423. *The Propagation of Flame in Electric Fields. Part II. The Effects of Transverse Fields.*

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SEVERAL investigators, to whose work we referred in Part I (J., 1931, 195), have studied the effects of an electric field transverse to the direction of travel of the flame in explosive gaseous mixtures. Some of their observations, which related more particularly to the mean speeds of the flames, are apparently contradictory. In the present work an attempt is made to analyse the manner of propagation of flame under the influence of an electric field, and to adjudge the effects of the factors involved

The effect of the shape of the flame front on the speed of the " uniform movement " has been clearly demonstrated by Coward and Hartwell (this vol., p. 1996), who recall that Gouy (*Ann. Chim. Phys.*, 1879, **18**, 5) had postulated that the amount of a gaseous mixture burnt in a flame is proportional to its surface area, and that Ellis (see, *e.g.*, *Fuel*, 1928, **7**, 195) has consistently maintained this to be true under certain conditions. Coward and Hartwell's work proves that, during the uniform movement in mixtures of methane and air, unit area of flame surface burns a certain volume of the mixture in unit time, so that the effective speed of propagation of flame is proportional to the area of the flame surface during its travel.

In a study of the speed of propagation of flame under any conditions, *e.g.*, along a tube, the following factors must be taken into account: (i) The speed of transmission of the chemical reactions of combustion from " layer to layer " of the mixture; *i.e.*, the " absolute " speed of the flame. (ii) The movement of the gas mixture as a whole, either by conditions purposely imposed on it or by reason of pressure gradients induced by the flame itself. (iii) Cooling of the hot products of combustion, *e.g.*, by contact with the walls of the vessel containing the explosive mixture. (iv) The shape assumed by the flame surface, dependent on (ii) and (iii) and on the operation of convection currents in the immediate vicinity of the flame.

Under the influence of an electric field, other factors may be presumed to operate, *viz.*: (v) Change in the speed of the chemical reactions owing to the movement of gaseous ions. (vi) Change in the movement of the flame gases due to the mechanical pull of the field on the electrically charged positive ions. (vii) Alteration in the area of the flame surface as a result of (vi).

For our study of the effects of transverse electric fields, flames have been produced under three different conditions: (*a*) Moving downwards in a tube against a steady upflow of explosive mixture (cf. Malinowski, *J. Chim. physique*, 1924, **21**, 469; Bernackyj and Retaniw, *Ukrain. Phys. Abhand.*, 1928, **2**, 9; Haber, *Sitz. Preuss. Akad. Wiss., Phys.-Math.*, 1929, **11**, 162; and Malinowski and Lawrow, *Z. Physik*, 1930, **59**, 690); (*b*) travelling upwards from an open to a closed end of a vertical tube; and (*c*) travelling from the lower to the upper end of a closed vertical tube (cf. Thornton, *Phil. Mag.*, 1930, **56**, 260).

From our observations we conclude that, under the conditions of experiment, changes in the speeds of the flames following the imposition of transverse electric fields are due mainly to changes in their surface areas.

Experimental.

In all the expts., the electrical condenser, between the plates of which the field was produced, consisted of an axial rod of steel and a helical winding, outside the glass tube, of fine Cu wire. This arrangement made it possible to observe the flames closely and to obtain snapshot photographs of them. The internal diam. of the glass tubes was about 3 cm., and the diam. of the axial rod was such that the width of the annular space was in no case less than 1 cm. Cooling of the flame by the walls of the tube was therefore never a prominent factor.

One plate of the condenser, continuously charged by means of a transformer and a synchronous mechanical rectifier, was connected to an external condenser to maintain a steady field; the other plate was earthed. The effective potential gradient across the highly conductive flame gases was less than that across the complete condenser, for most of the drop in potential occurred across the glass wall of the tube. With potentials exceeding 12,000 volts, conduction through the flame was so rapid as to cause the momentary neutralisation of the charge on the axial rod and the building up of a charge on the inner surface of the glass tube. This caused an intermittent alteration, or oscillation, of the electric field and a consequent breaking up of the flame surface, which greatly increased its area.

(a) *Downward Movement of Flame Against a Gas Stream.*—The apparatus used, which resembled that of Malinowski (*loc. cit.*), is illustrated in Fig. 1. The internal diameter of the glass tube was 3·2 cm., and the length of the electrical condenser 20 cm.

Air and inflammable gas were stored separately in cylinders under press. and delivered through orifice flow-meters to a mixing chamber and thence to the apparatus. Currents of mixtures of any composition could thus be caused to flow at the desired speeds through the annular space between the plates of the condenser. Ignition was effected by an electric spark over the open top of the tube.

Acetylene and air. With a mixture containing 3·5% C_2H_2, the speed of the current was adjusted so that the flame just could not move downwards against it. The axial rod of the condenser was then charged positively to a potential of 5,000 volts. The flame moved rapidly downwards.

With a rather richer mixture, 4% C_2H_2, and the same speed of current, the flame could move slowly downwards when no electric field was imposed. With the axial rod charged positively to 5,000 volts, the speed of the flame was trebled. From the series of snapshot photographs obtained, at intervals of 145 millisecs., by the method of Ellis and Robinson (J., 1925, **127**, 764), Fig. 2 has been constructed (prints from the photographs being too faint for reproduction). The increased speed and larger area of the flame under the influence of the electric field are clearly shown.

FIG. 1.

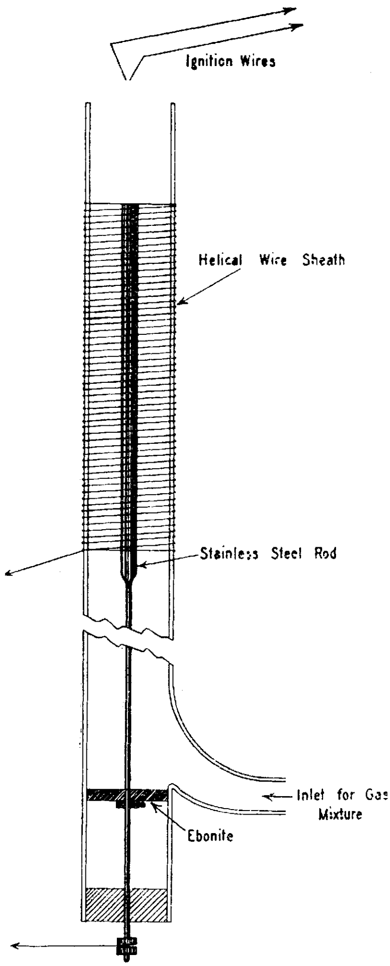
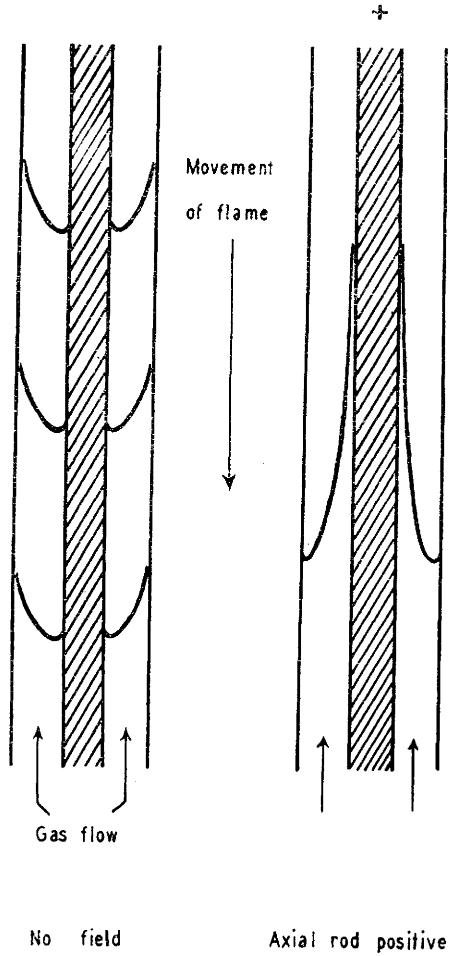


FIG. 2.



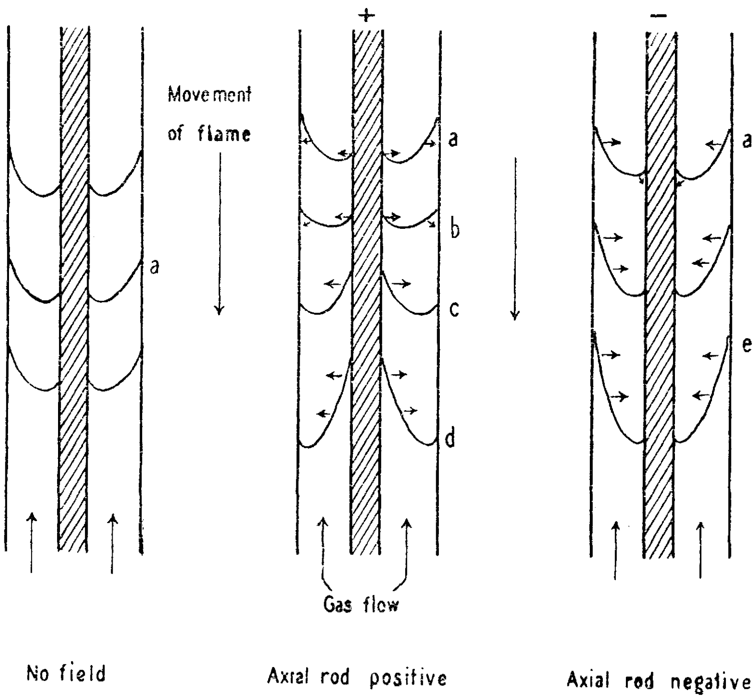
With a mixture containing a large excess (22%) of C_2H_2, only the primary flame moved downwards, and C was deposited on the surfaces of the tube and axial rod. An increase in the speed of the flame was obtained when either plate of the condenser was charged positively to 5,000—10,000 volts.

Carbon monoxide and air. With mixtures of CO and air, the flames can readily be photographed. The following experiments were made with a mixture containing 29·4% CO.

With no electric field, the current was so adjusted that the flame passed down the condenser at a mean speed (relative to the tube) of 41·5 cm./sec. The shape of the flame front, through the " nose " of which the axial rod of the condenser passed, is illustrated in Fig 3 at *a*.

With the axial rod charged positively, no change was observed until the voltage reached 4,000, whereupon the flame front became rather flatter, as at *b* (Fig. 3), and its speed fell to 39·3 cm./sec. With a voltage of 5,000, the speed of the flame was 38·6 cm./sec. On increasing the charge to 6,000 volts, a further change in the shape of the flame front occurred, the foremost part

FIG. 3.



occupying a position within the annulus nearer to the wall of the tube than to the axial rod, as at *c* (Fig. 3). This change was accompanied by an increase in the mean speed of the flame to 52·8 cm./sec. Further increase in the voltage caused this change of shape to become more marked, as at *d* (Fig. 3), the flame front becoming more elongated and sometimes broken. Typical snapshot photographs from which Fig. 3 was constructed are reproduced on Plate I. Measurements of the speeds were :

Charge (+), volts.	8,000	10,000	16,000
Mean speed of flame, cm./sec.	53·5	55·5	75·0

When the axial rod was charged negatively, up to 8,000 volts, the shape of the flame front became slightly elongated, as at *e* (Fig. 3), and its speed was about 47 cm./sec. At higher potentials, the flame front became broken and parts of it showed a tendency to revert to the shape *c* (Fig. 3), probably because of the momentary break down and reversal of direction of the field to which reference has been made earlier. Measurements of the speeds were :

Charge (—), volts	6,000	8,000	9,000	12,000
Mean speed of flame, cm./sec.	41·8	47·0	52·0	70·4

When the outer helical wire was charged, either positively or negatively, similar results were obtained to those under the reverse conditions, but rather higher voltages were required.

(b) *Upward Movement of Flame in a Vertical Tube Closed at the Upper End.*—A glass tube, 96 cm. long and of 3 cm. internal diam. was used. The condenser was formed by an axial rod of steel, 0·62 cm. in diam., extending from the upper, closed end of the tube to within 18 cm. of the open end, and a helical winding of Cu wire, 48 cm. long, beginning 18 cm. from the open end. Thus, when an inflammable mixture was ignited (by an electric spark) at the open end of the tube, the flame travelled 18 cm. before it entered the annular space of the condenser.

In many expts. in which no electric field was imposed, the flame surface during the early stages of its movement was unsymmetrical, being tilted at an angle to the axis of the tube (see a, Plate II). This was probably due either to a slight asymmetry of the spark used to cause ignition or to some movement of the air across the open end of the tube at the moment of ignition. When an electric field was imposed, the flame surface became symmetrical as soon as it entered the condenser (see b, Plate II), as though the pull of the field controlled the shape of the flame.

With mixtures of CO and air containing 28·5% CO and saturated with H_2O vapour at 17°, snapshot photographs of the flames were taken during the uniform movement that lasted over their first 38 cm. of travel. Although the flame front was sometimes slightly broken on entering the annulus of the condenser, a number of photographs of stable flames were obtained from which, on enlargement, the approximate areas of the flame surfaces could be measured.

With the axial rod charged positively, the following results were obtained :

Potential across condenser, volts.	Speed of flame, cm./sec.	Area of flame surface, sq. cm.	Ratio speed/area.
Nil	52·5	10·15	5·2
6,000	46·8	9·70	4·8
10,000	52·5	10·05	5·2
14,000	71·0	14·00	5·1

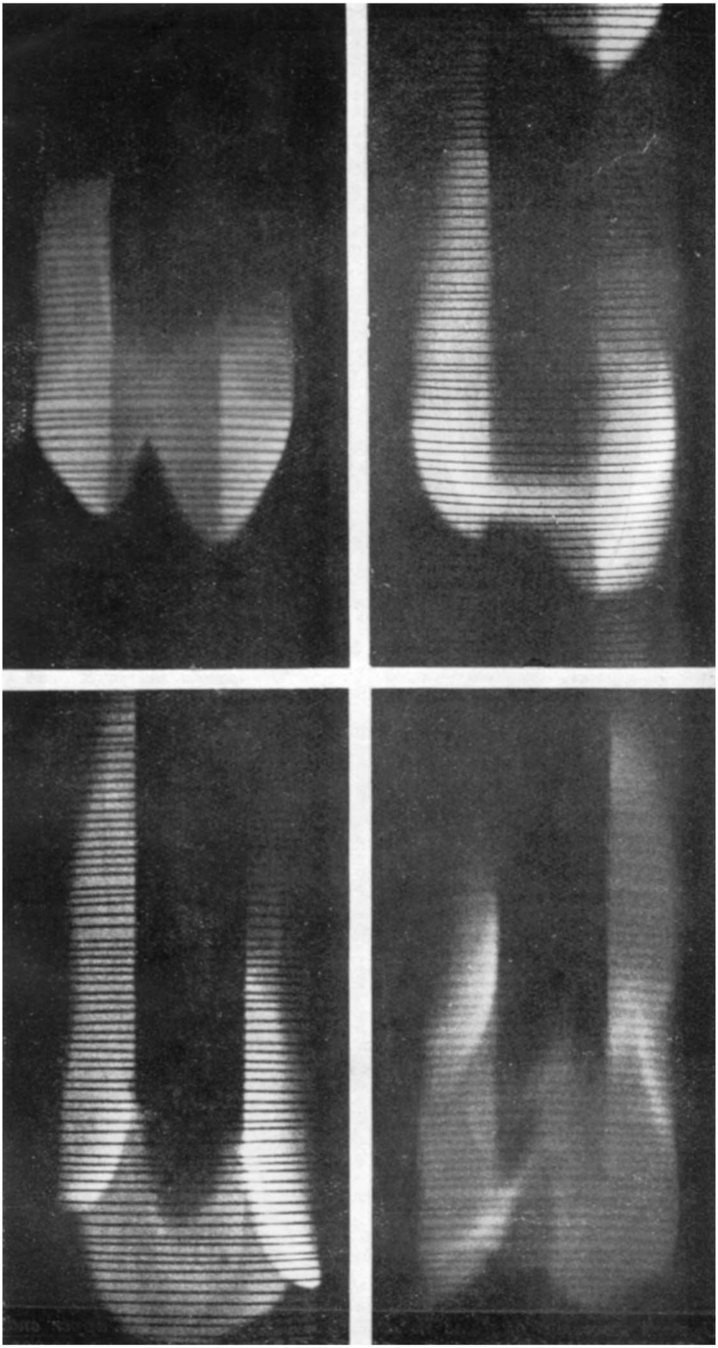
Typical series of snapshot photographs, taken at intervals of 77 millisecs., are reproduced on Plate II. The black bands across some of the photographs are caused by strips of paper placed as reference marks 20 cm. apart.

(c) *Upward Movement of Flame Within a Vertical Closed Tube.*—A glass tube 1 m. long and of 3 cm. internal diam. was used. This was fitted with an axial rod of steel and an outer helical winding of Cu wire over the middle 80 cm.

With a weak mixture of CO and air (13% CO), ignited by an electric spark at the lower end of the tube, electric fields with charges up to 16,000 volts had but little effect on the movement of the flame. Apparently, the dominating factors in controlling the shape of the flame under the experimental conditions were the press. gradients of the explosion. With mixtures of C_2H_2 and air, however, the speed of the flames, which are known to be

PLATE I.

(a) (b)



(c) (d)

Downward movement of flame against a gas stream. Carbon monoxide and air.
(a) *No field*; (b) 4,000; (c) 8,000; (d) 16,000 *volts*.

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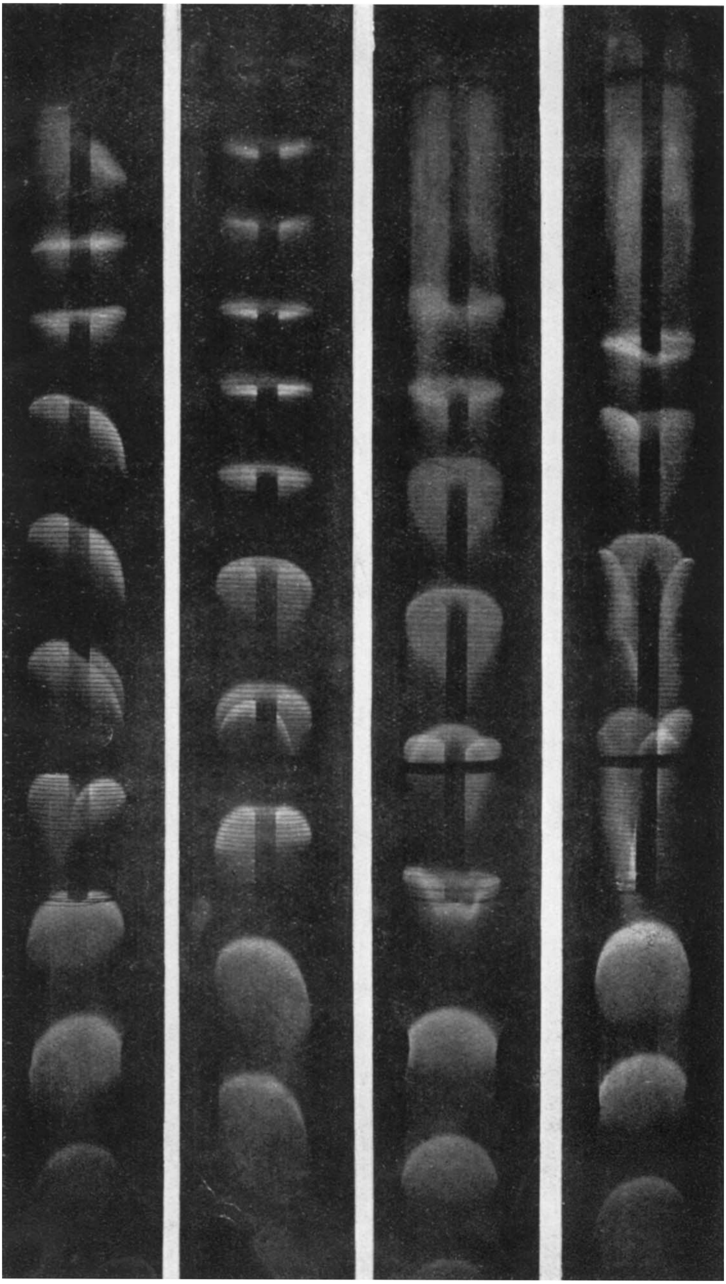
PLATE II.

(a) (b) (c) (d)



Upward movement of flame in a vertical tube closed at the upper end. Carbon monoxide and air. (a) *No field*; (b) 6,000; (c) 10,000; (d) 14,000 *volts.*

highly ionised, increased markedly when the axial rod of the condenser was charged positively at 10,000 volts or more.

DISCUSSION.

It is evident that assessment of the effect of an electric field on any particular form of moving flame necessitates a careful analysis of the separate effects of other factors that may govern its propagation.

Our experimental results, which confirm those of Thornton (*loc. cit.*) and Lewis (*J. Amer. Chem. Soc.*, 1931, **53**, 1304) with mixtures of methane and air, demonstrate that the changes produced by a transverse electric field on the speed of propagation of flame are due to changes in the shape and area of the flame surface. It is probable that the extinction of flames in rich mixtures of hydrocarbons with air by a transverse electric field, observed by Malinowski and others, was due to the flame surface becoming enlarged and, in consequence, excessively cooled by the metal walls of the narrow annular spaces (never more than 5 mm. wide and often as little as 1·5 mm.) through which the flames had to travel.

From the nearly constant relationship between the speed of flame under the influence of an electric field and the area of its surface with or without the field, we conclude that in our experiments the field had no effect on either the character or the speed of the chemical reactions. The changes that occurred in the shapes and areas of the flames (see Fig. 3) can be explained as being due to a mechanical drag exerted by the field on flame, which behaves, as illustrated in Part I of this research, as a positively charged mass of gas. The short arrows in Fig. 3 indicate the directions of the drag on the flames in those experiments.

The nature of the ions present in the flames, and the mechanism of their production, have not yet been fully elucidated. Experiments now in progress are directed to those problems.

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