CXIX.—*Explosions in Closed Cylinders. Part IV. Correlation of Flame Movement and Pressure Development in Methane–Air Explosions.*

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IN a previous paper (J., 1928, 3203) we have shown that methane–air explosions travelling from one end to the other of a cylinder 10 cm. in diameter are vibratory or non-vibratory according to the length of the cylinder : if this exceeds 140 cm., an explosion of any mixture containing between 8 and 11% of methane becomes vibratory and is accompanied by a shrill screech ; but if it is less than 140 cm., explosions of all methane–air mixtures, initially at atmospheric temperature and pressure, are silent, and the movement of flame and the development of pressure are regular.

We have made a further study of both non-vibratory and vibratory explosions of methane and air with new apparatus whereby continuous photographic records, on rapidly revolving sensitised paper, of the movement of flame could be correlated with simultaneous records of the development of pressure. The explosion vessel (of gun-metal, 10 cm. internal diameter) could be modified in length, as desired, by bolting together sections. Four sections were available, three 50 cm. and one 25 cm. long (see Fig. 1). For the principal series of experiments described in this paper, the internal length of the cylinder was either 46·5 or 171·4 cm. A number of longitudinal windows of quartz, 1 cm. wide and 14 cm. long, enabled the flame of the explosion to be photographed during its passage throughout the length of the cylinder, save where the view was obstructed by the joints of the sections or by strengthening bands. One end-plate of the cylinder carried at its centre an ignition plug with platinum electrodes forming a spark-gap of 4 mm. To the other end-plate a manometer was fitted.

For the design of the manometer used for the majority of the experiments, we are indebted to Dr. J. D. Morgan. It consisted of a concentrically corrugated disc, C, Fig. 2, of phosphor bronze, 7 cm. in diameter and 0·079 cm. thick. The disc was clamped at its circumference by a steel ring, D, which was screwed to the end-plate, A, of the explosion cylinder. Both the steel ring and a washer, H, were shaped to correspond with the corrugations of the disc, so that no distortion occurred when they were assembled. To the flat centre of the disc was screwed a light but rigid steel pin, E, which was covered by a sleeve of thin rubber. This acted as the pivotal support for the knife-edge of a plate, F, carrying a small mirror of stainless steel. The mirror-plate was mounted and freely pivoted on a movable arm, G, which could be locked in position by thumb-screws. The quartz window, M, of the explosion vessel ended flush with the diaphragm of the manometer.

Non-vibratory Explosions.—Some of the records of pressures and times of explosion for a series of methane–air mixtures, with the cylinder 46·5 cm. long, are given in Table I, where T_m is the time (measured from the time of ignition) for the attainment of maximum pressure and T_f is the time taken for flame to travel throughout the length of the cylinder, as determined from photographic records.

TABLE I.

Explosions of Methane and Air in a Cylinder (46·5 × 10 *cm.*).

CH_4, %.	P, atm.	T_m, sec.	T_f, sec.	CH_4, %.	P, atm.	T_m, sec.	T_f, sec.
8·40	4·56	0·226*	0·198	11·60	4·96	0·240	0·194
9·45	5·30	0·203*	0·149	13·05	3·87	0·597	0·498
10·20	5·51	0·187*	0·142	13·30	—	0·842	0·663

* The "piston" manometer described in Part I of this research was used for these experiments.

In each instance the maximum pressure is attained after the flame-front has reached the far end of the cylinder. This is demonstrated on Plate I, where four of the flame photographs are reproduced with the corresponding time–pressure records transferred to them. The flame photographs on Plates I and II, having been taken direct on sensitised (Lumière) paper, are negatives, darkness of the image corresponding with brightness of the flame. At the outset, the flame darts forward at a rapidly increasing speed. When it has travelled about half the length of the cylinder, however, there

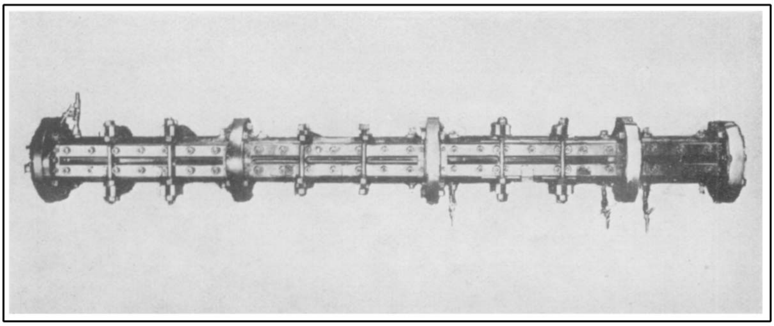
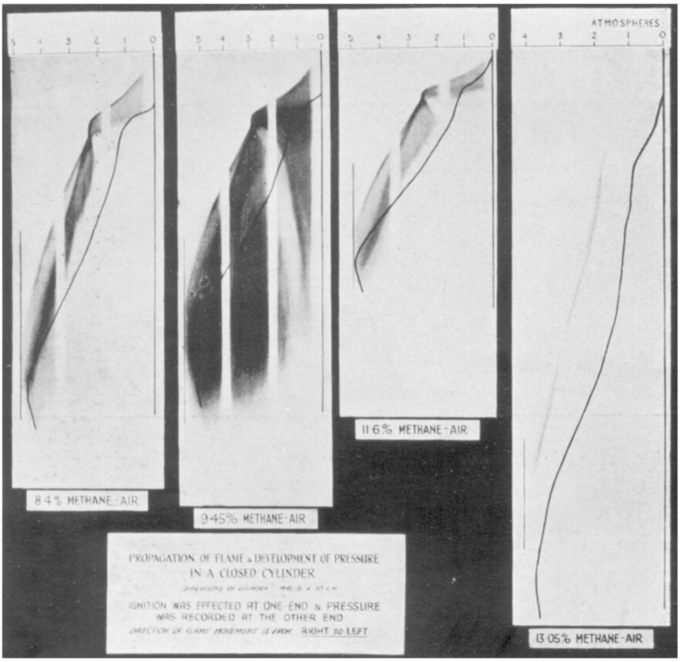


FIG. 1.

[*To face p.* 848.

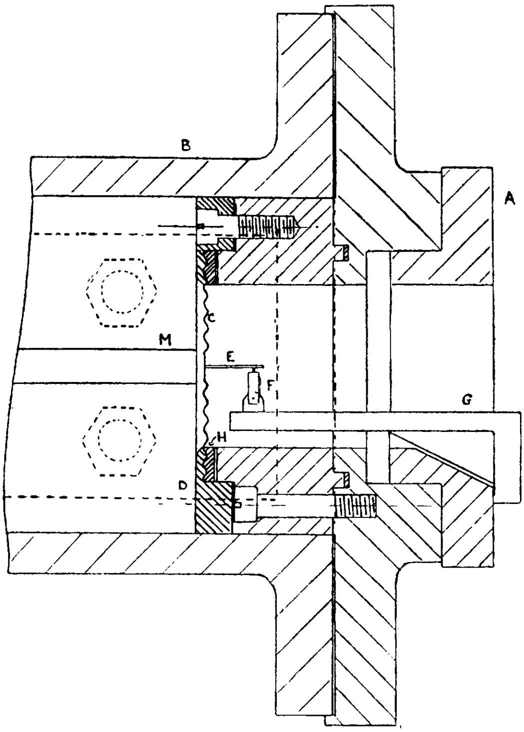
PLATE I.



Non-vibratory explosions of methane and air.

is a sudden arrest of its movement and the flame-front appears to be split into two portions, one of which lags behind the other. At the moment of arrest, the "skirt" of the flame (see Part III, *loc. cit.*, p. 3215) has come in contact with the walls of the cylinder and has been extinguished, whilst the flame-front has assumed the form of a disc occupying the cross-section of the cylinder. Immediately after this arrest, cooling of the products of combustion behind the flame-front draws the middle of the disc backwards, so that a hollow cone

FIG. 2.



is formed. The base of this cone is in advance and its periphery is that of the cylinder, whilst the apex travels behind, at first along the axis and later canting over towards the floor of the cylinder. It thus results that a portion of the flame reaches the end of the cylinder, and can be photographed at a window there, before the whole of the mixture has been traversed by flame. Complete inflammation, corresponding with the attainment of maximum pressure, only occurs when the hindermost (and most luminous) portion of the flame surface reaches the end of the cylinder, as can be seen in the photographs on Plate I. The development of pressure follows closely the movement of the flame, there being a mechanical lag of about 0·001 sec. In particular, it will be observed that an arrest in the development of pressure synchronises with the arrest of the flame.

Vibratory Explosions.—Typical records of the movement of flame and the development of pressure for a vibratory explosion of methane and air are reproduced on Plate II (much reduced in size). This explosion was of a 10% methane–air mixture, initially at atmospheric temperature and pressure, the internal length of the cylinder being 171·4 cm. It will be seen that the earlier history of the flame is similar to that of the non-vibratory explosions in the shorter cylinder but that, after the flame front has travelled 140 cm., it vibrates. The vibrations continue, of the same frequency (about 240), until the flame-front reaches the end of the cylinder. The time–pressure curve, transferred to the flame photograph on Plate II, also shows vibrations which synchronise with those of the flame-front. The amplitude of the rapid fluctuations in pressure during this period is exaggerated. The maximum pressure is attained at the moment when the flame-front reaches the end of the cylinder, the vibratory explosions differing from the non-vibratory in this respect.

The critical length of cylinder of 10 cm. internal diameter for the production of a vibratory explosion in 9—10% methane–air mixtures is 140 cm. In cylinders of greater length than this, it has been observed that the vibrations begin after the flame has travelled 140 cm. The vibrations appear, therefore, to be those of a longitudinal stationary wave maintained in the column of gases behind the flame-front, a conclusion supported by the fact that their frequency does not alter as the flame travels. If the whole column of gases within the cylinder were in resonance, the frequency of the vibrations should increase as the flame travelled, owing to the increasing speed of sound with increasing mean temperature of the gases. Calculated from the rise in pressure, the increase in mean temperature during the vibratory stage of the 10% methane–air explosion amounts to about 400°, which would cause a difference of about 50 in the frequency of the vibrations. The fact that the frequency remains nearly constant can be explained by the effect of increased temperature being compensated for by the increasing length of the column of gases in resonance, in accordance with the equation $n = V/2L$, where n = frequency, V = speed of sound, in m. per sec., and L = length of column in m. Calculations of the fundamental frequencies of the columns of gases behind the flame-front for three positions of the flame-front, *i.e.*, 140, 156, and 171 cm.

from the end of the cylinder, the mean temperature being calculated from the observed mean pressure, give values of 234, 233, and 230, which are in good agreement with the frequency of the vibrations measured from the photographs, *viz.*, 240.

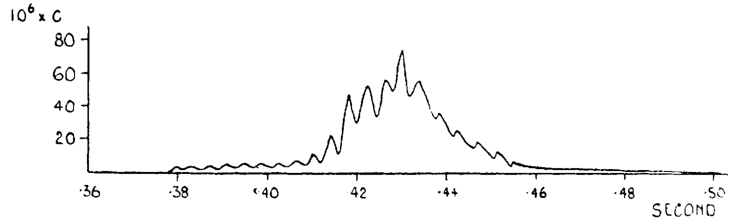
The preservation of what may be termed a " balanced frequency " of vibration of flame in the cylinder may account for its increase in speed as it nears the end of its travel. As the flame-front approaches the end of the cylinder, the rate of production of heat rapidly increases by reason of the increased pressure at which the gas is burned. To maintain the same frequency of vibration of the flame, therefore, the length of the column of gases behind the flame-front must rapidly increase, which is equivalent to saying that the speed of the flame-front must increase. Once the vibrations have begun, the column of gases behind the flame-front can be regarded as the " driver " in the resonating system and the flame-front as the object " driven."

Accompanying the vibrations of the flame, alternate dark and light bands appear in the photograph of the burning gases behind the flame-front. The photograph being a " negative," the dark bands represent luminescence and the light bands the absence of luminescence. These striations continue for an appreciable time after the flame has reached the end of the cylinder (compare Egerton and Gates, *Proc. Roy. Soc.*, 1927, *A*, **116**, 516). In similar vibratory explosions, *e.g.*, of pentane and air at several atmospheres initial pressure, in a cylinder of shorter length and wider diameter, striations in the " after-burning " gases are observed to extend throughout the length of the cylinder (see *Nature*, 1928, **122**, 995). They may do likewise in the vibratory methane–air explosions but they are not apparent, perhaps because the " after-burning " is insufficiently actinic.

In the original photographs, it can be seen that the bands are not quite parallel, but that the speed of the disturbance responsible for them is faster at the moment of complete inflammation than at the outset of the vibratory period, by an amount corresponding with the effect of a rise of temperature of 400° on the speed of sound.

As bearing on the nature of the striations, a time–current curve, recorded by an Einthoven galvanometer measuring the electrical conductivity of the gases during the vibratory period of an explosion of a 10% methane–air mixture in the long cylinder, is reproduced in Fig. 3. The method used is described in detail elsewhere (this vol., p. 878). The conductivity was recorded as the flame passed between two platinum electrodes 15 cm. from the end of the cylinder to which the explosion travelled. The electrodes were diametrically opposite each other, 1·5 cm. apart, and were maintained at a potential difference of 5·8 volts. In Fig. 3, the abscissæ represent times after ignition. It will be seen that the frequency of the fluctuations in current, 237, is nearly the same as that of the striations behind the flame-front, 240, and the general character of the time–current curve is similar to that of the time–pressure curve over the same period (compare Plate II). In particular, the rapid increase in the ionisation current just before it attains its maximum value corresponds with the rapid rise to a maximum value of the mean temperature of the explosion as indicated by the time–pressure curve. It can be concluded, therefore, that, whatever may be the cause of the ionisation, each " dark " (*i.e.*, luminescent) band of the striations as photographed represents a recombination of ions, corresponding with a forward movement of the vibrating flame, and a consequent sudden increase of pressure.

FIG. 3.



The problem of the manner in which heat energy liberated during flame propagation can be communicated to a column of gases in such a way as to induce resonance is in some respects analogous to that of the " singing " flame. With a forced vibration of a point, the optimum effect with respect to the kinetic energy of the vibration is obtained if the impressing force is at a maximum when the displacement is zero, but for vibrations that are maintained by heat, Rayleigh (" Theory of Sound," Vol. II, p. 227) has shown that the impulse given to the resonator by the impressing force must occur at a point of maximum displacement. This has been confirmed for singing tubes by Knipp and Kunz (*Physical Rev.*, 1922, **19**, 400), who have shown that, to produce the maximum vibratory effect, heat must be applied midway between a loop and a node.

Considering the whole column of gases, burnt and unburnt, in our cylinder, vibrations of the flame during an explosion began midway between a node at the end and a potential loop at the centre. It can be understood that the supply of energy from the flame-front at such a position would initiate a stationary wave. Only the column of gases behind the flame-front is in resonance, however, no doubt because of the wide difference in temperature and density that exists between the unburnt and the burning gases, the flame-front acting as a septum. The layer of unburnt gases just ahead of the advancing flame-front provides a sufficiently dense medium for the reflexion of a sound-wave and acts as a node of the column of burning gases in which the stationary wave system exists.

The Manner of Movement of Vibrating Flames.—The movement of a vibrating flame during an explosion has been analysed by " snap-shot " photography on a stationary plate (see Ellis, Safety in Mines Research Board Paper No. 32, 1927). A mixture of carbon monoxide and air was used, because of the high actinic value of the flame in such mixtures, and the explosion vessel was a glass cylinder 206 cm. long and of 9 cm. internal diameter. The cycle of changes in the shape of the flame, from the beginning of a single vibration and throughout its forward and backward movement, is shown by the series of snapshots on Plate III, where also a photograph of the vibration thus analysed, taken on rapidly revolving sensitised paper, is reproduced. In the snapshots, whiteness of the image corresponds with brightness of the flame. In the photograph on revolving sensitised paper, blackness of the image corresponds with brightness of the flame.

The duration of exposure for each snapshot was 2·5 millisecs., whilst each vibration in this explosion lasted about 6 millisecs. At stage (i) the forward movement of the flame has just begun and stages (ii) and (iii) mark its further progress forward. During stages (iv)—(vii) the flame is moving backwards. These two groups of snapshots correspond, (i)—(iii), with a rise to a crest on the time–pressure curve for the explosion and, (iv)—(vii), with a fall to a trough. When the forward movement of the flame occurs, dark bands (due to luminescence) are observed in photographs of the gases behind the flame-front taken on a revolving drum. When the flame has just completed its backward movement, and is poised ready for another forward movement, it is a thin disc. Light bands (there being no luminescence) are then observed in revolving-drum photographs of the gases behind the flame-front. On comparing this succession of snapshots with the track of the flame as photographed, along the axis of the tube only, on revolving sensitised paper, the reasons for the gradations in " thickness " and intensity of the latter are apparent.

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