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抄録

オープン・ノッズルを用ふる噴射系統に於ける導管の太さと噴射の切れ方に就て

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オープン・ノッズルを用ふる噴射系統では導管の太さが噴射の切れ方に大きな影響を及ぼすので、この影響を調べてみた。噴射が鋭く切れるためには導管内の油の速度に或る制限がある。換言すればノッズルに比して導管があまり太すぎたり細すぎたりしてはいけないのである。導管が太すぎる場合、即ち導管内の油の速度が壓力の割合に遲すぎる場合には、燃料噴射ポンプの方で油壓を急に切つても、ノッズルでは急には切れないで、其處の油壓は階段形に下る筈である。此等のことについては實驗も行つてみたが、豫想した通でりであつた。

導管が細すぎる場合、即ち導管内の油の速度が壓力の割合に速すぎる場合にも、ノッズルに於ける油壓の下り方はやはり階段的になる筈である。然し實驗結果から見ると導管の細い場合には噴射は可なりよく切れる。そして導管が非常に細い場合に漸く油壓の階段が認められるやうになる。

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On the Effect of Pipe Bores on the Cut-off of Fuel Spray in Injection Systems with Open Nozzles.

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Abstract.

The conditions for sharp cut-off of fuel spray in the ordinary injection system with open nozzle were sought. For sharp cut-off, there is a lower limit to oil speed in the injection pipe; or expressed differently, the pipe must not be too large compared with the nozzle. When the oil speed is lower than this limit, the pressure cannot be cut-off sharply, and the pressure-time curve takes the form of steps. These facts were ascertained by experiments.

There is also an upper limit to oil speed for sharp cut-off, and if the oil speed exceeds this limit, the form of the pressure-time curve must also be steplike. In this case, however, experimen's show that the steps can be seen clearly only when the oil speed is very high, or the pipe is very small.

1. Introduction.

If the cut-off of the fuel spray is not sharp in compression-ignition engines, the last part of the injected fuel will not become a good spray and we have the phenomenon of "dribbling", to avoid which, the fuel must not be discharged under a low pressure difference. In the case of open nozzles, the injection pressure must be suddenly lowered from one fairly high to one lower than that in the cylinder.

It is already well known that the pressure at the nozzle can be cut-off more sharply the smaller the volume of oil in the injection pipe. In fact, the pressure fall in the pipe after the pressure has been cut-off at the injection pump is a function of the volume alone, if we assume that no vibration of oil occurs in the pipe or that the frequency of the vibration is very high. Some writers treat the problem of cut-off with this assumption. But, in reality, the oil in the pipe vibrates violently and the period of the vibration is of the same order as the duration of injection in high-speed compression-ignition engines, so that the pressure fall in the pipe differs entirely from that considered statically. For instance, the fall of pressure when the pipe is short and wide differs considerably from that when the pipe is long and narrow, even though the volumes may be equal.

Assuming that, with pipes of the same bore, the volume of oil from the fuel pump to the nozzle is proportional to the length of the pipe, the pressure variation will be quite similar though the lengths may not be equal. Compared with that in a long pipe, the from of the pressure-time curve in a short pipe is contracted only in the direction of the time axis. If therefore the pressure fall in a pipe of certain length is known, that for a pipe of like bore but of different length can be easily guessed. Since, however, the vibration that occurs in the pipe after the cut-off is dependent on the pressure and velocity of oil at the time of cut-off, the vibration and consequently the pressure fall will differ greatly with the pipe bore.

In this paper the effect of pipe bores on pressure variation after the cut-off is investigated both theoretically and experimentally.

Experiments on pressure variation at the nozzle have already been carried out by various investigators with various methods; experiments with Schweitzer's method(1) and those using the Farnboro' indicator(2) for example. The vibration after the pressure cut-off, however, has not yet been made very clear.

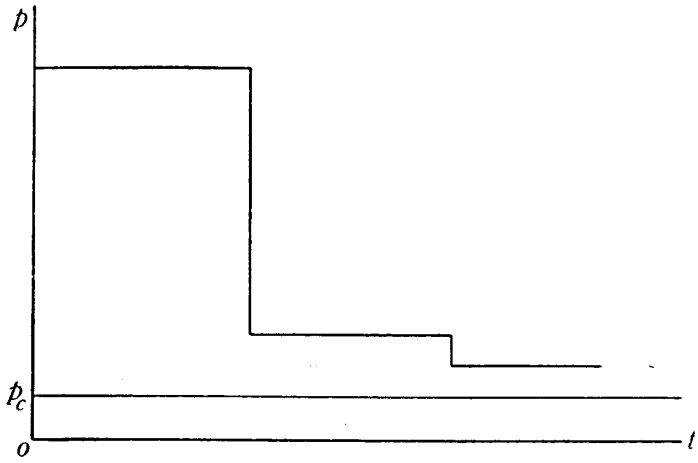
2. Upper Limit of Oil Speed for Sharp Cut-off.

In the ordinary injection system, the oil that is discharged from the fuel pump through a discharge valve arrives at the nozzle after passing through an injection pipe of a certain length. In such a system, the pressure at the nozzle generally cannot be cut-off sharply on account of the vibration of oil set up in the pipe.

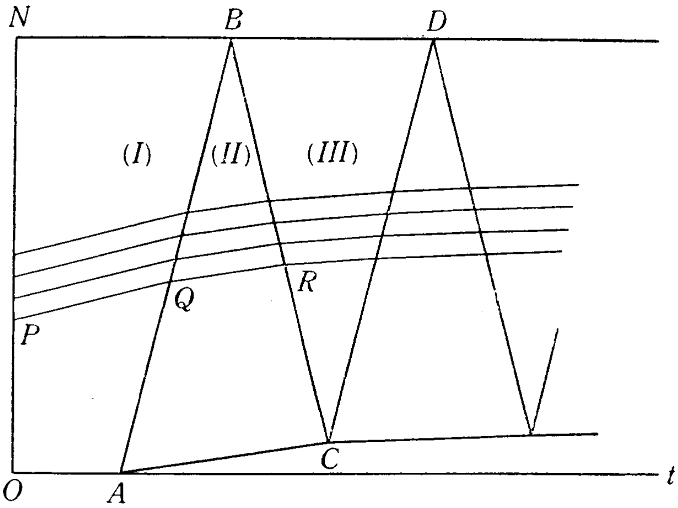
We neglect here the effect of viscosity, and moreover assume that the pressure and the velocity of oil everywhere in the pipe just before the cut-off is equal.

Fig. 1-*b* shows diagramatically the vibration of oil when the velocity before the cut-off is very high. In the figure, time is taken as abscissa and the position of the oil as ordinate. ON is the length of the pipe, O being the pump end and N the nozzle. During the injection, the oil at P moves as shown by the line PQ. If we assume that the pressure in the pump is cut-off at A, then this effect is transmitted through the pipe as an expansion wave AB. The oil in the pipe, which is made to expand suddenly by this wave, partakes of the motion as shown by the line QR. This motion may be directed either to the nozzle or to the pump according to the magnitude of pressure and velocity before the cut-off. Here, the velocity being assumed to be very high, the direction of motion is to the nozzle as shown in the figure. The compression wave, such as BC, then returns from the

(1) Joahim, VDI Bd. 75 (1931), S. 69. Juhasz, Aut. Eng., 1931, p. 299.
(2) L'Orange, VDI Bd. 75 (1931), S. 326. Nixon, Aut. Eng., 1932, p. 31.



(a)



(b)

Fig. 1.

nozzle, and the oil is compressed by this wave. Thus the oil has a certain pressure in region (*III*) in the figure. If this pressure is higher than that in the cylinder, the injection will not yet be cut-off. And if the pressure difference is not very great, the phenomenon of "dribbling" takes place.

For sharp cut-off it is necessary that the pressure in region (*III*) shall be lower than that in the cylinder. For this, the velocity in region (*II*), and consequently that in region (*I*), must be lower than a certain value. In other words the pipe must not be too narrow.

Let v_1, v_2, and v_3 = velocities of oil in regions (*I*), (*II*), and (*III*) respectively,

p_1, p_2, and p_3 = pressures of oil in regions (*I*), (*II*), and (*III*) respectively, and

p_c = pressure in the cylinder.

The condition that the pressure in region (*III*) shall be equal to that in the cylinder then becomes

$$\left.\begin{aligned} p_3 &= p_c\,, \\ v_3 &= 0. \end{aligned}\right\} \tag{1}$$

As the discharge valve of the pump is ordinarily held down in its seat by a spring of considerable strength, it may be supposed that

$$p_2 = 0\,. \tag{2}$$

Referring to Fig. 2, the ratio of the specific volumes of the oil in regions (*II*) and (*III*) is

$$\frac{1}{1-\dfrac{p_c}{E}} = \frac{RT}{SR'} = \frac{(a+v_2)dt}{adt} = \frac{a+v_2}{a}\,, \tag{3}$$

where E = modulus of elasticity of the oil,

a = wave velocity in the oil.

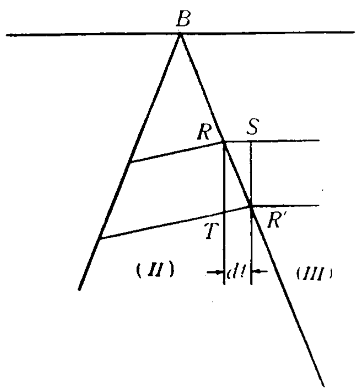


Fig. 2.

It is assumed here for the sake of brevity that E and a are constants. Moreover we have neglected the expansion of the pipe due to pressure as it is generally very small compared with the contraction of the oil. From (3), neglecting the higher order of $\frac{p_c}{E}$ as it is very small, we have

$$\frac{v_2}{a}=\frac{p_c}{E}\,. \tag{4}$$

Similarly from the ratio of the specific volumes of the oil in regions (I) and (II), we have

$$\frac{a-v_1}{a-v_2}=1-\frac{p_1}{E}\,. \tag{5}$$

Substituting (4), we obtain

$$\frac{v_1}{a}=\frac{p_1+p_c}{E}\,. \tag{6}$$

This is the upper limit of oil speed in the pipe for sharp cut-off. If the speed of the oil is higher than this, the oil spray cannot be cut-off sharply and the pressure variation will become as shown in Fig. 1–a.

3. Lower Limit of Oil Speed for Sharp Cut-off.

The oil spray will be cut-off sharply when the velocity of the oil is a little lower than that expressed by (6). But if the velocity is too low it is impossible to obtain a sharp cut-off again.

Fig. 3–b shows diagramatically the vibration of the oil when the velocity of oil in the pipe before the cut-off is low. At A the pressure is cut-off at the pump, and this effect is transmitted as an expansion wave AB. As the velocity in region (I) is low, that in region (II) must be directed to the pump in order that the oil may fully expand. But since

the discharge valve between pump and pipe closes immediately, the oil cannot expand fully. Thus, in region (*II*', the velocity is zero while the pressure has yet a certain value, but if this pressure is higher than that in the cylinder the spray cannot be cut-off sharply.

When

$$p_2 = p_c \, , \qquad (7)$$

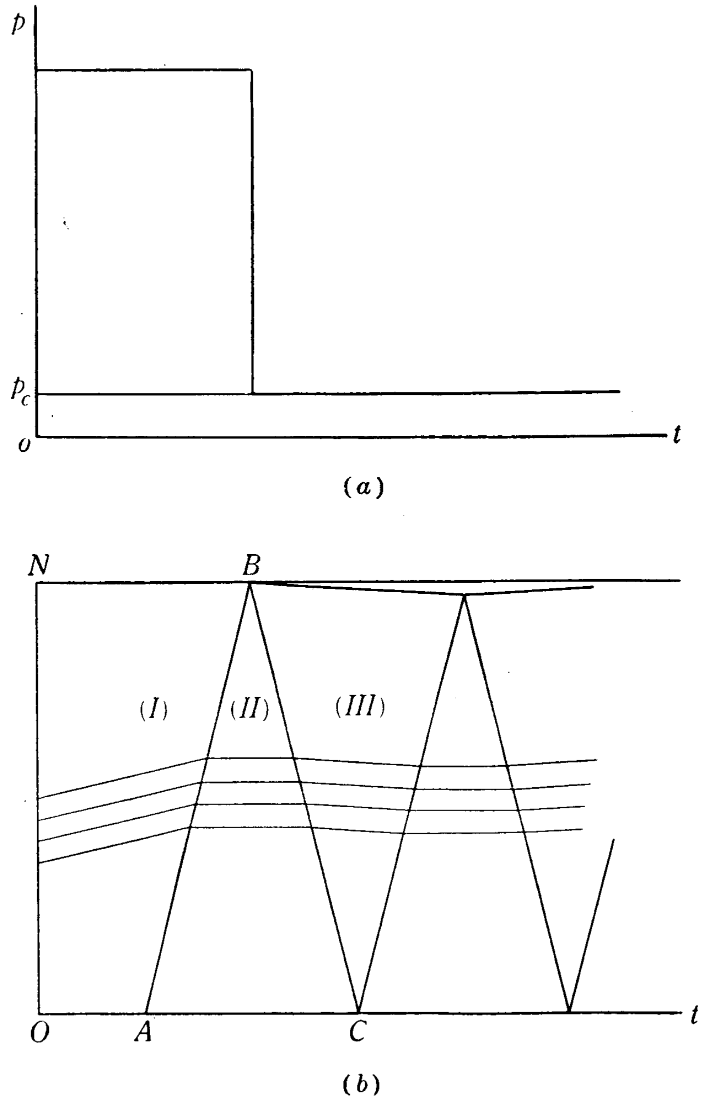


Fig. 3.

we have

$$\frac{v_1}{a} = \frac{p_1 - p_c}{E} . \tag{8}$$

This is the lower limit for sharp cut-off.

But, when the pressure in the cylinder becomes lower in the exhaust or suction stroke, the oil in the pipe will expand and sometimes flow out. To prevent such a contingency, we must see that the pressure in region (*II*) in Fig. 3–*b* is lower than the lowest pressure in the cylinder. If we let this lowest pressure be p_l, then when

$$p_2 = p_l , \qquad (7)'$$

we have

$$\frac{v_1}{a} = \frac{p_1 - p_l}{E} , \qquad (8)'$$

which is another lower limit for oil speed.

In Fig. 4, equations (6), (8), and (8)′ are shown diagramatically, in which $E = 20{,}000 \text{ kg/cm}^2$, $a = 1{,}500 \text{ m/sec}$, $p_c = 35 \text{ kg/cm}$, and $p_l = 1 \text{ kg/cm}^2$.

The rate of discharge through the nozzle is

$$q = cs\sqrt{\frac{2(p_1 - p_c)}{\rho}} , \tag{9}$$

where q = quantity of discharge per second,

c = coefficient of discharge of the nozzle,

s = area of nozzle,

ρ = density of oil.

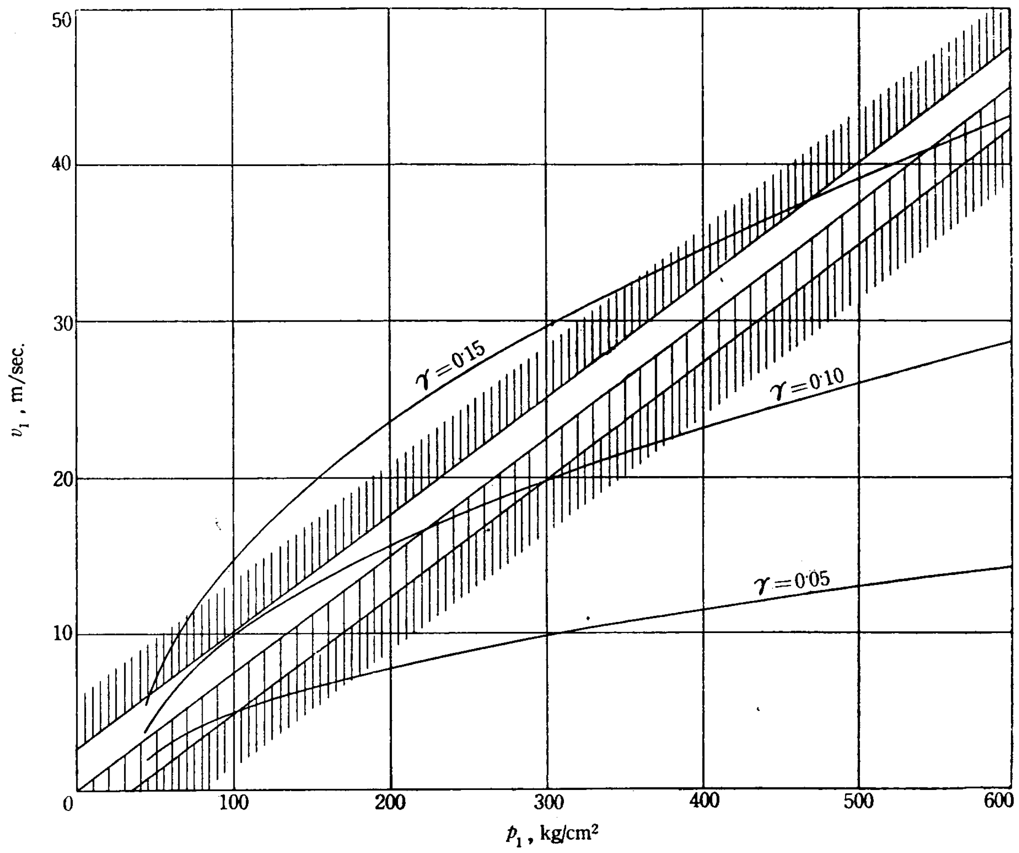


Fig. 4.

In this equation the velocity in the pipe is neglected. For pipes of ordinary size, it may be neglected without much error.

Let γ = ratio of area of nozzle to that of pipe, then

$$v_1 = c\gamma\sqrt{\frac{2(p_1 - p_c)}{\rho}}\,. \qquad (10)$$

This relation is shown by the curves in Fig. 4, c being taken to be equal to 0·8. As will be seen in the figure, the region in which the spray is cut-off sharply is very narrow and limited.

4. Pressure Variation in Pipes of Large Bore.

Fig. 5-*a* shows, diagramatically, the pressure variation and Fig. 5-*b* the vibration of the oil, when the bore of the pipe is fairly large. *AB* is an expansion wave and although the pressure in region (*II*) becomes lower than that in (*I*), yet it is higher than that in the cylinder, for in region (*I*) the pressure is high and

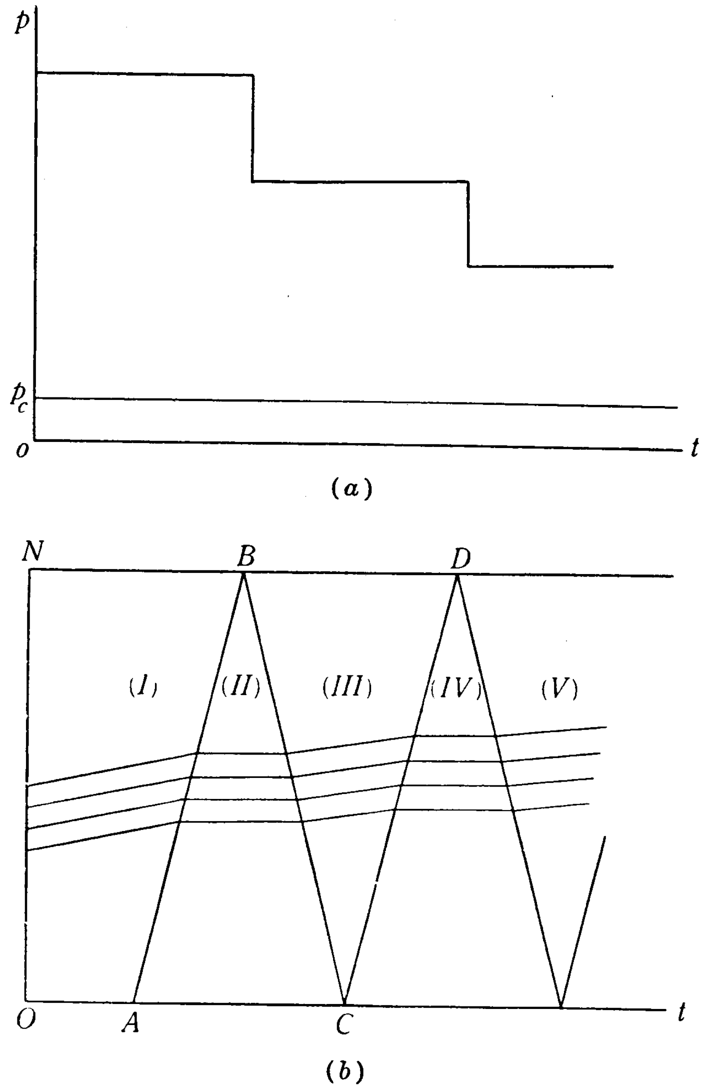


Fig. 5.

the velocity is relatively low. *BC*, *CD*, etc. are also expansion waves, and the pressure in (*III*) is lower than that in (*II*), and so on. Thus the pressure at the nozzle falls suddenly at *B*, remains constant during *BD*, and falls suddenly at *D* again as shown in the figure.

The pressure in region (*II*) can be calculated from the ratio of the specific volumes in regions (*I*) and (*II*).

$$\frac{p_2}{E}=\frac{p_1}{E}-\frac{v_1}{a}\,. \tag{11}$$

The pressure in region (*III*) may be obtained from the following two relations :—

$$\frac{p_3}{E}=\frac{p_2}{E}-\frac{v_3}{a}\,, \tag{12}$$

$$v_3=c\gamma\sqrt{\frac{2(p_3-p_c)}{\rho}}\,. \tag{13}$$

Or

$$\frac{p_3}{E}=\frac{p_2}{E}+c^2\gamma^2-c\gamma\sqrt{\frac{2(p_2-p_c)}{E}+c^2\gamma^2}\,. \tag{14}$$

The pressure falls step by step as shown in Fig. 5–*a*, and the height of each step can be obtained by repeating the above method. The step is higher as v_1 is greater or the pipe is smaller, and if v_1 is greater than that given by equation (8), the pressure at the nozzle falls at once to a pressure that is lower than that in the cylinder.

5. Low of Similarity.

From (11) we have

$$\frac{p_2-p_c}{E}=\frac{p_1-p_c}{E}-\frac{v_1}{a}\,,$$

or

$$\frac{p_2-p_c}{p_1-p_c}=1-\frac{v_1}{a}\cdot\frac{E}{p_1-p_c}\,. \tag{11)'$$

And from (10)

$$\frac{p_1-p_c}{E}=\frac{v_1^2}{2c^2\gamma^2a^2}\,.$$

So that (11)', may be written in the form

$$\frac{p_2-p_c}{p_1-p_c}=f_2\left(\frac{c^2\gamma^2a}{v_1}\right). \qquad (15)$$

That is, the ratio of p_2-p_c to p_1-p_c is a function of $\frac{c^2\gamma^2a}{v_1}$ alone.

Similarly, from (14), (11), and (15) we have

$$\frac{p_3-p_c}{p_1-p_c}=f_3\left(\frac{c^2\gamma^2a}{v_1}\right). \qquad (16)$$

The ratio of p_3-p_c to p_1-p_c is also a function of $\frac{c^2\gamma^2a}{v_1}$ alone.

Thus,

$$\frac{c^2\gamma^2a}{v_1}=\text{const.} \qquad (17)$$

is a low of similarity. When this relation holds, the forms of the variation in the pressure difference at the nozzle are similar.

6. Experiments.

Experiments were made to ascertain the effect of pipe bores on the pressure variation at nozzles after the cut-off of oil pressure at the fuel pump.

As was explained in the previous chapter, since the form of the variation in the pressure difference at the nozzle is a function of $\frac{c^2\gamma^2 a}{v_1}$ alone, and does not depend on p_c, in investigating the pressure variation, it is quite immaterial what value the pressure in the cylinder, p_c, may have. Here, for the sake of brevity, the fuel was discharged into the atmosphere.

The oil pressure was recorded by an optical indicator, which is shown in Fig. 6. Its optical path is indicated in Fig. 7. This indicator is a modification of the high speed indicator[1] invented by the authors. The diaphragm was interchanged with a small piston to render it suitable for measuring high pressure.

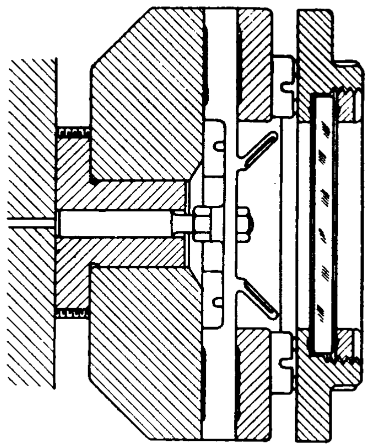


Fig. 6.

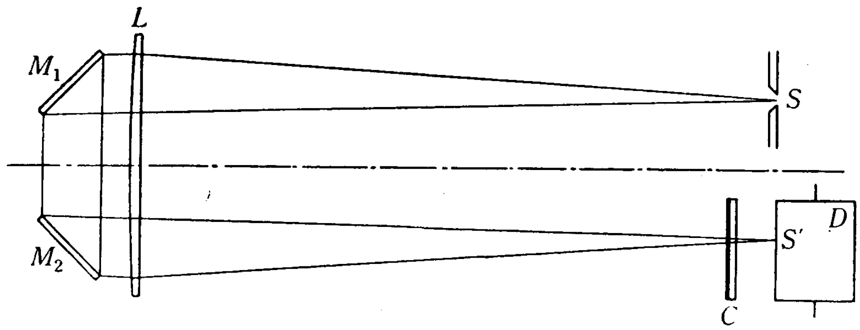


Fig. 7.

To indicate accurately the rapidly varying pressure of the oil, the indicator must fulfill the following two conditions:

(i) The natural frequency of the moving part of the indicator must be high.

(1) Report of the Aeron. Research Inst., No. 87 (1932).

(ii) The volume change owing to the motion of the indicator piston must be very small, as the oil pressure varies greatly even with a small change of volume.

The natural frequency of the present indicator is very high, over 10,000 per sec. As to the volume change, the diameter of the piston is 3 mm and the maximum motion about 0·02 mm. Assuming the elasticity of oil to be equal to 20,000 kg/cm^2, the contraction of oil is 2% under a pressure of 400 kg/cm^2; that is, the motion of the indicator piston corresponds to the contraction of an oil column of only 1 mm under this pressure. Such a small volume change may be regarded as having almost no effect on the pressure of oil.

The position in the pipe where the oil pressure was measured is very near the nozzle, the distance from the nozzle being about 45 mm.

The fuel pump used was of the Bosch type, the diameter of the plunger being 7 mm. The discharge valve of the Bosch fuel pump has a special form, but in this experiment it was replaced with a valve of ordinary form. The position of the pump shaft was marked on the pressure record by light passing through the slits fixed to the flywheel.

As fuel, *Nisseki No. 2*, an oil of specific gravity 0.86–0.87 was used.

7. Results of Experiments.

Several experiments were made, using various pipes and nozzles. As examples, a few of them are shown in Figs. 8–12. On the pressure record, 0° is the position where the plunger of the pump just covers the hole, and the angles, 20°, etc., are angles of the pump shaft measured from that point.

The length of the pipe — from the discharge valve to the nozzle — is 1,090 mm. The diameters of pipes, etc., are shown in Table I.

TABLE I.

Figure	Dia. of pipe in mm	Nozzle. No. of holes × Dia. of hole in mm	r. p. m. of pump shaft
Fig. 8	2·85	1×0·28	435
Fig. 9	2·85	1×0·50	1100
Fig. 10	1·86	1×0·50	850
Fig. 11	1·86	4×0·36	1087
Fig. 12	1·36	4×0·36	1000

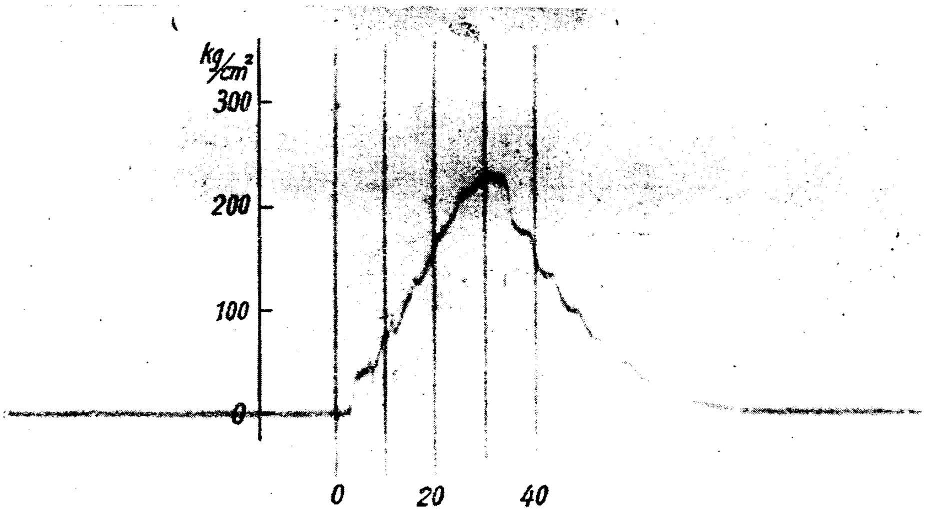


Fig. 8.

Fig. 8 is a pressure record for the case when the nozzle is very small and the pipe very large. It will be clearly seen that the pressure falls step by step. In the calculation it was assumed that the velocity of the oil in the pipe before the cut-off is everywhere equal, but as the pressure is still ascending at the time of cut-off, this assumption will not be wholly correct. And yet the pressure falls step by step just as shown in Fig. 5–*a*.

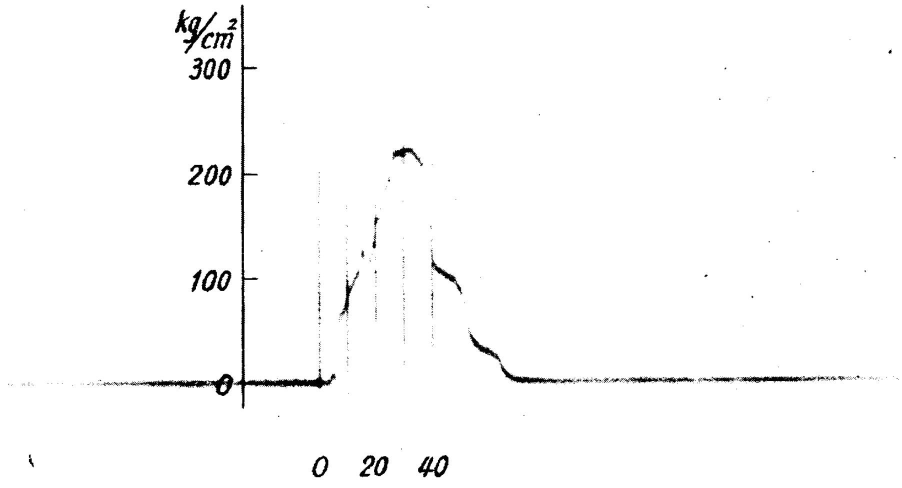


Fig. 9.

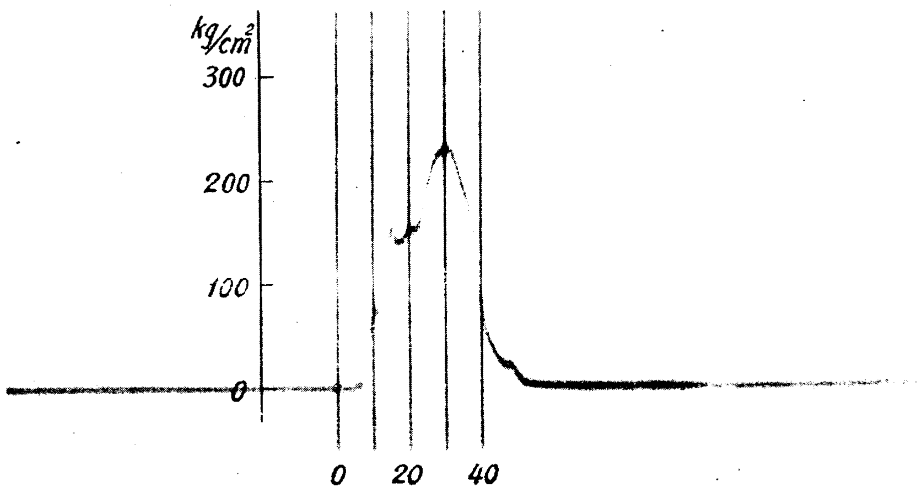


Fig. 10.

Fig. 9 is a record for the case when the nozzle is larger than that in Fig. 8; that is, the velocity of the oil before the cut-off, v_1, is higher. It will be seen that the heights of the steps became higher. Since the diameter of the pipe in Fig. 10 is smaller than that in Fig. 9, the value of v_1 is still greater, and the step became very high. In Fig. 11 the nozzle is larger than that in Fig. 10, and in this case the step almost disappeared. Fig. 12 is a case in which the pipe is very small and the nozzle relatively large. Here only a trace of the step can be seen.

The effect of viscosity was neglected in the calculation of pressure variation. In reality, however, viscosity seems to have considerable effect.

The wave velocity calculated from the pressure record is lower than that calculated from E and ρ. Moreover, though it was assumed to be a constant, the measured velocity is not constant. These are probably due to the effect of viscosity.

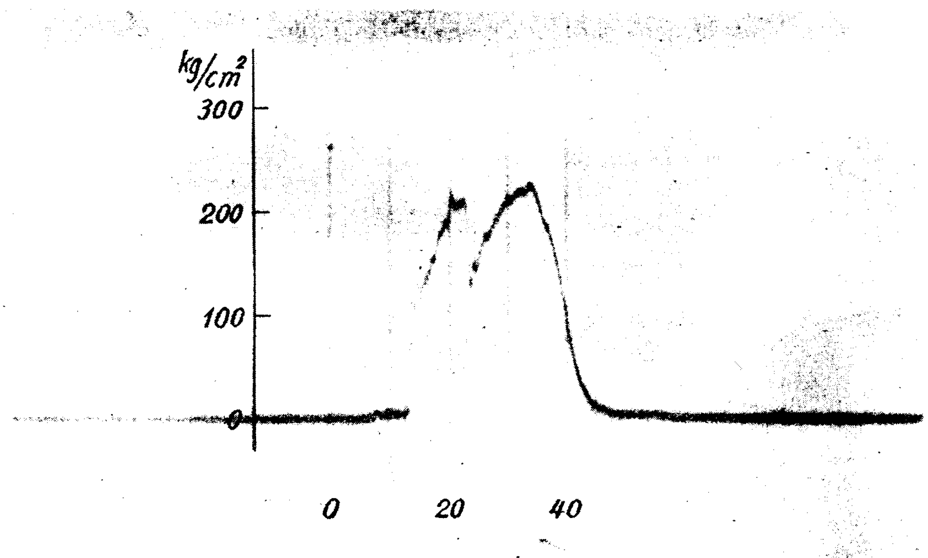


Fig. 11.

Since in the cases shown in Figs. 11 and 12, the velocity of the oil before the cut-off considerably exceeds the upper limit expressed by equation (6), the form of the pressure variation must be as that shown in Fig. 1–a. Actually, however, the pressure is cut-off almost sharply and the step is hardly visible in Fig. 11, while only a trace of it can be seen in Fig. 12. Probably this is also the effect of damping due to viscosity. The very small sizes of the pipes in these cases may have seriously affected the velocity and pressure.

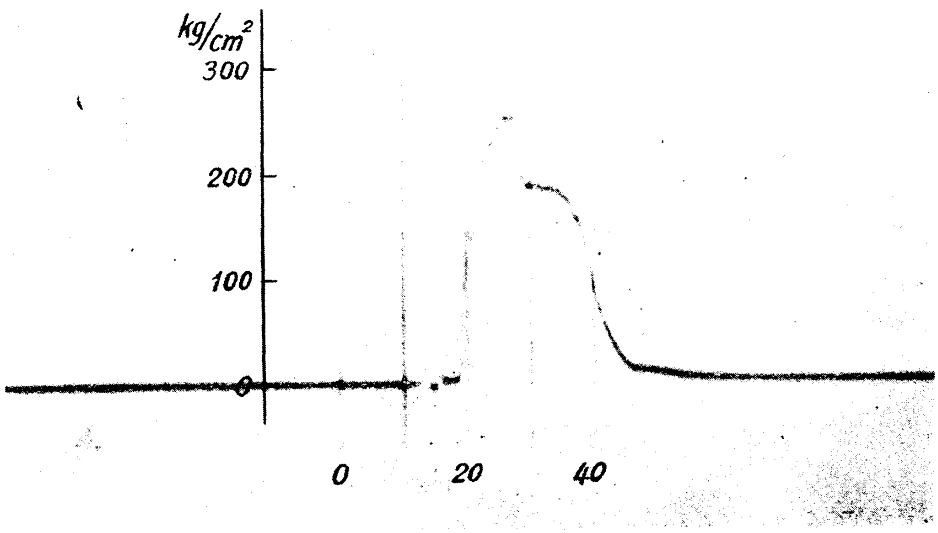


Fig. 12.

8. Summary.

1. In the ordinary injection system with open nozzle, there is a lower limit to oil speed in the injection pipe for sharp cut-off of fuel spray.

2. When the oil speed is lower than this limit, or the pipe is large compared with the nozzle, the pressure at the nozzle falls step by step.

3. These facts were ascertained by experiments.

4. There is also an upper limit to oil speed for sharp cut-off, and if the oil speed exceeds this limit, the pressure-time curve must also take the form of steps.

5. But experiments show that the steps can be seen clearly only when the oil speed is very high, or the pipe is very small compared with the nozzle.