# V.—*The Propagation of Flame in Mixtures of Methane and Air. Part I. Horizontal Propagation.*

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IN previous communications to this Society a study of the initial "uniform movement" of flame in gaseous mixtures has been presented (T., 1917, **111**, 267, 1044; 1919, **115**, 578). The majority of the experiments of which an account has been given have been with methane as the combustible gas. The general conclusions drawn as to the character and rationale of the uniform movement are, however, applicable to all inflammable mixtures.

The uniform movement is one phase in the propagation of flame, and is of comparatively short duration. The speeds attained by the flames during its regime are comparatively slow; very slow compared with that of the detonation-wave, but slow also compared with the speeds during other phases in the propagation of flame in mixtures wherein the detonation-wave normally does not develop.

The value of determinations of the speeds of flames during the uniform movement lies in the measure thereby afforded of the general behaviour of a given inflammable mixture or range of mixtures immediately after ignition, the measurements, when made under standard conditions, being physical constants. Knowledge is, however, often necessary of the maximum speed attainable at any time during the course of the propagation of flame in mixtures of a given combustible gas with air or oxygen. Such knowledge is of prime importance, for example, in respect of mixtures of methane and air, in connexion with the safe working of coal mines.

In the present paper a description is given of the phases, other than the uniform movement, during the horizontal propagation of flame in mixtures of methane and air.

The several series of experiments were carried out in tubes of different dimensions and materials. It is important when comparing one series of experiments with another that due regard should be paid to the details given respecting the tubes employed. In the majority of the experiments measurements of speeds were made by the "screen-wire" method, of which full details have been given in earlier papers (T., 1914, **105**, 2610; 1917, **111**, 1053). Supplementary information was obtained by photographic analysis of the flames. In order to obtain the photographs the flames were caused to travel along a tube of brass, 5 cm. in diameter, furnished with a window of quartz which was focussed on a rapidly revolving film by means of a quartz lens. The use of quartz enabled the light falling on the film to be sufficiently actinic to record the movements of the flames with considerable detail.

### (I) *Ignition at the Open End of a Tube Closed at the Other End.*

The initial phase of propagation of flame when the mixture is contained in a horizontal tube closed at one end and open at the other, and ignition is at the open end, constitutes the "uniform movement."

The linear duration of the uniform movement is controlled by the speed of the flame (and thus by the composition of the inflammable mixture); by the length, diameter, and uniformity of bore of the tube; in short, by such factors as influence the establishment of resonance in the column of gases in the tube. Eventually, as a direct outcome of the establishment of resonance, the flame-front acquires a periodic undulatory motion (see T., 1919, **115**, 584) leading sooner or later to violent vibrations which vary considerably in amplitude but remain periodic.

This phase in the propagation of flame was discovered by Schloesing and de Mondésir, and was termed "le mouvement vibratoire" by Mallard and Le Chatelier (*Ann. des Mines*, 1883, [viii], **4**, 331). Although accurate record can be obtained of the development of the "vibratory movement" under chosen conditions, the measurements—of the mean speed of the flame, for example—are not of much theoretical significance or practical value, for the speed of the flame during any one vibration, and the amplitude of the vibrations, is very susceptible of changes, designed or inadvertent, in the experimental conditions.

So far as mixtures of methane and air are concerned, it is perhaps sufficient to record a few of the data obtained as indicative of the general character of this phase in the propagation of flame for comparison with the uniform movement which precedes it. Thus, with mixtures containing between 10 and 10·5 per cent. of methane, and with a tube of brass 240 cm. long and 5 cm. in diameter, the significant measurements, obtained by photographic means, are as follow:

| | |
|---|---|
| Speed of flame during uniform movement ... | 90 cm. per second. |
| Linear duration of uniform movement ... ... | 80 cm. |

Faint undulations of the flame-front appear after the flame has travelled 32 cm. The mean speed of the flame is not affected by these undulations; their amplitude is small, and their period is that of the resonating column of gases in the tube. The amplitude of the undulations increases gradually from 1·7 cm. over the distance 32—50 cm. to 1·9 cm. over the distance 50—60 cm. and 2·2 cm. over the distance 60—80 cm. It then begins to increase rapidly, becoming 3·6 over the distance 80—90 cm. During this period of rapid increase in amplitude of the undulations the mean speed of the flame falls to 64 cm. per second. Eventually, the "vibratory movement," which owes its origin to an undulation of abnormal amplitude, is established.

During the vibratory movement the oscillations of the flame are of wide amplitude—25 cm. or more—and the mean speed of translation of flame is considerably enhanced. It will be seen on examination of Plate 1, Fig. 1, that the change of speed from that of the uniform movement (90 cm. per sec.) to that of the vibratory movement (278 cm. per sec.) is fairly abrupt, and that the latter speed is maintained at a constant mean value over a considerable distance. Finally, as the flame approaches the closed end of the tube, its mean speed decreases, although it still continues to vibrate to the end.

In the table that follows, data are given respecting successive portions of the vibratory movement, each portion being specified by the distance along the tube over which the flame travelled.

*Vibratory Movement of Flame.*

(Tube of brass 240 cm. long and 5 cm. in diameter. Methane 10—10·5 per cent. in air.)

| Distance along tube. | Mean speed of flame. Cm. per sec. | Maximum speed during forward motion of flame. Cm. per sec. | Amplitude of vibrations. Cm. | Frequency of vibrations. Mean values. |
|---|---|---|---|---|
| 0—80 cm. | — | Uniform movement | — | — |
| 80—90 | 64 | 292 | 3·6 | 47·7 |
| 90—107 | — | Gradual change | — | — |
| 107—170 | 278 | 2,430 | 26·0 | 70·0 |
| 170—200 | — | Gradual change | — | — |
| 200—220 | 62 | 416 | 1·4 | 45·0 |
| 220—240 | 38 | — | — | — |

It may be noted that, as indicated by the frequency of the vibrations, the resonating column of gases is that lying between the closed end of the tube and the flame-front at any given moment. Thus the calculated mean value for the frequency of vibration of a column of gases in an unflanged tube of brass 5 cm. in diameter is 48 if the tube is 130—140 cm. long and 74·5 if it is 50—93 cm. long.

These measurements bear reference only to the particular conditions of experiment specified, but they could be reproduced with an exactness which must be considered remarkable when the complicated character of the phenomena is borne in mind. In this respect better fortune has attended the experiments than that which befel Mallard and Le Chatelier, who have stated: "En repétant plusieurs fois la même experience dans des conditions identiques à elles-mêmes, le mouvement vibratoire ne se reproduit jamais deux fois de la même façon" (*loc. cit.*, p. 333). No doubt the rapid speed of flame in the mixture ($CS_2 + 6NO$) employed by Mallard and Le Chatelier for their experiments would tend to emphasise irregularities in the results.

It has already been stated that the vibratory movement is the direct result of the resonance of the column of gases in the tube. It was shown, in connexion with experiments on the propagation of flame in mixtures of acetylene and air, that resonance, by whatever means induced, can be made manifest by the undulatory motion of flame as it travels along tubes, the periods of the undulations agreeing closely with the periods calculated for organ-pipes of the dimensions of the tubes employed. As the resonance becomes stronger, the amplitude of the undulations of the flame front perforce increases, since the flame acquires its motion from the vibrating column of gases. There is thus produced an agitation of the gaseous mixture which eventually becomes of sufficient importance to affect appreciably the speed of a flame travelling through it. (In this connexion, see T., 1919, **115**, 81.)

The vibratory movement is, indeed, an excellent example of the effect of agitation or turbulence in accelerating the translation of flame through a gaseous mixture. The effect is a mechanical one. During each forward impulse the flame is drawn rapidly through previously unburnt mixture by reason of the motion acquired by the resonating column of gases. In a certain degree, also, the forward motion of the flame is assisted by the expansion in volume of the burning gases, especially when the flame is at some distance from the open end of the tube, so that escape of the expanded gases there is retarded. The latter effect is more pronounced when the mixture is ignited at the closed end of a tube open at the other end, conditions which will be considered in the succeeding section of this paper.

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

The two phases in the propagation of flame, the "uniform movement" and the "vibratory movement," are characteristic of what occurs with mixtures of a combustible gas and air when ignition is at the open end of a tube closed at the other end. Under such conditions, with some combustible gases (for example, hydrogen) when mixed with air, and with all when mixed with pure oxygen, the vibratory movement is succeeded by the detonation-wave, provided that the combustible gas and oxygen are in suitable proportions.

With no mixture of methane and air (at atmospheric temperature and pressure) is the detonation-wave thus developed, but the vibratory movement continues until the flame is extinguished, either on reaching the closed end of the tube or, occasionally, during an abnormally extensive backward movement, before the end is reached.

When ignition of a mixture of methane and air is at the closed end of a tube open at the other, no uniform movement takes place, but the speed of the flame increases rapidly as it travels towards the open end.

For comparison with the uniform and vibratory movements, experiments were made with a series of mixtures in a horizontal tube of glass 5 cm. in diameter and 500 cm. long. Fine screen-wires of copper were stretched across the tube at half-metre distances, and the times taken for the flames to travel between these screen-wires measured by the method described in previous communications. The mixtures were ignited at a spark-gap 3 cm. from the closed end.

The speed of the flame in some of the mixtures reached 29 m. per second over the last half-metre length of the tube, and, so far as could be judged, was nearly uniformly accelerated from the beginning. It seemed possible, therefore, that with a tube of greater length and larger diameter a permanent maximum velocity of flame, such as is characteristic of the detonation-wave, might eventually be attained.

A steel tube 30·5 cm. in diameter and 90 m. long was used to test this supposition. It was found that flame did not continue to propagate in any mixture beyond a distance of 15 m. from the closed end, at which ignition was effected. Violent vibrations were developed after the flame had travelled 10 m., in the course of which the flame was extinguished. The same result was obtained when the mixtures were ignited a few cm. (ten to twenty) from, instead of at, the closed end, a condition which would have the effect of imparting an impetus to the flame at the beginning, thereby hastening the development of the detonation-wave (compare Dixon, *Phil. Trans.*, 1903, A., **200**, 345).

The extinction of the flame after travelling such a short distance in a long tube under the conditions of these experiments is no doubt caused by the products of combustion, when cooling, tending to produce a partial vacuum behind the flame (the end of the tube from which the flame started being sealed), which is therefore dragged back over part of the path it has already travelled. This may occur several times, the flame alternately leaping forward and being drawn back, but eventually a sufficient proportion of the burnt mingles with the unburnt gases to prevent further propagation of flame.

### (III) *Ignition at One End of a Tube open at Both Ends.*

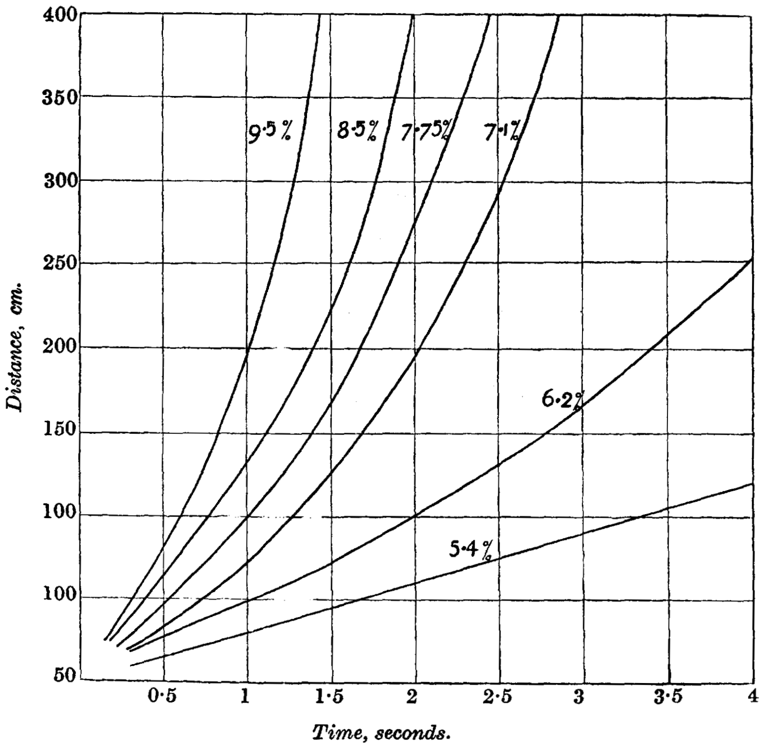
If the reason assigned for the extinction of the flame when travelling from the closed to the open end of a long tube is correct—a reason intended to apply only to such comparatively slowly-moving flames as are obtained with mixtures of methane and air *—extinc-

* With mixtures of coal-gas and air, for example, in which the flames are initially more rapid than with methane and air, the vibratory movement continues (in a steel tube 30·5 cm. in diameter) until the detonation-wave is developed. The speed of the wave, in a mixture containing 17 per cent. of coal-gas, is 1750 m. per second.

tion should not occur when both ends are open (so that the cooling of the products of combustion cannot create a partial vacuum behind the flame), and the speed at which the flame travels should be rapid.

Several series of experiments were made to test this point, it being important to determine the conditions under which the most rapidly moving flames are obtained in mixtures of methane and air, and the order of magnitude of the speeds.

FIG. 1.




The first series of experiments was in a tube of glass 5 cm. in diameter and 500 cm. long, for comparison with the series, carried out in the same tube, in which ignition was at a closed end. The results are shown graphically in Fig. 1, in which distance along the tube is plotted against time, zero time being the moment of fusion of the first screen-wire, which was 10 cm. from the point of ignition.

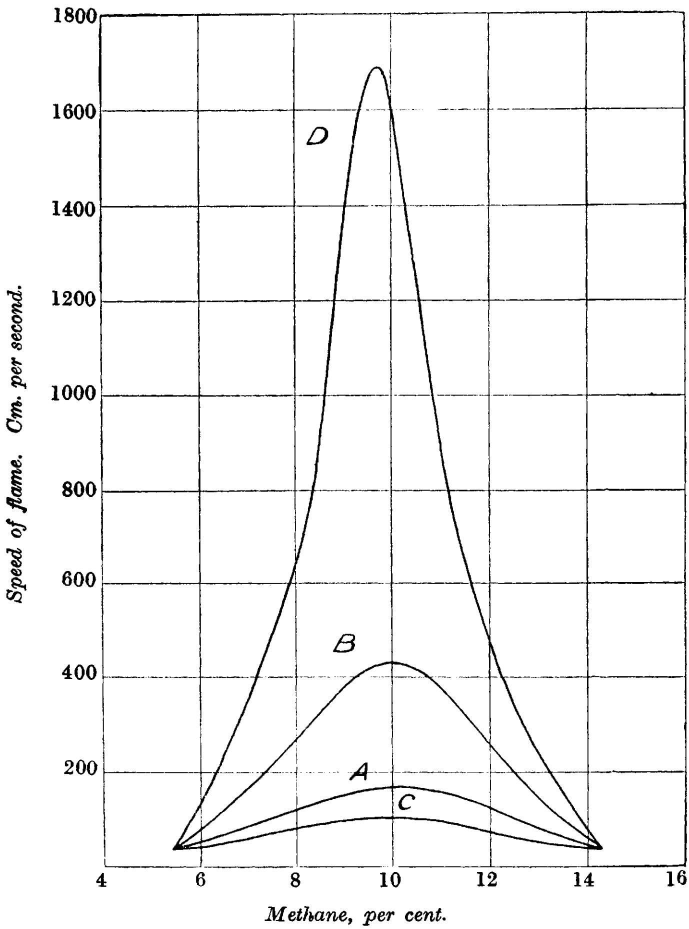
With all but the lower-limit mixture (5·40 per cent. methane), in which the speed of flame is uniform, there is a gradual and, so far as the records can indicate, regular acceleration of speed as the flame travels from end to end of the tube. In no instance did extinction of the flame occur, although in most of the experiments slight vibrations were noticed at different stages in the development of the propagation, the incidence of these vibrations being earlier the more rapid was the flame. There was, also, with the mixtures richer in methane, a noticeable check in the progress of the flame as it approached a particular point, succeeded by a spurt forward after that point had been passed. This effect seemed traceable to a slight ridge around one of the small holes with which the tube had been pierced (by means of a blow-pipe flame) to receive the screen-wires used to record the time of passage of the flame. This ridge projected less than 1·5 mm. within the tube; the fact that it could markedly affect the progress of a flame in a tube 50 mm. in diameter is a striking example of the sensitiveness of flames to turbulence in the mixture, even such slight turbulence as the small projecting ridge would cause. This subject will be dealt with in a subsequent communication.

Another series of experiments covered the whole range of inflammable mixtures of methane and air, and was made in a glass tube 9 cm. in diameter and 620 cm. long. This series is of value for comparison of the mean speeds of the flame over measured distances with the speeds of the uniform movement in a tube of the same diameter. Such a comparison is made diagrammatically in Fig. 2, which records speed-percentage curves ($A$) for the distance (measured from the point of ignition) 50—100 cm., and ($B$) for the distance 407—467 cm. in the tube open at both ends, the speeds being the mean speeds of the flames over those distances; and ($C$) for the uniform movement. In addition, a curve ($D$) is given showing the mean speed of flame over the distance 20—120 cm. in a tube 5 cm. in diameter closed at one end and open at the other, ignition being at the closed end.

The mean speed over the distance 407—467 is seen to be greatest in the mixture containing 10 per cent. of methane, and to be about four times the speed of the uniform movement in that mixture in a tube of the same diameter. The speed of the flame in all mixtures (except the limit mixtures) was found, as with the tube of 5 cm. in diameter, to increase continuously over the whole distance travelled, and, as when ignition was at the closed end of a similar tube, it seemed possible that the detonation-wave might be developed if the flame could travel far enough. If not, it was necessary to know what change in the character of the propagation would interpose to prevent it.

The steel tube, 30·5 cm. in diameter, was brought into requisition to test this. The length of the tube in the first instance was 15·25 m., and records were obtained of the times taken for the flame to travel measured distances from the point of ignition in different mixtures. As usual, the fastest speed of flame was obtained with mixtures containing between 9·5 and 10·5 per cent.

FIG. 2.




of methane, but no speed approaching that of the detonation-wave was recorded, the maximum being 917 cm. per second, attained after travelling 14 m. in a mixture containing 10·25 per cent. of methane.

It appeared from the records that the flame, which could not be directly observed, had acquired a vibratory character after travelling half the length of the tube. No indication of this was given by the sound of the flames as they travelled, and the vibrations were presumably of small amplitude. Vibratory propagation in the steel tube, such as was obtained when one end of the tube was closed, had hitherto been accompanied by a staccato note, but the flames now produced seemed, to the ear, to travel unhaltingly from one end of the tube to the other, issuing into the air with a sharp report.

The length of the tube was therefore increased to 90 m. in the expectation that, if the flame had indeed become vibratory in character after travelling 6 or 7 m., a greatly increased distance of travel would produce readily recognisable vibrations of large amplitude. Such was, in fact, the result; the propagation ultimately became strongly vibratory, but the early stages of the propagation were profoundly modified by the increased length given to the tube. Instead of increasing rapidly in speed from the beginning, as when the tube was 15·25 m. in length, the flames now travelled from the point of ignition at a constant and comparatively slow speed over a distance of between 12 and 15 m. (dependent on the composition of the mixture) and then began to vibrate. The vibrations acquired their greatest amplitude about half-way along the tube and continued throughout the remaining distance.

In mixtures containing between 9·5 and 10·5 per cent. of methane the speed of the flame over the first 12—15 m. averaged 200 cm. per second. Thus, the records obtained over this range of mixtures were:

| Methane, per cent. | Initial speed of flame. Cm. per second. |
|---|---|
| 9·60 | 198 |
| 9·70 | 188 |
| 9·75 | 203 |
| 10·10 | 213 |

This speed is a little faster than that of the uniform movement in similar mixtures in the same tube (170 cm. per second). The important point is, however, that the speed should remain constant over so great a distance. Although open at both ends, a long tube is thus found to impress upon a flame started at one end conditions similar to those obtaining with a shorter tube closed at the distal end. The resistance to the expansive force of the burning gases afforded by the long column of unburnt mixture in advance of the flame corresponds (nearly) in effect with the resistance of a closed end; so close is the correspondence that the flame is caused to proceed at the outset with a "uniform movement," but little faster than the uniform movement as ordinarily developed in mixtures of the same methane-content in a tube of the same diameter.

### *Photographic Analysis of the Flames.*

In Plate 1 are shown time-distance curves, obtained photographically, for the propagation of flame in a 10 per cent. mixture of methane and air in a tube of brass 5 cm. in diameter and 240 cm. long.

The flames travelled horizontally from right to left, and the photographic film can be regarded as moving vertically upwards, its speed of travel being 30 cm. per second. The full length of the tube, 240 cm., is shown in the photographs, each of which is composite, being obtained by joining together photographs of successive sections of the tube 30 cm. in length.

For Fig. 1 the tube was closed at the left-hand end, and ignition was at the right-hand, open, end; for Fig. 2 the tube was open at both ends, and ignition was at the right-hand end; and for Fig. 3 the right-hand end of the tube was closed, and ignition was effected there, the left-hand end being open.

The relative speeds at which the flame traversed the full length of the tube are readily deduced from these photographs, which also illustrate the general behaviour of the flames under the different conditions of ignition of the mixtures, and require no description. It should be noted, however, that Fig. 3 discloses the presence of rapid vibrations during the progress of the flame which, as stated earlier in this paper, was judged by visual observation to travel unchecked through the tube at a speed which, according to determinations by the screen-wire method, seemed to be nearly uniformly accelerated.

In Plates 2 and 3 details of the flames as they passed through a section of the tube 30 cm. in length are shown, the section chosen being that indicated in Plate 1 by the vertical white lines. To obtain these photographs the speed of the film was increased to 90 cm. per second. Calculations made from them are as follow:

PLATE 2.

Tube closed at one end; ignition at open end.

| | |
|---|---|
| Mean speed of flame ... ... ... | 245 cm. per sec. |
| Maximum speed during forward movement of vibration ... ... ... | 1,990 cm. per sec. |
| Average frequency of vibrations ... | 76 |

The calculated frequency for the fundamental tone of the tube during the longitudinal vibration of air within it is 68 if the length

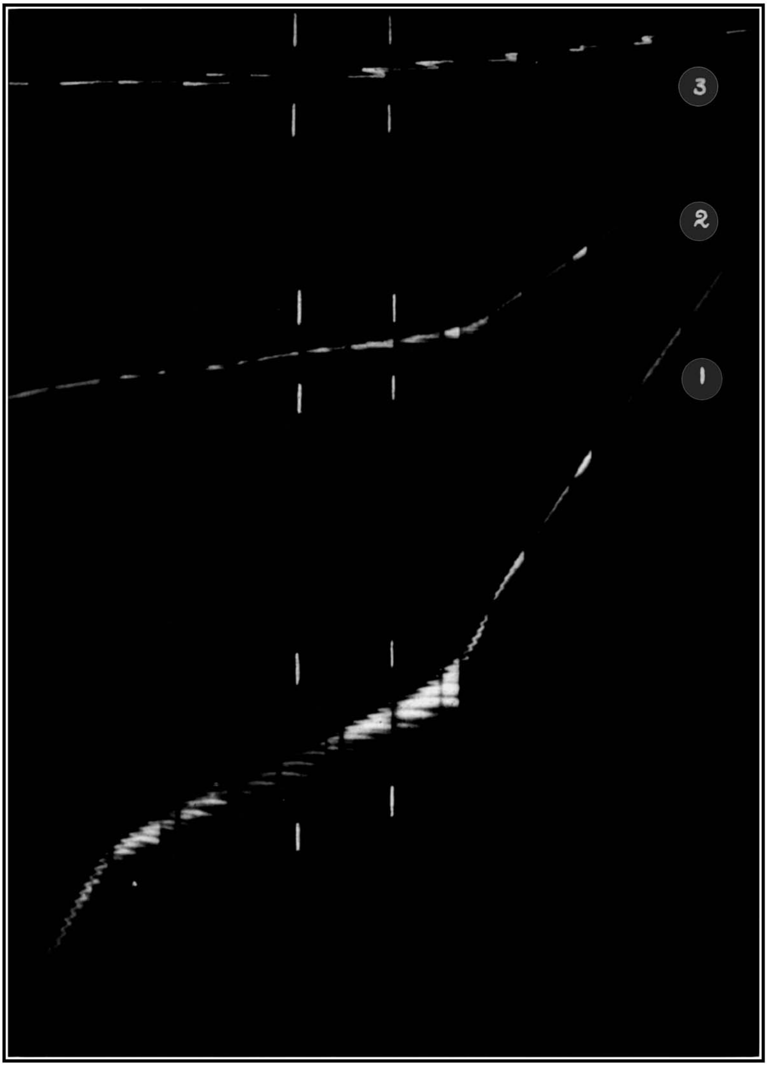



PLATE 1.

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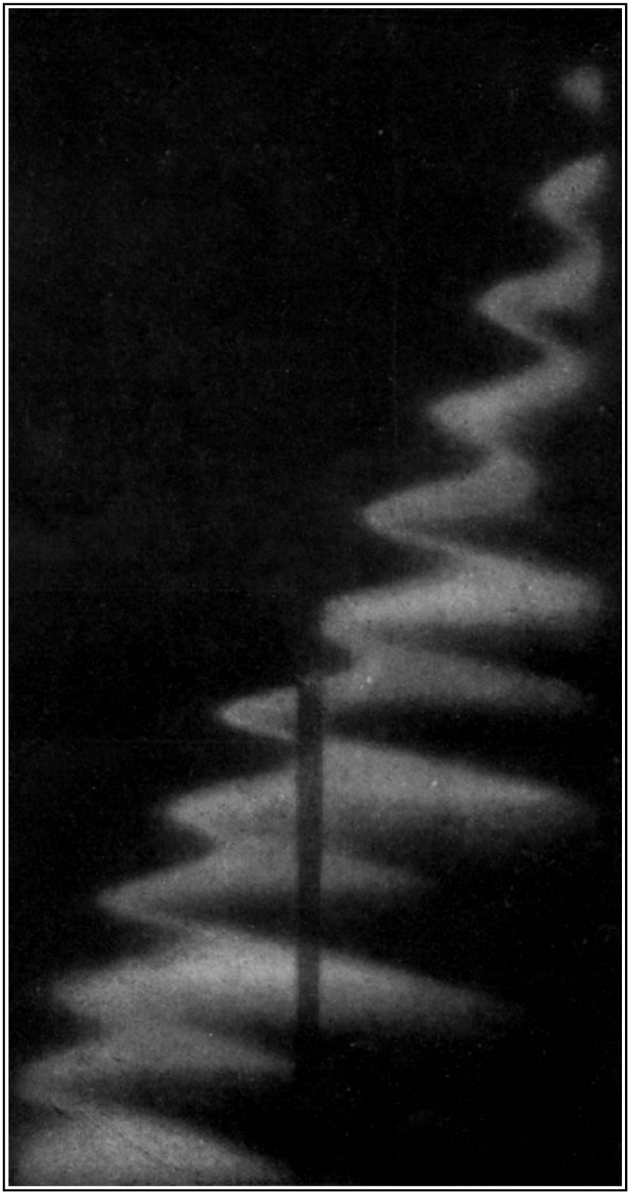

PLATE 2.

Fig. 1.

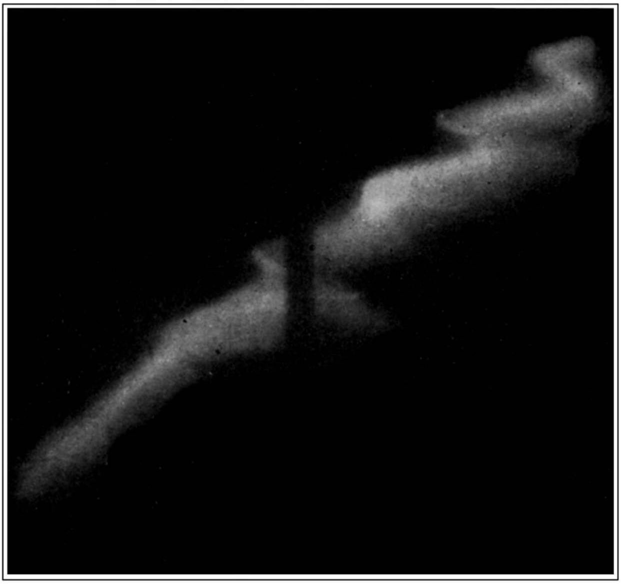

Fig. 2.

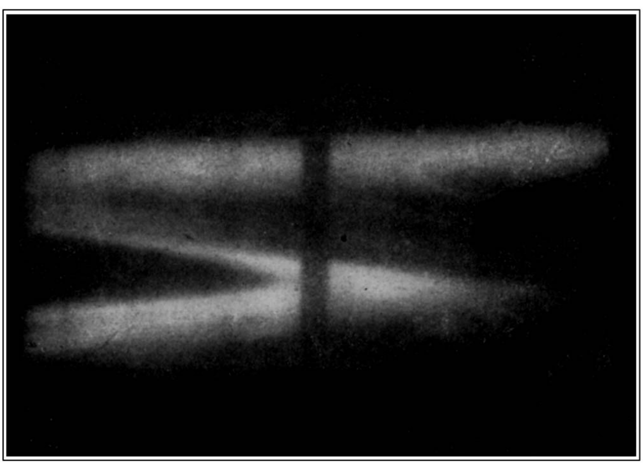

Plate 3.

of the vibrating column be assumed to be 125 cm. and 88 if 95 cm. These are the distances of the flame-front from the closed end of the tube at the beginning and end of the photograph respectively. The mean value is 78.

PLATE 3, FIG. 1.

Tube open at both ends; ignition at one end.

| | |
|---|---|
| Mean speed of flame ... ... ... | 480 cm. per sec. |
| Maximum speed during forward movement of vibration ... ... ... | 3,730 cm. per sec. |

PLATE 3, FIG. 2.

Tube closed at one end; ignition at closed end.

| | |
|---|---|
| Mean speed of flame ... ... ... | 1,050 cm. per sec. |
| Maximum speed during forward movement of vibration ... ... ... | 5,760 cm. per sec. |
| Amplitude of vibrations ... ... | 30 cm. |

Of the three conditions under which the ignition of mixtures of methane and air has been effected in these experiments, that which would lead to the most disastrous results in industry is the third—ignition at one end of a tube or gallery open at both ends. For although the initial speed of the flame is not then so great as when ignition is at a closed end, continued propagation is assured, and there may be developed momentarily during the vibratory motion velocities and pressures as great as any produced throughout the life of a flame started at a closed end.

The fastest speed of flame recorded in any experiment was about 60 m. per second, and was of short duration. This is not of the same order of magnitude as the speed of the detonation-wave in gaseous mixtures. It would not be wise to conclude, however, that the detonation-wave cannot, in any circumstances, be developed in mixtures of methane and air at normal temperature and pressure. On the contrary, in several experiments in the steel tube, 90 m. long and open at both ends, in which restrictions were introduced at two points (consisting of steel rings which reduced the diameter of the tube to 28·6 cm. at those points), the development of the detonation-wave seemed imminent. Further description of these experiments, which are being continued, is reserved until the subject of the effects of turbulence on the propagation of flame in gaseous mixtures is discussed.

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