621-347:621.318.4

A New Electromagnetic Gas Sampling Valve*

By Ichiro HIGASHINO**

A new gas sampling valve working at high speed was prepared for the study of the scavenging in a two-stroke engine, and its own performance was examined to obtain the basic data for the future design. This new valve is a kind of an electromagnetic solenoid valve, and it is actuated by passing an instantaneous heavy current into a coil that generates an inverse magnetic field against the fixed magnetic field.

The experiments were done to determine the working region of the valve, the time lag of the opening, the duration of valve opening, the volume of the sampled gas, etc.

As a result, the time lag for the opening, t_a , was about 0.5~1.0 milliseconds, the duration of valve opening, t_f , could be obtained for 1~10 milliseconds and the gas could be sampled at a rate of about 10 cc/m sec under the pressure difference of 1 kg/cm².

In an investigation of combustion or scavenging in internal combustion engines, it often happens that an instantaneous gas sampling from a cylinder at the desired time is required to make clear the details within the cylinder. Moreover, it is desirable to sample as plenty of gas as possible, because if the volume of gas is so little for analysis, there may arise a doubt that it may not represent the contents within the cylinder. For this purpose, many types of gas sampling valves have been contrived by many persons; one which is operated automatically by the internal pressure overcoming the mechanical spring force⁽¹⁾⁽²⁾⁽³⁾, and another which is operated by oil pressure, and a third using an electromagnetic solenoid valve⁽⁴⁾⁽⁵⁾. However it is a difficult matter to find a valve which can be opened for an extremely short interval and yet can sample as large volume of gas as possible without time delay at the desired time. Such a valve seems not to exist at present. Comparing the mechanical, oil-pressured and electrical types with one another, the electrical type valve seems to have a remarkable advantage with respect to time delay and easiness of controlling. A conventional electromagnetic valve is a device which actuates by a solenoid coil, and usually requires a large number of turns to produce a strong electromagnetic force, therefore it is compelled to have a large value of self-inductance. It lacks in fidelity of time response and does not satisfy a demand for high speed gas sampling. Hence, a valve which has a strong force enough to

operate fast without increasing its self-inductance is required. The electromagnetic force is proportional to the magnitude of ampere-turns, therefore it will be noted that the same effect can be expected provided the current in the coil is only increased even if the turn number is few; in other words, while decreasing the turn number of the coil, a heavy current is necessary to operate. But usually it is extremely difficult to pass a heavy current for a desired duration. Accordingly, a valve which actuates by generating instantaneously an inverse magnetic field against the fixed field was contrived. The obtained characteristics are satisfactory enough to use for the present purpose, although there exist a few points to be improved hereafter.

This gas sampling valve was applied to the investigation of scavenging in two stroke engines, and an appreciable merit was proved. The characteristic and the performance of this new gas sampling valve will be described.

1. Gas sampling valve

1.1 Principle of operation

(i) Attractive force of solenoid coil When a current I is supplied to a solenoid coil wound in N turns with an iron core, the electromagnetic attractive force P is given by

$$P \propto \mu IN \dots\dots\dots (1)$$

in which μ is the permeability of material of core; if another coil is superposed on the coil to contradict the polarity of the magnitude of IN , the force P may cancel each other, where the following equation is substantiated with ampere-turn IN

* Received 29 th July, 1960.

** Assistant Professor, Faculty of Engineering, Osaka City University, Kita-ku, Osaka.

$$IN = I_1 N_1 = I_2 N_2 = \dots \dots \dots (2)$$

in which suffixes 1, 2, ... represents arbitrary combinations with I and N .

(ii) An electromagnetic valve with a coil generating inverse magnetic field. It is necessary to reduce the valve of self-inductance of the coil for actuating an electromagnetic solenoid valve so rapidly, but the magnitude of currents to be passed into the coil amounts to a large quantity. Hence, the following valve was contrived, in which the force required to close the valve was obtained by the flowing of small, steady constant currents into the multi-turned coil (hereafter to be called a fixed field coil), and an instantaneous force required for the opening of the valve was obtained by supplying instantaneous heavy currents I_a into another coil with a small number of turns (hereafter to be

called an inverse magnetic field-generating coil) having such a winding direction as to cancel the fixed magnetic field. At this moment a magnetic attractive force is released into the void, then the valve can be free from the seat for opening by a forced spring which has previously been pulled against the fixed magnetic force.

(iii) Construction and operation of the valve

A cross sectional diagram of the electromagnetic solenoid valve which was produced on trial and its appearance are illustrated in Fig. 1. For sampling the gas with use of this valve, in the first place, a steady, constant d.c. current I_m is passed into the fixed magnetic coil A, and the valve is pushed down manually against the spring force to the valve seat to seal and to hold the internal gas pressure in the cylinder of engine. At the time when the valve is to be opened, an inverse heavy current I_a is flooded in the inverse magnetic field-generating coil B with the aid of a discharge-tube by an external trigger device, then the valve is released to open and fly away till it reaches the upper valve-seat, where the valve is sealed off again. Only the duration of the valve flight the gas sampling can be achieved. The features of the valve are listed in Table 1.

(iv) Driving unit of the valve. This gas sampling valve is wholly driven by electronic means. A steady, constant d.c. current I_m is supplied from a constant-current power supply as shown in Fig. 2. A current for generating an inverse magnetic field is fed by discharging the capacitor C_s through a Xenon-discharge-tube using a circuit as shown in Fig. 3. The Xenon-discharge-tube may be replaced by a strobo-discharge-tube SN 4 A 1; in brief, it has only to be able to endure the allowable maximum peak current. A smaller capacity of the power supply can suffice provided that the resistor R_s is chosen to have a suitable value. To drive this gas sampling valve, a trigger signal is applied to the input terminal of the circuit at the desired time for gas sampling, then the discharge-tube is fired, thereby supplying the current into the coil B.

(v) Waveforms of current in the coil B

The magnitude of the current I_a flowing into the

A: coil for a fixed magnetic field
B: coil for generating an inverse magnetic field
C: valve stem
D: nylon bushing
E: bakelite plate

(a) Construction of gas sampling valve

(b) Appearance of gas sampling valve

Fig. 1

Table 1 The features of new gas-sampling valve

Diameter of air inlet	15 mm
Stroke of piston of valve	4~15 mm
Material of magnet	Soft iron
Coil for a fixed field	0.16 mm enamele wire ×20 000 T
	d.c. resistance 4100 Ω
Coil for an inverse field	0.55×30T or 1.0×45T
Spring force	10, 20, 30, and 40 kg
(at maximum deflection)	

coil B for generating an inverse magnetic field is given as a solution of the following differential equation, denoting a current which flows in a series circuit with R , C , and L by I_a .

$$Ri + L \frac{di}{dt} + \frac{1}{C} \int i dt = 0 \quad (3)$$

With the initial condition, $i=0$ at $t=0$, and $\frac{1}{C} \int i dt = E$, one of the solutions of Eq. (3) is given by, provided $R^2 > 4L/C$ (non-oscillative)

$$I_a = \frac{E}{\gamma L} e^{-\alpha t} \sinh \gamma t \quad (4)$$

where

$$\alpha = \frac{R}{2L} \quad (5)$$

$$\gamma = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \quad (6)$$

A photograph of the waveforms of discharged current, I_a , on the screen of CRT is illustrated in Fig. 4.

In the photograph, the values of capacitors C are $1000 \mu\text{F}$, $800 \mu\text{F}$, $600 \mu\text{F}$, $400 \mu\text{F}$, and $200 \mu\text{F}$, from the upper curve, respectively. The maximum peak current reaches to about 370 amperes where

V_1 : 5Y3GT
 V_2 : 6L6G
 $V_3 \sim V_5$: Neon tubes

Fig. 2 Power supply for exciting a fixed magnet that flows a constant current

V_1 : SN4A1
 V_2 : Xenon-discharge-tube
 T_1 : pulse transformer
 L : coil B
 C_3 : capacitor for charging

Fig. 3 Circuit for discharge-tube

$C=1000 \mu\text{F}$, and the sweeping speed of time axis of CRT is $500 \mu\text{sec/cm}$.

2. Performance of gas sampling valve

(i) Attractive force of magnet Generally, the maximum peak pressure in the cylinder of internal combustion engine rises up to about several tens of kg/cm^2 , and in addition to this pressure, the valve is pulled by the spring force. It is, therefore, necessary to know the force required to close the valve tightly against the external forces. In order to find this critical pressure to keep the valve closed, a pressure is applied to the valve with use of an oil piston pump, and its critical pressure to allow releasing the valve from its seat was observed. The result is plotted against the fixed magnetic current in Fig. 5. This curve resembles closely the hysteresis

Fig. 4 Photograph shows displaying on the screen of CRT with discharging current, I_a ; was multi-photographed at $C=1000 \mu\text{F}$, $800 \mu\text{F}$, $600 \mu\text{F}$, $400 \mu\text{F}$ and $200 \mu\text{F}$ from the upper curve. Sweeping speed of horizontal axis is $500 \mu\text{sec/cm}$

Fig. 5 Relation between critical pressure and exciting current of magnet, I_m

curve of iron of magnet material. From this curve, if the applied pressure to the valve is known, the minimum fixed exciting current I_{m0} for the magnet can be decided considering the force of spring employed.

(ii) Operating region of gas sampling valve

This electromagnetic gas sampling valve is so actuated by the inverse magnetic field currents that it may not often operate when I_m is so large or I_a is so small. Also when I_m is too small, the valve is opened independently by the spring force. Therefore, there is a finite region of operating. In order to find this region, measurements were done at various conditions of I_m , of spring force, and of the capacitor for charging, and the results are illustrated in Fig. 6, in which the areas enclosed by the curve plotting the same value of spring forces represent the operating regions.

(iii) Time delay t_d for opening the valve It would be ideal that no time delay exists for opening the valve, but it would be difficult for various reasons to have no delaying time at all, while the discharge-tube is fired by a trigger pulse, wherein a delaying time of about $10 \mu\text{s}$ exists, which can be negligible since it is very small compared with t_d . Therefore, t_d was defined as the interval from

the time when a discharge current flows into the coil to the time when the valve leaves the valve-seat actually. The values of t_d under the conditions of various values of I_m , of capacitors, and of the spring forced were measured by the method as shown in Fig. 7. The results of the measurement are illustrated in Fig. 8 and Fig. 9, respectively. Since the valve is insulated from the body of magnet by two nylon bushings and a thin bakelite plate, when the valve is closed tightly on the valve-seat, it becomes conductive to the body, whereas once it leaves the valve seat, it comes to be insulated from the body; and when it reaches the upper valve-seat after the flight, it becomes conductive again to the body. Provided the current is passed between the valve and the body of magnet, a square-wave current is obtained, thereby facilitating transmission of a gating signal which permits operating an electronic counter for digital indication.

(iv) Opening time t_f of valve Apparently from the construction, the opening time t_f of the valve is defined as a time interval from the time it is released from the lower valve-seat to the time it reaches the upper valve-seat, which is equal to the

Fig. 6 Operating region of gas sampling valve

Fig. 7 Measuring method of t_d and t_f

Fig. 8 Effect of spring force on t_d and t_f

Fig. 9 Effect of exciting current of magnet on t_d and t_f

duration that the current is interrupting as above mentioned. The time t_f was measured by means of using this rectangular waveform as a gating signal thereby permitting the electronic counter to count the clock pulses, whose frequency was at 10 kc. The results are illustrated together with t_a in Fig. 8 and Fig. 9, respectively.

(v) Sampled volume of gas The sampling valve was contrived to take out a large amount of gases from a cylinder of engine during a short time interval. The ability of sampling of the valve was tested with use of air. The sampling of the air was achieved under applying the atmospheric pressure to the valve, and besides using a gas-container exhausted to vacuum. The sampled volume of the gas was defined as the volume at NTP. Under various conditions of valve stroke and of spring forces, with the value of t_f varied indirectly, the measurement was achieved. The results are illustrated in Fig. 10. The volume of the gas-container employed was 55 cc and the applicable strokes of valve were 4 mm, 6 mm, and 14 mm, respectively. It is necessary to adjust the valve and the valve seat for rubbing with oil completely to keep them in vacuum tight condition. A nylon bushing would be useful for this purpose. It has to be noticed that the gas entering into the sampling container is a part of sampled gas, and the rest remains in the valve. This residual gas amounted to 24 cc in volume. This matter will be further discussed later.

(vi) Bouncing of valve At the moment, when the valve closes in collision with the upper valve seat, the former often bounces; this is an elastic collision. The circumstances are shown in Fig. 11, in which twice or more times bouncings are observed. However often it may bounce, if it is pressed tightly to the valve seat by the spring force,

Fig. 10 Sampled volume of gas by sampling valve versus opening time of the valve

the lift of the bouncing would be so small that it would be damped soon. But this phenomenon cannot be neglected when the spring force is weak, for the sampling period is effectively prolonged by just the duration of the bouncing. If the sampling interval is restricted, it would be unfavourable. For instance, in the case of the sampling of the gas after combustion in the cylinder of a 2-stroke engine, the sampling has to be completed before the exhaust port will be opened, therefore, it has to be completed very early in consideration of the bouncing, which leads to the restriction of the outlet volume of the sampled gas.

3. Consideration

(i) Time delay of opening Two reasons are conceivable for the fact that the value of time delay amounted to a larger one than had been expected. One of them is a friction which is caused by a plenty of sticky greases squeezed along the stem of the valve to reduce a leakage of gas, and by the tight nylon bushing. The other reason is by the discharge of the current in the coil B for generating an inverse magnetic field. In the former case, the friction can be reduced to a minimum consistent with leakage prevention, or the leaking air may be exhausted all the time by a vacuum pump through a small drilled hole at the space along the stem of the valve. In the latter case, considering the discharge current given by Eqs. (4), (5), and (6), it is necessary that the self-inductance L and the resistance R of the coil B should be made small in order to get a fast rise time. The wire used at first in the coil was a double silk enamel wire of 0.5 mm diameter, lately it was replaced by a cotton wire of 1.0 mm diameter, by which the delay time was reduced to 0.5~1.0 m sec. Consequently, it is concluded that the thicker wire is better than the thinner one in the coil B. When the discharge current was flooded into the coil B, it was found that a current was generated due to the principle of transformer so as to increase the exciting current I_m in the fixed magnetic field coil A, whose waveform was shown in Fig. 11, in which its peak

$I_m = 20 \text{ mA}$, $C = 1000 \mu\text{F}$, spring force = 20 kg

Fig. 11 A typical record of transient character of fixed exciting current of magnet, I_m

current amounted to 108 mA for $I_m = 20$ mA. At this time, the force required to separate the valve from the seat reaches a magnitude of 135 kg i.e., about 3.4 times that of the case when $I_m = 20$ mA. This effect makes the valve hard to release from the valve seat. Considering the waveforms of I_m in Fig. 11, it is clear that the waveform consists of two components as shown in Fig. 12. The curve I represents the transient waveform of I_m when the heavy current I_a is discharged into the coil B with a motion of released valve, and the curve II represents the waveform of I_m when only the current I_a is discharged without any motion of the valve. Therefore, the curve III is obtained as the difference of both curves of I and II. The curve III is regarded as a current generated by the motion of the valve. In other words, the current I_m was compelled to have a transient and increased value owing to the flow of a discharge current in the coil and to the motion of the valve. Consequently, this leads to an undesirable result, contrary to the expectation of reducing the time delay to a minimum value. But this trouble may be avoidable, provided the current I_m will be cut off at the same time when the discharge current I_a begins to flow. The value of t_d can be decreased by increasing the spring force, while it seems to be not affected by varying the magnitude of current I_a . There may be no objection to which t_d is determined uniquely under certain operating conditions; since the necessary value of capacitor C is mechanically determined, if the spring force and the current I_m are decided.

(ii) Duration of the opening the valve In considering the time of opening and closing the valve which determines the sampled volume of gas, in the first place, a dependency of t_f upon the stroke length of the valve was studied, with the results as illustrated in Fig. 13, in which the case of 20 kg of spring force is shown. It is observed that the spring force is predominant up to the value of t_f ,

Fig. 12 Analysis of the transient current I_m

and the stronger the force, the shorter the value of t_f becomes. Under certain operational conditions, the values of I_m , and of spring force, and the magnitude of the capacitor C are determined uniquely as mentioned before, consequently the factor predominant up to the value of t_f is only the stroke length of the valve. Apparently from Fig. 13, the valve is not moving with constant speed, because it is always being pulled by a spring, and the motion is given by the solution of the following differential equation. Denoting the mass of the movable part of the valve by M , the spring constant by K , and the friction along the stem of the valve by rx , one obtains

$$M\ddot{x} + r\dot{x} + Kx = 0 \quad (7)$$

Assuming $x = x_0$, $\dot{x} = 0$, at $t = 0$, and

$$n = \sqrt{\frac{K}{M}}, \quad k = \sqrt{\frac{r}{2M}} \quad (8)$$

in this case generally, $|k| < n$

$$x = x_0 e^{-kt} \left\{ \cos \sqrt{n^2 - k^2} t + \frac{k}{\sqrt{n^2 - k^2}} \sin \sqrt{n^2 - k^2} t \right\} \quad (9)$$

From Eq. (9), the velocity and the acceleration are given, respectively, by

$$\text{velocity: } \dot{x} = -\frac{n^2 x_0}{\sqrt{n^2 - k^2}} e^{-kt} \sin \sqrt{n^2 - k^2} t \quad (10)$$

acceleration:

$$\ddot{x} = \frac{n^3 x_0}{\sqrt{n^2 - k^2}} e^{-kt} \sin \left(\sqrt{n^2 - k^2} t + \tan^{-1} \frac{\sqrt{n^2 - k^2}}{k} \right) \quad (11)$$

If k is small, $n = \sqrt{\frac{K}{M}}$ is most predominant;

therefore if k is once determined, there is no means but to reduce the mass of the valve as far as possible. Duralumins or titanium alloys may be

Fig. 13 Plot of the stroke of the valve versus the opening time of the valve, t_f

suitable for the purpose.

(iii) Quantity of sampled gas In this case, the quantity of gas obtained actually in the sampling container has to be distinguished from the one sampled out of the cylinder. In an ideal case, both will be identical, but in practice they are not identical as there exists a dead space inside the valve. Denoting the volumes of sampled gas, of sampling container, and of dead space by V_e , V_s , and V_d , respectively, the efficiency of sampling, η , is given by, assuming the temperature is constant,

$$\eta = \frac{V_s}{V_e} = \frac{1}{\left(1 + \frac{V_d}{V_s}\right)} \cdot \frac{p_e}{p_s} \quad (12)$$

in which p_e is the pressure of the gas sampled, and p_s the one in the sampling container after the sampling has been completed. Apparently from this equation, the smaller the value of V_d/V_s the better the efficiency becomes, so it is necessary that V_s should be as large as possible, otherwise at large values of V_e , it will be saturated as shown in Fig. 10 when V_s is small.

The effective cross sectional areas of the passage for gas while the valve is opening is calculated numerically with actual valve and the result is illustrated in Fig. 14, in which the varied strokes are plotted as parameters. If the stroke-length is small, as the backside of the valve approaches to the upper valve seat, the valve soon begins to close before it will be thoroughly opened. Evaluating on this stroke-cross-sectional area with actual dimensions, Fig. 15 was obtained. From the diagram, it was found that these areas were so small at the beginning of the valve opening. Consequently, the volume of sampled gas dose not show a linear proportion to the change of the stroke length.

Fig. 14 Relation between the stroke and the opening areas

4. Conclusion

From the results of the tests, the characteristics of this new gas sampling valve has been made clear as follows:

(1) The valve is actuated as desired, but the operation is limited within a certain region, which is determined by the values of the spring force, of the current I_m , and of the capacity for the discharge-tube.

(2) Even if the value of the current I_m for fixed magnetic field is varied, the time delay t_d is scarcely affected. However, it can be decreased a little provided the spring force is increased.

(3) The duration of the opening of the valve t_f can be prolonged if the value of I_m is increased, while it is decreased if the spring force is increased.

(4) When the discharge current I_a is supplied into the coil B, a transient current is generated in I_m such as the increased value of I_m , and an effect of increasing the value of t_d arises. In order to prevent this effect, the following methods would be considered.

(a) A controlling system should be prepared, in which the current I_m is abruptly switched off at the same time when the current I_a is discharged.

(b) A permanent magnet is provided for exciting a fixed magnetic field, but in this case, an adjustment of the magnetic field is impossible and the magnet is exposed to a risk of demagnetization.

(5) Concerning the volume of the sampled gas, it would be better to employ as large a container as possible. The flow-rate is approximately 10 cc per

Fig. 15 Relation between the stroke and the stroke $\times$ areas

1 millisecond, under the pressure difference of 1 kg/cm². Under the larger pressure difference, the more volume of gas will be sampled. The sampling may be more effective provided the cross-sectional area of the gas passage is widened.

The intended purposes were accomplished on the whole, although some problems remain to be discussed.

The author wishes to express his gratitude to Professor S. Ohigashi of Osaka City University for suggesting this study as well as for constant guidance in the course of the work. Thanks are also due to

Mr. M. Kitao for his in testing, and to Shinmitsubishi Heavy-Ind. Co. and Daihatsu Ind. Co. for materials and technical assistance in making the gas sampling valve.

References

- (1) A. Naegel: *VDI-Z*, Bd. 67 (1923), S. 733.
- (2) J. W. Drinkwater and A. C. Egerton: *Proc. Inst. Mech. Engr.*, Vol. 138 (1938), p. 423.
- (3) C. F. Taylor and A. R. Rogowski: *SAE Trans.*, Vol. 62 (1954), p. 486.
- (4) I. Hamabe and F. Nagao: *Trans. Japan Soc. Mech. Engrs.*, Vol. 3, No. 13 (1937), p. 313.
- (5) W. J. Levedahl: *Autom. Engr.*, Vol. 49 (1959), p. 381.

621. 928. 3:66. 067. 5:620. 168. 336

The Free-Running-Type Equilibrium Ultracentrifuge*

By Yasuyuki GOTO**, Yuji MIYAZAWA***,
and Takuro SUDO****

The construction of a free-running-type equilibrium ultracentrifuge is reported in this paper. A centrifuge rotor, made of steel, weighing about 12 kg, is suspended magnetically in the vacuum chamber, the pressure of which is less than 10^{-5} mmHg, and its position is controlled automatically. Acceleration of the rotor to operating speed and braking of the running rotor are done by the driving motor whose shaft is connected to the rotor by a stainless steel rod. During the sedimentation experiment, the rod is disconnected from the rotor and then the rotor is kept running freely by its own moment of inertia. The sedimentation is observed with either a Rayleigh interferometer or a Schlieren optical system. Experiments on molecular weight determinations of digitonin gave good results.

1. Introduction

In the fields of physical chemistry and biology, the ultracentrifuge study is recognized as one of the most valuable methods for measuring the molecular constants of solute molecules. There are two ways of approach⁽¹⁾⁽²⁾, that is, 1) sedimentation velocity method, and 2) sedimentation equilibrium method. Sedimentation velocity method is carried out in a strong centrifugal field in order to make the solute molecules sediment rather fast. Molecular weight of solute molecules is calculated from the sedimentation constant using the theoretical formula based on hydrodynamics. Comparing the sedimentation

velocity method with the sedimentation equilibrium method, the latter has the advantage of being able to measure molecular weights of substances having relatively low molecular weights in a rather weak field of centrifugal force. Despite this advantage of the sedimentation equilibrium method, however, the sedimentation velocity method is used in many cases because of the speed of the measurement. Further reason is the many difficulties mainly involved in the stabilized rotation of ultracentrifuge rotor and the temperature control of the testing solution over a long period. To overcome these difficulties, Beams and his colleagues⁽³⁾ proposed a new type ultracentrifuge with a magnetically suspended rotor in a vacuum.

In this paper, the construction of a new well-improved sedimentation equilibrium ultracentrifuge of magnetic suspension type is reported as well as some experimental results obtained with this ultracentrifuge.

* Received 30th November, 1959.

** Research Fellow, Hitachi Central Research Laboratory, Kokubunji, Tokyo.

*** Postgraduate, Faculty of Science, Tokyo Kyoiku University.

**** Chief Research Fellow, Hitachi Central Research Laboratory.