MEASUREMENT OF SUCTION AIR AMOUNT AT RECIPROCATING
ENGINE UNDER STATIONARY AND TRANSIENT OPERATION

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ABSTRACT

The air-fuel ratio of an internal combustion engine must be controlled with accuracy for the improvements of exhaust emission and fuel consumption. Therefore, it is necessary to measure the exact instantaneous amounts of fuel and suction air, so we carried out the experiments for measuring the air flow velocity in a suction pipe of an internal combustion engine using three types of instantaneous air flowmeter.

The results obtained can be summarized as follows:
(1) The laminar-flow type flowmeter is able to measure both the average and the instantaneous flow rate, but it is necessary to rectify the pulsating air flow in the suction pipe.
(2) The a spark-discharge type flow velocity meter is able to measure the instantaneous air velocity, but it is necessary to choose the suitable electrode form and the spark character.
(3) The tandem-type hot-wire flow velocity meter indicates the instantaneous flow velocity and its flow direction.

1. INTRODUCTION

Combustion in an automotive engine and its exhaust emission depend on the strength of mixture charged in the cylinder. When an experimental investigation of internal combustion engine is carried out, it can be said that the engine performance cannot be determined in detail without measurements of the average and instantaneous suction air flow quantity during one cycle under steady operation as well as the quantitative measurement of suction air under transient operation. Recent progress of electronic control technology has made it possible to control the mixture optimumly. Even for this purpose, however, it is necessary to detect the flow quantity of suction air accurately. Since air flow in the suction pipe is intermittent or pulsating, it is difficult to measure accurately the flow quantity without affecting to the engine performance. It is likely that the flow

quantity of suction air can be determined with an orifice-type flowmeter (a circular nozzle, a venturi meter, etc.), a laminar-flow type flowmeter, a sonic nozzle method, a positive displacement flowmeter (a gas meter, a water displacement method), a heat-type flowmeter (a Thomas gas meter, a boundary layer flowmeter), an ultrasonic flowmeter and with various flow velocity meters such as a heat-type one (a hot-wire flow velocity meter, a thermal-pulse flow velocity meter), a spark-discharge flow velocity meter, a Karman vortex flow velocity meter, a correlation flow velocity meter, a laser flow velocity meter, a pitot tube, etc.

High precision of those measurements requires the following steps:

Correction depending on the variation in suction air state (pressure, temperature, humidity, kinematic viscosity, thermal conductivity, etc.).

Removal of the influences of flow velocity distribution and flowing state in the pipe.

Elimination of various errors caused by the pulsating flow.

Improvements of the calibration precision for a flowmeter and the precision for an electric measuring apparatus.

Moreover, it is to be desired that a flowmeter satisfies such conditions as follows:
(1) A simple structure with low pressure loss and it can be operated easily.
(2) Flow coefficient is constant at wide range of flow rate.
(3) It does not affect the performances of the engine and the carbureter.
(4) For determinating the flow quantity, no complicated device or calculation formula is necessary.

Since there exists no such flowmeter as to satisfy all these conditions, it is inevitable to select a suitable flowmeter according as the experimental objects.

In this study, the authors tried to measure simultaneously the instantaneous flow amounts of suction air with three types of flowmeter.

2. EXPERIMENTALLY MANUFACTURED INSTANTANEOUS FLOWMETERS

2.1 Laminar-flow type flowmeter[1]

Fig.1 shows the structure and the dimension of a laminar flow type flowmeter. Its flow element is composed of spirally wounded alternate layers of stainless steel plate 30 μm thick and the same pressed into a corrugated form.

The pressure drop in the flow element was measured using a reluctance-varying type pressure transducer with precision 1 % FS which installed in the pressure tap (see Fig.1). The change in inductance which depend on the pressure difference was detected with a bridge circuit and after its amplification and demodulation it was converted into DC output. To avoid the influence of piping to the difference pressure transducer, a thin plate 30 to 50 μm thick of phosphor bronze was fitted to the central part of flowmeter and strain gage, used as difference detector, was stuck to the plate. The air amount Q_a passing through a laminar-flow type flowmeter can be linearly related with the pressure drop ΔP only when the pressure loss in the flow element ($= 64\mu v/(\rho d^2)$) is larger than that in before and behind of the element [$\{\lambda_1 + \lambda_2(A_1/A_0)^2\}v^2$].

For this condition, it is desirable that a ratio ℓ/d between the element length ℓ and the hydraulic diameter d is large. If the flow acceleration $\partial v/\partial t$ is high, it is impossible to neglect the effect of inertial difference pressure $\Delta P_a = \rho \int_0^\ell (\partial v/\partial t)d$ in motion equation of air column, so that the flow coefficient does not coincide with that for steady flow. To make ΔP_a lower, it is desirable to decrease the flow velocity by increasing the total path area of the flow element and to decrease the length ℓ. The authors manufactured three flowmeters A, B and C of dimensions shown in Fig.1 and these static calibration curves are shown in Fig.2 with solid line. These are sufficiently linear and a calibration coefficient K, given by a relation $Q=K \cdot \Delta P$, has values written in the figure.

An equivalent diameter of the flow element, approximately calculated from the enlarged photograph, Fig.1, is about $d \approx 0.3$ mm.

In the next place, the authors measured the average flow quantity of suction air with a laminar-flow type flowmeter by producing intermittent air flow with a rotary valve and a vacuum pump. As can be seen from the results drawn in Fig.2 with dotted line, the value of coefficient K is smaller than that in steady flow. Consequently, the correction for unsteady flow is necessary. Although a method utilizing the liquid damping was adopted in order to eliminate the errors caused by vibration of the water column in manometer, it was impossible to attain perfectly the object. On the other hand, the authors inserted the laminar-flow type flowmeters (LF) in the inlet of the surge tank and in the suction pipe line and measured the suction air. As shown in Fig.3, insertion of the flowmeter in a suction pipe system attenuated the undulation of the suction air amount curve and the attenuation is more remarkable with increasing the engine speed and the flow element length. Except the operation with very low engine speed (lower than 1300 and 1900 rpm for C and B types, respectively), it is not desirable to insert a laminar-flow type flowmeter into the suction pipe and a surge tank should be used in combination. A pressure plate used for measuring instantaneous flow quantity was made of phosphor bronze plate etched with aqueous solution of HNO_3 and its thickness was 30 to 50 μm. The plate was made to adhere to a ring while tension of 15 kgf being given to it, in order to improve a linearity of the relation between the working difference pressure and the strain of the plate.
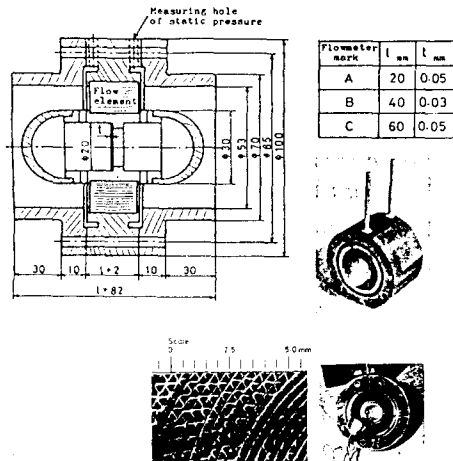

Fig.1 Structure of laminar-flow type flowmeter and enlarged photograph of flow element
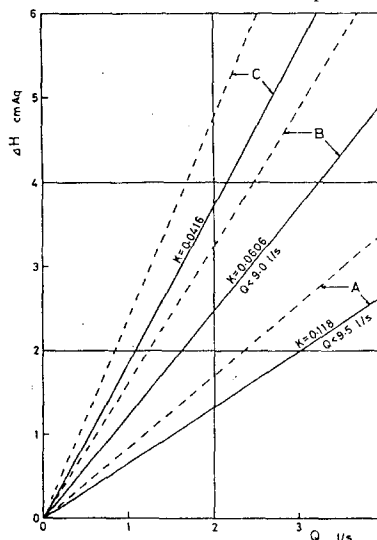
Flowmeter mark	ℓ mm	t mm
A	20	0.05
B	40	0.03
C	60	0.05

Fig.2 Calibration curves of laminar-type flowmeters

(a)

(b)
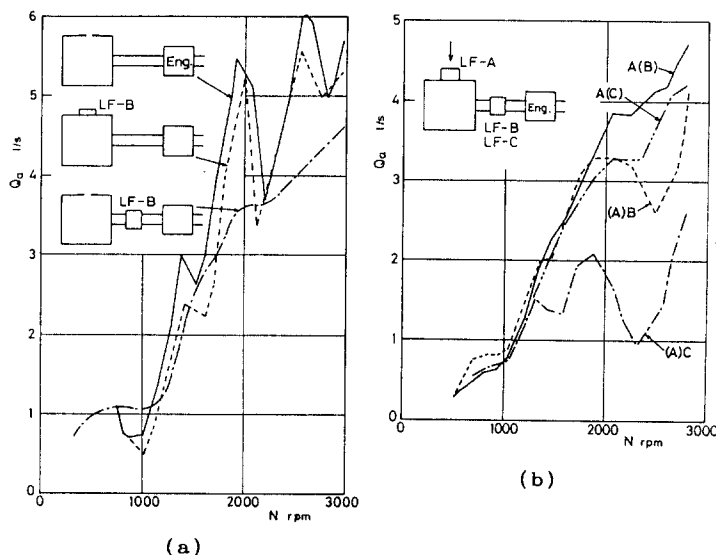
Fig.3 Suction air amounts and positions of laminar-flow type flowmeter

Fig.4 Instantaneous flow quantity (laminar-flow type flowmeter)

When the pressure plate is a disc fixed at edge, the natural frequency f_0 of the plate under uniform load is given by

$$f_0 = \frac{\lambda^2}{2\pi} \cdot \frac{t}{r^2} \sqrt{gE/12(1-\nu^2)\phi}$$

where ν : poisson's ratio, E: modulus of longitudinal elasticity, g: gravitational acceleration, ϕ : weight per unit volume, λ : constant, r: radius.

Substituting in the above expression r=7.5 mm, E=11200 kgf/mm^2, t=0.03~ 0.05 mm, g=9.8 m/s^2, ϕ =8.78× 10^{-6}, λ =10.21 and ν =0.3, f_0=30~ 50 kHz can be obtained.

Fig.4 shows the measured values of the instantaneous flow quantity Q_a with a laminar-flow type flowmeter.

2.2 Tandem-type hot-wire flow velocity meter

Since the output of a hot-wire flow velocity meter is not directional, it is not always easy to discriminate, as shown in Fig.5, the flow direction as far as it is complicated such as a pulsating flow in the suction pipe of an internal com-
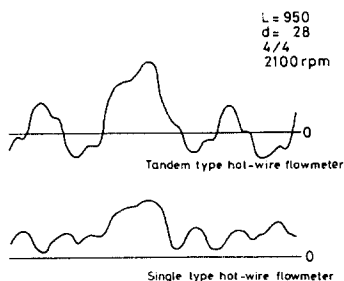
bustion engine. The authors tried to avoid such a disadvantage as this and to improve further the response by applying a tandem-type flow velocity meter of constant temperature system developed by Asanuma et al [2].

In this meter, two hot wires were arranged, as shown in Fig.6, perpendicularly to the flow, the hot wire at the downstream side was placed in a wake of that at the upstream side and based on the difference between thermal conductivities of them, the flow velocity and the flow direction were simultaneously measured. Its electronic circuit diagram is shown in Fig.7.

Fig.6 shows a static calibration curve and this can be transformed into a linear relation by means of a suitable linearizer. With this tandem-type hot-wire flow velocity meter, it is possible, as shown in Fig.5, to discriminate precisely the flow direction even when the meter is applied to measurement of the pulsating flow in the suction pipe.

In general, the response of the meter is expressed with a ratio of the heat capacity of its hot wire to the quantity of heat transfer from the wire per unit time and temperature, that is, a time constant τ . A theoretical calculation resulted in about 0.7 ms of its time constant with ϕ 10 μ m tungsten wire for an air flow of the Reynolds number R_e=900 and it may be said that response is approximately satisfactory when it is applied to measurement of the instantaneous suction air velocity of IC engine.

Fig.5 Measuring example of air velocity in suction pipe
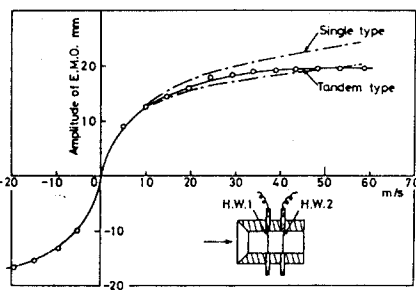
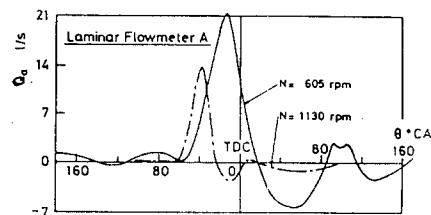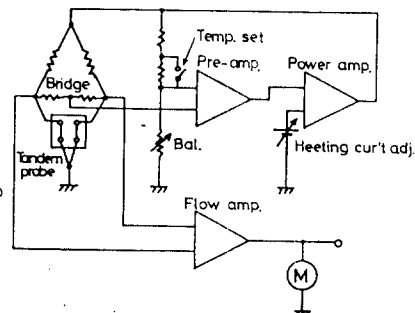
Fig.6 Calibration curves of hot-wire flow velocity meter

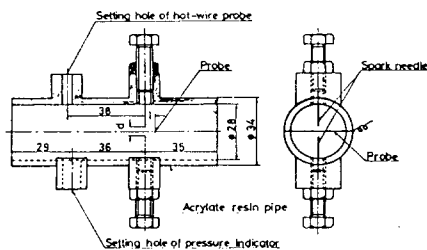Fig.7 Electronic circuit of tandem-type hot-wire flow velocity meter
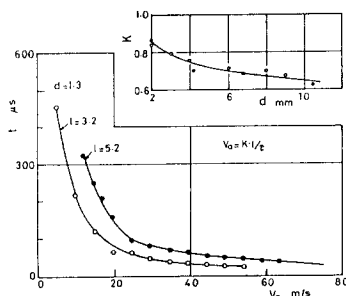
Fig.8 Shape of spark-
discharge flow
velocity meter
probe

Fig.9 Calibration curves
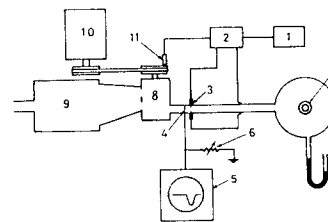of spark-discharge
flow velocity meter

1 Electric power source	7 Nozzle & surge tank
2 Tr ignitor	8 Engine
3 Spark needle	9 Silencer tank
4 Probe	10 Variable speed motor
5 C.R.T	11 Magnetic senser
6 VR to adjust gain	

Fig.10 Experimental apparatus
on spark-discharge flow
velocity meter

2.3 Spark-discharge type flow velocity meter [3]

While various methods for measuring air velocity by means of spark-discharge are proposed to respective objects, a phenomenon that the path of arc discharge shifts with air velocity was utilized in the present experiment. In this method, spark was discharged perpendicularly to the flow, at its suitable down-stream position the discharging path was detected and the flow velocity was determined from the time, required to the shift. For detecting the discharging period, the induction current was measured by means of a coil wound on a high-voltage cord and a side probe prepared with copper wire of ϕ 0.1 mm was arranged, as shown in Fig.8, at the down-stream side of a discharging electrode.

The discharging electrode is made of a sewing needle of ϕ 0.8 mm fitted to the tip of a bolt, so that the inter-electrode distance can be arbitrarily adjusted. Since the suction air velocity in a crankcase compression two-stroke cycle engine fluctuates within a range from 0 to about 70 m/s, it is necessary that the discharging energy is high and the duration of induced discharge is long. After experimental investigation of various ignition systems, the authors adopted a transistor ignitor: its discharge time=2.8 ms, total discharging energy=170 mJ and inductive component=140 mJ.

The time required to shift of the discharging path t is, as shown in Fig.9, inversely proportional to the air velocity V_a, which is related with the probe distance l and the discharge arrival time τ through an equation $V_a = K \cdot l / \tau$. This constant K decreases with increasing the inter-electrode distance d.

A transistor ignitor was used as discharge source but since the air velocity is wide variation so that it was inevitable to change the probe distance l into 5.0 and 3.2 mm for high engine speed and low speed, respectively (d=3 mm). In engine test, the transistor ignitor was driven with the output of an electromagnetic pickup mounted, as shown in Fig.10,
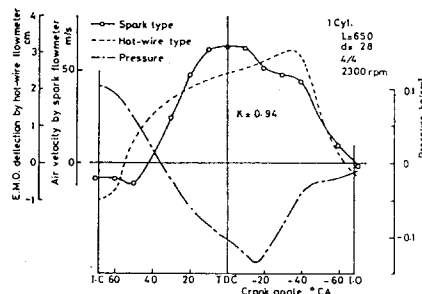

Fig.11 Comparison of air velocities in
suction pipe measured by tandem-
type hot-wire and spark-discharge
flow velocity meter

in the vicinity of a driving pulley at the engine side to make the ignitor discharge only once a rotation and the instantaneous suction air velocity was measured during one suction port opening period while output-producing time of the electromagnetic pickup being changed each 10℃ A of crank angle by means of turning a discharge timing adjusting plate fitted to the pulley. The measured value shown in Fig.11 does not always coincide with the values indicated by the tandem type hot-wire flow velocity meter. Its reason is still unknown. In engine test, however, the tandem type hot-wire flow velocity meter was mainly used, because the flow velocity in the first half of the suction period in tandem type hot-wire flow velocity meter is higher than that in the second half so that the indication of this meter seems to be more correct than that of the spark-discharge type and because the measurement is easier.

3. MEASUREMENT OF SUCTION AIR FLOW VELOCITY IN ENGINE

3.1 Experimental apparatus and method

The experimental apparatus is composed of a surge tank (V=0.2 m^3) with a round nozzle, a carbureter, a suction pipe system fitted with various instantaneous

Table 1 Specifications of the engine used

Engine type	2 cycle gasoline engine		
Number of cylinders	2 cylinders, in-line type		
Cylinder bore X stroke	61.5 mm X 60.0 mm		
Total stroke volume	356 cc		
Compression ratio	6.5		
Cooling system	Forced air cooled		
Type of scavenging	Crankcase compression, Schnürle type		
Port timing	suction	open	BTDC 68°25′
		close	ATDC 68°25′
	exhaust	open	BBDC 53°17′
		close	ABDC 53°17′
	scavenging	open	BBDC 52°38′
		close	ABDC 52°38′
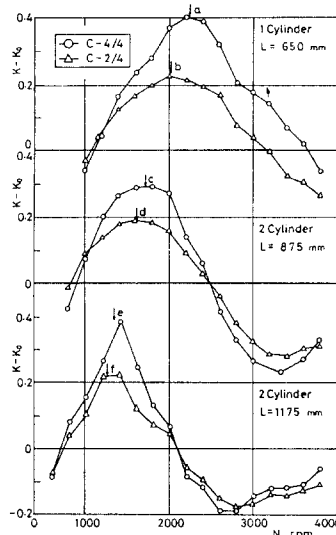
Fig.12 Experimental curves
of delivery ratio
$(K-K_0)$

Table 2 Cyclic variation ratio suction air amount G_a

	T_{w_0}	C= 1/4		C= 4/4	
	℃	Tr.	St.	Tr.	St.
Motoring	10	2.33	2.29	2.31	2.47
	65	2.20	2.30	2.13	2.24
Firing	80	4.26	4.26	3.36	4.47

Fig.13 Comparison of air velocities
and pressures in suction pipe
system at $(K-K_0)_{max}$ condition

flowmeter and a pressure indicator, a test engine and an exhaust pipe line.

Variation of the suction air velocity due to dynamic effect, in particular, of air column in the exhaust pipe was avoided by connecting the exhaust port with the exhaust surge tank through a duct of 220×310 mm in suction. THe test engine was a crankcase-compression two-stroke cycle and its specification were as shown in Table 1.

The average flow quantity of suction air, that is, the delivery ratio at each engine speed was measured with the round nozzle. Utilizing the delivery ratio curves, the suction air velocity was measured with the tandem type hot-wire velocity meter, simultaneously the pressure variation in the suction pipe with a strain gage type pressure indicator, near an engine speed where the delivery ratio was the highest.

3.2 Experimental results
3.2.1 Steady operation

Fig.12 shows the so-called suction pipe effect, that is, a difference $(K-K_0)$ between the delivery ratio K at an arbitrary length of the suction pipe and the delivery ratio K_0, as standard, at a length L=80 mm. In the figure, the engine speed N_{max} under the optimum condition of the suction pipe effect, that is,
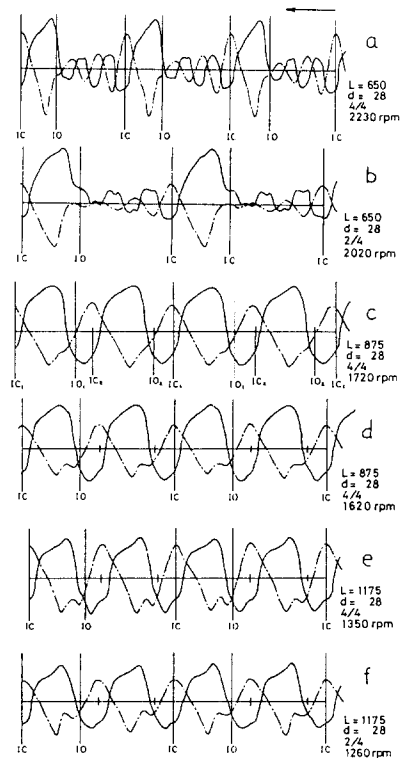
at which $(K-K_0)$ is the highest, shifts towards the low engine speed side with increasing the suction pipe length and with decreasing the carbureter opening and this tendency coincides qualitatively with the fact so far pointed out. Fig.13 (a to f in this figure correspond to a to f in Fig.12, respectively) shows the suction air flow velocity and pressure variation. According to the data represented in Fig.13, $(K-K_0)$ is not always the highest when the suction port is closed at zero flow velocity of suction air, in other wards, when no back flow from the crankcase appears during a suction period. The suction pipe effect can be rather fully utilized and $(K-K_0)$ becomes the highest by closing the suction port when the first positive wave is maximum. Since the suction air amount is fundamentally an integration of instantaneous inflowing velocity during one suction period and the inflowing velocity depends on the engine speed, it is no wonder that the integration value of the inflowing velocity with back flow is larger than that without back flow.

3.2.2 Transient operation

Figs.14 and 15 shown the mean density $\bar{\rho}_m$ and the mean suction air amount $\bar{G}_a$ during a suction period θ_s at the every cycle, with the experimental results ob-
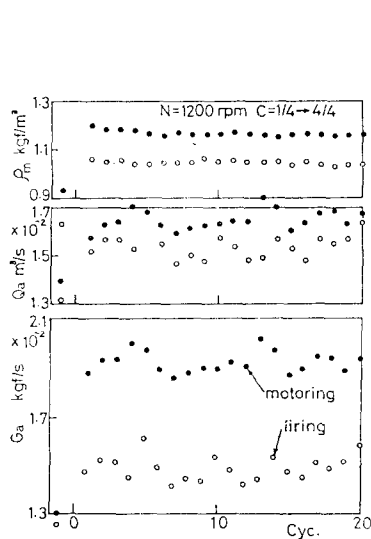
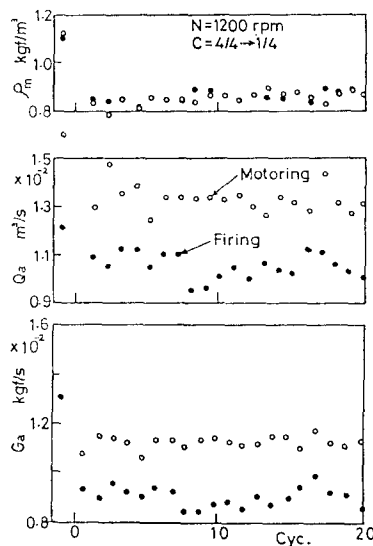Fig.14 Behaviors of G_a, Q_a and ρ_m (stepwise opened)

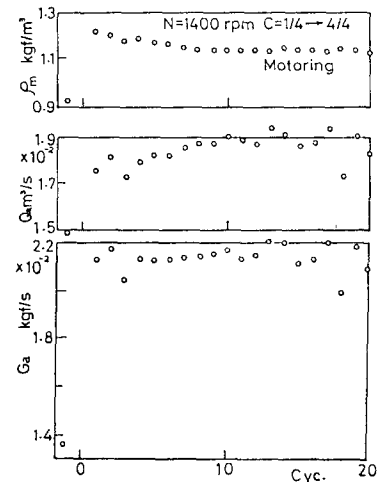Fig.15 Behaviors of G_a, Q_a and ρ_m (stepwise closed)

Fig.16 Behaviors of G_a, Q_a and ρ_m (stepwise opened)

tained, which can be calculated from the next equations:

$$\bar{\rho}m = \frac{1}{\theta_s} \int_0^{\theta_s} \frac{P}{RT} \cdot d\theta \qquad \bar{G}a = \frac{1}{\theta_s} \int_0^{\theta_s} Ga \cdot d\theta$$

In the Fig.14, $\bar{\rho}_m$ increases immediately after rapid opened throttle valve of carbureter and soon later it decreases gradually a little. On the other hand, $\bar{G}_a$ increases quickly too and reaches about a certain value with remarkably fluctuation at every cycle.

$\bar{\rho}_m$ decreases as soon as when the throttle valve of carbureter is rapid closed (Fig.15), and then it increases slightly and then $\bar{G}_a$ immediately decreases to keep a certain value.

However, $\bar{G}_a$ do not reach instantly a certain value in case of high engine speed and low temperature of engine, that is, there is response lag as shown in Fig.16.

Now, the time constant t_a calculated

from approximate $A(t)=1-e^{-t/t_a}$, that was $t_a=0.05\sim 0.06$ sec. at motoring operation and $t_a=0.025\sim 0.06$ sec. at firing operation, and these values were considerable below compared with one cycle time. Consequently, there is not necessary to consider such the response time lag of suction air amount in single cylinder IC engine.

Calculated cycle variation rate under the transient operation is shown in Table 2, which is well understood no different one of a stationary operation at a same condition.

4. CONCLUSION

The authors manufactured experimentally laminar-flow type flowmeter, spark-discharge type and tandem-type hot-wire

flow velocity meters, etc. and measured the suction air amount in crankcase compression two-stroke cycle engine. The results obtained can be summarized as follows:

(1) It is possible to measure the average and instantaneous flow quantities of suction air amount with a laminar-flow type flowmeter but if it is inserted into the suction pipe system, the measurement error can easily occur and since it damps the pulsation of air column in the suction pipe, it affects remarkably the suction air amount.

(2) Though is complicated in operation, a spark-discharge type flow velocity meter can be useful for measuring the instantaneous inflowing velocity during a suction period. It is necessary, however, to select suitable electrode form, spark discharge characteristics, etc.

(3) A tandem type hot-wire flow velocity meter makes possible to measure continuously the instantaneous flow velocity and is also directional, so that it is useful for measuring the flow velocity in suction pipe.

(4) Concerning the amount of suction air, there is no time lag of response when the carbureter is opened rapidly.

But its amount fluctuates at every cycle and every cylinder of multi-cylinder engine considerably.

REFERENCES

[1] I.Kawai, et al. : Trans. of JSME (in Japanese), 38-306,(1972),295
[2] T.Asanuma, et al. : SAE Trans. 700439,(1970),1781
[3] S.Oohigashi, et al. : Trans. of JSME (in Japanese), 34-260,(1968),750