VI.—*The Propagation of Flame in Mixtures of Methane and Air. Part V. The Movement of the Medium in which the Flame Travels.*

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PART IV of this research (J., 1926, 2139) described the determination of the conditions under which the flame travelling along a tube in a mixture of methane and air, initially quiescent and at atmospheric temperature and pressure, acquired its maximum speed. When the tube was 2—3 m. in length and 5 cm. in diameter, the conditions were that both ends should be open (ignition of the mixture being at one end) and that a number of restricting rings, reducing the diameter of the tube to one-half, should be introduced close together a short distance (50—100 cm.) from the point of ignition. Under these conditions, a speed as high as 420 m./sec. was obtained beyond the restrictions, the highest speed in an unrestricted tube of the same dimensions being about 6 m./sec.

It was shown that, during the propagation of flame in a tube open at both ends, the unburnt mixture in advance of the flame-front travels as a current in the same direction, and the flame is therefore moving in a medium which is itself in motion. The flame-speed at any point in the tube thus depends largely on the speed acquired by the medium, and the effect of restrictions is explained as being mainly an effect on the movement of the medium.

We have continued the study of the propagation of flame under different conditions in tubes restricted at certain points so as to control the movement of the unburnt mixture ahead of the flame. In this manner, we hoped to gain further information regarding the extent to which the movement of the flame depends on that of the medium in which it travels. All the experiments were made with a mixture of methane and air containing 9·5—10·0% of methane, using the brass tube, 5 cm. in diameter and 240 cm. long, previously described. The behaviour of the flame was studied by photographing it through a quartz lens on a rapidly revolving film as it passed a quartz window, 40 cm. long and 4 mm. wide, which could be placed in any desired position along the tube.

We have attempted to explain all the following results on the assumption that, under all conditions, there is a movement of the unburnt mixture ahead of the flame caused by the expansive force of the burning gases.

(A) *Ignition at One End of a Horizontal Tube Open at Both Ends.*

It has been recorded that when the tube is fully open at both ends the speed of the flame increases regularly over the first 80 cm. and is then slightly retarded (undulations making their appearance) to increase again after this temporary check. The initial acceleration of the flame is assumed to be due to the increasing speed with which the unburnt mixture is caused to move under the expansion of the burning gases. The acceleration would no doubt continue regularly throughout the length of a sufficiently short tube, but, in such a long tube as that used, cooling and condensation of the products of combustion cause a fall in pressure behind the flame which reduces the rate of acceleration of the unburnt mixture. As the flame travels further from the open end, the deficiency of pressure due to cooling and condensation being then less readily rectified by communication with the external atmosphere, the unburnt mixture, and therefore the flame, is retarded.

(a) *The Influence of a Restriction at the Ignition End of the Tube.*—The mean speeds of the flame over successive intervals when the end of the tube at which ignition was effected was reduced in diameter to 1·5 cm. are recorded in Table I. The speeds when the tube was fully open at both ends (see Part IV, Table I) are given for comparison. Similar, but less marked, results were obtained when the diameter of the tube at the ignition end was reduced to 2·5 cm.

Fig. 1, Plate I, is a composite photograph,* obtained in the manner described in Part IV, illustrating the manner in which the flame travels in a 9·75% methane–air mixture. This photograph should be compared with Fig. 1, Plate I, of Part IV.

TABLE I.

The Effect of Restricting the Ignition End of a Tube Open at Both Ends.

Distances from point of ignition (cm.).	Mean speed of flame (cm./sec.). Tube fully open at both ends.	Mean speed of flame (cm./sec.). Diam. at ignition end reduced to 1·5 cm.	Distances from point of ignition (cm.).	Mean speed of flame (cm./sec.). Tube fully open at both ends.	Mean speed of flame (cm./sec.). Diam. at ignition end reduced to 1·5 cm.
5—15	106	192	85— 95	249	827
15—25	134	220	95—125	229	1034
25—35	152	260	125—135	285	900
35—65	194	412	135—145	350	791
65—75	240	618	145—175	441	1016
75—85	254	721	175—205	575	1800

* This photograph is reduced to about $\frac{1}{5}$th of the size of the original; allowing for this, the speed of travel of the film can be regarded as 11·5 cm./sec.

The partial closure of the ignition end impedes the release of pressure at that end, so that a greater and more prolonged pressure is available to propel the column of unburnt mixture ahead of the flame. The speed of the flame is thus more rapidly accelerated than when the ignition end of the tube is fully open, and a further distance is travelled (125 cm. as compared with 80 cm.) before the influence of cooling behind the flame causes a retardation. This retardation is, however, greater in the former case, there being a 25% as compared with a 10% reduction in speed, because communication with the outside air is restricted.

(b) *The Influence of a Restriction at the Ignition End of the Tube together with Restrictions in the Path of the Flame.*—When the end of the tube at which the mixture was ignited was partly closed and one or more restricting rings were introduced at intervals along the tube, the speed of the flame during its passage depended upon the amount of restriction at each point, except that reduction of the diameter of the tube at the ignition end to 1·5 cm. or less was no more effective than reduction to 2·5 cm. Indeed, when there were two or three restrictions in the tube, the maximum effect on the speed of the flame was obtained when the diameter at the ignition end was 2·5 cm., whilst, as recorded in Part IV, when there were several restrictions close together, the maximum effect was obtained with both ends of the tube fully open.

The mean speeds of the flame before and after passing one restricting ring, 110 cm. from the ignition end of the tube, the diameter of which was reduced to 2·5 cm., are recorded in Table II.

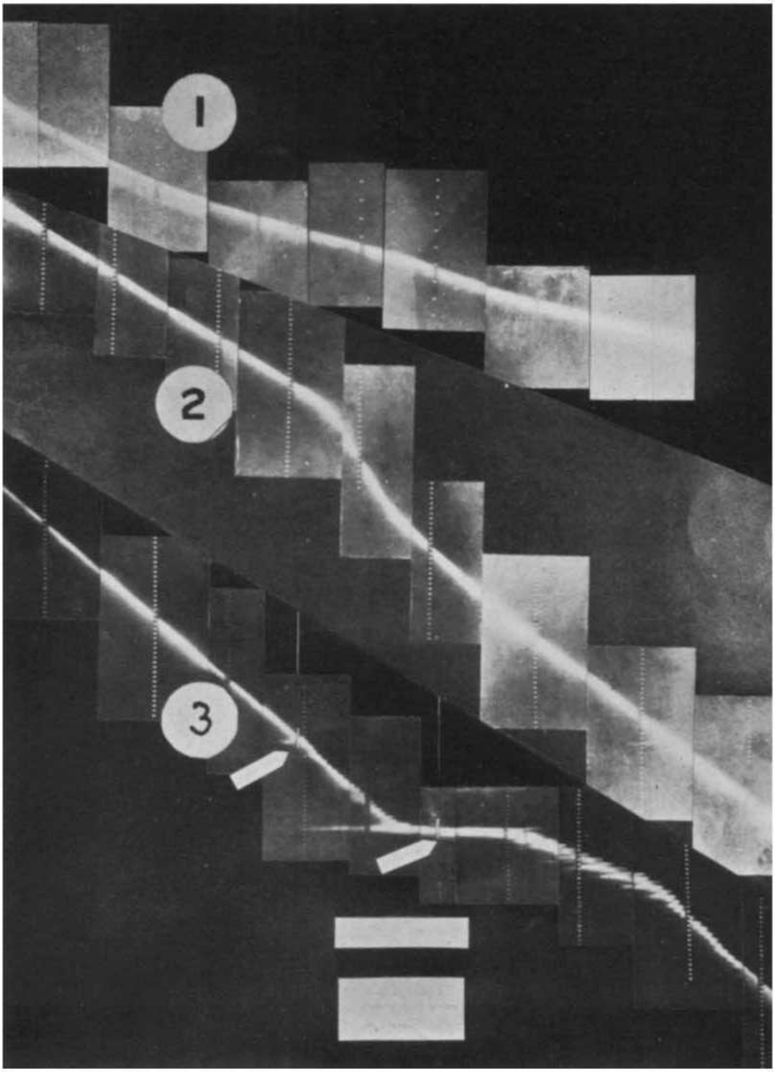
TABLE II.

The Effect of One Restriction in a Tube with Restricted Ignition End.

Distance from point of ignition (cm.).	Mean speed of flame (cm./sec.). Aperture in restriction 2·5 cm. diam.	Mean speed of flame (cm./sec.). Aperture in restriction 1·0 cm. diam.	Distance from point of ignition (cm.).	Mean speed of flame (cm./sec.). Aperture in restriction 2·5 cm. diam.	Mean speed of flame (cm./sec.). Aperture in restriction 1·0 cm. diam.
75— 85	256	95	135—145	1766	5,077
85— 95	289	84	145—155	1527	6,455
95—105	307	83	155—165	1319	7,833
105—115	Restriction at 110.	Restriction at 110.	165—175	1424	10,070
			175—185	1458	14,100
115—125	1860	2200			
125—135	1882	3666			

The movement of the mixture away from the point of ignition is checked by the restriction at 110 cm., the more so the narrower the passage, and the speed of the flame is therefore slow. When the flame has passed the restriction, however, there is no resistance

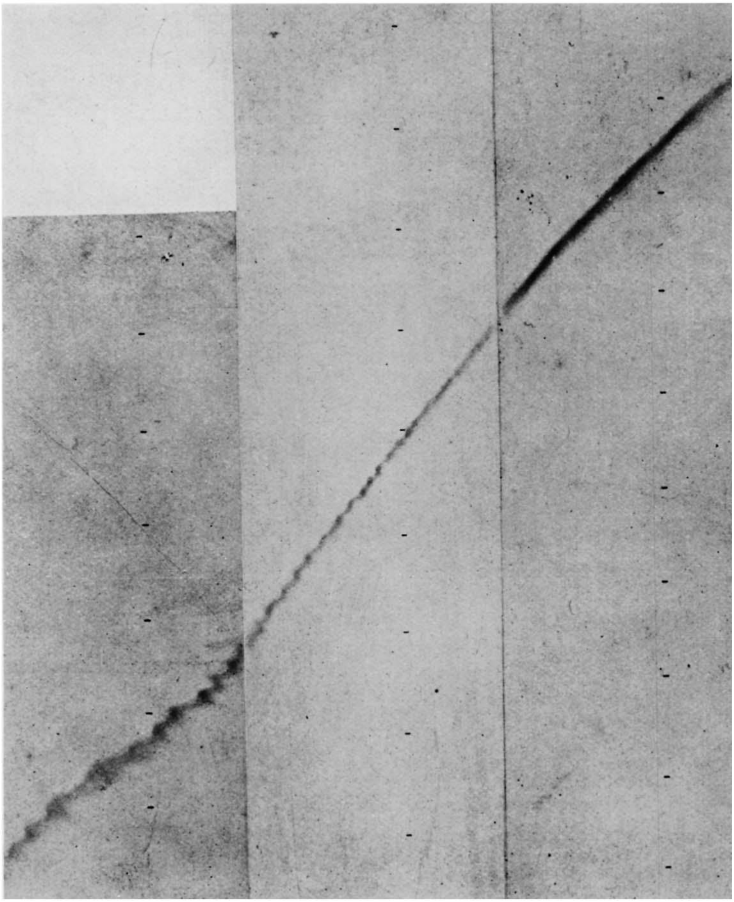
PLATE I.



1. *Tube open at both ends. Diameter reduced to 1·5 cm. at ignition end.*
2. *Tube open at both ends. Diameter reduced to 2·5 cm. at far end.*
3. *Tube closed at one end. Ignition at open end. Restrictions* 90 *and* 130 *cm. from open end.*

[*To face p.* 40.]

PLATE II.



The "uniform movement" in a 30·9% hydrogen–air mixture.

(other than frictional) to the passage of the mixture along the tube, whilst release of pressure towards the ignition end of the tube is impeded, in proportion as the aperture of the restricting ring is smaller. The speed of movement of the mixture, and thus of the flame which travels in it, therefore rapidly increases.

TABLE III.

(In sections A, B, C, and D the mean speed of flame is that measured over a distance of 30 cm. immediately beyond the last restriction.)

(A) *Diameter at ignition end reduced. Two restrictions, apertures each* 1 *cm. in diameter,* 90 *and* 130 *cm. respectively from ignition end.*

Diam. at ignition end (cm.).	2·5	1·5	1·0
Mean speed of flame (m./sec.).	131·3	58·7	Flame extinguished.

(B) *Diameter at ignition end reduced to* 2·5 *cm. One restriction* 110 *cm. from ignition end.*

Diam. of aperture of restriction (cm.).	2·5	2·0	1·5	1·0	0·5
Mean speed of flame (m./sec.).	17·3	27·0	28·7	30·1	46·0

(C) *Diameter at ignition end reduced to* 2·5 *cm. Two restrictions, apertures each* 1 *cm. in diameter, at different distances from ignition end.*

Positions of restrictions, measured from ignition end (cm.).	(i)	20	40	60	40	60	50	60	60	90	120	150
	(ii)	80	80	80	110	110	90	90	110	130	150	180
Mean speed of flame (m./sec.).		48·2	83·3	66·7	89·5	67·8	92·9	164·5	86·5	131·5	84·6	53·4

(D) *Diameter at ignition end reduced to* 2·5 *cm. Three restrictions, with apertures of different diameters, at different distances from ignition end.*

Diam. of aperture of restriction (cm.).	(i)	2·0	2·0	2·0	2·0	2·0
	(ii)	1·5	1·5	1·5	1·5	1·0
	(iii)	0·5	1·0	1·0	1·0	1·5
Positions of restrictions, measured from ignition end (cm.).	(i)	60	60	40	20	20
	(ii)	90	90	70	50	50
	(iii)	130	130	110	90	90
Mean speed of flame (m./sec.).		Flame extinguished.	60·9	100·9	75·0	83·8

(E) *Diameter at ignition end reduced to* 2·5 *cm. Two restrictions, with apertures of different diameters,* 90 *and* 130 *cm., respectively, from ignition end. (Mean speeds of flame between the restrictions, in cm./sec.)*

Distance from point of ignition (cm.).	95—105	105—115	115—125
Apertures 1·0 cm. diam.	1247	796	388
Apertures 1·5 cm. diam.	1182	732	461
Apertures 2·0 cm. diam.	866	709	600

When two restricting rings were present, each with apertures of 1 cm. and placed 40 cm. apart, the highest speed of flame, measured over a distance of 30 cm. just beyond the second restriction, was obtained when the ignition end of the tube was reduced in diameter to 2·5 cm., the mean value being 130 m./sec. as compared with 58·7 m./sec. when the diameter at the ignition end was 1·5 cm. Increasing the number of restrictions to three or more, the ignition end being 2·5 cm. in diameter, did not always result in an enhanced speed of flame. If the diameter of the apertures was only 1 cm., a greater number of restrictions than two decreased the speed attainable by the flame, or sometimes caused its extinction. When their aperture was 2·5 cm., three and four restrictions enabled speeds of flame of 310 and 390 m./sec., respectively, to be attained, the removal of the restriction at the ignition end reducing these velocities to 225 and 280 m./sec., respectively.

The results of typical experiments with a number of different arrangements of the restricting rings, made in an endeavour to develop the fastest flames, are given in Table III.

Beyond the first of two restrictions, the flame moves more rapidly the greater the reduction in diameter of the tube, for the reason given when considering the effect of one restriction, but the second restriction impedes the movement of the current of mixture ahead of the flame, and hence the speed is not so great as in its absence (compare Table II). The resistance offered by the second restriction is greater the smaller the aperture, so that the speed of the current, and of the flame, as it approaches the second restriction is lowest when the aperture is smallest.

(c) *The Influence of a Restriction at the Far End of the Tube.*—The result of reducing to 2·5 cm. the diameter of the end of the tube towards which the flame travelled, the ignition end remaining fully open, is recorded in Table IV.

TABLE IV.

The Effect of Restricting the Far End of a Tube Open at Both Ends.

Distance from point of ignition (cm.).	Mean speed of flame (cm./sec.). Tube fully open at both ends.	Mean speed of flame (cm./sec.). Diam. at far end reduced to 2·5 cm.	Distance from point of ignition (cm.).	Mean speed of flame (cm./sec.). Tube fully open at both ends.	Mean speed of flame (cm./sec.). Diam. at far end reduced to 2·5 cm.
5—15	106	98	85— 95	249	—
15—25	134	110	95—125	229	63
25—35	152	117	125—135	285	—
35—65	194	122	135—145	350	90
65—75	240	125	145—175	441	91
75—85	254	127	175—205	575	93

A composite photograph recording the progress of the flame throughout the length of the tube is shown in Fig. 2, Plate I. The speed of travel of the film in this photograph can be regarded as 3·5 cm./sec.

The comparatively slow speed of the flame throughout the tube can be attributed to the resistance offered by the restriction to the movement of the current of unburnt mixture ahead of the flame, the conditions approximating to those obtaining with a longer tube. In this connexion, the experiments of Mason and Wheeler (J., 1920, **117**, 36) with a tube 30·5 cm. in diameter may be recalled. When this tube, fully open at both ends, was 15·25 m. long, the flame in a 9·5% methane–air mixture travelled from end to end with increasing speed; but when the length was increased to 90 m., the general behaviour of the flame was as though the far end of the tube were closed, its velocity over the first 12—15 m. being slow and nearly uniform.

(B) *Ignition at the Open End of a Horizontal Tube Closed at the Other End.*

In an unrestricted tube, closed at one end, ignition of an inflammable mixture at the open end leads to the "uniform movement" of flame, which persists over about one-third of the length of the tube. When a restriction is introduced at some point along the tube, the movement of the flame is disturbed locally, its rate being reduced before the restriction is reached and increased over a short distance beyond it. Thus the speed of the uniform movement in a 10% methane–air mixture in the unrestricted tube was about 90 cm./sec., whereas when two restrictions were introduced reducing the diameter to 3·2 and 2·5 cm., respectively, at points 90 and 130 cm. from the open end, the velocity fell to 80 cm./sec. An acceleration occurred beyond each restriction. These effects are illustrated by Fig. 3, Plate I.* There can be no extensive movement of the mixture from an open to a closed end of a tube. The speed of the flame is therefore comparatively slow and is not greatly affected by the introduction of an impediment to movement of the mixture. The propagation of flame during the "uniform movement" is discussed later.

(C) *Ignition at the Closed End of a Horizontal Tube Open at the Other End.*

In short, wide, unrestricted tubes the fastest flame in any mixture of methane and air is normally obtained when the mixture is

* The speed of travel of the film in this photograph can be regarded as 3·0 cm./sec.

ignited at the closed end of a tube which is open at the other end. For long tubes, however, the flame becomes vibratory and does not reach the open end, because cooling of the products of combustion periodically causes a backward movement of the unburnt mixture and of the flame, with the eventual extinction of the latter by the burnt gases.

In the comparatively short tube used in these experiments, the flame was extinguished by a restriction unless this was placed fairly close to the point of ignition and its aperture was of not less than 2·5 cm. diameter. Even if these conditions were fulfilled, the introduction of a second restriction resulted in the extinction of the flame at the latter; when both apertures were 2·5 cm. in diameter and they were 80 and 120 cm. from the closed end, the mean speed of the flame increased from 26·2 to 77·5 m./sec. on passing the first restriction, whilst a retrograde secondary flame was set up at this point, as in the case of the tube open at both ends.

(D) *The "Uniform Movement" of Flame.*

We have pointed out that when a flame is travelling from an open towards a closed end of a tube there cannot, at the outset, be any extensive movement of the unburnt mixture ahead of the flame, and that the comparatively slow speed of the flame is thus explicable. Nevertheless, some movement must take place (although we have been unable to detect any current with certainty by direct measurement during the propagation of flame) and, if the assumption be correct that the speed of propagation of flame is affected under all conditions by the movement of the medium in which it travels, it is not to be expected that there should be a strictly "uniform movement" of flame over one-third the length of the tube. Rather would one expect an initial acceleration, slight but appreciable, followed by an equally slight retardation.

With a view to detect slight departures from strict uniformity of movement, we photographed the flame travelling in a 9·75% methane–air mixture over the first 80 cm. of the tube, on a film revolving at such a rate that slight differences in the velocity of the flame could readily be measured. The results are recorded in Table V.

TABLE V.

The Uniform Movement of Flame in a 9·75% Methane–Air Mixture.

Distance along tube (cm.).	0—10	10—20	20—30	30—40	40—50	50—60	60—70	70—80
Speed of flame (cm./sec.).	87·7	89·45	91·5	92·5	91·75	91·2	90·8	90·55

Although the speed of the flame is nearly uniform, there are just such slight variations as would be anticipated if some motion, affecting the speed of the flame, were imparted to the mixture. In conformity with the general argument now advanced, the implication is that the speed of the uniform movement of flame is compounded of (1) the normal rate of propagation of flame by conduction of heat, and (2) the initial motion of the unburnt mixture towards the closed end of the tube. The speed of the latter should increase with increase in the diameter of the tube. There should therefore be a definite relationship between the speed of "uniform movement" of flame in a given mixture and the diameter of the tube in which it travels.

Such determinations for mixtures of 10% of methane in air were made by Mason and Wheeler (J., 1917, **111**, 1044) for the last five tubes shown in Table VI and by Payman and Wheeler (J., 1918, **113**, 656) for the smaller tubes.

TABLE VI.

The Uniform Movement of Flame in Tubes of Different Diameters.
10% *Methane–Air Mixture.*

Diam. of tube (cm.).	0·45	0·56	0·72	0·81	0·90	2·5	5·0	9·0	30·5	96·5
Speed of uniform movement (cm./sec.).	33·5	41·2	46·3	47·4	48·0	66	92	104	168	250

On plotting the logarithm of the diameter of the tube against that of the flame-speed, the points are found to lie on a straight line. There appears, therefore (for the range of diameters considered), to be a relationship between the speed of the uniform movement of flame, V, and the diameter, D, of the tube in which it travels, of the form $V = cD^k$, k and c being constants.

Mason and Wheeler, in their discussion of the cause of variation of the speed of the uniform movement with the diameter of the tube (*loc. cit.*, p. 1052), assumed that when the diameter exceeds 10 cm. the speed is affected by the coming into play of heat transference by convection. It is clear from the relationship now given, whatever may be its full meaning, that such an assumption is unnecessary, and that no new factor affecting the propagation of flame is introduced after a certain diameter of tube is exceeded. Further, if it be correct to regard this relationship as indicating the effect of increased diameter on the speed of movement of the medium in which the flame travels, a satisfactory explanation, hitherto lacking, is available for the increased speed observed with increased diameter of tube when the flame is propagated downwards from an open towards a closed end (J., 1920, **117**, 1227)—

conditions which should render the effects of heat transference by convection negligible.

Although this communication is directly concerned only with the propagation of flame in mixtures of methane and air, it is not out of place to refer to recent experiments in which Miss E. H. M. Georgeson and Mr. F. J. Hartwell, by photographic analysis, determined the speed of the "uniform movement" in mixtures of hydrogen and air, for they have a direct bearing on the suggestion that the mixture in which the flame is moving is itself in motion. The results are of particular interest to us since they exhibit the initial acceleration of speed, followed by a retardation, which we anticipated; presumably because of the lesser density of the medium in which the flame is travelling, these phenomena are more marked than with mixtures of methane and air (see Table V). We are indebted to Miss Georgeson and Mr. Hartwell for the composite photograph reproduced as Plate II (about $\frac{1}{3}$ its original size), which illustrates admirably the changes of speed during the "uniform movement" of flame in a 30·9% hydrogen–air mixture. The mixture was contained in a horizontal tube of fused silica, 2·5 cm. in diameter, and the flame was photographed through a quartz lens on Lumière paper attached to a drum revolving at such a high speed as to render accurate analysis of the rapid movement possible. The flame is shown travelling from right to left over the first 78 cm. The time-intervals recorded are 0·02 of a second.

We are indebted also to Professor Statham, of this University, who has made a particular study of the problems of mine ventilation, for experimental evidence that in a tube open at one end and closed at the other an appreciable movement of a column of air takes place towards the closed end if a small pressure difference is created at the open end.

These experiments form part of a research that we are carrying out for the Safety in Mines Research Board, to whom our thanks are due for permitting publication.

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