CCCCXXVI.—*Explosions in Closed Cylinders. Part III. The Manner of Movement of Flame.*

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SOME of the phenomena of explosions of methane and air in closed cylinders described in Parts I and II (preceding paper) can be explained by a study of the movements of flames under similar conditions by means of " snapshot " photographs on a stationary plate (see J., 1925, **127**, 760). In the examples reproduced in this paper, the flames are of carbon monoxide with oxygen, because their high actinic value renders them so serviceable for photographic analysis. The manner of movement of flame in mixtures of methane and air is essentially the same.

Ignition at One End of the Cylinder (compare Part I, A).—The photographs reproduced on Plate I are successive snapshots, at equal intervals of 4·1 millisecs. after ignition, of flame travelling in a mixture $10CO + O_2$, saturated with water vapour at 13·5°, after ignition at the centre of one end of a glass cylinder, 2·5 cm. in diameter and 20·3 cm. long, closed at both ends by rubber pads. The speed of flame in this mixture is comparable with that in a 9·5% methane–air mixture.

In the first snapshot, the flame appears as a small hemisphere centred on the point of ignition. In Fig. 2, no part of the tubular flame surface has as yet made contact with the walls of the cylinder, but its domed front has made rapid progress along the axis. In Fig. 3, the domed front has travelled still further, but the fringe of the luminous " skirt " has been extinguished. In Fig. 4, and thereafter, only the front portion of the flame surface remains, and that has changed its shape, having been turned inside-out owing to the sudden cooling of products of combustion behind it when the whole of the " skirt " came in contact with the walls of the cylinder.

The rapidly increasing speed of flame and development of pressure during the early stages of the explosion, remarked upon in Part I, are thus seen to be due to the increasing area of flame surface; the marked retardation and subsequent comparatively slow movement of flame and development of pressure are due to the sudden decrease in the area of the flame surface, consequent on the contact of all but its front with the walls of the cylinder, and to the sudden increase in the area over which the products of combustion are cooling. Although discussion of the matter is outside the scope of the present paper, we should mention that we regard the initial retardation of movement of the flame surface as being due to the retardation of movement of the medium in which it is travelling. This initial retardation is accentuated by the sudden cooling of the products of combustion behind the flame surface (see *Fuel*, 1928, **7**, 195; compare Payman, *Proc. Roy. Soc.*, 1928, *A*, **120**, 90).

The individual snapshots of Plate I, together with subsequent snapshots at equal intervals until the flame had wholly expired, are shown as a composite photograph on Plate II. A record of the same flame taken on a revolving film is reproduced for comparison. The sudden retardation in the progress of the flame occurred when it had travelled about one-third of the length of the cylinder. Thereafter, its speed was nearly uniform until it reached the end. In this respect the explosion of $10CO + O_2$ in this comparatively short cylinder differed from the 9·5% methane–air explosions in a cylinder 10 cm. in diameter and 200 cm. long (described in Part I), inasmuch as in the latter the flames exhibited vibrations, and an increased speed, towards the end of their travel. In a glass cylinder 2 cm. in diameter and 40 cm. long, the flames in the mixture $10CO + O_2$ sometimes vibrated.

Position of Point of Ignition varied (compare Part I, B).—The effect of varying the point of ignition is illustrated in Figs. 1, 2, and 3 on Plate III. For these experiments the cylinder was 2 cm. in diameter and 40 cm. long, and the explosive mixture used was $10CO + O_2$. Ignition, on the axis of the cylinder, was at one end (Fig. 1), at the middle (Fig. 2), and midway between the middle and one end (Fig. 3). With ignition at the middle, the flame surfaces vibrated, and their mean speed increased, towards the end of their travel. The flame surface, being a mobile source of pressure in an enclosed space, tends to centre itself within the cylinder, so that when ignition is not at the middle it moves most rapidly towards the region of greatest volume. Cooling does not occur until the flame surface touches the walls, but, owing to its elongated shape at that moment (see Fig. 3, Plate III), cooling is then considerable. For this reason, and because of the sudden diminution in area of the flame surface, there is a sudden retardation in the movement of the flame (and in the development of pressure). The flame continues to propagate on two fronts (so that the rate of production of pressure tends to be double what it is when ignition is at one end of the cylinder), travelling faster towards the farther than towards the nearer end. It expires first at the nearer end, the system at that moment suffering both a reduced production of energy and an increased dissipation due to cooling. The speed of the remaining flame surface is therefore retarded. It thus results that, although when ignition is asymmetric the two flame surfaces nearly reach the two ends of the cylinder simultaneously, there is a comparatively

FIG. 1.

FIG. 2.

FIG. 3.

FIG. 4.

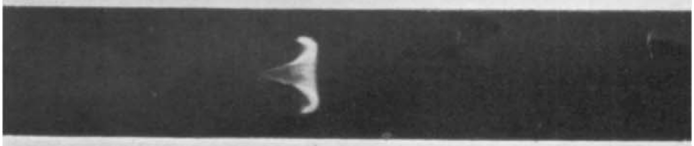

FIG. 5.

FIG. 6.

FIG. 7.

FIG. 8.

PLATE I.

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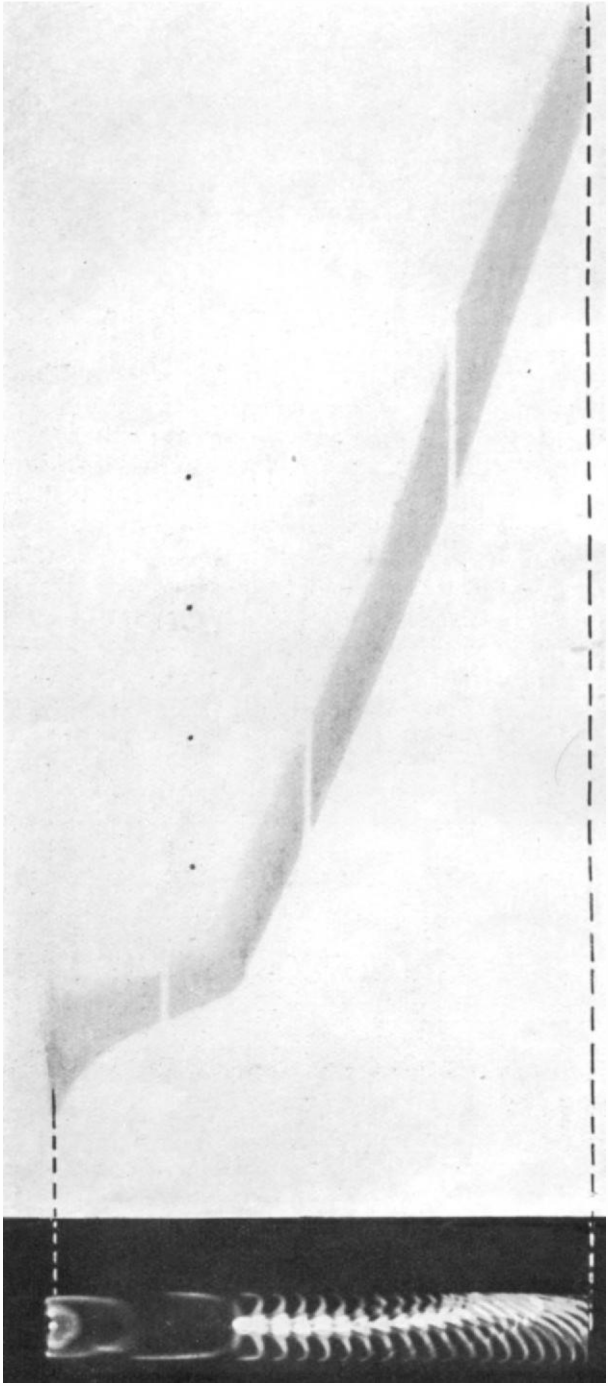

Plate II.


Fig. 1.


Fig. 2.


Fig. 3.

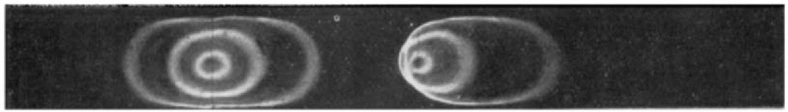
Fig. 4.


Fig. 5.

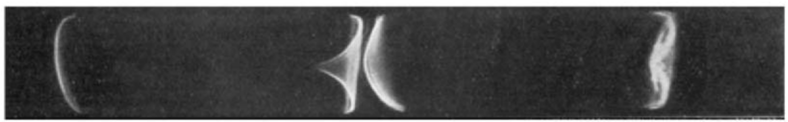
Fig. 6.

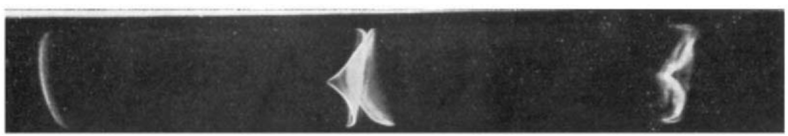
Fig. 7.

Plate III.

Fig. 1.

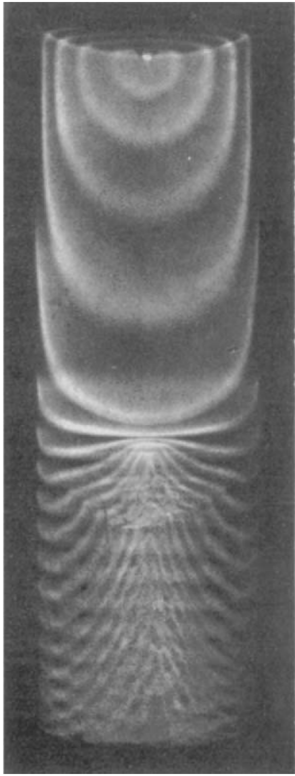

Fig. 2.

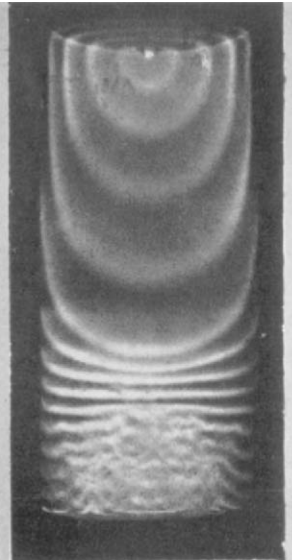

Fig. 3.

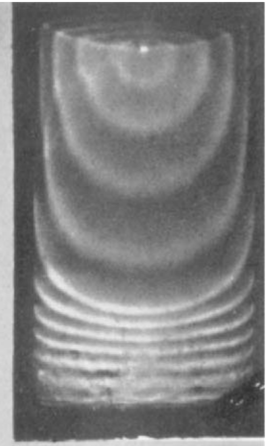

Plate IV.

long interval between the expiration of the flame at the nearer end and its final expiration at the farther end. The more asymmetric the point of ignition, the greater is this interval, and the less, in consequence, is the maximum pressure developed.

Simultaneous Ignition at Two Points (compare Part I, C).—When an explosive mixture within a cylinder is ignited simultaneously at two points, not too close together, the initial rate of rise of pressure should be twice as fast as with single ignition unless the two flames hinder each other's development. Actually, the two flames do hinder each other, each developing a smaller surface area in a given time than it would if the other were absent. This is illustrated in Fig. 4, Plate III, which is a composite photograph of three successive snapshots, at equal intervals of 9·63 millisecs. after ignition, of flames in a mixture $13CO + O_2$, saturated with water vapour at 14°, contained in a closed horizontal glass tube 4 cm. in diameter and 32 cm. long. The mixture was ignited simultaneously at the middle of the cylinder and midway between the middle and one end. The two continuous flame surfaces tend to dispose themselves symmetrically. That on the left centres itself within the left-hand half of the tube, not within the tube as a whole as it would tend to do if it were alone. The right-hand flame surface moves bodily towards the right.

When contact occurs between the flame surfaces and the walls of the cylinder, the area of contact is nearly twice that when ignition is at one point only, and the rate of cooling is nearly twice as great. The net rise of pressure subsequently is therefore small, though the pressure is maintained from four sources whereas with single ignition there are but two. Figs. 5, 6, and 7 on Plate III are single snapshots (taken, respectively, 48·15, 57·78, and 62·59 millisecs. after ignition) of the flame surfaces after contact with the walls of the cylinder had occurred. They show the remarkably slow approach of the two inner flame surfaces towards each other.

With a 25% carbon monoxide–air mixture, saturated with water vapour at 11·8°, a number of experiments were made with different conditions of ignition in a glass cylinder 6 cm. in diameter and 32 cm. long. The durations of the flames under these different conditions are recorded in Table I.

The shortest duration of flame was thus with symmetrical double ignition at such a distance from the ends of the cylinder that there is no initial cooling; and the longest was with single-end ignition.

The Effect of the Length of the Cylinder (compare Part II).—Fig. 1 on Plate IV shows a succession of snapshots, at intervals of 4·1 millisecs. after ignition, of the flame in a mixture $10CO + O_2$, saturated with moisture at 15°, ignited at the end of a vertical closed

TABLE I.

Carbon Monoxide and Air (25% CO), *ignited within a Horizontal Glass Cylinder* (6 × 32 cm.).

	Distance along tube, cm.					Duration of flame, centisecs.
	0.	8.	16.	24.	32.	
Ignition at points indicated (I).	I	—	—	—	—	22·1
	I	I	—	—	—	17·5
	I	—	I	—	—	12·3
	I	—	—	I	—	11·0
	I	—	—	—	I	14·2
	—	I	—	—	—	15·1
	—	I	I	—	—	11·4
	—	I	—	I	—	9·3
	—	—	I	—	—	14·4

cylinder, 5·0 cm. in diameter and 17 cm. long. The cylinder was placed vertically to secure symmetry of the flame surfaces and thus render their movement during the later stages clearer than it is when the cylinder is horizontal (see, *e.g.*, Fig. 1, Plate III). Fig. 1, Plate IV, should be compared with Figs. 2 and 3, for which the conditions of experiment were identical save that the cylinder was reduced in length to 12 cm. (Fig. 2) and 9·5 cm. (Fig. 3). It is evident that the greater the length of the cylinder the more freely does the flame surface move along its axis. It is evident, also, that at the moment when the flame surface has made contact with the walls, and rapid cooling of the products of combustion has begun, a greater proportion of the mixture has been burnt in the shortest than in the longest cylinder, so that a higher maximum pressure would be recorded in the former.

The experiments described in this paper were carried out in connexion with work that we are doing for the Safety in Mines Research Board, to whom our thanks are due for permission to publish these results.

SAFETY IN MINES RESEARCH LABORATORIES,
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