306. *Studies in the Mechanism of Flame Movement. Part IV. The Vibratory Period.*

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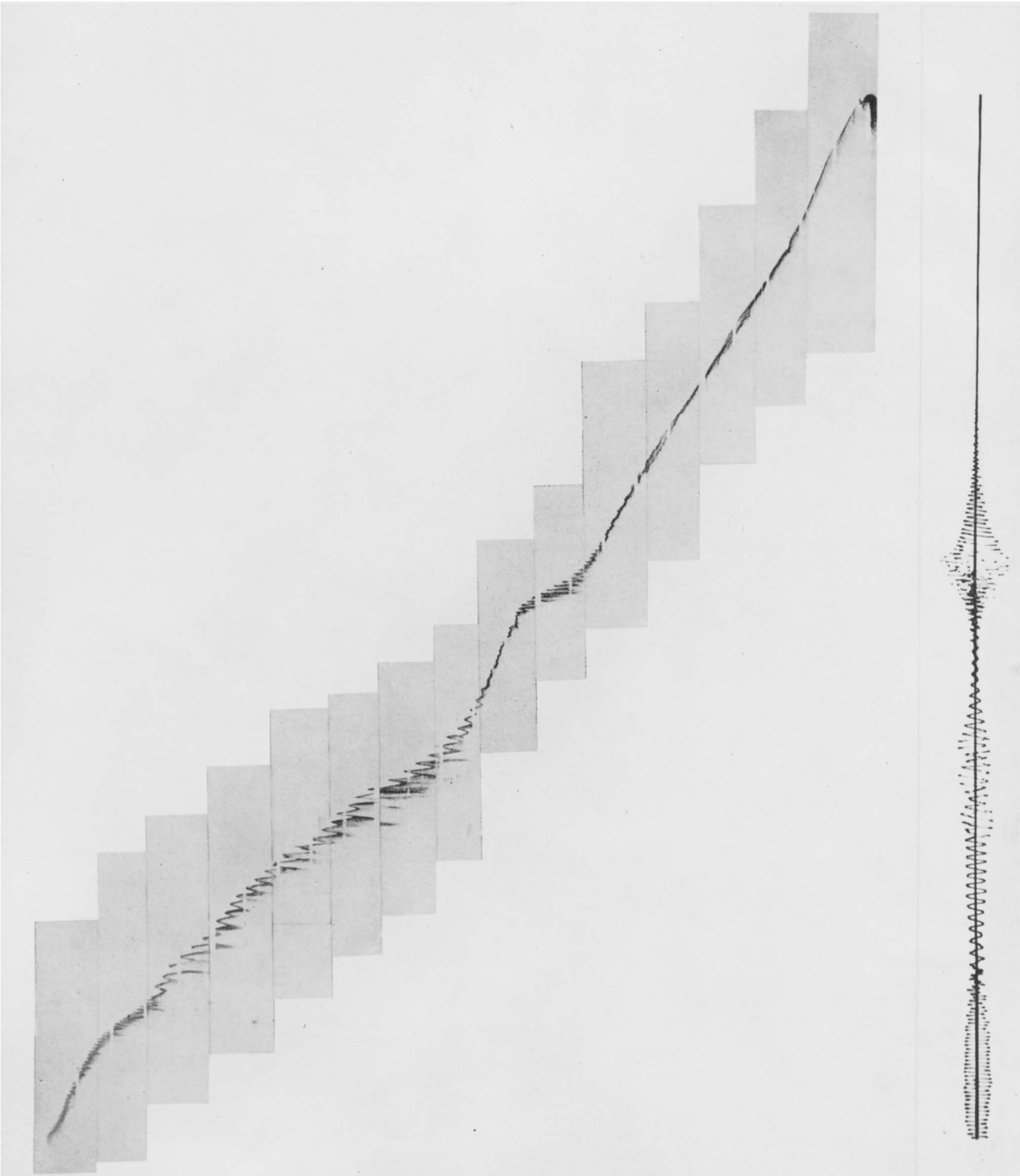
The vibratory movement during the propagation of flame in various mixtures of methane and air contained in tubes of various dimensions, the flame travelling from an open towards a closed end, has been examined. Each of the frequencies observed in tubes up to 10 metres in length corresponded with the fundamental note or with a low overtone of the whole column of gas in the tube, as calculated from Lees's formula. In a tube 32·3 metres in length the vibrations were less regular but many of them corresponded with the fundamental note.

Various means were discovered for suppressing the vibrations of such a flame, including a partial closure of the open end of the tube and a provision of gauze releases along the wall of the tube. In a certain tube of square cross-section the flame failed to vibrate, whereas in a tube of equal length and equal (but circular) cross sectional area the vibrations were large in amplitude.

Mallard and Le Chatelier (*Ann. Mines*, 1883, **4**, 274) obtained moving-drum photographs of the vibratory movement of flame during the explosion of the mixture $CS_2 + 6NO$ in a horizontal tube which was open at the firing end and closed at the other. With this mixture, the period and amplitude of the vibrations varied from point to point as the flame travelled along a tube; it was very rare that several consecutive vibrations had exactly the same period; and in repetition experiments the vibratory movement was never reproduced in the same manner twice. Mason and Wheeler's records of methane–air explosions (J., 1920, **117**, 36) were much more regular, and suggested to them that resonance in the column of gas governed the frequency. The present communication contains some tests of this hypothesis.

A resonating column of gas through which flame is travelling is divided by the flame-front into parts which have different acoustic properties. Lees (*Proc. Physical Soc.*, 1929, **41**, 204) has deduced the resonance frequency, n, of a column of gas, one portion of which is at a temperature T_1 and the other at a temperature T_2, for vibrations in a tube closed at

FIG. 1.



Composite photograph of explosions of 10% methane–air mixtures.

[*To face p.* 1483.

both ends, open at both ends, or closed at one and open at the other. In the last-named circumstances, the frequency should satisfy the condition

$$(n_1/F_1) \tan p_1\pi/2 = -(n_2/F_2) \tan (p_2 - 1)\pi/2$$

in which n_1 and n_2 are the fundamental frequencies when the whole length of the column is at T_1 or T_2 respectively; F_1 and F_2 are the moduli of adiabatic elasticity for the longitudinal displacements in the column; p_1 and p_2 are nl_1/n_1L and $n(L - l_1)/n_2L$ respectively; L is the length of the tube and l_1 the distance between the junction (flame-front) and the open end of the tube.

The exact application of Lees's formula to the problem under consideration would be possible only if the hot gases were at a constant known temperature during an experiment; but this is not so, for they are rapidly losing heat to the walls of the vessel. An upper limit to their temperature may, however, be assigned on the assumption that the products lose no heat during the explosion, and a lower limit for their mean temperature may be determined by a simple experiment. The observed frequencies should then lie between those calculated from the estimated limits of temperature.

When, as in the present experiments, the tube is open at the firing end, the hot products are propelled towards the open end of the tube, but their mean speed can be shown not to exceed about 12 m./sec. and may therefore be neglected in comparison with the speed of sound in the mixture.

EXPERIMENTAL.

Methods.—Four tubes were used, three for laboratory experiments, one for field work. Their lengths and diameters were, severally: (1) 5·004 m., 10 cm.; (2) 5·07 m., 20 cm.; (3) 10·17 m., 20 cm.; and (4) 32·3 m., 30·6 cm. The first three were built of sections, each 1 m. in length. One section of each was fitted with a row of quartz windows, 0·5 cm. in width, through which the flame was photographed by a revolving-drum camera. By moving this section to successive positions along the tube, a series of photographs of repeated explosions could be obtained, and when these were joined together they formed a composite picture of the movement of flame through the whole length of the tube. Fig. 1 gives an example of this; it represents the explosion of a 10% methane–air mixture in the first tube. Somewhat similar results were obtained for explosions in the second and third tubes; a reproduction of the composite picture for the third tube is given in the Annual Report of the Safety in Mines Research Board for 1928.

On the right-hand side of Fig. 1 is a record of the pressure changes corresponding with the flame movements in an explosion in the first tube. The record was made by a manometer attached to the closed end of the tube. At any moment during the vibratory period, the frequencies of the pressure variations were equal to those of the flame vibrations; hence for the purpose of determining frequencies the manometer could replace the camera, and one experiment could replace the 15 or 30 needed with the shorter tubes. The manometric method was therefore used alone with the largest tube.

General Review of Laboratory Results.—The original photographs, on which a time-scale had been recorded, show that the flame of a 10% methane–air explosion, travelling in a horizontal tube just over 5 m. in length, began to vibrate, at about 1·5 m. from the point of ignition, with a frequency of about 70 per sec. These vibrations reached a maximum amplitude, died away, and were followed by vibrations of frequency 33 per sec., which persisted until the flame was near the closed end of the tube, whereupon the frequency became less regular at about 70—90 per sec. (Fig. 1).

In all experiments in which comparative records were made photographically and manometrically, the measured frequencies were equal for the same position of the flame; the amplitudes recorded were usually not equal, however, for when the flame was near a node of the resonating column (as, *e.g.*, when it was near the closed end of the tube) the amplitude of its vibration was necessarily small although the amplitude of the pressure variations might be large.

Measurements of the frequencies of the chief vibrations are collected in Table I. A comparison of the first and second columns of frequency figures shows the essential agreement of the results of the manometric and the photometric measurements. A comparison of these two columns with the third shows that, in general, the frequency was increased slightly when the diameter of the tube was doubled, the length being unchanged; an effect characteristic of a resonance of the column of gas, with an allowance for somewhat less cooling in the wider tube.

TABLE I.

Frequencies of vibrations (number per sec.).

Length of tube, m. ...	5·004		5·07		10·17	10·17	10·17
Diameter of tube, cm.	10		20		20	20	20
Mixture, CH_4, %	10		10		10	7	12
Vibrations recorded by	Manometer.	Photo.	Photo.		Photo.	Photo.	Photo.
1st half metre	—	—	—	1st metre	—	—	—
2nd ,, ...	—	—	—	2nd ,,	—	—	—
3rd ,, ...	—	—	—	3rd ,,	—	—	—
4th ,, ...	69	69	71	4th ,,	35	33	33, 11
5th ,, ...	71	69, 30	71	5th ,,	32, 15	14	14
6th ,, ...	31	31	33	6th ,,	16	14	15
7th ,, ...	32	32	35	7th ,,	17	15	16
8th ,, ...	30	30	35	8th ,,	17	17	17
9th ,, ...	31	31	97	9th ,,	16, 45	42	39
10th ,, ...	70—90	70—90	87	10th ,,	(100, 70, 40)	36	37

The last three columns of figures show that, when the length of the 20 cm.-diameter tube was doubled, the results were much the same at equal fractional distances along the tubes, except that the frequencies were halved; this was so in spite of the fact that the speed of flame in the 7 and 12% methane mixtures was much less than that in the 10% mixture. The results leave little doubt that the vibrations are resonance effects.

Comparisons between Calculated and Observed Frequencies of Vibrations of Flame.—Calculation of resonance frequencies by means of Lees's formula requires a knowledge of the temperature of the hot products of combustion. This must lie well below the observed flame temperature, which, for a 10% methane–air mixture, is 1880° (Jones, Lewis, Friauf, and Perrott, *J. Amer. Chem. Soc.*, 1931, **53**, 869). A lower limit was determined by the following means : Immediately after the flame of an explosion had reached the closed end of the tube, a cover was fixed over the open end and the cooling products of combustion were allowed to draw air into the tube through a tap until the room temperature had been reached. The tap was then closed and the contents of the tube were well mixed by circulation, sampled, and analysed. The fractional partial pressure of the flame gases, including the water vapour which has condensed, is nearly equal to the ratio between the absolute temperature of the room and the absolute mean temperature of the contents of the tube at the moment of greatest expansion. The figures for the lower limit estimated in this manner are given in Table II, together with other data used for calculations with Lees's formula.

TABLE II.

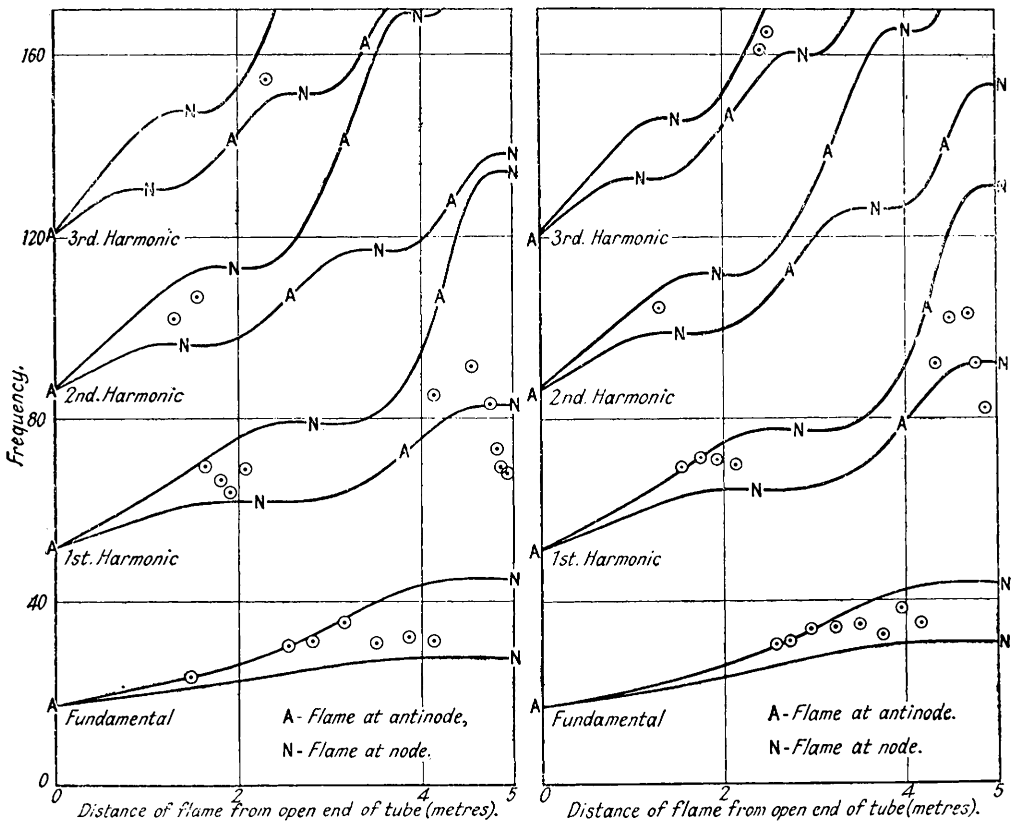
Length of tube, m.	5·004	5·07
Diameter of tube, cm.	10	20
Mixture, % CH_4	10	10
Room temperature	15°	22°
Estimated lower limit of mean temperature of products	526°	750°
C_p/C_v, original mixture, room temperature	1·387	1·386
C_p/C_v, products, 1880°	1·252	1·252
C_p/C_v, products, at estimated lower limit of temperature	1·316	1·295
Speed of sound in original mixture at room temperature, m./sec.	346	350
Speed of sound in products at 1880°	901	901
Speed of sound in products at estimated lower limit of temperature	557	633
n_1	17·2	17·0
n_2 at 1880°	44·7	43·7
n_2 at estimated lower limit of temperature	27·6	30·7

It may be noted that, although the mean temperature of the products is estimated between very wide limits, *e.g.*, 750° and 1880°, the corresponding values of n_2 have a ratio, in this example, of about 0·7 : 1. The crudeness of the estimate of the mean temperature is, therefore, of less importance than might appear.

Figs. 2 and 3 contain the values of the measured frequencies of flame vibrations in the laboratory tubes. Each pair of curves represents the frequencies of vibration of the whole column of gas in the tube, calculated from the two limits ascribed to the temperature of the products of combustion; one pair for the fundamental frequency, others for the lower harmonics. There would seem to be no doubt that, in these experiments, the most intense vibrations of the flame (see Fig. 1) represent the fundamental vibrations of the gas, and that the first harmonic is represented by vibrations in both the early and the latest stages. A few small vibrations representing the second and third harmonics can be detected on the original photograph.

The incidence of vibrations seems to depend on the relative positions of the flame and of the nodes and antinodes of the lower harmonics. In Fig. 1, for example, the first observed vibrations belong to the second harmonic and occurred just before the flame reached a node. Just after the flame had passed the nodal position a well-marked series of first harmonic vibrations appeared; their amplitude rapidly increased but almost suddenly fell to zero just before the flame reached the node of the first harmonic. For a short interval some weak vibrations of the third harmonic occurred, just in front of a node. They were soon replaced by the chief phase of the vibratory period, in which for a considerable distance along the tube the flame vibrated with frequency equal to the fundamental and with an amplitude that rose to a high value. This phase was replaced by a first harmonic vibration as the flame approached the closed end of the tube.

FIG. 2. FIG. 3.



Observed [⊙] *and calculated frequencies of vibration of flame.* Fig. 2: *Tube* 5·004 *m. in length,* 10 *cm. in diameter.* Fig. 3: *Tube* 5·07 *m. in length,* 20 *cm. in diameter.*

In general, it may be concluded that the various phases of the vibratory period, characterised by frequencies corresponding with the fundamental and over-tones of the tubes used, tend to develop between antinode and node of one of the possible modes of resonance, their amplitudes rising to a maximum and falling away. When the flame, which provides the energy for the vibrations, is about half-way along the tube, the fundamental is developed, but at earlier and later stages of the flame the harmonics appear.

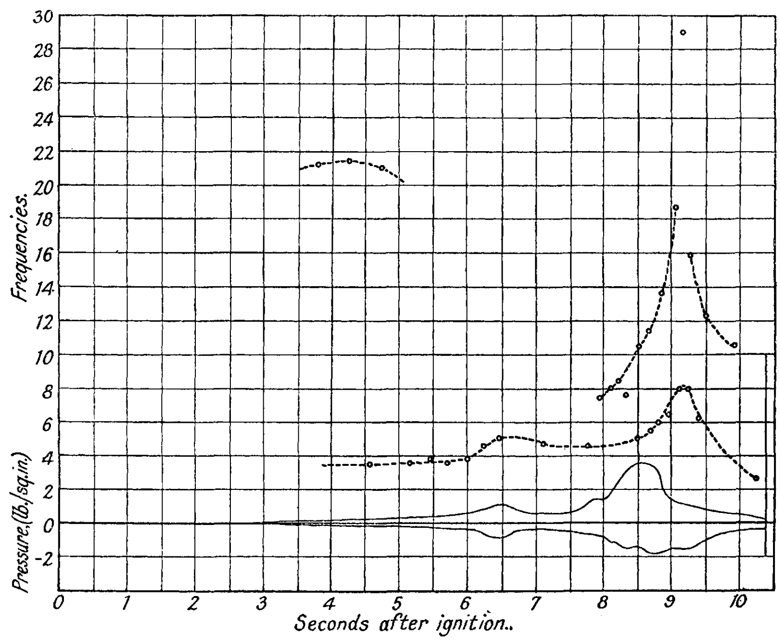
Experiments on a Larger Scale.—A tube 32·3 m. in length and 30·5 cm. in diameter, supported horizontally, was fitted with a manometer at one end, which was closed to the air. The other end was fitted with a sliding plate which was removed at the moment when the mixture in the tube was ignited there.

The explosions in this tube proved to be neither so regular nor so reproducible as those in the smaller tubes. In Fig. 4, which shows the results of a typical experiment, the frequencies are indicated by the points on the broken curves, the amplitudes of vibrations by the continuous curves which envelop the record (unreproduced) of the manometer. The first vibrations observed are of about 21 frequency but small amplitude; shortly afterwards they are found superposed on a low-frequency vibration of 3·4 per sec. which rises to about 5 and later to 8 before it falls away. Between the eighth and the tenth second a higher-frequency vibration appears, superposed on the others. None of these is instrumental, for the natural period of the manometer system was 370.

The fundamental resonance frequency when the tube is full of cold gas is about 3 per sec. The lowest of the broken curves probably represents the fundamental in the whole column of gas behind and in front of the flame.

The Suppression of Vibrations of Flame.—We had observed (J., 1926, 1522) that flame vibrations in upper-limit mixtures of methane (about 14%) in air, in a tube 5 cm. in diameter, could be suppressed by a pad of cotton-wool held loosely over the open end of the tube. As there might be useful applications if the vibrations of more violent explosions could be damped in some such way, trials were made with the most explosive mixture of methane in air, first in the laboratory and then in the large tube.

FIG. 4.

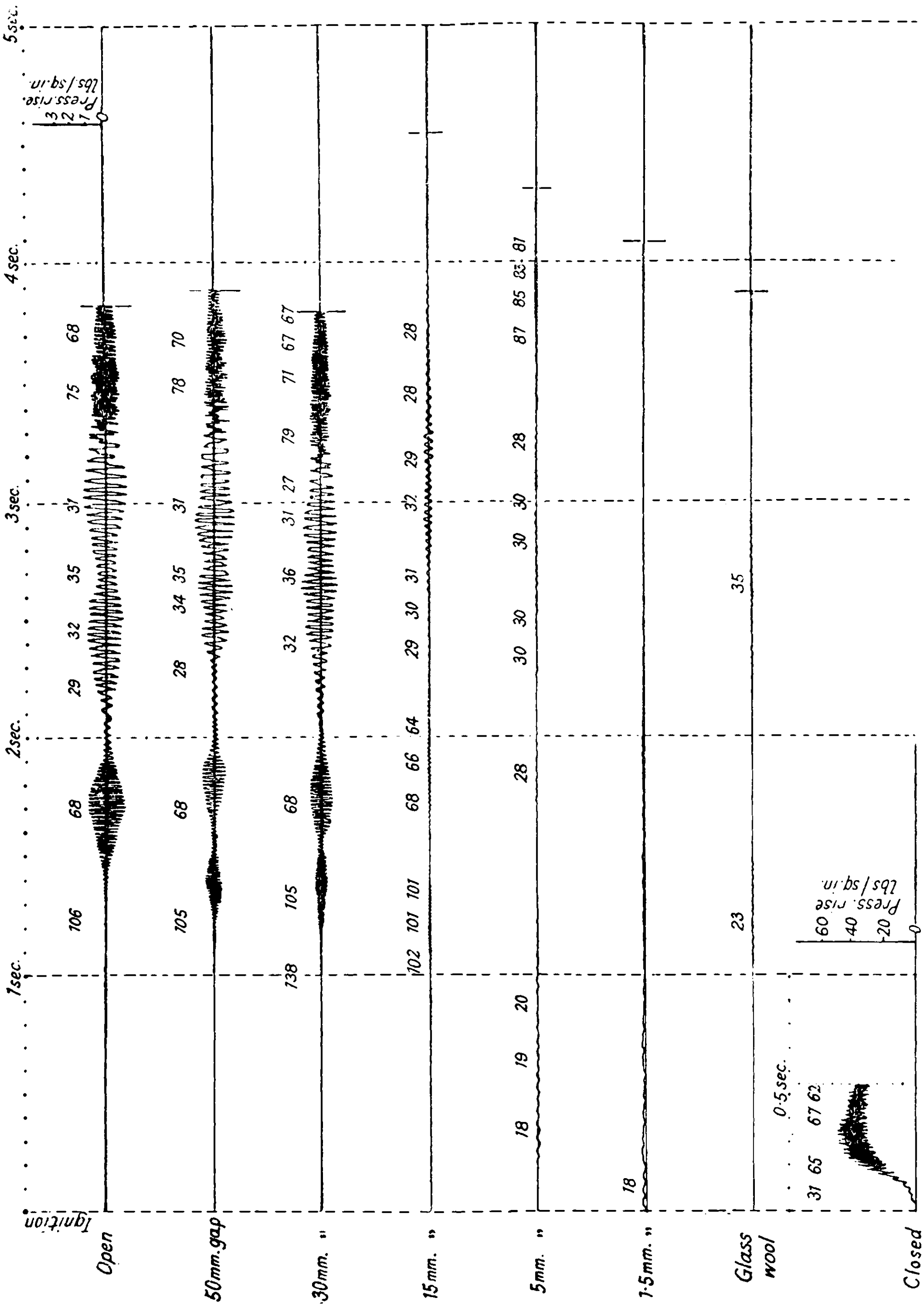


Frequencies (broken lines) and pressure variations (whole lines) of the explosion of a 10% methane–air mixture in a tube 32·3 metres in length, open at the firing end.

The laboratory observations are summarised in Fig. 5, which is a collection of manometer records of 10% methane–air explosions in the tube 5 m. in length, 10 cm. in diameter. The first record was obtained with the tube fully open at the firing end; it is a repetition of the experiments recorded in Fig. 1. The numbers at various points above this and the following records are frequencies of the pressure alternations at those points. The amplitudes of the pressure changes may be read on the scale to the right. A rigid metal plate was brought, in successive experiments, nearer and nearer to the firing end. The records show that when the gap between the plate and the tube was 5 cm. or 3 cm. the character of the explosion was almost the same as in the open tube. With a gap of 1·5 cm. the vibrations were almost suppressed; also with gaps of 0·5 and 0·15 cm. and with a pad of glass-wool instead of the plate. When the tube was completely closed, however, the character of the explosion was quite different; the combustion, instead of taking 4 secs., was complete in about 0·5 sec., a large positive pressure was developed, and the amplitudes of the vibrations were multiplied some ten-fold.

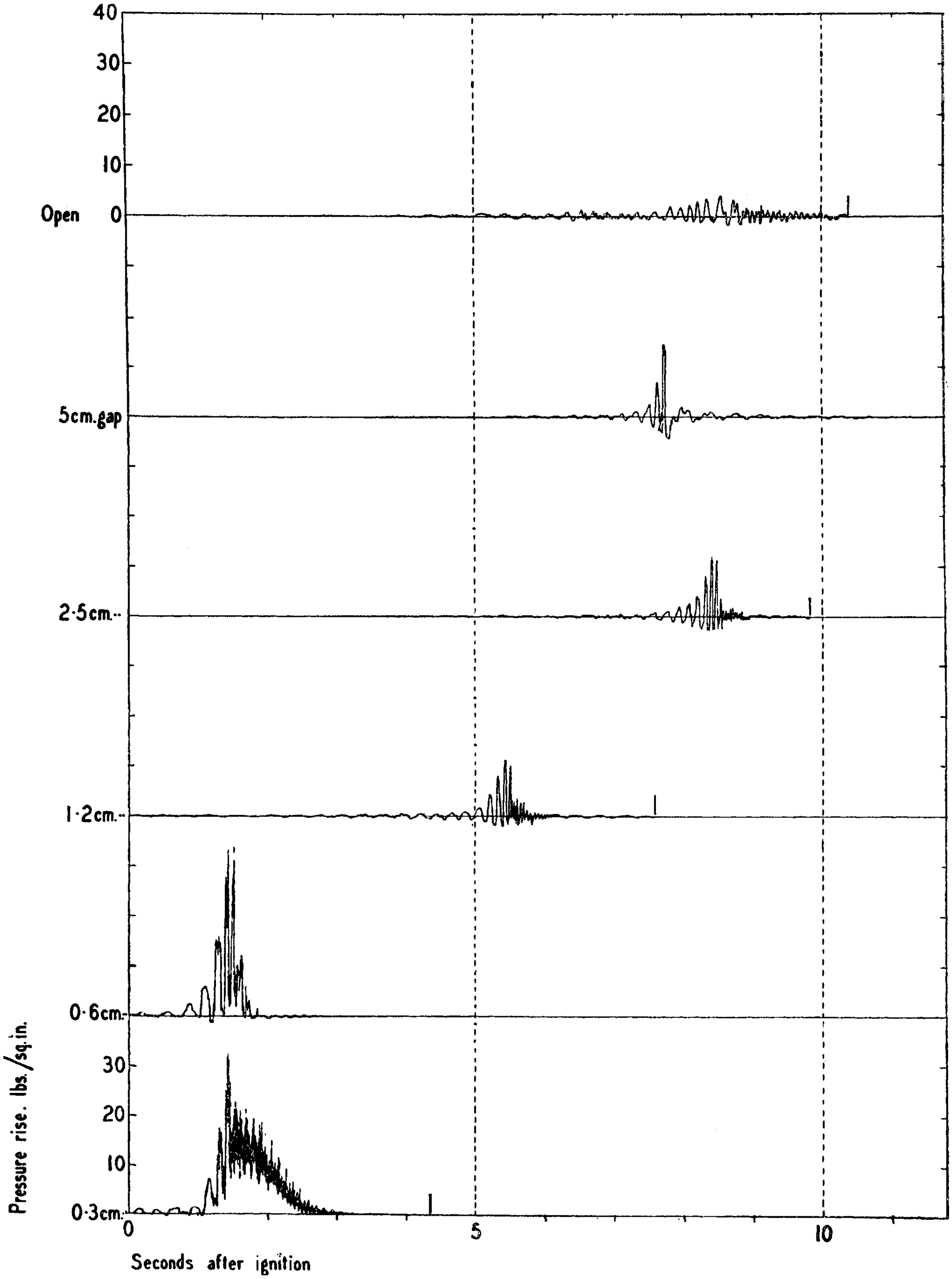
Observations with the largest tube (32·3 m. in length, 30·6 cm. in diameter) are summarised similarly in Fig. 6. The results were in marked contrast to those obtained in the smaller tubes. The vibrations were not suppressed when gaps of 5, 2·5, 1·2, 0·6, and 0·3 cm. were left between a

FIG. 5.



Manometric records of successive explosions of a 10% methane–air mixture in a tube 5 m. in length, 10 cm. in diameter, the aperture at the end being reduced in stages.

FIG. 6.



Manometric records of successive explosions of a 10% *methane–air mixture in a tube,* 32·3 *metres in length, the aperture at the end of the tube being reduced in stages.*

plate and the end of the tube, but with each decrease in the size of the gap the total time of explosion decreased and the violence of the vibrations increased considerably. Finally, in a repetition of the experiment with the smallest gap, the far end of the tube was shattered.

The time of arrival of the flame at the closed end of the tube is indicated in Figs. 5 and 6 by bars. In two of the experiments of Fig. 6 the flame did not reach the end of the tube, but was self-extinguished, apparently during a violent vibration.

The experiments just described suggest that the provision of a suitable narrow gap in a flame-proof enclosure may serve not only to relieve the pressure of an explosion of firedamp within it, but also to eliminate violence due to vibrations; the violence of a firedamp explosion in a long gallery is, however, increased by reducing the size of an opening near the point of ignition in the gallery.

Miscellaneous Observations on the Suppression of Vibrations of Flame.—It may be of value to record some isolated observations on the vibrations of flame:

(1) The vibratory movement did not occur in a tube of square cross-section, 122 cm. in length and 4·4 cm. side, during the propagation of flame in a 10% methane–air mixture. A slight hum indicated weak undulations, but their amplitude was not large enough to alter the shape or speed of the flame from those of the uniform movement. Flames in the same mixtures contained in a tube of circular cross-section of the same area and of the same length began to vibrate strongly at a distance of 60 cm. from the open end. The difference may be due to a release of pressure in the corners of the square tube, into which the flame penetrates tardily.

(2) When a slit was cut in a tube, 110 cm. in length and 2·5 cm. in diameter, and the slit was covered by fine copper gauze, the propagation of flame in any methane–air mixture within the tube was almost or quite noiseless. In some experiments the tube was held horizontally in the air, the slits being below; in others the tube was surrounded by a wider tube full of the same mixture, and very little air passed through the gauze during an experiment.

(3) In a rubber tube, 73 cm. in length, 2·5 cm. internal diameter, walls 0·31 cm. thick, flame travelled through a 10% methane–air mixture with only a low purr. When the tube was fitted with a glass end-piece, 15 cm. in length, vibrations of about 5 cm. amplitude were seen. When the tube was replaced by one with walls only 0·08 cm. thick, the flame was noiseless.

Observations (2) and (3) are consistent with the interpretation of the vibratory period of flame as a resonance phenomenon, the resonating column being damped either by a release of pressure through gauzes along the walls, or by walls of flexible material.

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