A Study on the Exhaust System of the Internal Combustion Engine

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Abstract

In this paper, the relation between the back pressure and the length of the exhaust pipe of small internal combustion engines was studied, and it was ascertained that the value of the back pressure (i.e. the reading of the manometer) could be shown by a fluctuating curve of a definite pattern in accordance with the length of the exhaust pipe.

Introduction

Many papers[1)–7)] have been published regarding studies on the dynamic effect of pipe systems of internal combustion engines. Most of them are studies on the suction pipe effect, but those on the exhaust pipe effect are comparatively few.

In this study, by placing importance on the characteristics of the pressure waves and back pressures at the entrance of the exhaust pipe, and taking hundreds of wave photographs, it was confirmed that the characteristic curves of the back pressure which were obtained in accordance with JIS D 1002 or 1003 show a certain pattern of fluctuation. The physical meaning of the generation mechanism of fluctuation, which was not clear, has been studied. Moreover, an interesting conclusion regarding the characteristics of output fluctuation is given.

Experimental Apparatus and Procedures

Engine Specifications Two kinds of single cylinder engines are provided, one of them being a small sized air cooled 4-cycle gasoline engine for agricultural use and the other a crank case scavenging type air cooled 2-cycle gasoline engine for motorcycles.

The specifications of these engines are shown in Table 1 and the experimental apparatus is shown in Fig. 1. The experimental apparatus consists of a suction pipe system, a test engine, an exhaust pipe system and a power transmission system. Since the main points of this experiment are on the exhaust pipe system, the choke valve and the throttle valve of the carburettor are adjusted

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Table 1. Specifications of the engines

Engine		Engine A	Engine B
Cycle		4-cycle	2-cycle
Bore × Stroke, mm		$75\phi \times 65$	$45\phi \times 50$
Stroke volume, cc		287	79
Compression ratio		5.8	6.7
Rated horse power		5 PS/3600 rpm	6.9 PS/7000 rpm
Suction	S.O	19°	59°
(Scavenging)	S.C	75°	59°
Exhaust	E.O	63°	73°
	E.C	35°	73°

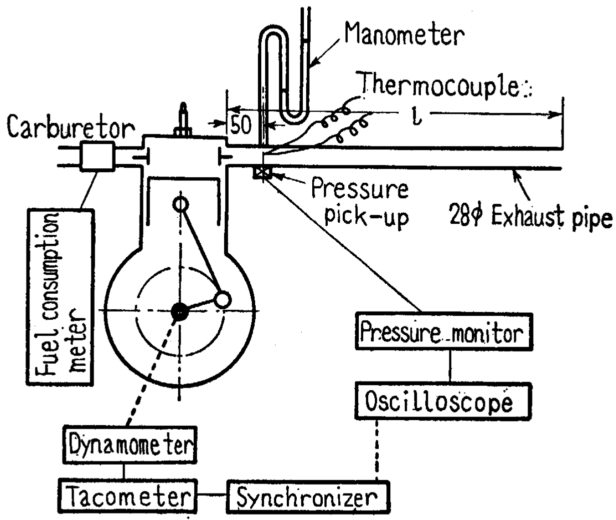


Fig. 1 Schematic diagram of experimental equipment

to be fully open in order to minimize the effect of the suction pipe system. An electrical dynamometer is provided as the driving motor for a motoring test and as the load for a firing test.

Determination of Pressure and Temperature of Exhaust Gas The determination of the back pressure is made at the point 50 mm in the direction of the exit port from the exhaust manifold fitting flange, with a 5 mm (I. D.) U-tube manometer for measuring static pressure. Determination of the exhaust gas temperature is made by an almel-chromel thermocouple at the same point mentioned above.

Photography of Fluctuating Pressure Wave In order to investigate the fluctuation of the pressure wave, a resistance wire type low pressure pick-up, (manufactured by Kyowa Dengyo), is installed at a position 50 mm from the entrance of the exhaust pipe, and oscilloscopic observation and photography are used.

The inner diameter of all the exhaust pipes is 28 mm.

Method of Experiment The length of the suction pipe system, with a carburetor attached within it, is kept minimum and, in order to eliminate the charging gas throttle effect, the throttle valve is set to "full-open." The length of exhaust pipe is extended up to 13 m in intervals of 0.2 m.

The range of the revolving speeds of engine A is from 2000 rpm to 3800 rpm, 5 steps in between, and strict adjustment is made so that the revolution may be constant. For engine B, two kinds of speeds are adopted. The determinations of fuel consumption, exhaust gas pressure, pressure fluctuation and gas temperature inside the exhaust pipe are made simultaneously, and analysed by a data recorder.

Special attention is paid to processing the connecting parts of the exhaust pipe so that no gas leak will occur.

Characteristics of Back Pressure Fluctuation by Changing the Length of the Exhaust Pipe

It is assumed that the back pressure observed on the manometer increases due to the frictional resistance of the gas flow when the length of the exhaust pipe is increased gradually.

However, under constant engine operating conditions, the values of the back pressure and brake output fluctuate with the length of the pipe. In this section, a theoretical and experimental study on the characteristics of back pressure is described.

Fig. 2 shows an example of the fluctuation of back pressure affected by an increased length of straight exhaust pipe of engine A (4-cycle) under constant engine speed and motoring operation. The engine speeds are 2000 rpm and 3600 rpm.

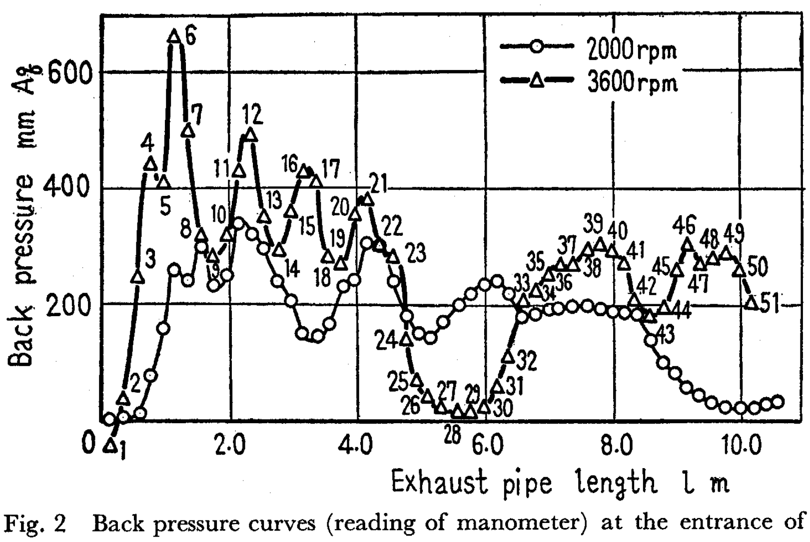


Fig. 2 Back pressure curves (reading of manometer) at the entrance of the exhaust pipe of engine A (Motoring)

As shown in this figure, the characteristic curves of the back pressure affected by changing the revolution are comparatively similar in shape. It is observed from the curves that a pipe length exists at which the back pressure shows an extremely low value. A similar tendency, with regard to engine B (2-cycle), is also recognized.

The cause of back pressure fluctuation resulting from the extension of the exhaust pipe is presumed to be a wave phenomenon; i.e. due to the pressure wave periodically being exhausted from the cylinder of the engine to the exhaust pipe, and its reflecting wave. Changing the pipe length under constant revolution causes a variation in the reflection intervals, and in Fig. 2 it is presumed that the greater the revolving speed, the farther the tendency of fluctuation of back pressure characteristic moves toward the shorter side of the pipe length, i.e. toward the left side. From this fact, it is presumed that a certain relation between the engine revolution (corresponding to the exhaust interval) and the pipe length exists, and also, that the fluctuation of back pressure at an optional length of the pipe and engine revolving speed is regulated by a certain parameter.

A Study of Physical Meaning of Characteristic Curves of Back Pressure Fluctuation and Parameter

It is presumed that the back pressure fluctuation is caused by the interference of the pressure wave in the pipe, and a further detailed study made on this point. In order to make the analysis of the phenomenon easier, a straight exhaust pipe is taken into consideration and a study is made on the motoring operation of a 4-cycle engine (engine A) with poppet valves.

The gas in the cylinder flows out from the valve as the valve opens and generates a pressure wave which makes a round trip inside the exhaust pipe.

Since the exhaust pipe end opens into the atmosphere, this can be treated as an open pipe, but as for the exhaust valve side, there remains a problem of whether the part is to be considered as an open pipe or a closed pipe, because the situation differs according to each case. In studying the wave phenomenon in the exhaust pipe, two cases, separating the cylinder part from the exhaust pipe part, can be considered. In the first case the cylinder part is considered also to have an effect upon the back pressure during the opening period of the exhaust valve, and during the closing period only the exhaust pipe is taken into account. In the second case the pressure fluctuation is considered to develop only in the exhaust pipe, neglecting the effect of the cylinder part, and regarding the exhaust valve part as a closed pipe all the time.

In the first case, with the exception of the latter part of the opening period of the exhaust valve, the negative pressure wave reflected from the end of the exhaust pipe, reflects from the cylinder wall keeping its state as a negative pressure wave and propagates to the end of the pipe through the valve part, when the exhaust valve is open. When the exhaust valve is closed, the negative pressure wave is reflected at the valve part and propagates toward the end of the pipe. Therefore, these negative pressure waves pass through the measuring point of back pressure, twice. The case of a positively reflected pressure wave can also be treated similarly.

However, when a negatively reflected pressure wave returns at the latter part of the opening period of the exhaust valve, the negative pressure wave passes through the measuring point of back pressure only once, since the exhaust valve closes immediately after the negative pressure wave is delivered from the valve part into the cylinder. In this case, the negatively reflected pressure almost overlaps the blow down positive pressure wave, so that the back pressure does not decrease very much. When the positively reflected pressure wave returns at the latter part of the opening period of the exhaust valve, the back pressure does not rise very much.

In the second case, the pressure wave p generated by combining two pressure waves p_i and p_r, for the case of the air, conforms to the expression below, (F. J. Wallence, F. K. Bannister, etc.)[8)]

$$\left(\frac{p}{p_0}\right)^{1/7}=\left(\frac{p_i}{p_0}\right)^{1/7}+\left(\frac{p_r}{p_0}\right)^{1/7}-1 \qquad \cdots\cdots\cdots(1)$$

where p_0 denotes the atmospheric pressure.

If the pressure wave interferes linerarly, the combined pressure p should conform to the expression:

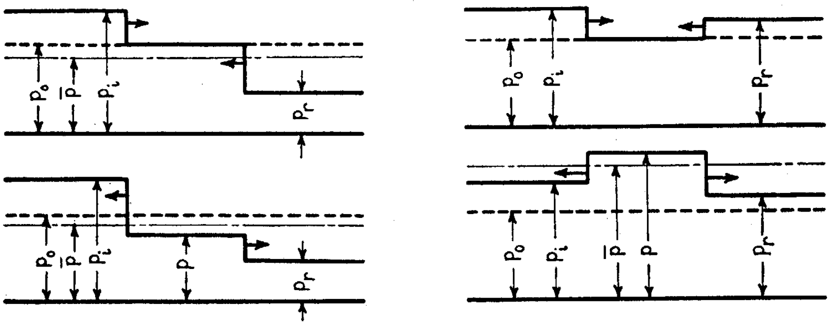
$$\left(\frac{p}{p_0}\right)=\left(\frac{p_i}{p_0}\right)+\left(\frac{p_r}{p_0}\right)-1 \qquad \cdots\cdots\cdots(2)$$

When the composition of the pressure wave conforms to the expression (2), it is obvious that the back pressure fluctuation is not generated by an increased length of the exhaust pipe.

In motoring operations of the engine, expressing the exhaust blow down pressure p_i and reflected pressure p_r, the relations of both pressures are expressed as $p_i < p_0$, and $p_r < p_0$, when the negatively reflected pressure wave overlaps the blow down pressure. In this case, $p < \bar{p}$ is as shown in (a) of Fig 3.

According to the characteristics of back pressure, by extending the length of the exhaust pipe during motoring operation, at the length of the exhaust pipe where the negatively reflected pressure overlaps with the blow down pressure, the pressure shows a lower value than in the case where these pressures do not overlap: as a result, a lower back pressure is observed. At a length of the exhaust pipe where the positively reflected pressure overlaps with the blow down pressure, the pressure shows a higher value than in the case where these pressures do not overlap: as a result, a higher back pressure is observed.

The exit part of the exhaust pipe of the engine may be regarded as an open pipe, but at the exhaust valve part the flow resistance caused by the throttle effect is very large. Especially in the case of a small sized engine with its long



(a) $p_i > p_0$ $p_r < p_0$ (b) $p_i > p_0$ $p_r > p_0$

Fig. 3 Compound of pressure waves

exhaust pipe, the valve part may be refarded as a closed pipe even when the exhaust valve is open. (This is confirmed by the air model engine which is described in a later section).

The positive pressure wave developed in the exhaust pipe by blow down, turns into a negative pressure wave when the number of oscillations in the exhaust pipe is odd, and it remains a positive pressure wave when the number of oscillations is even. If the water manometer reading for measuring the back pressure shows the mean pressure inside the exhaust pipe correctly, the manometer shows a lower value at the length of the pipe where the pressure wave that makes an odd number of oscillations in the exhaust pipe synchronizes with the blow down pressure. At a length of the pipe where the pressure wave that makes an even number of oscillations in the pipe synchronizes with the blow-down pressure, the manometer show a higher value. However, in the case when the reflected pressure wave returns immediately before the exhaust valve closes, the phenomenon somewhat differs for the above-mentioned reason.

Now let τ_{rm} be the time taken, for travelling m times by the pressure wave which is developed at the entrance part of the exhaust pipe (valve part) by the exhaust blow-down, then τ_{rm} may be expressed as:

$$\tau_{rm} = m(2l/c) \qquad \cdots\cdots\cdots(3)$$

where l is the length of the exhaust pipe, c is the mean pressure propagating velocity, and m is a positive integer.

Let τ_{Nn} be the time from the beginning of the exhaust, τ_{Nn} may be expressed as:

$$\tau_{Nn} = n(60i/N) \qquad \cdots\cdots\cdots(4)$$

where N is the rpm of the engine, n is a positive integer and i is 1 for the case of a 4-cycle engine and 2 for a 2-cycle engine.

Now, in the case where the exhaust blow-down pressure, just having completed one round trip, synchronizes with the ensuing blow-down pressure; i.e. $m=1$ and $n=1$, and making the ratio between τ_{r1} and τ_{n1} as ξ, it may be expressed as follows:

$$\xi = \frac{Nl}{30ic} \qquad \cdots\cdots\cdots(5)$$

Now, making the ratio between the time $2(2m-1)l/c$, the period the negative pressure wave returns from the first exhaust blow-down, and the period of the exhaust blow-down n $(60\ i/N)$ as $\xi_{2m-1,\ n}$,

$$\xi_{2m-1,\,n} = \frac{2m-1}{n}\ \frac{Nl}{30ic} \qquad \cdots\cdots\cdots(6)$$

and when $2m-1$, n is 1, the value on the back pressure curve should show lower extremes.

Making the ratio between the time $4m\ l/c$, the period of the positive pressure wave returns from the first exhaust blow-down, and the period of exhaust blow-down as $\xi_{2m,\ n}$,

$$\xi_{2m,n} = \frac{2m}{n}\ \frac{Nl}{30ic} \qquad \cdots\cdots\cdots(7)$$

When $\xi_{2m,\ n}$ is 1, the value on the back pressure curve should show higher extremes. Substitution of *Eq.* (5) into these equations results in the back pressure to show the lower extremes when $\xi_{2m-1,\ n} = (2m-1)\xi/n = 1$,

that is
$$\xi = \frac{n}{2m-1} \qquad \cdots\cdots\cdots(8)$$

and the back pressure to show higher extrems when

$$\xi_{2m,}n = 2m\xi/n = 1$$

that is
$$\xi = \frac{n}{2m} \qquad \cdots\cdots\cdots(9)$$

where the denominator is the number at compleie oscillations of the pressure wave in the pipe, and the numerator is a positive integer that indicates the number of exhausts.

From this fact, it is pressumed that the curve of the back pressure will show lower extremes when ξ is an integer multiple of one over an odd number, and that it will show higher extremes when ξ is an integer multiple of one over an even number. The effect, however, will decrease as the numbers m and n increase.

Regulation by Parameter ξ

Four Stroke Cycle Engine Fig. 4 shows the result of regulation of Fig. 2 by using the parameter ξ described in the preceding section. It is evident that the fluctuation curves coincide at any number of revolutions. It is also understood from the curves that the minimum value of back pressure occurs at the position $\xi \doteqdot 1$ where the negatively reflected pressure wave of the first order in the exhaust pipe synchronizes with the blow-down pressure.

Fig. 5. shows the photographs of the pressure fluctuation waves shown in the

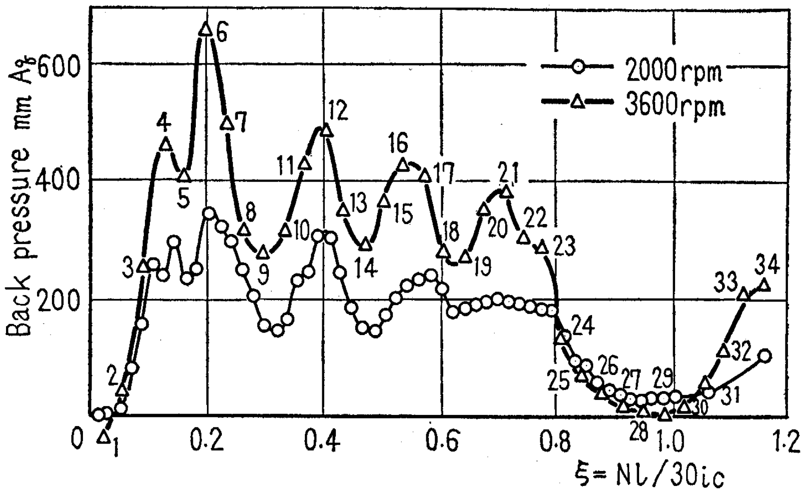


Fig. 4 Back pressure curves regulated by parameter ξ

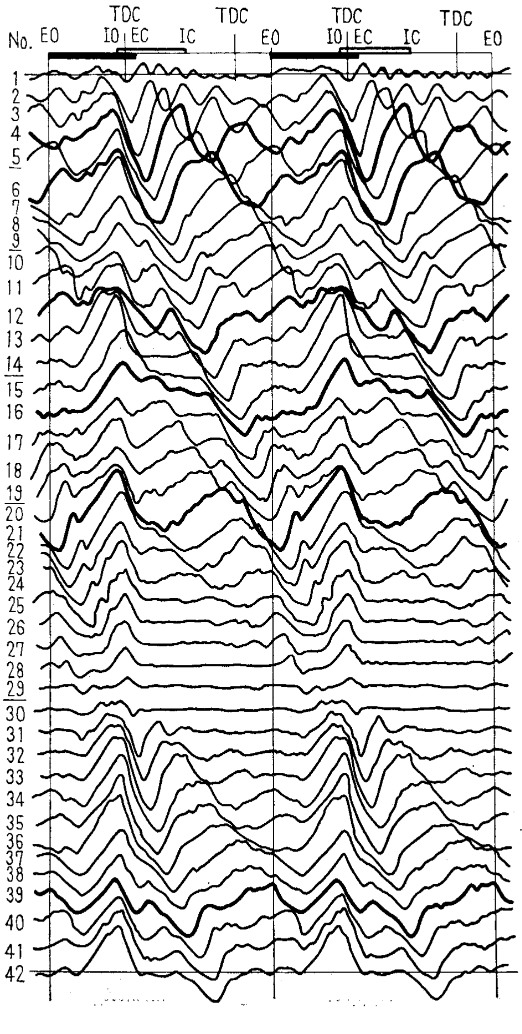


Fig. 5 Pressure waves at the entrance of the exhaust pipe of engine A (Motoring, 3600 rpm, Figs. 2 and 4)

form of a line diagram, at the entrance of the exhaust pipe, at 3600 rpm in Fig. 4. (The numbers in Fig. 5 are identical with those in Fig. 4)

Wave No. 29 is the case for which the first negatively reflected pressure wave, having completed 1 complete oscillation in the exhaust pipe, synchronizes with the blow-down pressure wave, and the amplitude of the pressure wave becomes very small. In this case, the back pressure shown in Fig. 4 is very low as indicated in the preceeding section. Wave No. 9 is the case for which the third negatively reflected pressure wave synchronizes with the blow-down pressure ($\xi \doteqdot 1/3$), and the back pressure in Fig. 4 is very low. Wave No. 19 ($\xi \doteqdot 2/3$), is also low. In the case of wave No. 5, the negative pressure wave that mekes 5 complete oscillations in the exhaust pipe, overlaps the blow down pressure ($\xi \doteqdot 1/5$), when observations of the preceding and following waves are made. In wave No. 4, $\xi \doteqdot 1/6$, the back pressure is higher, as the 6th positively reflected pressure wave overlaps the blow-down pressure. In wave No. 6, the back pressure is higher because the 4th positively reflected pressure wave overlaps the blow-down pressure. In waves No. 12 to No. 15, the 2nd possitively reflected pressure wave synchronizes with the blow-down pressure, and it is expected that the back pressure becomes higher, but, on the contrary, the back pressure does not become higher and it shows a lower value around $\xi \doteqdot 1/2$. In this case, the positive pressure wave synchronizes with the exhaust blow down wave, the negative pressure wave synchronizes simulatneouly with the exhaust blow down wave, and the fluctuation of the pressure wave shows a large change. It is supposed that this phenomenon includes a atransitional response problem of the manometer for measuring the back pressure; this problem

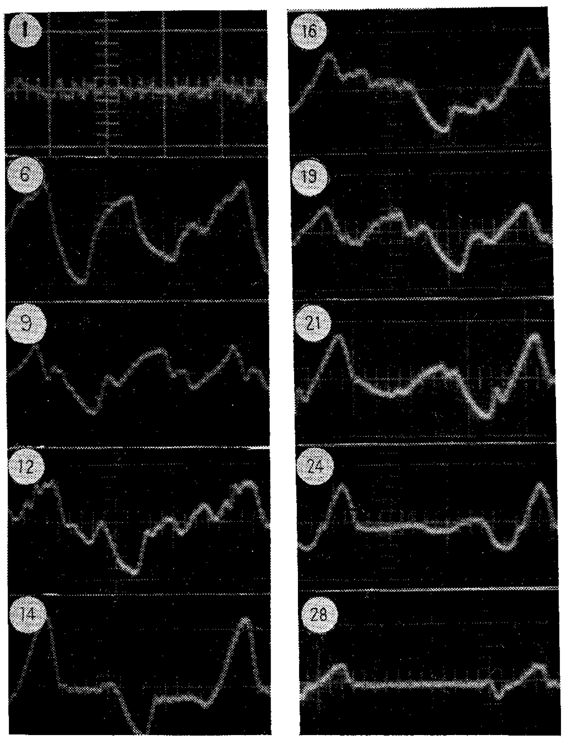


Fig. 6 Pressure wave photographs of Fig. 5

will be discussed in the following section. Considering the effect of the valve part, in addition, it seems that the 2nd positively reflected pressure wave returns immediately before the exhaust valve closes at wave No. 14.

The above-mentioned explanation is about the pressure fluctuation waves at 3600 rpm in engine A, and a similar explanation may be given for the case of the engine speed being changed. This experiment is carried out under the following conditions; installation of the carburettor at the minimum length on the suction system, setting the choke and throttle valves full-open, and keeping the number of revolutions within the range ± 5 rpm.

Fig. 6 shows the photographs of the pressure fluctuation wave in the exhaust pipe shown in Fig. 5.

Pressure Wave Propagating Velocity In relation to the explanation in the previous section that the value of back pressure due to changing the length of the exhaust pipe can be regulated using the dimensionless parameter, a discussion of the pressure wave propagating velocity c is given below.

Let p_1 and a_1 denote the pressure and sound velocity before the pressure wave passes, p_2 the pressure after it passes and κ the ratio of specific heat, respectively. The pressure wave propagating velocity c is given approximately by the following equation:

$$c=\sqrt{\left(\frac{1}{2\kappa}\right)\left[(\kappa-1)+(\kappa+1)\frac{p_2}{p_1}\right]}\,a_1 \qquad \cdots\cdots\cdots(10)$$

The value of sound velocity in the pipe is generally given by the following equation,[9]

$$a=332\sqrt{1+\frac{t_m}{273}}-\frac{0.8}{d} \qquad \cdots\cdots\cdots(11)$$

where, t_m is the temperature of the exhaust gas and d is the diameter of the exhaust pipe. In the case where, $p_1=p_2$, the pressure wave propagating velocity coincides with the sound velocity. Difficulties have been met in carrying out the experiment using Eq. (10), because the pressure p_1 and p_2 in the pipe and the gas temperature t_m are to be measured at various points of the exhaust pipe. Eq. (11) being derived from the experiment on the motoring operation, might not be suitable for high temperature exhaust gas.

As the temperature of the exhaust gas in the pipe reaches a very high value in the case of firing operation and the temperature reduction varies remarkably with the length of the pipe, the value cannot be calculated accurately. The calculated value of the sound velocity in the exhaust gas is liable to be in error according to the conditions, as Koizumi indicated, in the method calculating from the mean gas temperature.[10] In this paper, therefore, the mean pressure wave propagating velocity is calculated using the returning time of the 1st negative pressure wave from the exhaust blow-down, by investigating the figure of the pressure wave at the entrance of the exhaust pipe with the various lengths of the pipe, instead of using Eqs. (10) and (11).

Fig. 7 shows the returning time of the 1st negative pressure wave of engine A, in motoring and firing operation. When the revolving speed of the engine varies, the quantities of gas flow vary and this causes a variation of flow velocity in the pipe; especially in firing operations, the temperature in the pipe varies due to the combustion mechanism, and as a result the pressure wave propagating velocity varies remarkably.

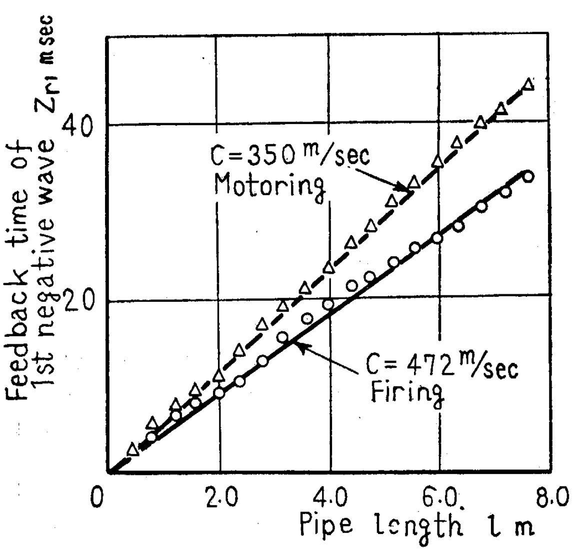


Fig. 7 Feedback time of the first negative pressure wave

Two-Cycle Engine An explanation is made in the preceding section of the regulation of back pressure in the range of $\xi \leqq 1$. Now, an investigation is made on the case, $\xi > 1$. A 2-cycle engine B is provided for the test.

Fig. 8 shows the characteristic curve of the back pressure which is regulated by a parameter when the engine speed is kept constant at 6170 rpm under the varied length of the exhaust pipe. The measurement is made by setting the throttle valve to full-open, the same as engine A. In this case, too, the phenomenon of the back pressure fluctuation distinctly shows a similar pattern.

The calculation of the pressure wave propagating velocity, in this case, is made by using the pressure wave photograph as described in the preceding section.

At the points $\xi \fallingdotseq 1$, 2, 3, 4, 5 and 6 in Fig. 8, the back pressure shows the lowest values. This is due to the fact that the first negatively reflected wave overlaps the exhaust blow-down pressure, and this is in agreement with the theory described in the preceding sections. The reason why the back pressure shows a lower value at the midpoints i.e. 1/2, 3/2, and 5/2 is that the exhaust port closes immediately after the entrance of the first positively reflected wave into the cylinder. The explanations for these is already given.

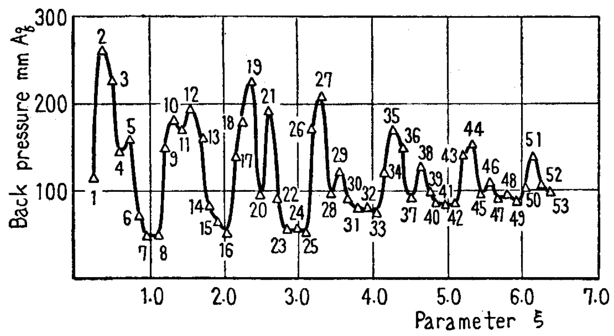


Fig. 8 Back pressure curves of engine B regulated by parameter ξ (Motoring, 6170 rpm, $0< \xi <6.5$)

Fig. 9 shows a detailed fluctuation of back pressure in engine B in the region $\xi<2$. The figure shows an excellent coincidence of fluctuations at different speeds.

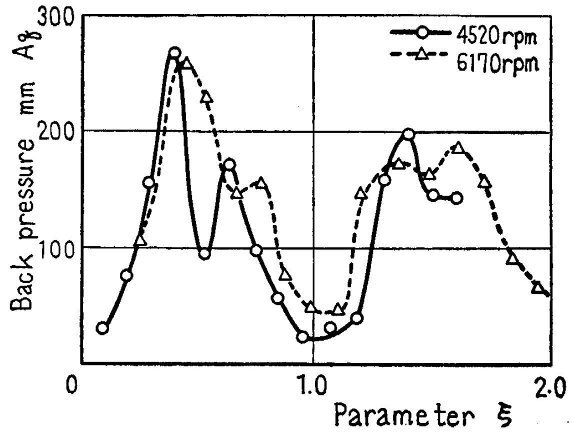


Fig. 9 Back pressure curves of engine B regulated by parameter ξ (Motoring, 4520 and 6170 rpm, $0<\xi<2$)

Characteristics of the Manometer for Measuring Back Pressure

As described above, the characteristic curves of the back pressure of engines A and B can be regulated by using the dimensionless parameter ξ, and the physical meaning of the fluctuation is clarified. However, on further inspection of Fig. 4, it is found that the value of back pressure in the vicinity of $\xi \doteqdot 1/2$ is actually low, despite the fact that it should be high as described in 5.1. This is considered to be caused by the exhaust valve, cylinder and the characteristics of the manometer described below.

Let us make an inspection to see how the pressure fluctuates at the entrance of the exhaust pipe in the manometer for measuring the back pressure. The equation of motion of the manometer, if the compression vibration of the air in the pipe neglected is in general, expessed as follows:

$$\frac{\gamma A l_1}{g}\frac{d^2x}{dt^2}+\frac{8\mu l_1 A}{r^2}\frac{dx}{dt}+2\gamma Ax=Ap(t) \qquad \cdots\cdots\cdots(12)$$

where

A=the sectional area of U-tube,
r=the inner radius of U-tube,
l_1=the height of the water column,
μ=the coefficient of viscosity of water,
γ=the specific weight of water,
t=the time,
$p(t)$=the pressure fluctuation at the entrance of the exhaust pipe,
g=the acceleration due to gravity.

In solving the linear differential equation (12), the displacement of water head from the balanced position of pressure, i.e. the value $x(t)$, is expressed by the following equation.

$$x(t)=\frac{W_n}{2\gamma\sqrt{1-\zeta^2}}\int_0^t e^{-\zeta W_n(t-s)}\{\sin W_n\sqrt{1-\zeta^2}(t-s)\}p(s)ds \quad \cdots\cdots\cdots(13)$$

where

$$W_n=\sqrt{2g/l_1},\quad \zeta=R/2\sqrt{M\kappa},\quad \kappa=2\gamma$$
$$R=8\mu l_1/r^2,\quad M=\gamma l_1/g$$

The dimensions of the manometer used in the experiment are $l=120$ cm, $r=0.25$ cm, $\mu=155\times10^{-7}$(gs/cm^3), $\gamma=1.0$(g/cm^3). Substituting these values in Eq. (13), and comparing the calculated values of back pressure, which is converted to the square wave from the pressure wave in Fig. 5, with the actual value, a coincidence is observed as shown in Fig. 10.

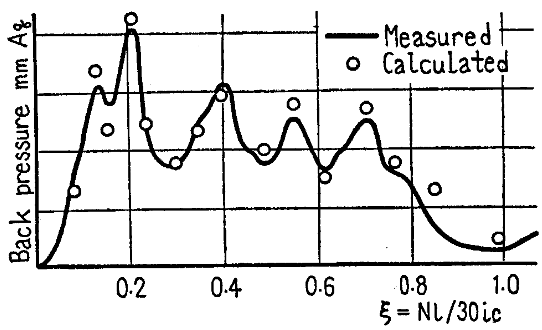


Fig. 10 Comparison between the calculated and experimental results (3600 rpm)

The relation between the value of displacement of water head $x(t)$ and fluctuating pressure $p(t)$ is a periodical phenomenon and does not always coincide, but it has a tendency to coincide to a certain degree. Especially, the positively reflected pressure wave overlaps the exhaust blow down pressure wave at the point $\xi \doteqdot 1/2$ in Figs. 4 and 9, and as a result, the value of the back pressure becomes lower, because the time functions on the manometer become shorter. This phenomenon is due to the relation of natural frequency of the water manometer and the revolving speed of the engine, and also the properties of the manometer.

In addition to the above properties of the manometer, the influence of the valve overlapping period, condition of the valve part and the conditions inside the cylinder must be considered. Thereore, we will investigate the air model engine in the next section.

Experiment with the Air Model Engine

Since it is very difficult to understand the state of an actual engine in firing, that is, how the pressure wave in the exhaust pipe functions at the exhaust valve part and how the reflection wave affects the cylinder part, an air model engine, modified from the single cylinder engine, is used in the experiment so that observation at only one arbitrary time is possible.

Fig. 11 shows an outline of the experimental air model engine. The piston is so devised that it can be fixed at an arbitrary position, and the cylinder volume is kept constant. Compressed air is introduced into the cylinder from the top of the cylinder head, and the exhaust valve is positioned so that the valve opening time and the valve clearance can be changed from outside the engine. The pressure pick-up is installed so that the pressure fluctuation wave in the exhaust pipe at a certain exhaust time can be observed, and recording is made on the oscilloscope.

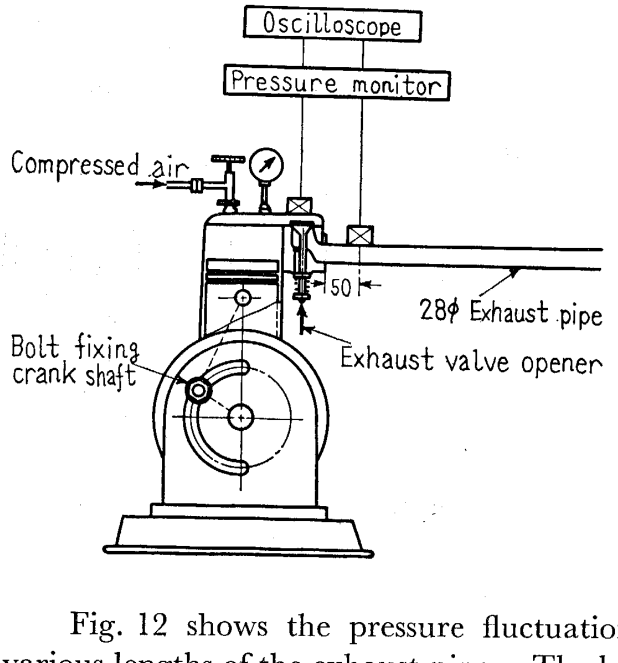


Fig. 11 Model engine equipment for pressure wave test

Fig. 12 shows the pressure fluctuation wave in the exhaust pipe under various lengths of the exhaust pipe. The longer the pipe is extended, the longer becomes the time the pressure wave requires to make a round trip, and its phases are observed as in the motoring operation of the engine.

It is presumed that such pressure waves are composed one after another

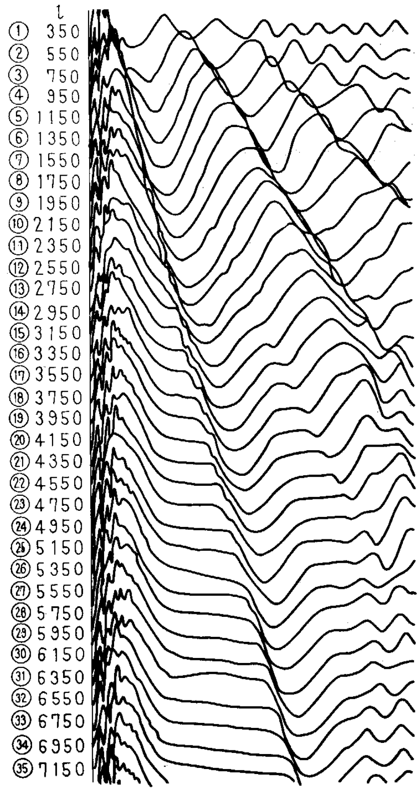


Fig. 12 Pressure waves at the entrance of the exhaust pipe of the model engine

and form the pressure waves as shown in Fig. 5, in the case of firing operations. Fig. 13 shows the pressure waves after the exhaust valve part of the model engine, when the exhaust part of engine A is connected to the end of the exhaust pipe of the air model engine, and a positive pressure wave is forced into engine A. As seen from the figure, the opening and closing of the exhaust valve scarcely affects the pressure wave, and it is confirmed that only the exhaust pipe needs to be considered in practice, excluding the vicinity of the valve during closing time, for the small engine used in this experiment.

a. Close

b. Half open

c. Open

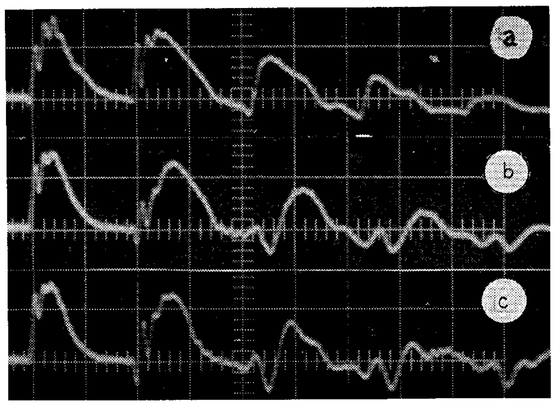


Fig.l 13 Influence of exhaust valve (Vave lift is 7 mm)

Experiment on Firing Operations

The characteristics of the fluctuation of the back pressure characteristic curve and its regulating method for motoring operation have been described in the preceding section, and the physical meanings have been considered. Now it is necessary to clarify the characteristics of back pressure in the case of firing operations. The density and the temperature of gas in the pipe are assumed to be constant in motoring operation, but these values are complicated in firing operations. A study of firing operations is made as follows:

Four-Cycle Engine Fig. 14 shows the characteristic curves of the back pressure at two different engine speeds in the case where the length of the exhaust pipe is changed. Fig. 15 shows the result of regulation by the parameter ξ. Fig. 16 shows a pressure wave photograph in the exhaust pipe.

Fig. 17 shows the pressure wave in the exhaust pipe in the case of the firing operations of engine *A* at 3600 rpm, in the order, starting from the short exhaust pipe to the longer ones.

In the case of firing operations, unlike motoring operations in which case the pressure waves make several oscillations in the pipe, the pressure waves make less mutual functions, and it is supposed that the reflected pressure waves have a comparatively small effect on the exhaust blow down pressure. Therefore, the characteristic curves of back pressure in Fig. 14 do not show any remarkable fluctuations as in the case of motoring operations. The back pressure shows a lower value at the point where the first negative reflected wave overlaps the exhaust blow down pressure, that is, at the point where the length of the exhaust

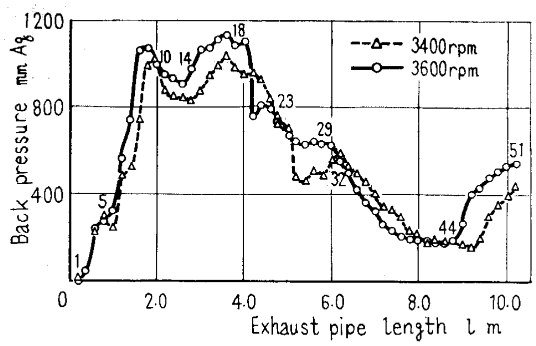


Fig. 14 Back pressure curves at the entrance of the exhaust pipe of engine A (Firing, 3400 and 3600 rpm)

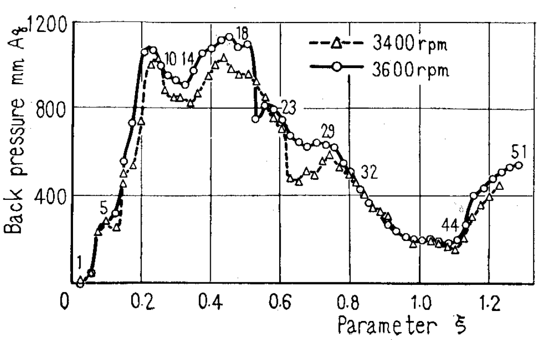


Fig. 15 Back pressure curves of Fig. 14 regulated by parameter ξ

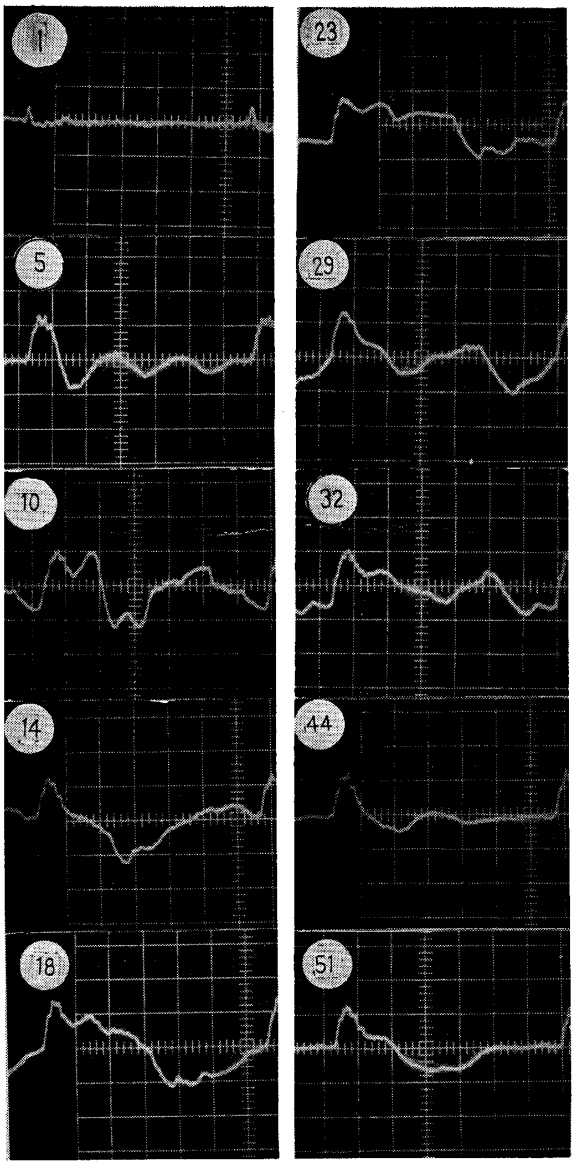


Fig. 16 Pressure wave photographs of Fig. 14

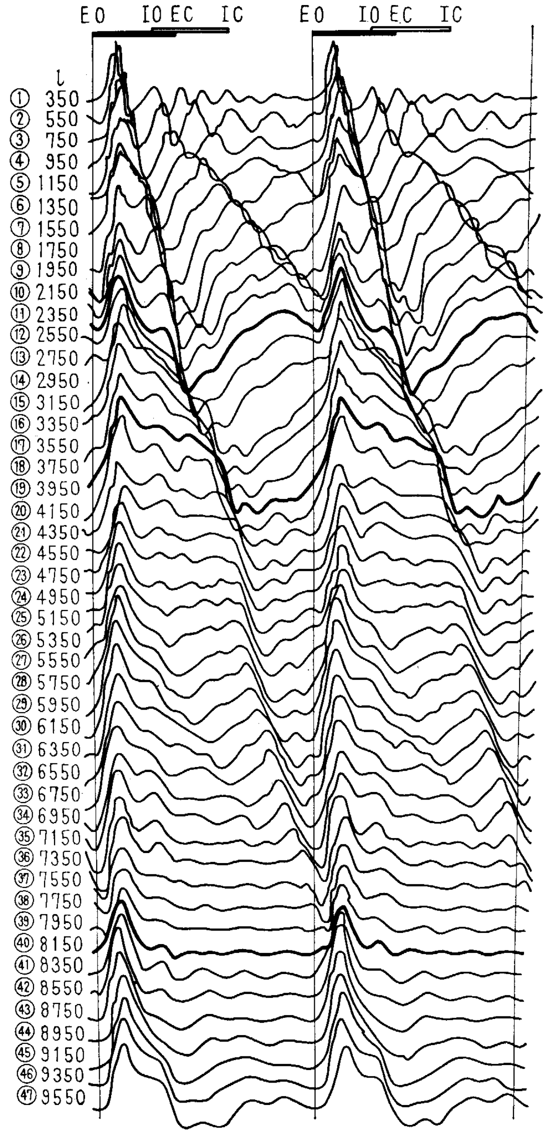


Fig. 17 Pressure waves of Fig. 14

pipe is 8 m. The regulation by ξ coincides well, as shown in Fig. 15. These are similar to the case of motoring operations.

In order to study the shape in the wave photograph, the composition of the pressure wave is taken into consideration. Let A be the exhaust blow down pressure in Fig. 18, and

A'=Negatively reflected pressure wave of A,
B=Positively reflected pressure wave of A',
B'=Negatively reflected pressure wave of B,
C=Positively reflected pressure wave of B',
C'=Negatively reflected pressure wave of C,

and let the suffixes 1, 2, and 3 denote the pressure wave by wave A of the previous cycle, one cycle before the previous cycle and two cycles before the previous cycle, respectively. Fig. 18 shows the result of positive and negative pressure waves using Eq. (1). The dark dotted line in the figure shows the theoretical composite wave, and this wave coincides with the photographic wave (experimental value) of Fig. 16.

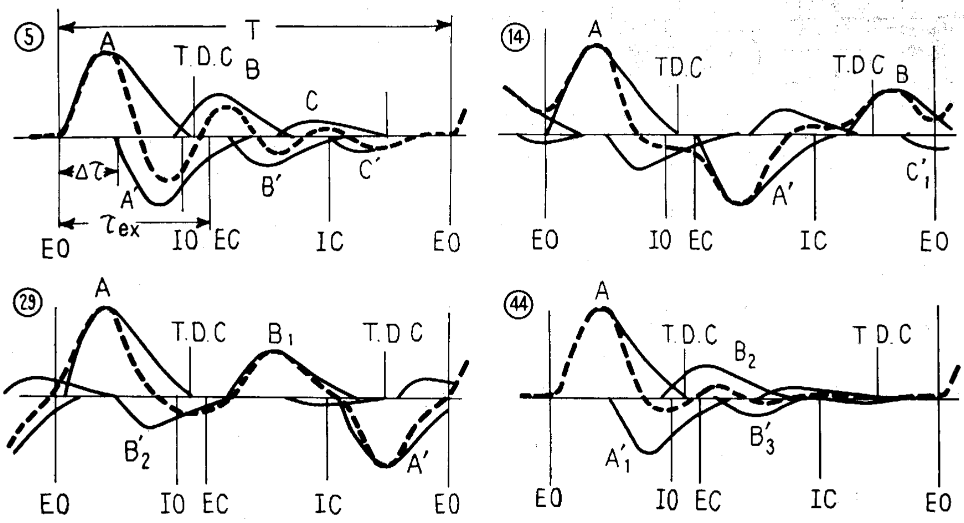


Fig. 18 Compound of positive waves and negative waves

Two-Cycle Engine Fig. 19 shows the characteristic curve of back pressure of the 2-cycle engine, i.e. engine *B*, on firing operation as shown in case of the 4-cycle engine, i.e. engine *A*, and Fig. 20 shows the regulated result by the parameter ξ. In the case of the 2-cycle engine, as well as the 4-cycle engine, it coincides well, since the error of calculating the pressure propagating velocity is small, due to the smaller reduction of the pressure wave until the first blowdown pressure of the exhaust, in the range where ξ is comparatively small. In the vicinity of $\xi=3$ where the exhaust blow-down overlaps the first negative reflection pressure of the cycle beofre the previous cycle, a slight discrepency is observed. It shows a tendency such that the longer the pipe is extended, the larger the discrepancy becomes.

However, it is understood that for tedulating the characteristic curve of the back pressure, the paramerter ξ is effective for motoring operations and firing operations on both 4-cycle and 2-cycle engines.

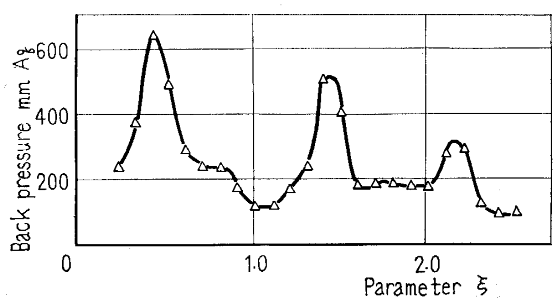


Fig. 19 Back pressure curves at the entrance of the exhaust pipe of engine B (Firing, 6170 rpm)

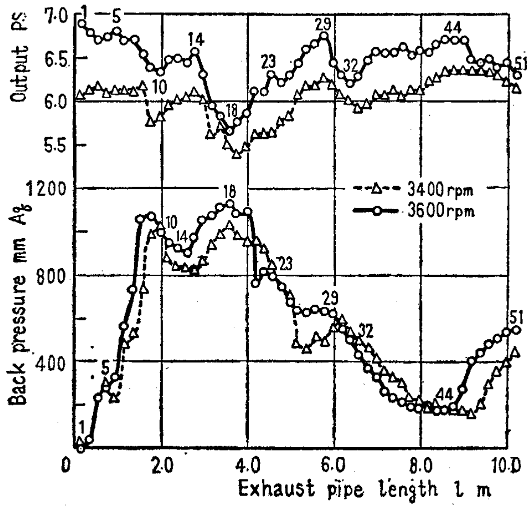


Fig. 20 Back pressure curves and output curves of engine A (Firing, 3400 and 3600 rpm)

Characteristics of Brake Output on Extending the Length of the Exhaust Pipe

A study on the fluctuation of brake output caused by extending the length of the exhaust pipe of the small engine is made as follows:

When the negatively reflected pressure wave synchronizes with the latter part of the exhaust period, it is assumed that the output should increase.

Let τ_{r2m-1} be the time in which the positive pressure wave, caused by the exhaust blow down after the opening of exhaust valve, returns after an oscillation in the pipe, changing its state to a negative pressure wave.

Thus

$$\tau_{r2m-1}=(2m-1)(2l/c) \qquad \cdots\cdots\cdots(14)$$

When τ_{r2m-1} (refer to Eq. 3) synchronizes after the time $\Delta\tau$ from valve opening time or after the time $(nT_N+\Delta\tau)$ at the nth period later, the brake output is to be increased, where T_N denotes the exhaust period. K is defined by $K=\tau_{ex}/\Delta\tau$, and it is called the synchronizing coefficient. τ_{ex} is the opening period of the exhaust valve.

The sychronizing condition is $\tau_{r2m-1}=nT_N+\Delta\tau$, and the dimensionless number Φ is defined as $\Phi=\tau_{r2m-1}/(nT_N+\Delta\tau)$.

Thus

$$\Phi=\left\{\frac{2l}{c}(2m-1)\right\}\Big/\left\{\frac{60in}{N}+\frac{\theta_{ex}}{6NK}\right\} \qquad \cdots\cdots\cdots(15)$$

where θ_{ex} is the crank angle (degree) of the opening period of the exhaust valve. Expressing Eq. (15) by the parameter ξ of back pressure, the relation between ξ and Φ is as follows:

$$\Phi=\frac{2m-1}{n+(\theta_{ex}/360iK)}\xi \qquad \cdots\cdots\cdots(16)$$

It is clear from the definition of Φ that the brake output increases when $\Phi=1$. Substituting $\Phi=1$ into Eq. (15), the most proper length of exhaust pipe l is expressed by the following equation.

$$l=\frac{30ic}{(2m-1)N}\left(n+\frac{\theta_{ex}}{360ik}\right) \qquad \cdots\cdots\cdots(17)$$

Fig. 20 shows the characteristic curves of brake output and back pressure of engine A at 3400 rpm and 3600 rpm. Fig. 21 shows the calculated and regulated figures of Fig. 20 based on Eq. (15). In this case, $i=2$, $c=472$ m/sec, $N=3600$ rpm and $\theta_{ex}=278$, and by comparing Fig. 18 with Fig. 16, it is found That the most proper value of K is 3. Substituting these values into Eq. (17), and calculating the most proper length of exhaust pipe l, Table 2 is obtained. It is observed that the length of pipe shown in Table 2 coincides with the results of experiments in which the length of the pipe shows the higher extreme of the brake output. When m and n are positive integers, the brake output should increase, and by the result of actual calculations, this is proved to be correct, as shown in Fig. 21.

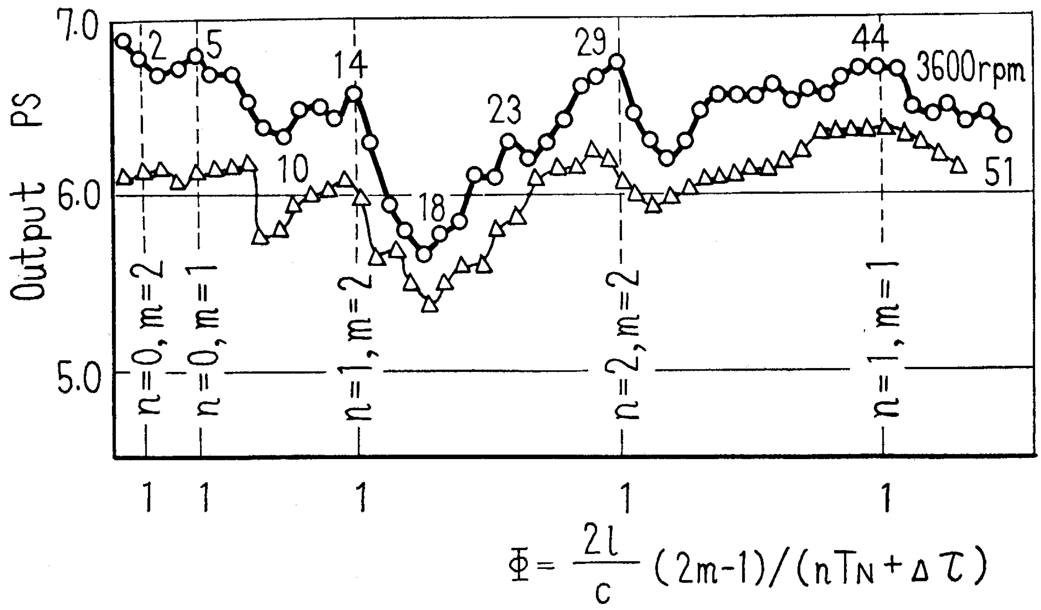


Fig. 21 Output curves of Fig. 20 regulated by parameter Φ

Table 2. Calculated values of the exhaust pipe length which shows the higher extreme of the output of engine A (refer to Fig. 20)

m \ n	0	1	2
1	1.01 ⑤	8.88 ㊹	16.8
2	0.34 ②	2.96 ⑭	5.60 ㉙
3	0.20	1.78	3.36

meter

In conclusion, both the regulating parameter of the back pressure and that of the brake output are fundamentally caused by the dynamical effect of the pressure wave in the exhaust pipe, but both of these are substantially different.

Conclusions

1) Small sized single cylinder engines are studied in this paper.

2) The value of the back pressure which is shown by the manometer, is given by the fluctuating curve of a definite pattern in accordance with the extension of the length of the exhaust pipe.

3) These values of back pressure fundamentally show lower extremes when $(2m-1)Nl/30nic$ equals 1, and show high extremes when $2mNl/30nic$ becomes 1, where m is the number of oscillations of the pressure wave, and n is a positive intefer showing the number of exhausts during the period.

4) In regulating the back pressure with the regulating parameter ξ, as defined by Eq. (6), the back pressure shows lower extremes at $\xi=n/(2m-1)$ and higher extremes at $\xi=n/2m$. The effect of m and n upon the back pressure decreases as the values of m and n increase. The back pressure shows the lowest extreme at the point where, $\xi=1$.

5) By using the regulating parameter Φ of Eq. (15) which shows the increase and decrease of the brake output developed by extending the length of the exhaust pipe, the brake output shows the higher extreme at the point $\Phi=1$. The calculated values of the length of the exhaust pipe, by substituting the numerical values of m and n, coincide with the measured values.

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