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抄　　錄

オープン・ノッズルを用ゐる噴射系統に於ける放出弁の形と噴射の切れ方に就て

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オープン・ノッズルを用ゐる普通の噴射系統では，燃料ポンプから放出弁を通つて出て來た燃料油は或る長さの導管を經てノッズルに達するやうになつてゐるが，この放出弁の有無，有ればその形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．

導管が或る程度以上に細いと，燃料ポンプで油壓を切つても，燃料油はその慣性のためになほ流れを止めないで，放出弁の上側に眞空を殘すことになる．この場合には放出弁の形の影響はない筈である．

幾分太い導管を用ひるときに放出弁の形の影響が強く表れる．普通の形の放出弁ではノッズルに於ける壓力は階段狀に下り，Bosch 型の放出弁では極めて激しい振動が起り，放出弁を取り去り，その代り逆止弁をノッズルのところに置いたものでは鋭く切れる筈である．

實驗の結果も予想の通りである．たゞ Bosch 型の弁を用ひた場合には導管內の油の運動が激しいので減衰作用も相當強く効いて，そのために適當の太さの導管を用ひると二次噴射が消えてしまふことがある．然しこの場合にも噴射壓力を少し高くすると，また二次噴射が出て來る．

Corrigenda for the Report No. 114.

Page 152,	*for*	Fig. 8-a	*read*	Fig. 9-a.
Page 154,	*for*	Fig. 9-a	*read*	Fig. 8-a.

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Effect of Shape of Discharge Valve on the Cut-off of Fuel Spray in Injection Systems with Open Nozzles.

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Abstract.

In an ordinary injection system with open nozzles, the fuel oil discharged from the fuel pump through a discharge valve arrives at the nozzle after passing through an injection pipe of certain length. This paper discusses the effect of shape of discharge valve on the cut-off of fuel spray in such a system.

Experiments showed that, with an injection pipe of large bore and a discharge valve of ordinary type, the pressure time curve after the cut-off assumes a steplike form, and also that with a discharge valve of the Bosch type, the pressure varies violently, whereas if the discharge valve is removed from the pump and replaced with a non-return valve at the nozzle, a sharp cut-off is obtained. The same result may be obtained with an injection pipe of proper size and a discharge valve of the Bosch type. In this case, however, a secondary discharge will take place with a slight rise of oil pressure.

With an injection pipe of very small bore, the cut-off will not be affected at all by the shape of the discharge valve.

1. Introduction.

In the ordinary injection system of a compression-ignition engine using open nozzles, the fuel oil discharged from the fuel pump through a discharge valve reaches the nozzle after passing through an injection pipe of a certain length. It was stated in a previous paper[1] that, in a system of this kind, there is an upper limit to oil speed in the injection pipe for sharp cut-off of fuel spray. Should the oil speed exceed this limit, or, in other words, should the bore of the injection pipe be less than a certain size, the pressure at the nozzle cannot be cut sharply even though the cut-off of the pressure at the pump may be fairly sharp. As the speed is very high the inertia is too great, with the result that the oil continues to flow through the nozzle, leaving a vacuum above the discharge valve. In such a case, therefore, the pressure fall at the nozzle is the same regardless of the shape of the discharge valve.

It is only when the interior of the pipe does not become a vacuum or when the size of the pipe exceeds a certain limit, that the pressure fall at the nozzle is affected by the shape of the discharge valve.

This paper discusses the effect of shape of discharge valve on the cut-off of fuel spray in connection with injection pipes with bores of not very small size.

2. Pressure Variation after Cut-off in the Injection System with a Discharge Valve of Ordinary Shape.

The effect of viscosity was ignored in our calculation for pressure variation after the cut-off, and it was assumed that the pressure and velocity of oil just before cut-off in the injection pipe is everywhere equal.

Fig. 1–b shows diagramatically the vibration of the oil when the velocity before the cut-off is not high, or in other words, when the

(1) Aeron. Research Inst., Report No. 108 (1934).

bore of the injection pipe is large compared with the nozzle. 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 in the manner indicated by line PQ. If we assume that the pressure in the pump is cut-off at A, the effect of it is then transmitted through the pipe as an expansion wave AB, which wave causes the oil in the pipe to expand.

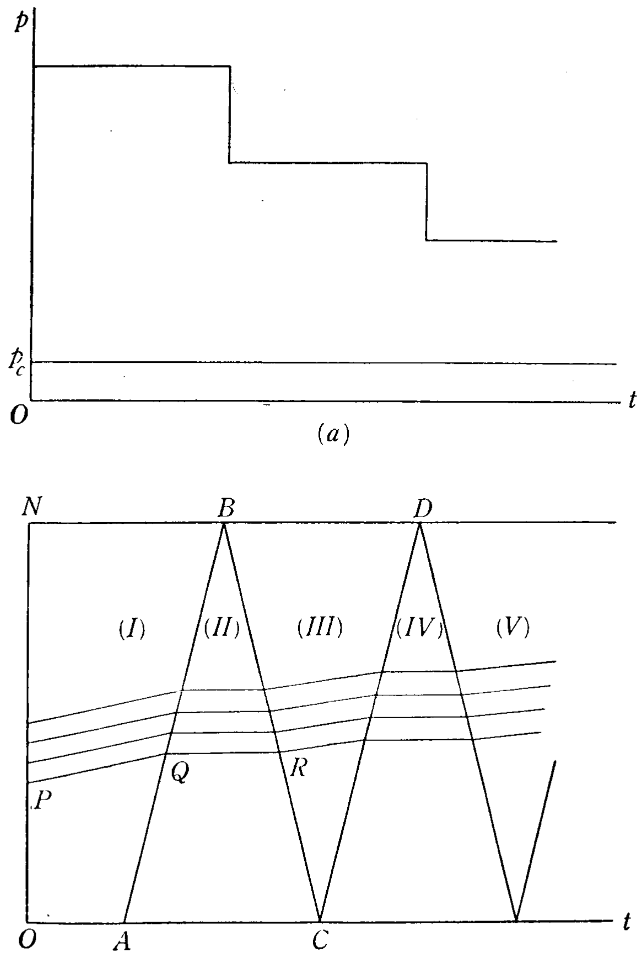

Fig. 1.

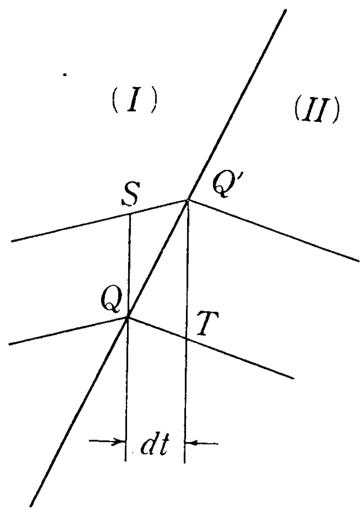

Fig. 2.

Since the pressure in region (I) in the figure is relatively high and the velocity low, the velocity in region (II) must be directed to the pump, as shown in Fig. 2, in order that the oil may fully expand. In practice, however, the oil cannot expand fully because the discharge valve closes almost instantaneously. In region (II) the velocity will be zero whereas the pressure has still a certain value.

BC is an expansion wave reflected from the nozzle. The oil, affected by this wave, gains a certain velocity directed to the nozzle, and the pressure in region (III) becomes lower than that in (II). Thus the pressure at the nozzle will fall suddenly at B.

CD, DE, etc., are also expansion waves, and the pressure at the nozzle falls suddenly at D again, and so on. Thus the form of the pressure-time curve will be step-like, as shown in Fig. 1-a.

The pressure at each stage can be easily calculated[1] by comparing the specific volumes of the oil. Or

$$\frac{p_2}{E} = \frac{p_1}{E} - \frac{v_1}{a}, \tag{1}$$

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

where p_c = pressure in the cylinder of the engine,

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

v_1 = velocity of the oil in region (I),

E = modulus of elasticity of the oil,

a = wave velocity in the oil,

c = coefficient of discharge of the nozzle,

γ = ratio of area of nozzle to area of pipe.

For brevity, E and a were assumed to be constants.

(1) loc. cit.

3. Pressure Variation after Cut-off in an Injection System with a Discharge Valve of the Bosch Type.

In the previous chapter it was explained that sharp cut-off of pressure at the nozzle cannot be obtained with a discharge valve of ordinary shape when the bore of the injection pipe is relatively large. The reason is that the valve closes immediately after the pressure is cut in the fuel pump, and prevents the oil in the pipe from flowing towards the pump, or in other words, prevents the oil from expanding fully. Sharp cut-off is obtained only by allowing the oil full expansion.

Fig. 5–b shows the discharge valve of a Bosch fuel pump. Its special shape allows expansion at the first stage. As the upper part of the valve forms a small piston, as shown in the figure, the oil in the pipe is made to expand when the valve closes.

Although the Bosch fuel pump is ordinarily used with the Bosch injector, if we assume, here, that it is used in an injection system with open nozzles, the pressure variation would then become generally highly complicated. A non-return valve at the nozzle would simplify matters somewhat. We shall now consider the pressure variation in that case.

Fig. 3–b shows diagramatically the vibration of the oil in the pipe, and Fig. 3–a the pressure variation at the nozzle. The pressure being cut-off in the pump at A_1, the effect is transmitted through the pipe as an expansion wave, A_1B_1. Since the oil in the pipe is able to expand fully at the initial stage, it agains a certain velocity that is directed to the pump, leaving a vacuum at the nozzle. Region $(II)'$ in the figure shows this stage.

The discharge valve closes perfectly at A_2, the flow of the oil toward the pump is checked, and a compression wave, A_2B_2, propagates through the pipe. Thus in region (II) the oil is in the compressed state, the amount of compression being such that the velocity is zero.

B_2C_1 is an expansion wave. In region $(II)''$ the pressure again becomes zero, while the oil gains a certain velocity directed to the nozzle. At B_3 the oil strikes the nozzle and is compressed, reflecting a compression wave, B_3C_2. Since the pipe is not very small and the initial pressure is high, the oil in region (III) has considerable pressure.

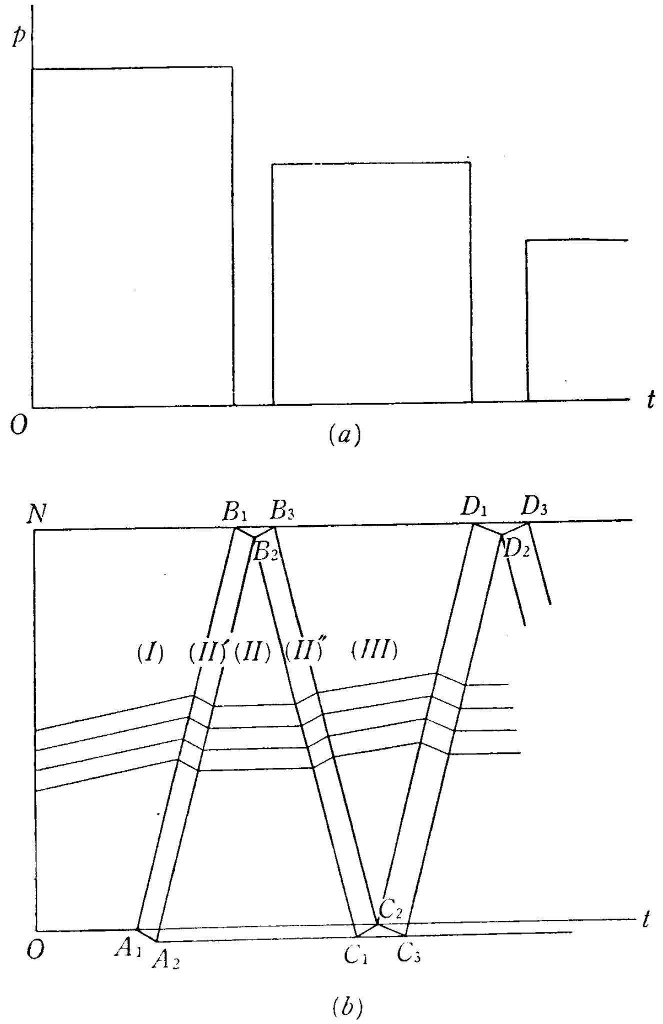

Fig. 3.

Thus the pressure at the nozzle falls suddenly at B_1, and rises suddenly at B_3, as shown in Fig. 3-a. Similarly it falls at D_1 and rises at D_3, and so on.

The pressure and velocity at each stage can easily be calculated by comparing the specific volumes of the oil. Let

p_1, p_2', p_2, p_2'' and p_3 = pressures in regions (*I*), (*II*)′, (*II*), (*II*)″, and (*III*) respectively, and

v_1, v_2', v_2, v_2'' and v_3 = velocities in regions (*I*), (*II*)′, (*II*), (*II*)″, and (*III*) respectively.

Then in region (*II*)′, we have

$$\left.\begin{aligned} &p_2' = 0\,, \\ &\frac{v_2'}{a} = -\left(\frac{p_1}{E} - \frac{v_1}{a}\right). \end{aligned}\right\} \tag{3}$$

and in region (*II*),

$$\left.\begin{aligned} &\frac{p_2}{E} = -\frac{v_2'}{a}\,, \\ &v_2 = 0\,. \end{aligned}\right\} \tag{4}$$

Inserting (3), we get

$$\frac{p_2}{E} = \frac{p_1}{E} - \frac{v_1}{a}\,. \tag{4$'$}$$

Comparing this equation with (1), we see that the pressure in region (*II*), Fig. 3, is equal to that in region (*II*), Fig. 1, which is as it should be, seeing that we have ignored the energy loss due to viscosity, etc.

Similarly the pressure in region (*III*), Fig. 3, must be equal to that in region (*III*), Fig. 1. Namely, in region (*II*)″,

$$\left.\begin{aligned} &p_2'' = 0\,, \\ &\frac{v_2''}{a} = \frac{p_2}{E}\,, \end{aligned}\right\} \tag{5}$$

while for region (*III*), p_3 and v_3 may be obtained from the following two equations:—

$$\left.\begin{aligned} \frac{p_3}{E} &= \frac{v_2'' - v_3}{a}, \\ v_3 &= c\gamma\sqrt{\frac{2(p_3 - p_c)}{p}}. \end{aligned}\right\} \qquad (6)$$

Or

$$\frac{p_3}{E} = \frac{v_2''}{a} + c^2\gamma^2 - c\gamma\sqrt{2\frac{v_2''}{a} + c^2\gamma^2 - 2\frac{p_c}{E}}. \qquad (7)$$

Inserting (5), we have

$$\frac{p_3}{E} = \frac{p_2}{E} + c^2\gamma^2 - c\gamma\sqrt{\frac{2(p_2 - p_c)}{E} + c^2\gamma^2}. \qquad (7)'$$

This equation is identical with (2).

4. Pressure Variation after Cut-off in an Injection System without Discharge Valve.

For sharp cut-off the oil in the pipe must be allowed to expand freely, for which purpose it is better that there is no valve checking the expansion of the oil. Of course there must be a non-return valve at the nozzle to prevent any inflow of gas from the cylinder. Fig. 4-b shows diagramatically the vibration of the oil after cut-off in such a case, and Fig. 4-a the pressure variation at the nozzle. As shown in the figure, a sharp cut-off will always be obtained.

5. Experiments.

Experiment were made to investigate the pressure variation after cut-off in the 3 cases enumerated above, viz.,

(a) with ordinary discharge valve,
(b) with the Bosch type discharge valve,
(c) without discharge valve.

The fuel pump used in these experiments was of the Bosch type, the diameter of the plunger being 7 mm. In case (a) the discharge valve of the fuel pump was replaced with a valve of ordinary shape, as shown in Fig. 5–a, while in case (c) it was removed.

In case (a) a pure open nozzle, as shown in Fig. 6–a, was used, while in cases (b) and (c) a non-return valve with a soft spring was placed at the nozzle, as shown in Fig. 6–b.

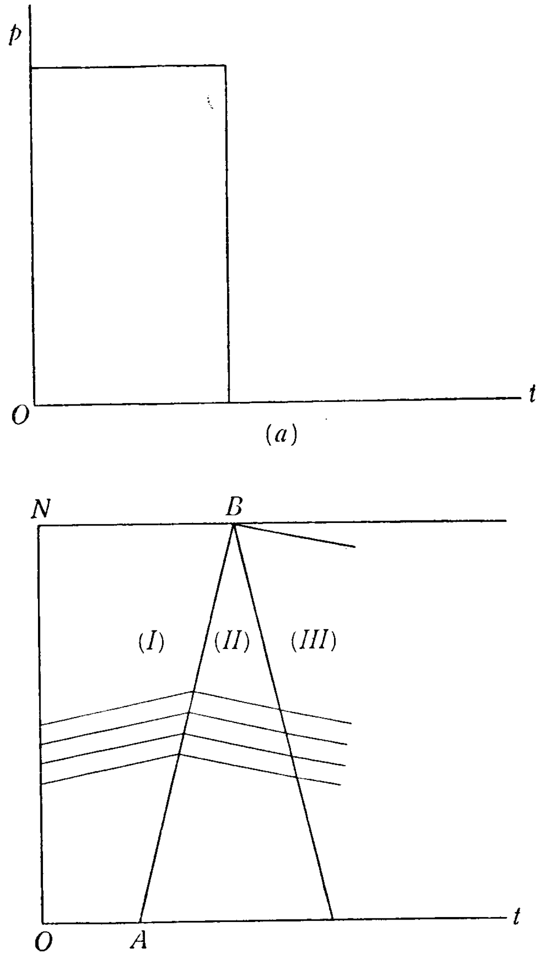

Fig. 4.

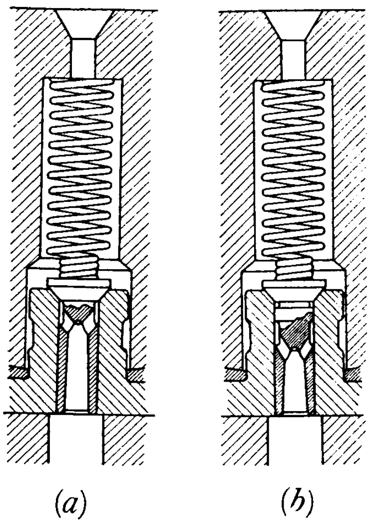

Fig. 5.

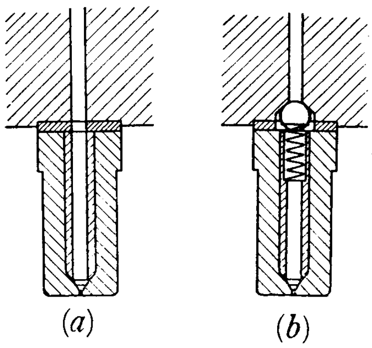

Fig. 6.

The fuel spray discharged into the atmosphere. The form of the pressure variation is not affected much by back pressure. The coefficient of discharge is, of course, slightly affected by the back pressure, but this effect is relatively small.

Experiments were made with injection pipes of various bores, but all 1 meter long. As has been explained in the previous paper, the length of the pipe, has almost no effect on the pressure variation after cut-off. The pressure-time curve is similar, only that it is lengthened in the direction of the time axis for longer pipes.

The experiments were arranged similarly to that described in the previous paper. The oil pressure was measured with a high-speed optical indicator invented by the authors(1). The natural frequency of its moving part is about 10,000 per sec. Moreover, the motion of its plunger is so small—about 0·02 mm for the maximum—that the volume change has virtually no effect on the pressure of the oil.

The position where the pressure was measured is about 45 mm distant from the nozzle. The construction of the nozzle and that of the indicator made it impossible to measure it closer to the nozzle.

The positions of the pump shaft were recorded on the pressure-time curve by means of light beams passing through slits in the fly-wheel attached to the pump shaft. 0° indicates the position where the plunger of the pump just covers the by-pass hole.

6. Results of Experiments.

A few examples of the pressure records are shown in Figs. 7-9. The diameter of the injection pipe and that of the nozzle and the number of revolutions of the pump shaft will be found in Table I.

Fig. 7 is that case in which the pipe is large compared with the nozzle. Fig. 7-a clearly shows that the pressure falls in step-like fashion. In Fig. 7-b the pressure at first falls suddenly, then rises to a considerable height, and falls again, and so on.

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

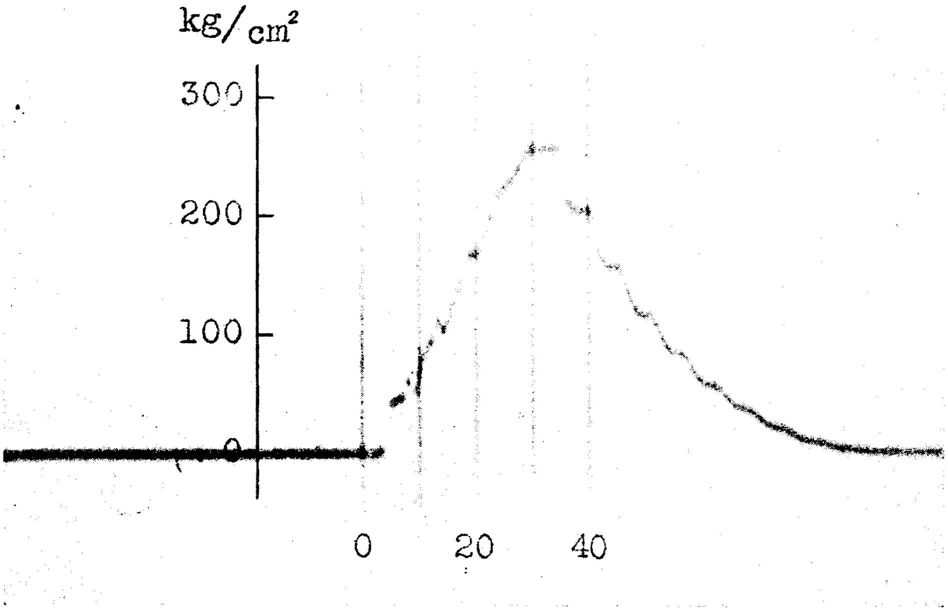

Fig. 7–a.

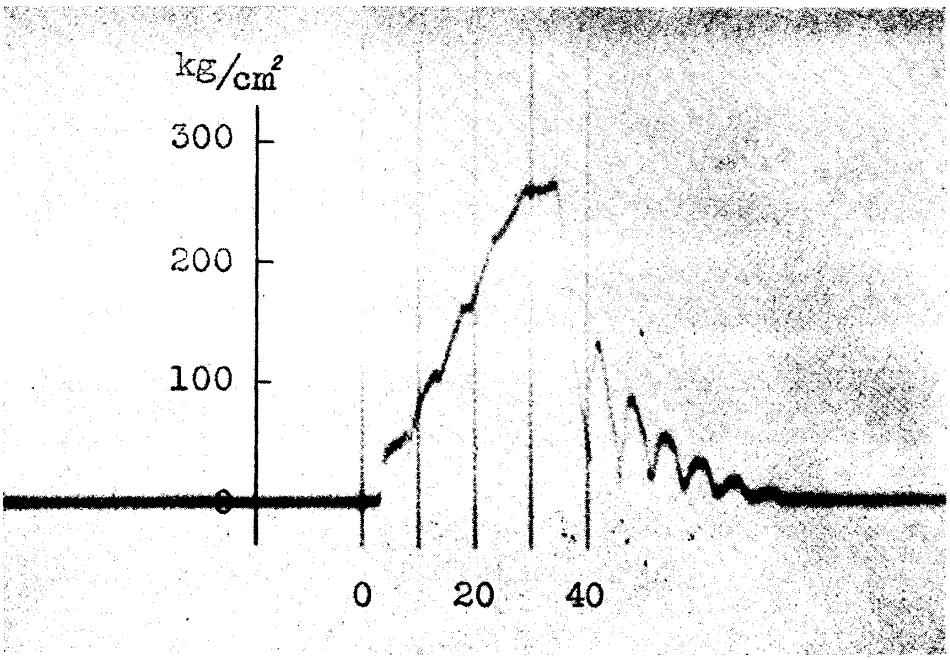

Fig. 7–b.

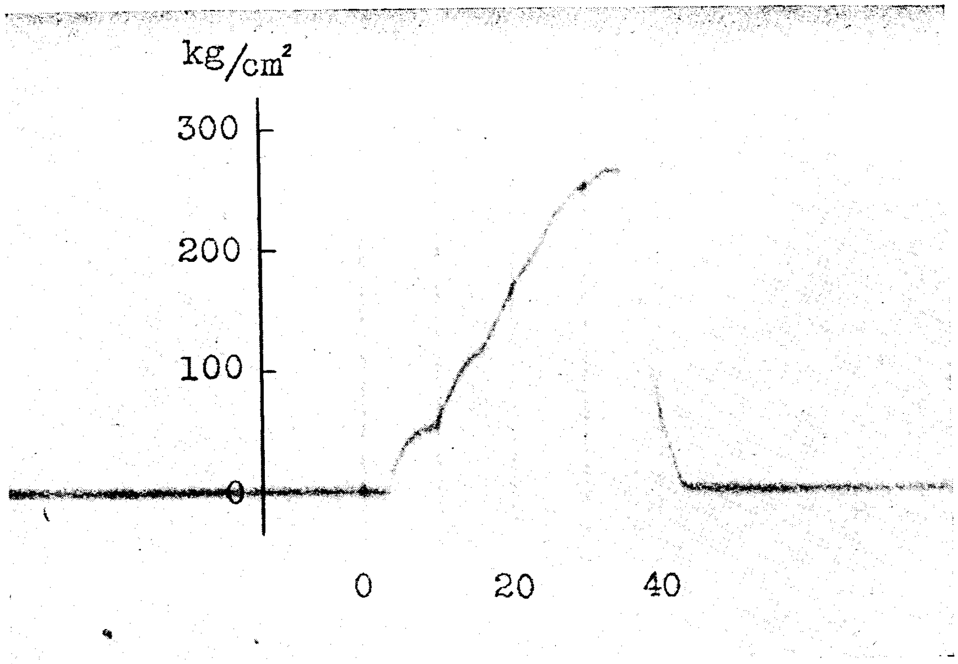

Fig. 7.–c.

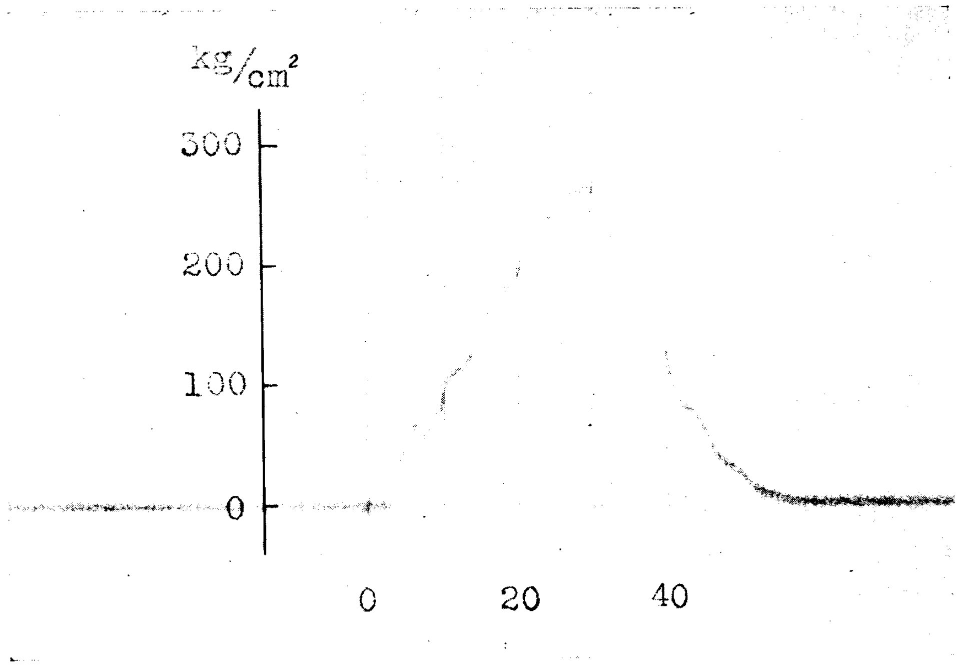

Fig. 8–a.

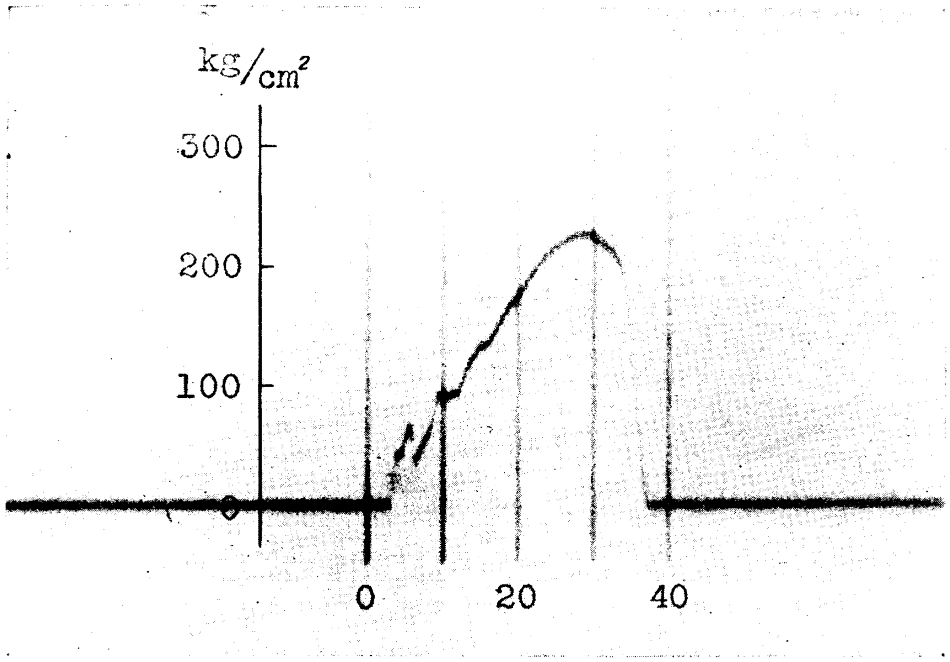

Fig. 8–b.

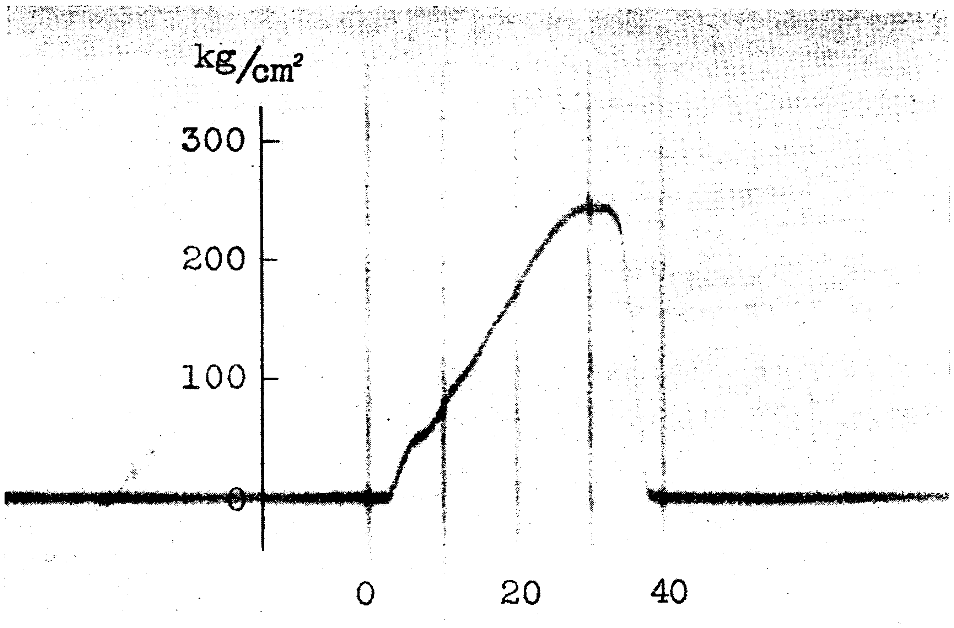

Fig. 8–c.

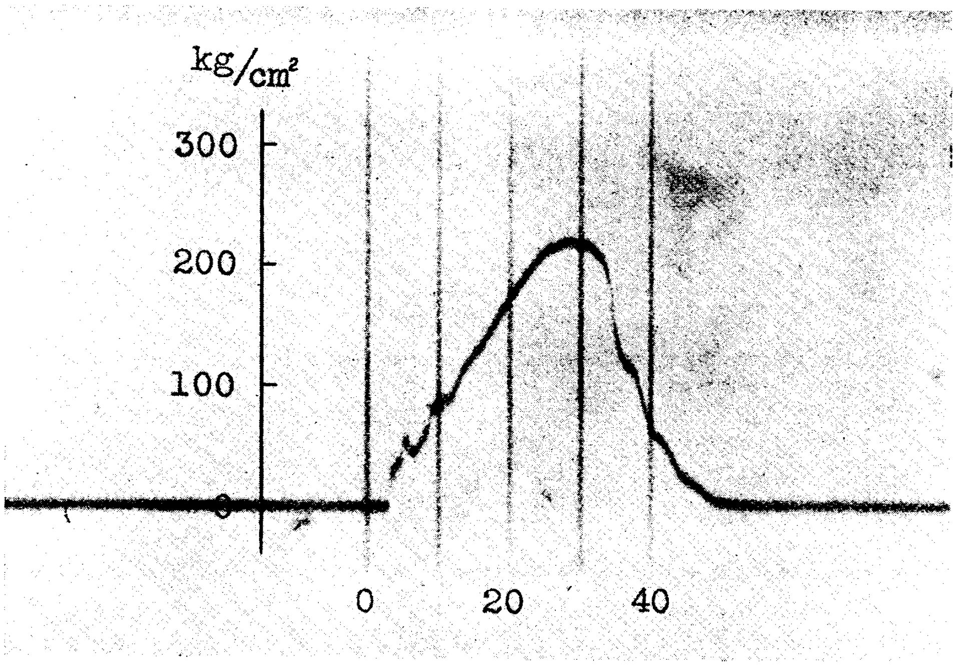

Fig. 9.–a.

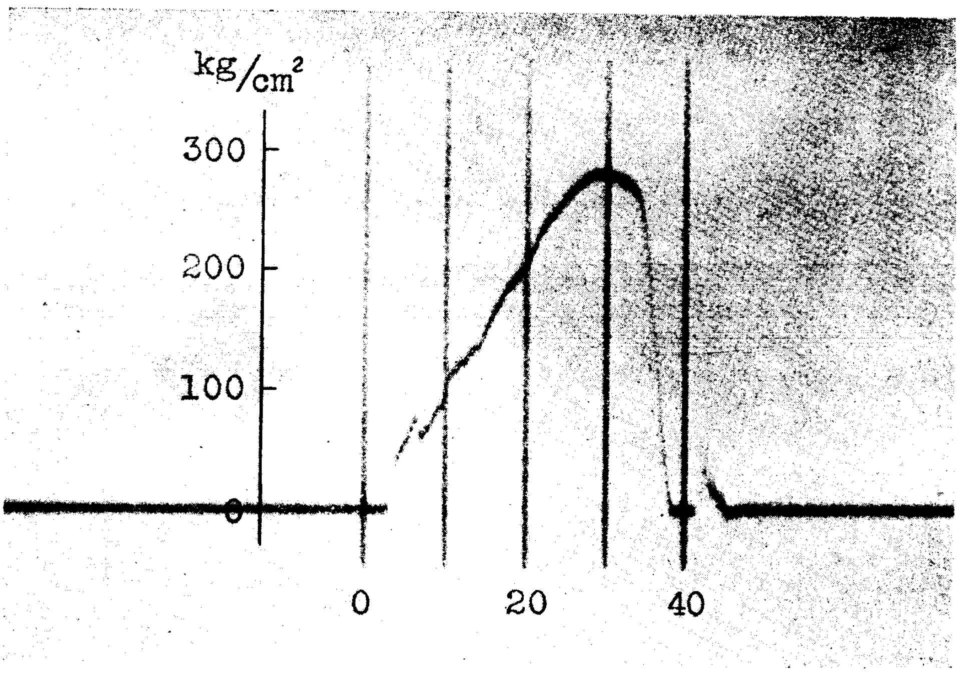

Fig. 9–b.

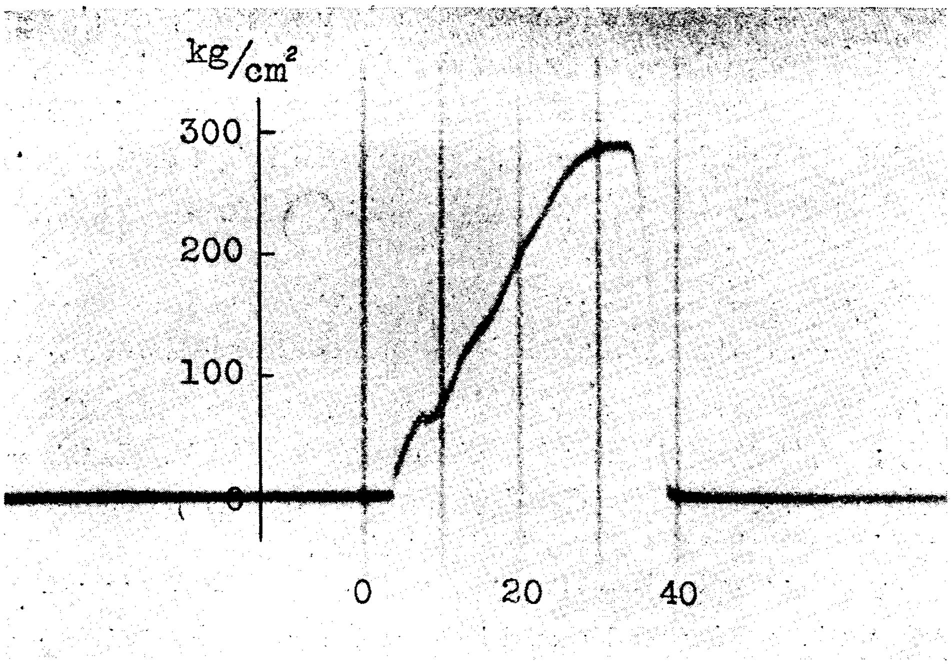

Fig. 9–c.

TABLE I.

Figs.	Discharge Valve	Dia. of Pipe in mm.	Dia. of Nozzle in mm.	r.p.m. of Pump Shaft
Fig. 7–a b c	With ordinary valve With Bosch type valve Without valve	2·85	0·28	500
Fig. 8–a b c	With ordinary valve With Bosch type valve Without valve	1·86	0·28	300
Fig. 9–a b c	With ordinary valve With Bosch type valve Without valve	1·86	0·28	367

From the calculation, the pressure, p_3, in a system with ordinary discharge valve was equal to the pressure, p_3, with the Bosch type valve, whereas in the experiment the pressure that corresponds to p_3 in case (b) is much lower than that in case (a). This is probably because the effect of viscosity was neglected in the calculation. In case (b) the vibration of oil in the pipe is very great, as shown in Fig. 3, so that the damping due to viscosity will be considerable, and the actual pressure corresponding to p_3 will become much lower than the calculated value. In case (a), however, the height of the pressure will not be greatly affected by the damping; the only effect being that the steps will alter in shape.

Fig. 7–c shows case (c); the cut-off is fairly sharp as was expected.

Fig. 8 illustrates the case of the pipe being smaller than that in Fig. 7. It will be seen from Fig. 8–b that the pressure is cut-off almost sharply; only a trace of secondary discharge being visible. In this case, the pipe being smaller the damping will be stronger. It is probably from this cause that the cut-off is almost sharp.

But should the pressure before the cut-off become higher, the damping will no longer be sufficient, and secondary discharge will occur. Fig. 9–b is such an example; the pipe and the nozzle in this case are the same as those in Fig. 8, only the revolution of the pump shaft is a little higher.

With removal of the discharge valve, sharp cut-off is always obtained, as shown in Figs. 8–c and 9–c.

7. Summary.

The effect of shape of discharge valve on the cut-off of fuel spray in injection systems with open nozzles may be summarized as follows:—

(1) When the discharge valve is of ordinary shape, and when the injection pipe is not so small compared with the nozzle, the form of he pressure-time curve is step-like.

(2) When the discharge valve is of the Bosch type, and when the injection pipe is large compared with the nozzle, variation of pressure after cut-off is very severe, at first the pressure at the nozzle suddenly falls then rises to a considerable height, falls suddenly again, and tso on.

(3) When the discharge valve is of the Bosch type, and when an injection pipe of suitable size is used, sharp cut-off is sometimes obtained.

(4) In the same injection system, however, a secondary discharge will take place should the pressure before the cut-off become higher.

(5) When the discharge valve is removed and a non-return valve placed at the nozzle, the cut-off is always sharp.