FLAME SPEEDS IN OSCILLATING GASES IN A TUBE

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ABSTRACT

Flow disturbances such as turbulence, have long been known to have important effects on flame propagation, affecting in particular the flame speed. Due to the difficulty associated with measuring turbulence and describing its effect on such a complex phenomenon as a flame, it has been pointed out that useful information can be obtained by restricting the study to the interactions of a simple form of flow disturbance and a flame.

This paper describes some experimental studies on the influence of oscillations on an otherwise normal flame propagating from either end of a tube open at one end. The experiments reveal that higher flame speeds invariably result with the imposition of oscillations irrespective of the strength of the combustible mixture. The flame speed increases lineraly with frequency of oscillations and the extent of this increase is determined by mixture strength. Rich mixtures show increasing flame speeds with increasing amplitudes, while lean mixtures exhibit a critical amplitude at which maximum flame speed occurs.

INTRODUCTION

All modern combustion equipment rely on the generation of high flame speeds for the attainment of high rates of specific heat release. The speed with which a flame proceeds in a combustible mixture is mainly governed by (*a*) the chemical nature of the mixture and its strength, (*b*) its physical state such as temperature and pressure and (*c*) the movement of the mixture prevailing in the system. In most practical applications high flame speeds are invariably obtained by providing some form of controlled movement of the combustible mixture. Therefore, knowledge of the nature of the influence of the various types of flow disturbances on flame propagation prove to be useful in the design of combustion apparatus. Flow disturbances could be either turbulence or some form of systematic disturbance which is not random.

Turbulence is known to have an immense effect on the mode and speed of flame propagation. Increased flame speeds are attained with increased intensities of turbulence. The maximum flame speed mixture strength is shifted further to the rich side in turbulent flames. A turbulent flame itself is known to produce additional turbulence.[1 to 4]

Vibrations produced by the flame itself as in the case of flame propagation from the open end of a tube or produced by external means, are known to be responsible for increased flame speeds.[5 to 8] Properly phased pressure waves can be made to promote or suppress flame propagation.[9, 10]

Theories to explain the mechanism by which turbulence increases flame speeds mostly assume that turbulence has little, if any, effect on the local burning velocity which remains at its laminar value. The apparent increase in turbulent burning velocity, then, is due to the wrinkling of the flame surface, thus increasing its area. The theories next proceed to relate the parameters of turbulence in the unburned gas with the burning velocity[1, 3, 4], completely neglecting their effect in the burning zone and the burned gas. This assumption seems to warrant further investigation. Greater insight into this phenomenon is hampered by the complicated nature of truly turbulent flames and paucity of sound methods of measurements of the turbulence parameters in the burning zone. Therefore, it seems fruitful to restrict the study to a system of flow disturbances which are simple and capable of accurate measurement.[11] Pressure oscillations imposed on combustible mixtures have been reported to be responsible for considerable increases in flame speeds. These constitute a fairly simple form of flow disturbances and can be easily produced in a tube by a piston moving to and fro at one of its ends.

This paper presents the results of a preliminary investigation to acertain the effects of one such simple form of flow disturbances, *viz.* oscillations produced by a piston, on flames propagating in a tube. A tube with one end open has been chosen for the experiments since this facilitates in obtaining a flame which is reasonably free from turbulent influences of the flame itself for a short distance when the flame is initiated at the open end.

EXPERIMENTAL DETAILS

Experimental Apparatus:—Figure I shows the schematic lay-out of the complete experimental arrangement. The flame tube used for the experiments was a galvanised iron pipe, two inches in internal diameter and 45 inches long, with four 9 × 0.2 inch windows on one side provided for visualising the flame movement. These were covered with perspex sheets to avoid gas leakage. The tube was mounted upright on the cylinder block of an engine which was used to produce oscillations in the gas column. A thin plastic membrane was fastened at the top between two flanges to hold the gas during the interval between the imposition of oscillations and ignition. Two spark plugs, one at each end, were provided to facilitate the study of flame travel from either the closed or open end. Provisions were made for gas inlet at the bottom and outlet at the top of the tube.

The oscillations were imposed by the piston of an engine (2″ × 2″ bore and stroke) with its head and other auxiliaries removed, and all paths of leakages in the engine blocked. The crank arrangement of the engine was slightly modified so that two more amplitudes of oscillations, $1\frac{1}{2}''$ and 1″, were possible. The engine was driven at speeds ranging from 500 to 4000 revolutions per minute (corresponding to 500 to 4000 cycles per minute of oscillations) by a variable speed DC motor. By proper fixtures of the engine, the motor and the tube, the tube was made free from the influence of any extraneous vibrations due to the engine.

The combustible gas used for the experiments was a mixture of acetylene and air. Both acetylene and air were led separately into a mixing chamber where they were mixed by convection due to external heating for about twelve hours. By varying the ratio of pressure of acetylene to that of the mixture in the mixing chamber, any desired mixture strength could be obtained. The combustible mixture before every test was analysed chemically to determine the mixture strength by volume.

The process of combustion was recorded by a photographic method using the light emitted by the flame itself. A drum camera, specially built for the purpose, enabled records with a maximum length of 21 inches to be taken at any peripheral speed between 18 in./sec. and 600 in./sec. The lens used was a Dallmeyer Pentac of 4 inches focus and 2.9 aperture. The lens arrangement gave a ratio of

$$\frac{\text{Length of flame travel in the tube}}{\text{Width of flame trace on the record}} = 20.5$$

as determined by flame photographs. The film speed was obtained from timing marks made on the film by a Strobolux giving powerful white flashes operated by a Calibrated Strobotac. A solenoid operated shutter permitted the timing marks to be made on the film during one revolution only when the actual flame progress was being photographed.

A set of timing contacts activated by a cam on an auxiliary shaft driven by the drum spindle was utilised to generate a spark for ignition of the combustible mixture and to energise the solenoid shutter. At the instant when cam actuated the timing contacts, both the spark and solenoid came into operation simultaneously. This instant was synchronised with the motion of the drum to avoid the joint on the film record. The solenoid shutter was kept open over the lift portion of the cam, corresponding to one revolution of the drum.

A battery operated Delco-Remy 12-volt ignition coil was used for the ignition arrangement. A push button switch served as the master control for operation of the camera timing contacts assembly. Separate ignition contact breakers mounted on the crankshaft of the engine made it possible for the ignition to be phased with the piston motion. The ignition circuit in this case remained as before but for the introduction of these points in place of those controlling the synchronisation of the drum motion with ignition. The entire set-up was housed in a dark room.

Experimental Procedure: A homogeneous combustible mixture was prepared by allowing acetylene and air at the desired pressures to the mixing chamber and slow external heating of the mixture was carried out for about twelve hours. A chemical analysis before each test established the correct mixture strength of the mixture. One complete charge of the mixing chamber was sufficient for about eight tests. The combustible mixture was then admitted into the flame tube which was previously sealed at the top with the help of a plastic membrane. The mixture was allowed to pass through the tube to atmosphere for sufficient length of time through the top outlet to ensure that all the air was displaced by the combustible mixture. The inlet and outlet of the tube were simultaneously closed so that the pressure in the tube was very nearly atmospheric. With this arrangement, it was noted that flame traces could be obtained with an amount of reproducibility considered quite satisfactory in the light of limitations imposed by the experimental apparatus.

The film (R 60 High Speed Panchromatic Recording film) was loaded into the camera. The oscillations were established in the tube, the camera was started and the combustion process was recorded. Then the film was processed for analysis. The flame traces obtained at high peripheral speeds of the drum were very weak and a special technique for processing (Latensification) was adopted in such cases.

Evaluation of flame records:—The photographs obtained from the tests were read on the screen of a Wilder Microprojector with a protractor attachment, which helped in determining the angles of inclination of the flame trace at any point. The flame speed was then calculated as follows:—

$$V_0 = u \times \tan\alpha \times k$$

where V_0 = flame speed

u = film speed (determined by the timing marks on the film)

$\tan\alpha$ = slope of the flame trace

k = constant, equal to the ratio of the distances of flame travel in the tube and the film, and

= 20.5 for the present set-up.

Experimental programme:—The experimental programme envisaged the study of the influence of mixture strength*, frequency and amplitude of oscillations and also timing of ignition with respect to piston motion on flame speeds. Mixture strengths were varied from 5 % on the lean side to 20 % on the rich side, stoichiometric mixture being 8.4 %. A frequency range of 1000 to 3500 cycles per minute was adopted for the investigation. Frequencies lower than 1000 cycles per minute could not be investigated since steady running could not be obtained at such low speeds. High frequencies above 3,500 cycles per minute were not possible because the plastic membrane at the top gave way even before ignition. Use of thicker plastic membrane was prohibited by the stipulation that the tube should be open at one end during combustion. The membrane used was a compromise and resulted in an increase of flame speed of about 5 to 6 % as noticed from several tests on quiescent mixture with the membrane just pasted and rigidly fixed. This also precluded the study of flame speeds under resonant conditions in the gas column which corresponded to 4800 cycles per minute with the present experimental arrangement. The entire frequency

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* In this paper the mixture strength denotes percentage of acetylene in air.

range was investigated only for 2″ amplitude oscillations, while for amplitudes of 1″ and $1\frac{1}{2}$″ higher frequencies could not be investigated because at these speeds the tube was noticed to be vibrating violently, possibly due to improper balance of the variable stroke crank mechanism.

The influence of ignition timing with respect to piston motion on flame speeds was studied when ignition was carried out at top dead centre, bottom dead centre, and the positions of piston which gave the maximum piston speed during upward as well as downward motion (75° before top and bottom dead centre).

The experiments were in the first instance conducted with ignition being initiated near the open end and later were extended to cover closed end ignition also for any possible corroboration of the results obtained with open end ignition.

EXPERIMENTAL RESULTS

Ignition at open end:—In the first instance experiments were conducted with different mixture strengths under quiescent conditions. The uniform burning velocity was computed from the portion of the flame travel which was free from flame front vibrations, as seen from photographs. Normal burning velocities could not be computed since the experimental arrangement did not permit any flame snapshots to be taken for calculating the area of the flame front surface. Experiments were then conducted with different mixture strengths at different frequencies and amplitudes of oscillations. Plate I shows two typical photographs with and without oscillations imposed on the flame. Figure II shows the variation of flame speed with mixture strength for quiescent conditions as well as oscillating conditions with different frequencies at an amplitude of 2″.

The curve for quiescent mixtures follows the familiar pattern of flame speed variation with mixture strength. The speeds obtained in this case were considerably higher than those quoted in the literature for such experiments. This can be explained partly to the nature of fixing of the plastic membrane and partly to the presence of moisture in the combustible mixture, since no effort was made to eliminate the moisture. Further the presence of moisture might also be one of the reasons for the wide scatter of points in the curves because the tests were conducted over a period of 8 to 10 months and there might have been quite a variation of humidity in the atmospheric air which was used for the experiments.

The curves for oscillating mixtures indicate that the relationship between flame speed and mixture strength is not drastically altered by the imposition of oscillations ; however the following two factors are clearly seen :

(*a*) The flame speeds are higher in oscillating gases. The maximum flame speed is boosted from 55 metres/sec. with quiescent mixtures to about 72 metres per sec. with oscillations of 3500 cycles per minute at 2″ amplitude.

(*b*) As the frequency of oscillations is increased, there is a slight shift in the mixture strength towards the rich side at which maximum flame speeds are obtained. The maximum flame speed is obtained for a mixture strength of 10 to 11 % at frequencies of 2500 to 3500 cycles per minute as against the maximum in the case of quiescent mixtures for a mixture strength of 9 to 10 %.

Figure III shows flame speed-mixture strength curves for 2 inches, 1.5 inches and 1 inch amplitude oscillations with a frequency of 2000 cycles/minute. The flame speeds, as seen from these curves, increase with the amplitude of oscillations on the rich side, while on the lean side there seems to exist a critical amplitude (which is between 1·5 inches and 2 inches in the present case) at which the maximum flame speed occurs. Similar results were obtained at the other frequencies studied.

A cross plot between flame speed and frequency of oscillations at several mixture strengths for the three amplitudes is shown in Figure IV. These curves show a linearly increasing flame speed with frequency for all mixture strengths and amplitudes in the range of present investigation. They also reveal that mixtures burning slowly (*i.e.*, mixtures which are very lean and very rich) stand to gain most by the imposition of oscillations. The slopes of these lines indicate that the effect of frequency in increasing flame speeds is gradually reduced as the fuel content in the mixture increases. But initially, *i.e.*, from quiescent conditions to 1,000 cycles per minute frequency, the effect of oscillations is felt to the greatest extent with the richest mixtures. (This range was not covered during the investigation and hence shown as dotted lines in the curves).* The variation of amplitude has a profound influence on 'initial effect' when compared with its influence on the portions of the curve in the range of frequency above 1,000 cycles per minute.

A close study of the flame photographs revealed that the imposition of oscillations did not materially change the manner of flame propagation in the tube. The flame front vibrations, which are invariably noticed during such investigations, do not seem to be influenced in any particular manner by the imposition of extraneous oscillations, as evidenced by their frequency, amplitude and position at which they start.

The following represents the effect of varying the instant of ignition with respect to the piston motion on the flame speed.

TABLE I

Ignition : Open end — Mixture strength : 7.95%
Freqency: 200 cycles per minute — Amplitude : 2″

Position of Ignition	Top Dead centre	75° before bottom Dead Centre	Bottom Dead Centre	75° before top Dead Centre
Flame speed Metres per sec.	61.2	59.8	55.0	52.6

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* This range hereafterwards is referred to as the 'initial effect' in the present paper.

Thus a distinct reduction in flame speed is noted when ignition takes place during the upward motion of the piston as compared with that obtained during the downward motion.

Ignition at closed end:—The above series of experiments were repeated with combustion being initiated near the closed end of the tube. Plate II shows two typical photographs of flame propagation with and without oscillations being imposed on the gas mass. In view of the fact that the flame speeds were continuously increasing along the length of the tube, they were measured at different points along the length of the tube, *viz.*, 200, 400, 600, 800 and 1,000 mm. from the point of ignition and the average speed over the entire length of the tube was also measured. Figure V shows speed-mixture strength curves corresponding to speeds at 1000 mm. distant from the spark, and the average speed. The curves follow the same pattren as noticed in the case of open-end ignition.

The effect of amplitude of oscillations on flame speeds for a frequency of 2000 cycles per minute (Fig. VI), follows a pattern similar to the one observed with open-end ignition. But the degree of variation of the flame speed is not so pronounced. Again, the same type of results were reproduced for the other frequencies studied.

A cross-plot between flame speed and frequency of oscillations for several mixtures reveals straight-line relationships between the two as in the previous case (Fig. VII). The nature of these variations with mixture strength is not so clearly brought out in this case, though trends similar to the open end ignition are clearly seen.

A study of the flame photographs reveals that the mode of flame propagation does not suffer any particular change due to the imposition of oscillations on the gas column. The flames are seen to be continuously accelerating from end to end of the flame tube, with the presence of a distinct point at which an abrupt change of slope of the time-distance curves occur. The exact location of the point with respect to the position of ignition, however, does not seem to bear any correlation with either the frequency of the oscillations or the mixture strength.

The speed-time relationships for the flame travel along the length of the flame tube are shown in Figure VIII. These bring out the fact that the flames initiated at the closed end are prone to be very erratic and the oscillations of the gas mass do not improve matters in this regard. However, they clearly show the effect of oscillations in achieving higher flame speeds. Further, the percentage increases in flame speeds near the beginning of the flame travel with oscillations are much higher than at the far end of the tube.

The following represent the effect of varying the instant of ignition with respect to the piston motion on the flame speed.

These data show a distinct reduction in flame speed when ignition is initiated during the downward motion of the piston.

TABLE II

Ignition : Closed end
Mixture strength : 8 %
Amplitude : 2″
Frequency : 2000 cycles per minute

(Only average flame velocities have been reported)

Position of Ignition	Top Dead Centre	75° before bottom Dead Centre	Bottom Dead Centre	75° before top Dead Centre
Average flame velocity metres/sec.	129	120	133	124

Discussion of Test Results:— The experiments clearly bring out the fact that high flame speeds result in combustible mixtures, when they are subjected to oscillations, irrespective of the end at which ignition is initiated. In general, a combustion wave propagates in a stream at a velocity which is the vector sum of the normal burning velocity and stream velocity. The oscillations imposed on the gas column in the present case subject the combustion wave to periodic distortions. This results in higher flame surface area per unit volume of the combustible mixture thus increasing the overall rate of flame propagation, assuming again that normal burning velocity is not affected by the imposition of oscillations.

The flame speed *vs* mixture-strength curves (Figures II and V) show that there is a distinct shift of the maximum speed mixture further to the rich side with increasing frequencies of oscillations. This has also been noticed by Wohl[2] in his experiments on bunsen flames disturbed by pipe turbulence. He has attributed this phenomenon to the formation of cellular structure on the flame surfaces of rich mixtures, thus augmenting the extent of flame surface. The formation of this cellular structure has also been claimed to be due to the interaction of pressure waves with the flame front.[12, 13] Whether such cellular flames are noticed with acetylene also is yet to be reported. The results of the present investigation indicate the possibility of such flame shapes for acetylene also, particularly in this case, where pressure waves are imposed on the flame.

The increase of flame speeds with amplitudes of oscillations can be adequately explained by the 'wrinkled flame front' theory. The results of the experiments with lean mixtures do not conform to the above but tend to support the experimental observation of Havemann on the existence of an optimum level of turbulence at which the beneficial effect in the form of high flame speeds is a maximum.[14]

The flame speed-frequency curves (Figures IV and VII) for both open and closed end ignitions are made up of two straight lines of different slopes, on the assumption that the 'initial effect' could be represented by a straight line.

Such an assumption seems to be justified by their strong resemblance to the curves obtained by Wohl[15] for bunsen flames disturbed by pipe turbulence. In the rich range of the mixtures tested, the initial effect lines are steeper than the rest of the portions, while it is quite opposite on the lean side of the stoichiometric, the transition taking place somewhere around the maximum speed mixture strength. Further, if the discussion is restricted only to the experimental range of frequencies, it is noticed that the beneficial effect of increasing the frequency of oscillations in obtaining higher flame speeds decreases as the mixtures become richer. These results indicate that any theory for predicting turbulent flame velocities should take into account the dominant role played by mixture strength. Further, the increasing slopes of initial effect lines with amplitudes, can also be seen in the curves of Wohl.[13]

There is a strong tendency for the oscillations to augment the speeds of slow moving flames to a larger extent than those of fast moving flames, as can be seen from curves (Figures IV and VII) for open end ignition and average velocity curves for closed end ignition. Additional support to the above is obtained from the experiments on flame propagation from the closed end where flames are continuously accelerating from start to finish. Imposition of oscillations on such flames gives rise to very high speed boosts in the early stages of flame propagation than in the final stages. Scurlock and Grover[3] from their theoretical analysis of turbulent flames were able to predict that turbulent flame speed increases as the laminar burning velocity is reduced and this probably explains the result.

Conclusions :—Oscillations, in general, speed up flame propagation in a tube with one end open, without drastic changes in the mode of flame propagation, irrespective of the end at which the combustion is initiated. The nature of relation between flame speed and mixture strength remains unaltered. The maximum speed mixture is shifted further to the rich side with increasing frequencies of oscillations. A linear relationship exists between flame speed and frequencies at all mixture strengths and amplitudes. The beneficial effect of increasing frequency in obtaining higher flame speeds decreases as the mixtures become richer. Increase of amplitudes results in increases in flames speeds with rich mixtures, while with lean mixtures there exists an optimum amplitude at which maximum speed occurs. The 'initial effect' increases as the mixtures become richer. Generally speaking, oscillations have a greater influeuce over the slow moving flames in increasing the flame speeds, than over the fast moving flames.

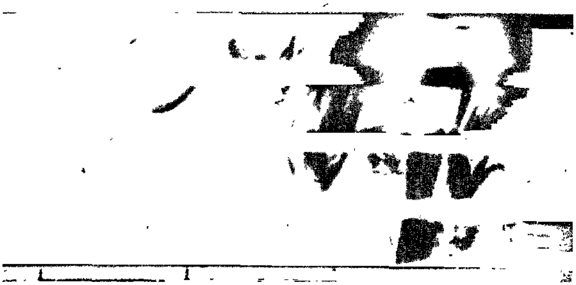

PLATE I *a*

Ignition : Open end ; Quiescent Mixture ; Mixture strength 8 65 %

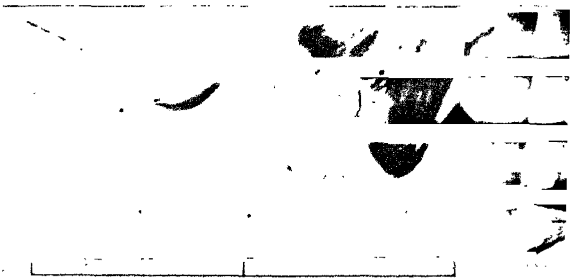

PLATE I *b*

Ignition : Open end ; Oscillating Mixture ; Frequency : 1500 cpm. Amp. 2″ ; Mixture strength 8.92 %

[Each division on the scale drawn below each flame trace represents 10 milliseconds. D lines have been drawn on the flame traces wherever the negatives were very weak due t insufficient light emitted by the flame.]

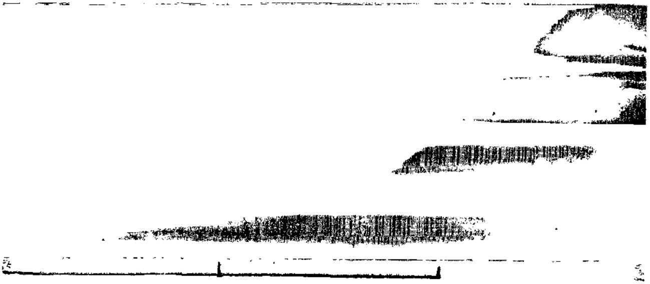

PLATE II *a*

Ignition : Closed end ; Quiescent Mixture ; Mixture strength : 18.82

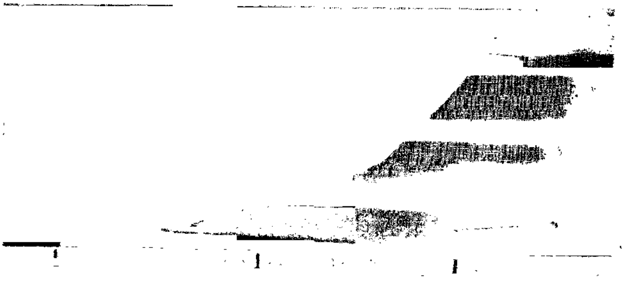

PLATE II *b*

Ignition : Closed end ; Oscillating Mixture ; Frequency ; 1500 cpm. Amp. 2″ ; Mixture strength : 19.55

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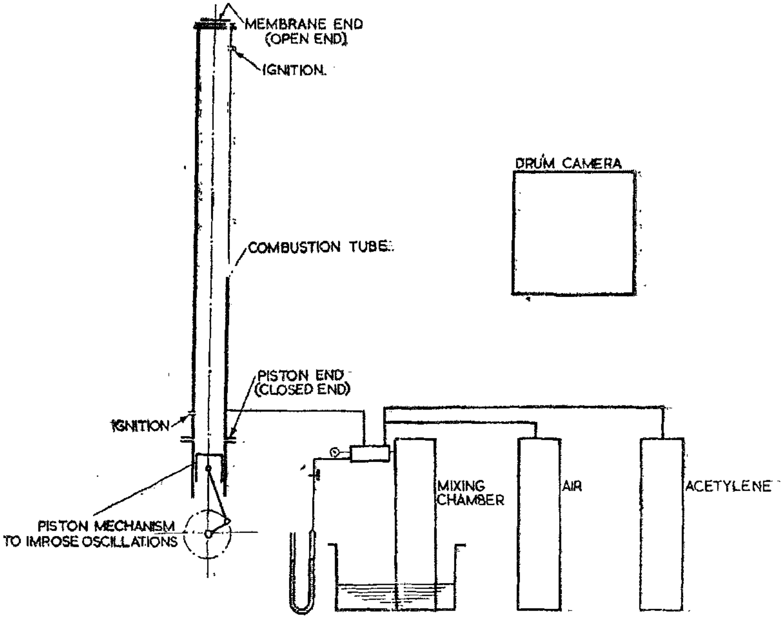

FIG. I
Layout of the Experimental Apparatus

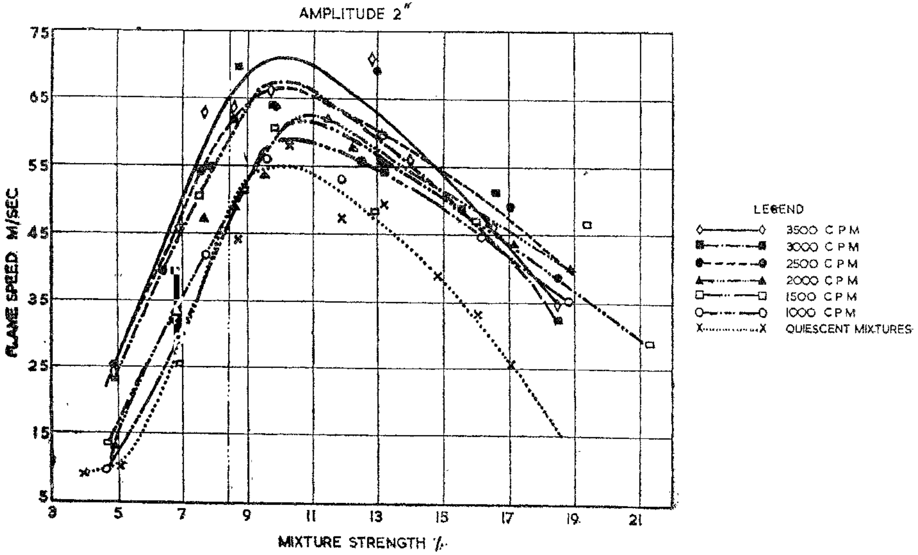

FIG. II

Variation of flame speed with mixture strength in mixtures oscillating at different frequencies and at an amplitude of 2". [Ignition at open end]

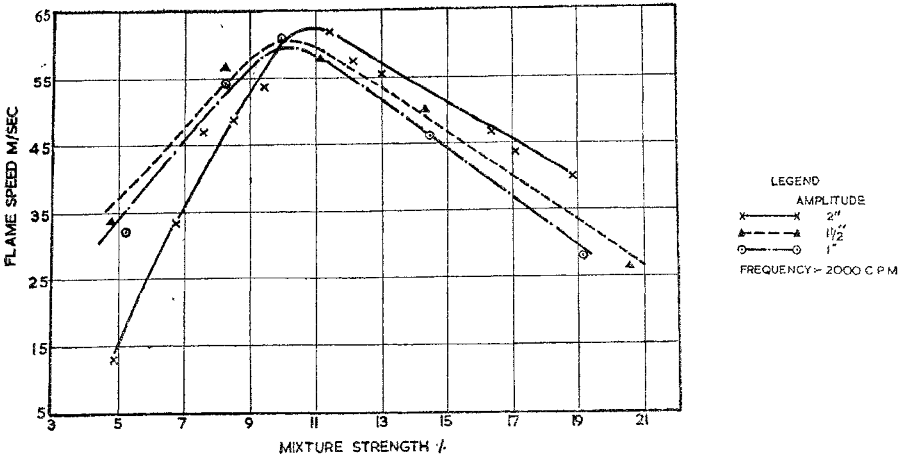

FIG. III

Variation of flame speed with mixture strength in mixtures oscillating at different amplitudes and a frequency of 2000 cpm. [Ignition at Open end

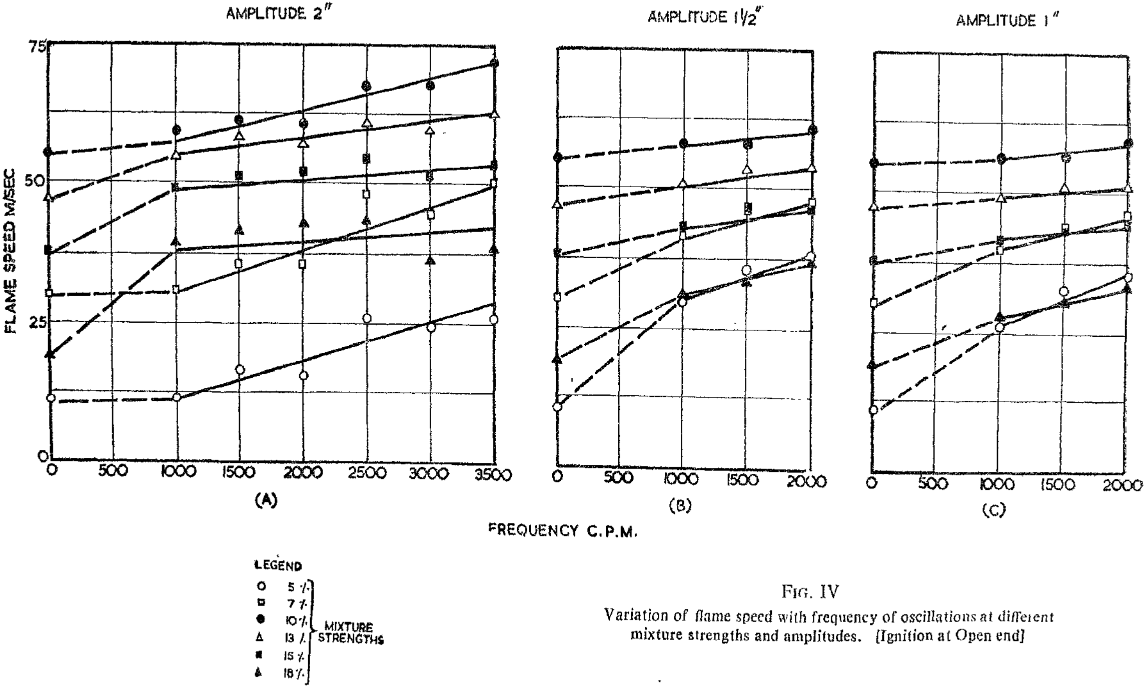

Fig. IV

Variation of flame speed with frequency of oscillations at different mixture strengths and amplitudes. [Ignition at Open end]

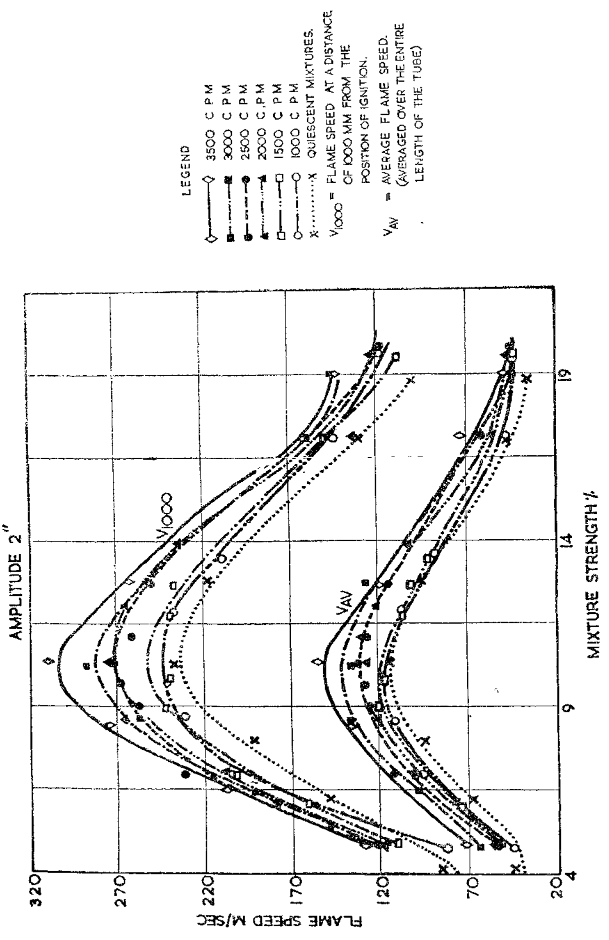

FIG. V

Variation of flame speed with mixture strength in mixtures oscillating at different frequencies and at an amplitude of 2". [Ignition at closed end

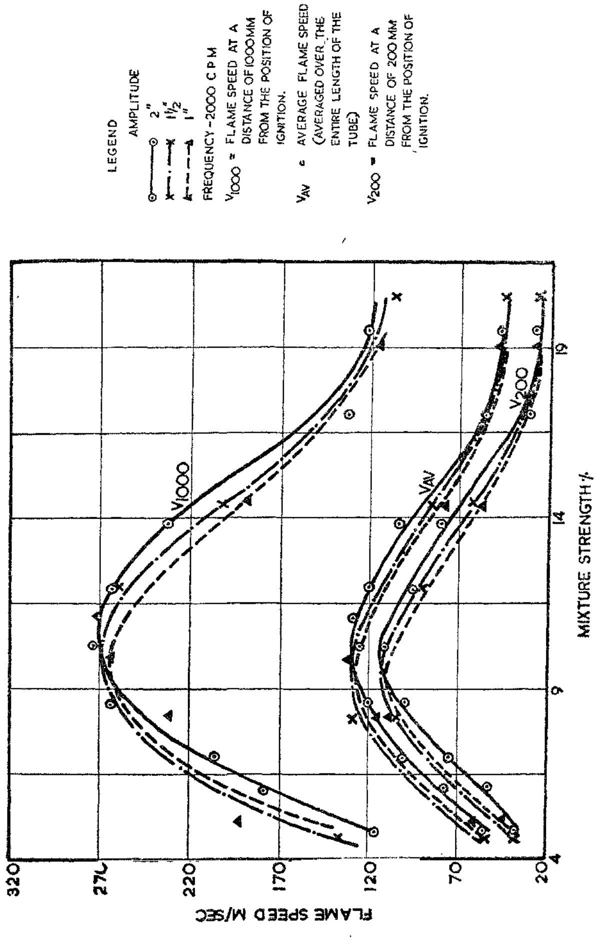

FIG. VI

Variation of flame speed mixture strength in mixtures oscillating at different amplitudes and a frequency of 2000 cpm. [*Ignition at closed end*]

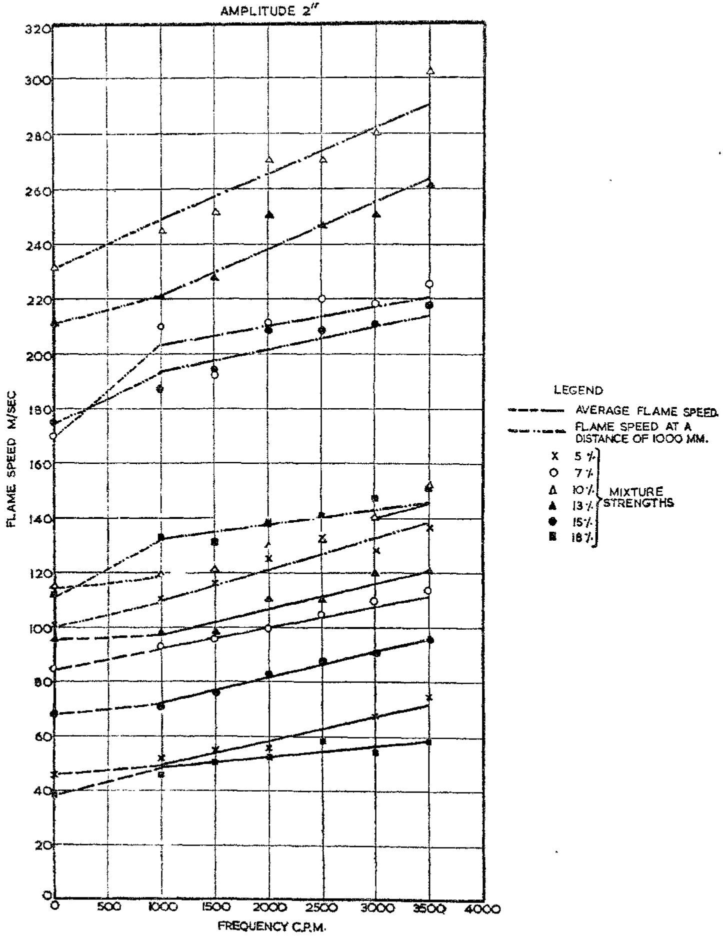

FIG. VII

Variation of flame speed with frequency of oscillations at an amplitude of 2" and at different mixture strengths. [Ignition at closed end]

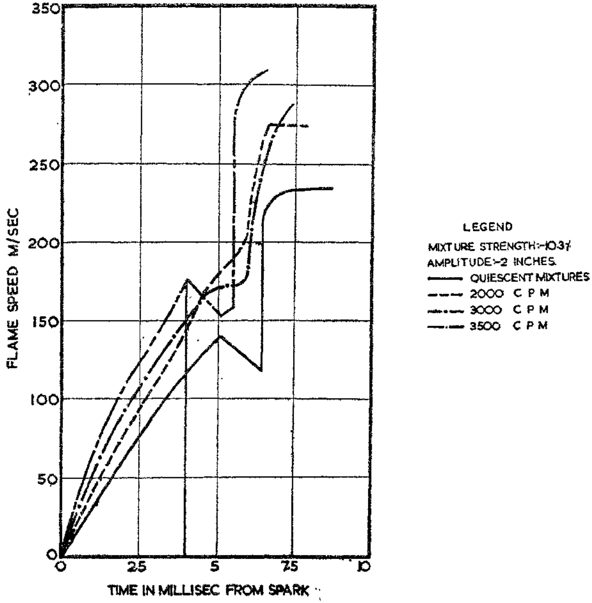

FIG. VIII
Speed time relationships for flame travel from closed end