminar flow meter was developed. This laminar flow meter is equipped with the laminar flow element optimized for a pulsating flow in the induction system, the differential pressure sensor and the pressure conduit line. A direct measurement without the surge tank was also implemented. This system was applied to the single cylinder HCCI engine and its performance was confirmed. For comparison, the traditional measurement with unoptimized pressure conduit line, low response differential pressure sensor (Tsukasa-sokken SDP-11) and the surge tank was done at the same time. Moreover the in-cylinder gas pressure (AVL GM12D) and the intake pressure were measured for consideration.

Table 1 shows the experimental conditions. Three types of the intake air flow measurement systems (with/without surge tank, 2 types of laminar flow elements, 2 sizes of pressure conduit lines and 2 types of differential pressure transducers) were prepared.

- Type 1; Measured by the traditional laminar flow meter with the surge tank. The pressure conduit line is not optimized and the responsivity of the differential pressure sensor is low.
- Type 2; Measured by the traditional laminar flow meter without the surge tank. Though the dead volume of the induction system is reduced, the pressure conduit line and the differential pressure sensor are not optimized for the instant flow rate measurement.
- Type 3; Measured by the fast-response laminar flow meter without the surge tank. Both the pressure conduit line and the differential pressure sensor are optimized.

Table 1 Three types of the intake air flow measurement systems for HCCI engine in this study
(with/without surge tank, 2 types of laminar flow elements, 2 sizes of pressure conduit lines and
2 types of differential pressure transducers)

	Type 1	Type 2	Type 3
	Traditional measurement system	Direct measurement sytem	←
with / without surge tank	with surge tank *dead volume 57500cc	without surge tank *dead volume 96cc	←
Dimensions and maximum flow rate of laminar flow element	$n=40000$ $d=0.3\text{mm}$ $l=20\text{mm}$ 10L/s	←	$n=120000$ $d=0.3\text{mm}$ $l=20\text{mm}$ 50L/s
Pressure conduit line and its frequent characteristics	$L=2000\text{mm}$ $D=2.0\text{mm}$ $F=3\text{Hz}$	←	$L=50\text{mm}$ $D=0.7\text{mm}$ $F=200\text{Hz}$
Type and manufacturer of differential pressure transducer and its diaphragm eigen frequency	SPD-11 by Sokken $F_n=10\text{Hz}$	←	PM283TC by Statham $F_n=2\text{kHz}$

*dead volume: the total volume from the end of the air flow element to the inlet valve of the engine (see Fig. 4, 5)

3.2 Responsivity to flow rate change

To analyze a transient property, the volumetric air charge changed by the Air throttle A angle and the measurement responsivity to the flow rate change was examined.

In this experiment, the engine speed was $Ne=1500\text{rpm}$, the compression ratio was $\varepsilon=10.76$ and the operation mode was motoring. The Inlet throttle B angle θ_B , the Exhaust throttle C angle θ_C and the Cold EGR throttle D angle θ_D were kept full-bore. The intake air flow rate was changed by the Air throttle A angle from $\theta_A=20\text{deg}$ to $\theta_A=60\text{deg}$.

Fig.8 shows the measurement results. The upper figure shows the volumetric air charge per 1 cycle. It is the time integration value of the history of the intake air flow rate. It is calculated by Eq. (3)

$$V_{Air} = \int_0^{720} \left[F_{Air}(\theta) \times \frac{60}{Ne \times 360} \right] d\theta \times 1000 \quad (3)$$

V_{Air} : volumetric air charge per a cycle [ml/cycle]
 F_{AIR} : instantaneous air flow rate [L/s]
 Ne : engine speed [rpm]
 $d\theta$: crank angle [degree]

The lower figure shows the Air throttle A angle (set signal). This angle is the set value and it took finite lengths of time until the actual angle change. The Air throttle A angle was $\theta_A=20\text{deg}$ until the 26th cycle and the set value was changed to $\theta_A=60\text{deg}$ in the 27th cycle. From this moment the throttle began to change. Therefore the intake air flow rate was changing in the 27th cycle.

With this view in mind, the result of Type 1, measured by the traditional laminar flow meter with the surge tank, since the pressure conduit line is not optimized and the responsivity of the differential pressure sensor is low, it took more than 15 cycles from the Air throttle A angle change to the volumetric air charge change. Regarding the result of the Type 2, measured by the traditional laminar flow meter without the surge tank, though some

Fig. 8 Time History of intake air flow rates against a step of air throttle angle measured by of Type 1, Type 2 and Type 3 shown in Table.1

Fig.9 Instantaneous air flow rate against a step change of air throttle angle measured by Type 3

improvement is shown, it took much time until the volumetric air charge changed, since the pressure conduit line is not optimized and responsivity of the differential pressure sensor is low. While on the other hand, the result of the Type 3, measured by the fast-response laminar flow meter without the surge tank, showed dramatic improvement. Since both the pressure conduit line and the differential pressure sensor were optimized, the measurement value of the volumetric air charge changed almost at the same time as the Air throttle A angle changed. The response lag is less than a cycle. From this result, we can say that the fast-response laminar flow meter can catch the volumetric air charge change and excels in responsivity.

To consider the result of the Type 3 in detail, the measured instantaneous intake air flow rate L/s and the actual Air throttle A angle are shown in Fig.9. Regarding the Air throttle A angle, though Fig.8 shows its set signal, the actual Air throttle A angle is shown in Fig.9. The order is the exhaust stroke – the intake stroke – the compression stroke – and the expansion stroke. Though the Air throttle A angle was $\theta_A=20\text{deg}$ until the expansion stroke of the 26th cycle, it was set to $\theta_A=60\text{deg}$ from the 27th cycle, it began to move and reached $\theta_A=60\text{deg}$ at the end of the intake stroke of the 28th cycle. According to Fig.9, the value of the intake air flow rate is increasing and the Air throttle A angle is changing in 27th cycle and the change of the intake air flow rate almost finished in the 28th cycle.

From these results, it is proved that the fast-response laminar flow meter can detect the instantaneous air flow rate change. Since it is possible to measure the intake air flow rate in the transient operation with few response lags, the measurement data with fast-response laminar flow meter is useful for an equivalent ratio control signal.

3.3 Instantaneous flow rate measurement in a single cycle

Figure 10 shows the measurement result of a cycle in the motoring operation. In this experiment, the engine speed was $N_e=1500\text{rpm}$ and the compression ratio was $\varepsilon=10.76$. The Air throttle A angle was $\theta_A=40\text{deg}$, the Inlet throttle B angle θ_B , the Exhaust throttle C angle θ_C were kept full-bore and the Cold EGR throttle D angle θ_D was fully-closed. Intake air flow rate was changed by changing the Air throttle A angle from $\theta_A=20\text{deg}$ to $\theta_A=60\text{deg}$.

Fig. 10 Time history of the in-cylinder gas pressure, the intake gas pressure and the intake air flow rate of a cycle in the motoring operation measured by Type 2 and Type 3 shown in Table. 1

From above, the cam profiles of the intake cam and the exhaust cam, the history of the in-cylinder gas pressure, the close-up of the history of the in-cylinder gas pressure, the intake air pressure and the intake air flow rate are shown. Regarding the result of the intake air flow rate, results of the Type 2, the traditional laminar flow meter without surge tank, and the Type 3, fast-response laminar flow meter without the surge tank, were compared. The exhaust stroke is 0-180 C.A. degree, the intake stroke is 180-360 C.A. degree and the compression stroke is 360-540 C.A. degree. 540 C.A. degree is the TDC of the compression stroke. The expansion stroke is 540-720 C.A. degree.

The bandgraph of the upper side indicates the exhaust valve opening duration and the lower side indicates the intake valve opening duration. Since this engine is modified for HCCI combustion, both the inlet valve and the exhaust valve are open during the intake stroke. Therefore hot EGR gas is re-breathed.

The piston descends from the top of the cylinder to the bottom in intake stroke and the in-cylinder gas pressure becomes a negative pressure. Therefore the history of the in-cylinder gas pressure was a negative pressure (below atmospheric pressure) during the intake valve open. Moreover since the in-cylinder and the induction system are an open system during the intake stroke, the measurement result of the intake air pressure sensor, which is located in the upstream of the inlet valve, was a negative pressure. The reason the intake air pressure rose before the negative pressure is considered as the backward flow from the combustion chamber, this was caused by the overlapping of the period of the intake valve opening and the exhaust valve opening and by the opening of the intake valve at the end of the expansion stroke. The oscillation of the intake air flow rate was caused by the pulsation in the induction system. Though the timing of negative pressure differs from the period of the intake valve opening, it is due to the frequent characteristics of the intake air pressure sensor. Focusing on the result of the history of the intake air flow rate, though the air was charged only in the intake stroke, the result of the Type 2, measured by the traditional laminar flow meter without the surge tank, was almost a constant value through a cycle. That is because the traditional laminar flow meter can not follow the change of the intake air flow, since the frequent characteristics of the pressure conduit line is about 3Hz and the eigen frequency of the differential pressure sensor is 10Hz. On the other hand, focusing on the result of the Type 3, the fast-response laminar flow meter detected the change of the intake air flow rate. During the period of the overlap of the intake valve and the exhaust valve opening, since the in-cylinder gas flew backward to the induction system, the intake air flow rate plunged to sub-zero. During the intake stroke, the history of the intake air flow rate was convex upward. Moreover, though the intake air flow rate became once 0 L/s when the intake valve closed, the intake air flow rate plunged to sub-zero, since not charged gas flew backward due to the intake inertial effect. It can be said that the fast-response laminar flow meter can measure the behavior of the intake air flow in the reciprocating engine. However the phase lag was also observed. Since the frequent characteristic between the laminar flow element and the differential pressure transducer is about 200Hz, it causes the phase lag.

It is important to confirm the accordance of the results of the Type 2 and the Type 3, since they measured the same flow rate. This confirmation was carried out by comparing the volumetric charge per 1 cycle. The value of the result of the Type 2, measured by the traditional laminar flow meter, was 179 ml/cycle. The value of the result of the Type 3, measured by the fast-response laminar flow meter, was 178 ml/cycle. The error is less than 1%. Therefore the fast-response laminar flow meter can measure with high accuracy.

From above results, it is confirmed that the behavior of cycle-to-cycle intake air flow is measurable with high responsivity using the fast-response laminar flow meter. It is also shown that the fast-response laminar flow meter excels also in accuracy. Consequently, the fast-response laminar flow meter is useful not only for cycle-to-cycle intake flow

measurement in the combustion control, but also for the induction system and the valve design.

3.4 Instantaneous flow rate measurement in HCCI combustion operation

One of the reasons for the difficulty of HCCI combustion is the combustion instability. Though there are several reasons for the combustion instability, the intake flow rate is also one of factors. Therefore it is necessary for stable HCCI combustion to understand the influence of the intake air flow rate. In this study, the measurement of the intake air flow rate was focused. The intake air flow was measured under combustion phase retarded condition. Cyclic combustion dispersion occurred in this condition. In this experiment, the engine speed was $N_e=1500\text{rpm}$, the compression ratio was $\varepsilon=10.76$ and the operation mode was HCCI combustion. Air-fuel pre-mixture, the hot EGR gas and the cold EGR gas were used.

Figure 11 shows the continuous 10 sequential cycles data of the history of the in-cylinder gas pressure. Though under the same experimental condition, the history of the in-cylinder gas pressure differed cycle-to-cycle. There were some misfire cycles and it is confirmed that combustion was very unstable. Figure 12 shows the intake air flow rate of the same 10 sequential cycles. The upper chart is the result of the Type 2, measured by the traditional laminar flow meter, and the lower chart is the result of the Type 3, measured by the fast-response laminar flow meter. Since the responsivity of the traditional laminar flow

Fig. 11 Cycle-to-cycle fluctuation of in-cylinder gas pressure of continuous 10 cycles in unstable HCCI combustion with a CA50 retarded condition

Fig. 12 Comparison of volumetric air charges measured by the Type 2 and the Type 3 of continuous 10 cycles in unstable HCCI combustion

Fig. 13 Instantaneous air flow rates in continuous 3 cycles of #2, #3 and #4 shown in Fig.12

meter is low, there was no change in cycle-to-cycle intake air flow rate also under unstable combustion. However cycle-to-cycle intake air flow rate changed significantly in the result of the fast-response laminar flow meter. Moreover the intake air flow rate tended to repeat every 3 cycles. Though it is impossible to confirm with the traditional laminar flow meter, the fast-response laminar flow meter brought out that, the intake air flow rate fluctuates cycle-to-cycle while unstable HCCI combustion. There is a possibility for the stabilization of HCCI combustion by validating the correlation between the intake air flow rate change and combustion.

Furthermore, in order to understand the behavior of the intake air flow rate during unstable combustion, the history of the intake air flow rates are shown in Fig.13. 2nd to 4th cycles in Fig.12 are focused. The intake air flow rates of each cycle were different. That is because the history of the intake air flow rate during 50-200C.A. degree was different. This period is the exhaust stroke and the intake valve was closing. Since the cold EGR gas passage is connected to the inlet side in this engine, it is expected that the exhaust gas flew through the cold EGR gas passage. It is necessary to consider the correlation with combustion more in detail.

For the stabilization of HCCI combustion, it is necessary to consider the correlation with many factors; the intake air flow rate, gas temperatures, gas compositions and so on. Using the fast-response laminar flow meter, it becomes possible to measure cycle-to-cycle intake air flow rate and the behavior of the intake air flow. The cycle-to-cycle combustion control is necessary for the internal combustion engine with high thermal efficiency and lower emissions, especially for HCCI combustion engine, which combustion depends on chemical reactions. Since cycle-to-cycle intake air flow measurement is very important for the cycle-to-cycle combustion control, the fast-response laminar flow meter is useful for the future engine development.

4. Conclusion

Cycle-to-cycle combustion control is necessary for next-generation engine development like HCCI combustion engine. From higher thermal efficiency and output and also lower emissions point of view, cycle-to-cycle combustion stabilization is required. Moreover it is important to measure the intake gas flow by cycle-to-cycle since the intermittent firing is done in the reciprocating engine. To measure cycle-to-cycle volumetric charge into cylinder with high responsivity and high accuracy, the fast-response laminar flow meter was developed. This laminar flow meter is equipped with the laminar flow element optimized for a pulsating flow in the induction system, the differential pressure sensor and the pressure

conduit line. This system was applied to the single cylinder HCCI engine and its performance was confirmed.

- 1) To measure the differential pressure from the laminar flow element, the length and the diameter of the pressure conduit line were considered in view of the viscosity and the inertia for fluid in the pressure conduit line. Through simulation, the best combination of the length and the diameter with little phase lag and reduced sympathetic vibration was selected. The frequent characteristics of the pressure conduit line is almost 200Hz. And the flat response frequency of the differential pressure sensor is $F_t=400\text{Hz}$. Therefore the frequent characteristic of developed fast-response laminar flow measurement system is 200Hz. It is able to measure the sixteenth-order harmonics of intake air flow rate at $N_e=1500\text{rpm}$.
- 2) To analyze the transient property, the laminar flow measurement systems were applied to the single cylinder HCCI engine and the volumetric air charge measurement was done by changing the intake throttle angle in motoring operation. Though there is more than 10 cycle response lag with the traditional laminar flow meter, the fast-response laminar flow meter could detect the change of volumetric air charge change with less than 1 cycle response lag at $N_e=1500\text{rpm}$, since its components are optimized for instant flow rate measurement. It is shown that the developed fast-response laminar flow meter excels in responsivity.
- 3) The fast-response laminar flow meter could pick up the behavior of the intake air flow rate accurately. During the period of the overlap of the intake valve and the exhaust valve open, in-cylinder gas flew backward to the induction system. During the intake stroke, the history of the intake air flow rate was convex upward. When the intake valve closed, the intake air flow rate plunged to sub-zero, since not charged gas flew backward due to the intake inertial effect. Moreover the time integration value of the history of the intake air flow rates of the traditional laminar flow meter and the fast-response laminar flow meter were accurately-matched.
- 4) The intake air flow rate was measured under combustion phase retarded condition on HCCI engine. Since the responsivity of the traditional laminar flow meter is low, there was no change in cycle-to-cycle intake air flow rate also under the unstable combustion. However cycle-to-cycle intake air flow rate changed significantly in the result of the fast-response laminar flow meter. The fast-response laminar flow meter could measure the behavior of cycle-to-cycle intake air flow.

Using the fast-response laminar flow meter, it became possible to measure cycle-to-cycle intake air flow rate and the behavior of the intake air flow with high responsivity and high accuracy. It is considered that the fast-response laminar flow meter is useful for the future engine development.

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