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PROJECT SQUID

TECHNICAL REPORT NO. 5

PHENOMENA IN ELECTRICALLY AND ACOUSTICALLY DISTURBED BUNSEN BURNER FLAMES

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CORNELL AERONAUTICAL LABORATORY

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PROJECT SQUID

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PHENOMENA IN ELECTRICALLY AND ACOUSTICALLY DISTURBED BUNSEN BURNER FLAMES

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ABSTRACT

The study of flame propagation under turbulent flow conditions by means of an indirect method is proposed, which comprises stroboscopic observation of Bunsen flames subjected to periodical disturbances of electrical or acoustical nature. It is found that the disturbances act on the flame only in the region immediately above the burner port, creating wave-shaped distortions of the flame front which travel upwards along the flame cone with a velocity equal to the velocity of gas flow within experimental accuracy. While the distortions travel up, their amplitude increases gradually for moderate intensities of the disturbance; for large intensities an initial increase is followed abruptly by a decrease. The surface area of the distorted flame cones is found to be constant during the whole cycle and independent of the intensity of the disturbance. The significance of these observations for the theory of flame propagation in a turbulent medium is discussed.

Investigation of electrically disturbed flames led to the discovery of an increase of the blow-off limit of Bunsen flames under the influence of direct and alternating electrical fields.

A. INTRODUCTION

(a) *Formulation of the Problem*

The investigation which forms the subject of this report has been undertaken in the desire to obtain a better understanding of the mechanism of flame propagation under turbulent flow conditions.

The existing theories on this subject [1,2] are based on the assumption that the burning velocity, i.e. the normal component of the velocity of the unburnt gas relative to the flame front, is independent of the gas flow and the shape of the flame front, provided the scale or the mixing length of the turbulence is large compared with the thickness of the flame front. In other words, the amount of gas burned in unit time is assumed to be proportional to the area of the flame front surface for a given composition, temperature and pressure of the gas mixture. One object of this work is the experimental verification of this fundamental assumption for the case of highly distorted flame fronts, since its validity has been established previously only in the case of laminar flow.

The theories mentioned above make use of the further assumption that the flame front is deformed by the turbulent flow in the unburnt gas and its surface area is thereby enlarged; it is essential that the deformation is assumed to be determined only by the turbulence level of the unburnt gas, and the possibility of an influence of the combustion process on the turbulent flow is not taken into account. The presence of such an influence appears likely, however, particularly in view of the theory of Landau[20] which predicts an instability of the flame front with respect to small flow disturbances. The main object of this work is to establish whether such an influence of the combustion process on the flow exists and to investigate its nature.

(b) *Experimental Approach*

In a turbulent flow a whole spectrum of intensities and scales (or frequencies) is present; a flame front in a turbulent stream therefore assumes a very complicated shape. It was realized that for this reason a method based on the observation of a flame front under actual turbulent conditions would not be successful for attacking the problem under consideration. An indirect method was therefore chosen, in which a stationary flame front in a laminar stream, in the form of a Bunsen flame cone, is subjected to periodical disturbances and observed stroboscopically. Previous work on the effects of alternating electrical fields and of sound waves on flames[3,4,5,6] suggested the selection of electrical and acoustical disturbances for the present investigation.

It is essential for the successful application of this method that the disturbances do not affect the burning velocity. In the case of acoustical disturbances it is reasonable to expect that no effect of this kind exists. For the case of electrical disturbances, contradictory results are found in the literature. Observations on the influence of an electrostatic field on a flame propagating in a pipe[7] led to the conclusion that the effect of the field on flame propagation velocity is caused only by a change of flame surface area, without a change of burning velocity. It is likely that also in other instances[16] the field acts only in this indirect way.

Preliminary work showed that the method was well suited for the study of the properties of distorted flame fronts. In the course of this early work an increase of the blow-off limit of Bunsen flames under the influence of electrical fields was observed. An investigation of this electrical flame stabilization in some detail, though not concerned with the original aim of this work, seemed worthwhile; the results of this part of the work are given in Section D.

It should be realized that the work performed so far has established the value of the method for the study of distorted flame fronts, but is still incomplete. Further work is needed in order to obtain a better insight into the observed phenomena, and particularly for obtaining quantitative data which could be applied for the treatment of flame propagation in a turbulent medium. It is fully realized by the authors that it remains still to be shown to what extent such a generalization of the results to the case of combustion in turbulent flow can be carried out.

B. APPARATUS AND PROCEDURE

(a) *Burner Tube Assembly*

Air and combustible gas are passed separately through calibrated capillary flow meters and are mixed before entering the burner tube. The latter consists of a vertical pipe of 4 cm. internal diameter ending in the nozzle of the type described by Mache[8]

(Fig. 2), in the following called Mache-type nozzle. This nozzle was chosen in order to obtain a nearly uniform velocity distribution and to reduce the level of turbulence at the exit. Nozzles of various internal diameters can be used interchangeably. Some experiments were performed with special types of nozzles, shown in Figs. 3 to 5 and referred to later.

In order to study resonance phenomena the effective length of the burner tube, i.e. the height of the gas column between tip of the nozzle and bottom of the pipe, can be varied by filling part of the tube with water.

The experiments described in this report were carried out with mixtures of air and technical propane (98.7% propane, 1.3% ethane, trade name, Natoxalene).

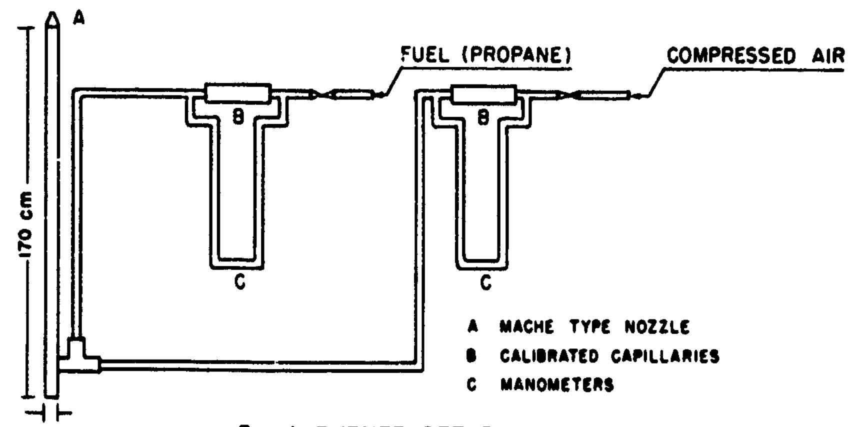
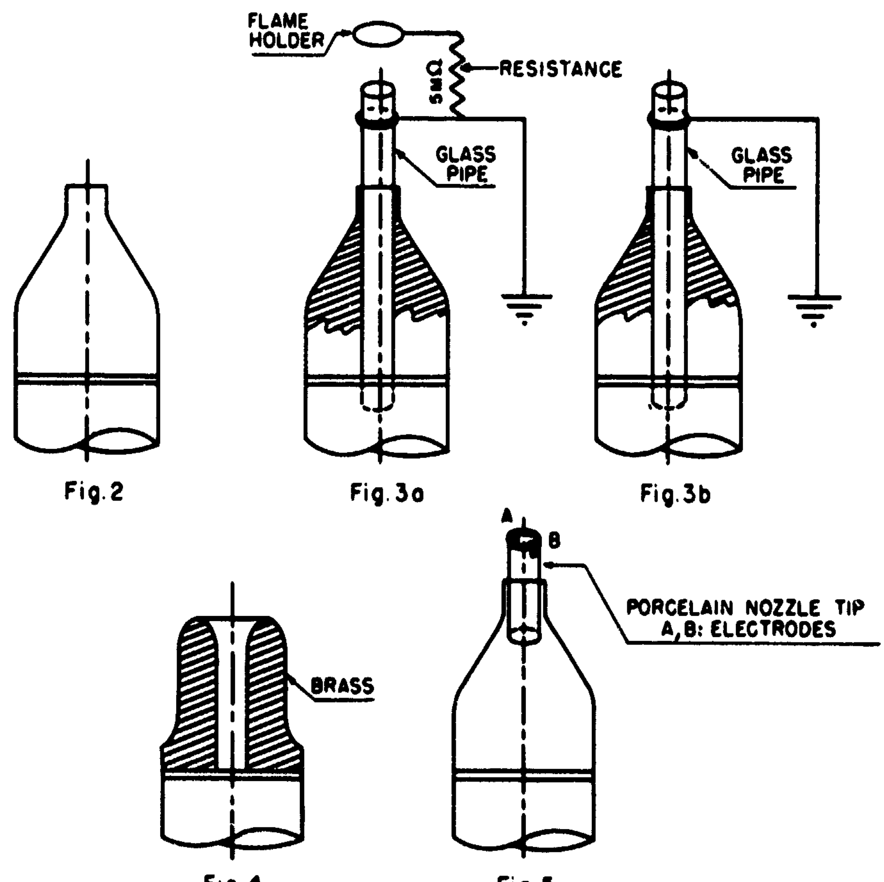


Fig. 1 BURNER SETUP



Figs 2-5 NOZZLES

(b) *Generation of Alternating Electric Fields and of Sound Waves Synchronized with a Stroboscopic Disc*

Photographic recording of the flame patterns was used throughout this work. Since the exposure time of flame photographs taken through a stroboscopic disc is of the order of 10 to 40 seconds, perfect synchronization of the disc with the disturbance applied to the flame is indispensable. This could be achieved by means of an arrangement which had been proposed originally by Zickendraht.[4] As shown in Fig. 6, the stroboscopic disc D interrupts a beam of light falling on a photoelectric cell C. The cell is connected to an amplifier A, the output of which is fed either into the primary of a high-voltage transformer Tr, or into a loudspeaker L, which in turn provide the electrical and acoustical disturbances, respectively. In order to observe the wave form of the voltage generated in this way, the output of the amplifier is also connected to the vertical plates of a cathode-ray oscilloscope O.

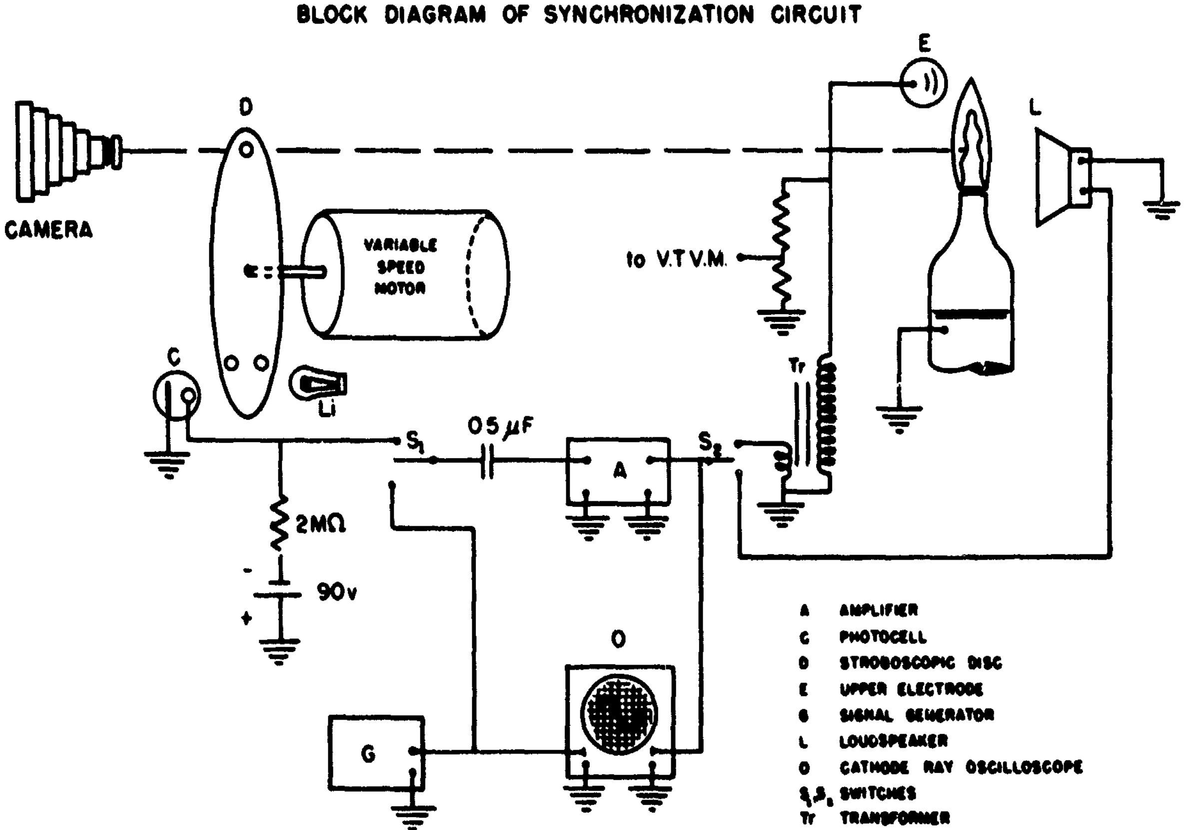
The frequency is measured by applying a sinusoidal voltage from the calibrated signal generator G to the horizontal plates of the oscilloscope and adjusting the frequency of the former so that a stationary single loop Lissajous pattern appears on the screen. The amplifier input can be connected by means of switch S_1 to the signal generator, instead of the photoelectric cell, for the stroboscopic observation of the flame pattern without synchronization. Fig. 7 is a photograph of the disc assembly. The photoelectric cell and the light scource are mounted on a lever which can be turned through an angle of 120° about the axis of the disc and clamped in any position. This feature has been added to enable the recording of the flame pattern at various phase angles without changing the position of the camera. Discs with three or six holes were found to be best suited for the frequency range from 60 to 600 c.p.s., which has been thus far investigated.

The voltage between electrodes was measured by means of a vacuum tube voltmeter connected through a voltage divider.

D-c potentials, which were used mainly for the study of the electrical flame-holding effect, were obtained from a conventional transformer-rectifier high voltage supply. Voltages up to 10,000 V. could be produced by the supply.

Fig. 6

BLOCK DIAGRAM OF SYNCHRONIZATION CIRCUIT



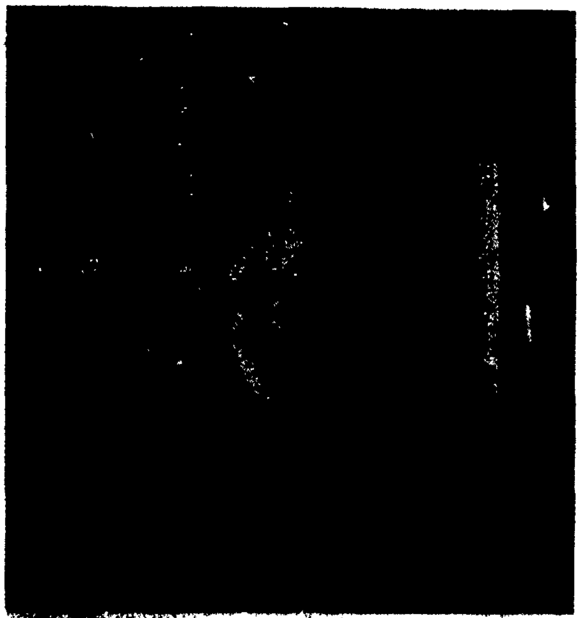


FIG. 7 STROBOSCOPIC DISC ASSEMBLY.

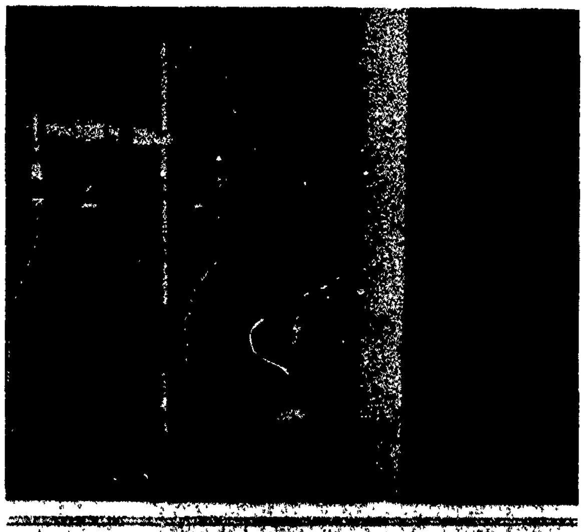


FIG. 8 MACHE TYPE NOZZLE WITH ELECTRODE AND LOUDSPEAKER.

(c) *Electrodes*

In the majority of the experiments on electrically disturbed flames, the tip of the nozzle was used as one electrode, which will be designated as the lower electrode; the other electrode was located close to but outside the luminous outer flame cone. This will be designated as the upper electrode. Special types of lower electrodes in combination with nozzles of nonconductive material (Figs. 3 and 5) were used in some experiments; these will be referred to later. Various forms of upper electrodes were tried in preliminary work; best results were obtained with ring-shaped and spherical electrodes, which were therefore selected for the main part of the work. Fig. 8 shows the assembly of Mache-type nozzle, spherical electrode and loudspeaker. The spherical and ring-shaped electrodes are also shown in Figs. 24 and 25, respectively.

C. QUALITATIVE OBSERVATIONS ON ELECTRICALLY AND ACOUSTICALLY DISTURBED FLAMES

If a Bunsen flame distorted by an alternating electrical field or a sound wave is observed with the unaided eye, the inner cone appears to be separated into two regions, an inner one with a well-defined conical boundary, and a more diffusely bounded outer one. Figs. 9 and 11 show a flame, undisturbed and disturbed by an a-c field, respectively. Fig. 10 shows the same flame under the influence of a d-c field, with positive potential applied to the upper electrode.

Observation of the flame through the synchronized stroboscopic disc resolves the outer region into a standing wave pattern; the conical boundaries form the envelopes of this pattern. Upon changing the phase of the disturbance with respect to the disc a change in the pattern is observed; this change indicates that the waves travel upward with constant speed. This fact is also brought out by the constancy of the wave length of the pattern, and is further confirmed by observing through a stroboscopic disc which is slightly out of synchronism with the disturbance. Fig. 12 shows a series of stroboscopic photographs of the electrically disturbed flame shown in Fig. 11, taken at phase angle intervals of 36°. (The zero point of the phase angle scale is chosen arbitrarily.) An analogous series for acoustical disturbances of the same frequency, acting upon the same flame, is shown in Fig. 13.

These flame patterns can be explained only by assuming that the disturbance acts on the flame exclusively in a region in the immediate proximity of the burner tip.

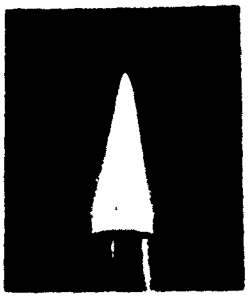


Fig 9
UNDISTURBED

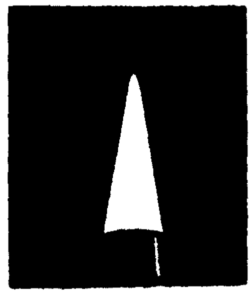


Fig 10
D.C FIELD

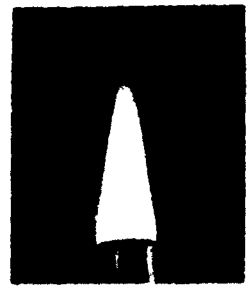
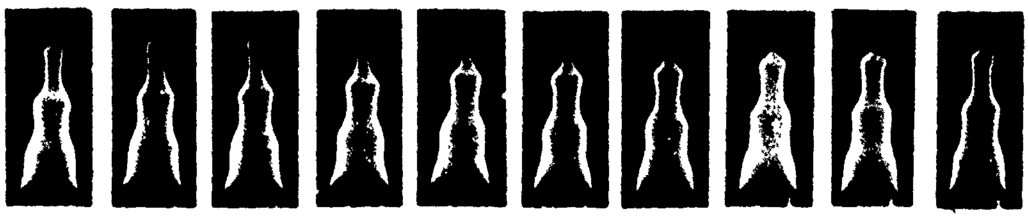


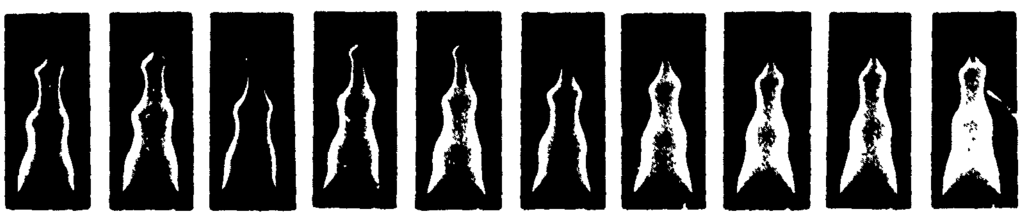
Fig 11
A C FIELD
WITHOUT STROBOSCOPE

Fig 12
A C FIELD



PHASE ANGLE 0° 36° 72° 108° 144° 180° 216° 252° 288° 324°

Fig 13
SOUND



WITH STROBOSCOPE

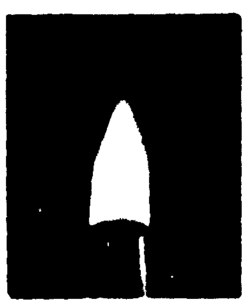


Fig 14
HIGH INTENSITY SOUND, WITHOUT STROBOSCOPE

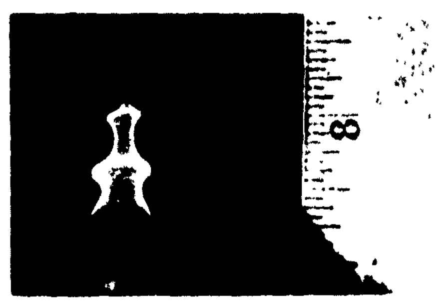


Fig 15
HIGH INTENSITY SOUND, WITH STROBOSCOPE

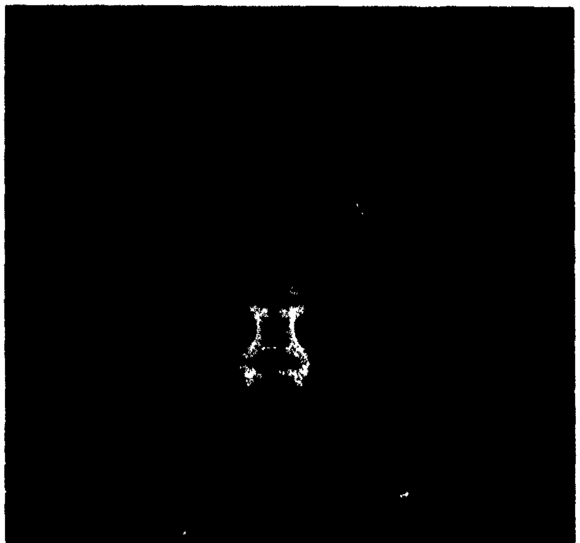
Fig 9 - 15 ELECTRICALLY AND ACOUSTICALLY DISTURBED FLAMES
180 cm^3/s AIR
8 cm^3/s NATOXALENE*
MACHE NOZZLE, 1.00 cm I D
FREQUENCY 253 c p s

*[illegible] PROPANE, [illegible] 3 % ETHANE

[illegible]

There are important differences between the electrical and acoustical effects. The effect of sound shows a number of sharply defined resonance peaks. By filling the burner tube partly with water, it could be shown that this resonance is due to oscillation of the gas column between the water level and the nozzle. Generally, two resonances, corresponding roughly to wavelengths equal to 4/3 and 4/5 of the gas column, were observed. With the experimental setup used, with the 4-inch loudspeaker situated close to the burner nozzle, the distortion of the flame could be observed well only at these resonance frequencies; for other frequencies the distortion was weak and asymmetrical Slight asymmetry in the acoustical case occurs often even at resonance, as seen in Fig. 13. With electrical disturbances, on the other hand, a slight decrease of amplitude of the wave pattern at or very close to the acoustical resonance frequency appears; otherwise the electrical effect can easily be observed over a continuous range of frequencies.

Much stronger distortions of the flame can be created by sound at resonance than is possible electrically. The appearance of the flame at low sound intensity is practically identical to the electrical case, see Figs. 12 and 13. Both show a gradual increase of the amplitude of the wave pattern towards the tip of the cone. This phenomenon is shown particularly well in the photograph, Fig. 16, obtained with an electrical disturbance of somewhat higher frequency. With



[illegible]

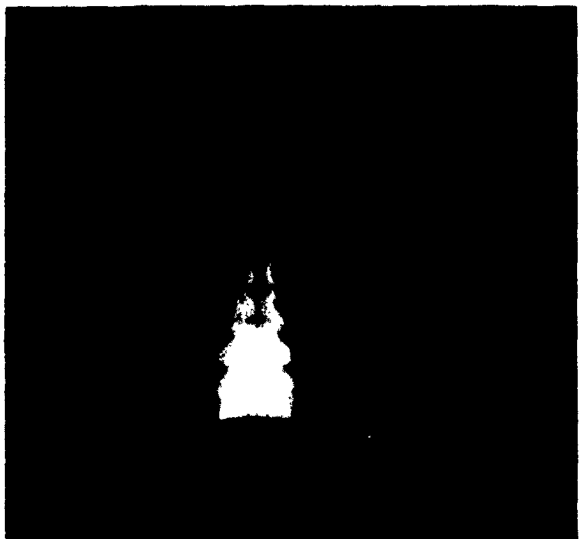


FIG. [illegible] [illegible] DISTURBED FLAME : [illegible] RESONANCE FREQUENCY.

higher sound intensities at resonance the pattern changes, as shown in Fig. 14, taken without disc, and the corresponding stroboscopic photograph, Fig. 15. Here a rapid increase in amplitude in the lower part of the cone is followed by a decrease in the upper part. Other examples of the same effect are shown in Figs. 17 and 18, taken with high sound intensity acting on a flame at the two resonant frequencies already mentioned.

With still higher intensities of sound at resonance, the flame lifts either periodically from the burner or blows off completely.

At an early stage of this work it was discovered that a-c fields have a strong influence on the stability of burner flames; an increase of the blow-off limit roughly by a factor of two could be observed with the strongest fields. The results of a detailed investigation of this effect, including the influence of d-c fields, are given in the next section. It should also be mentioned that because of this stabilizing effect electrically disturbed flames can be studied with flow values beyond the natural blow-off limit. This cannot be done in the acoustical case, except by stabilizing the flame at the same time with a d-c field.

D. RESULTS

(a) *Effects of Electric Fields on Flame Stability*

In the following consideration the stability of the flame is defined by its blow-off limit, i.e. the largest streaming velocity at which a stable flame is still maintained.[9,10,11] Streaming velocity values given here are based on the measured volume flow and the internal diameter of the nozzle at the tip.

The increase of the blow-off limit which was observed originally with a-c fields was found also for d-c fields if the upper electrode was made positive. With negative upper electrode no definite influence on the blow-off limit could be established, though in some instances very small increases or decreases were observed.

Fig. 19

ELECTRIC FLAME HOLDING EFFECT

MACHE TYPE NOZZLE, TIP I D 1.02 CM

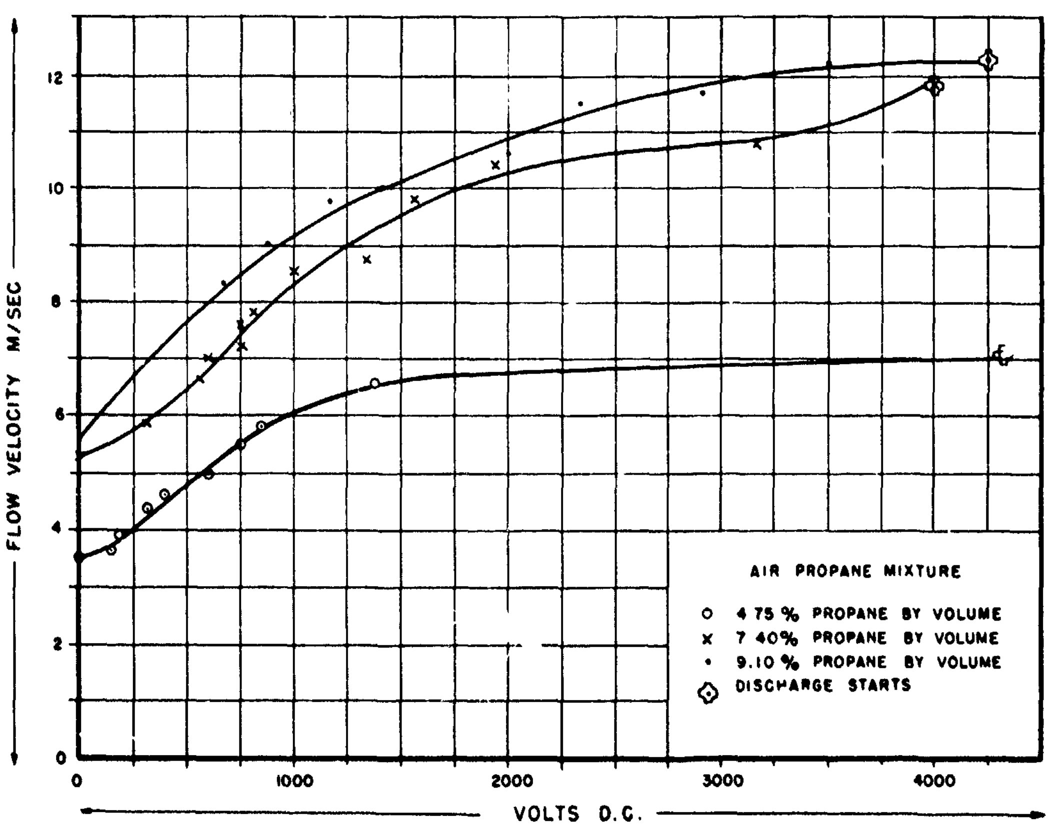
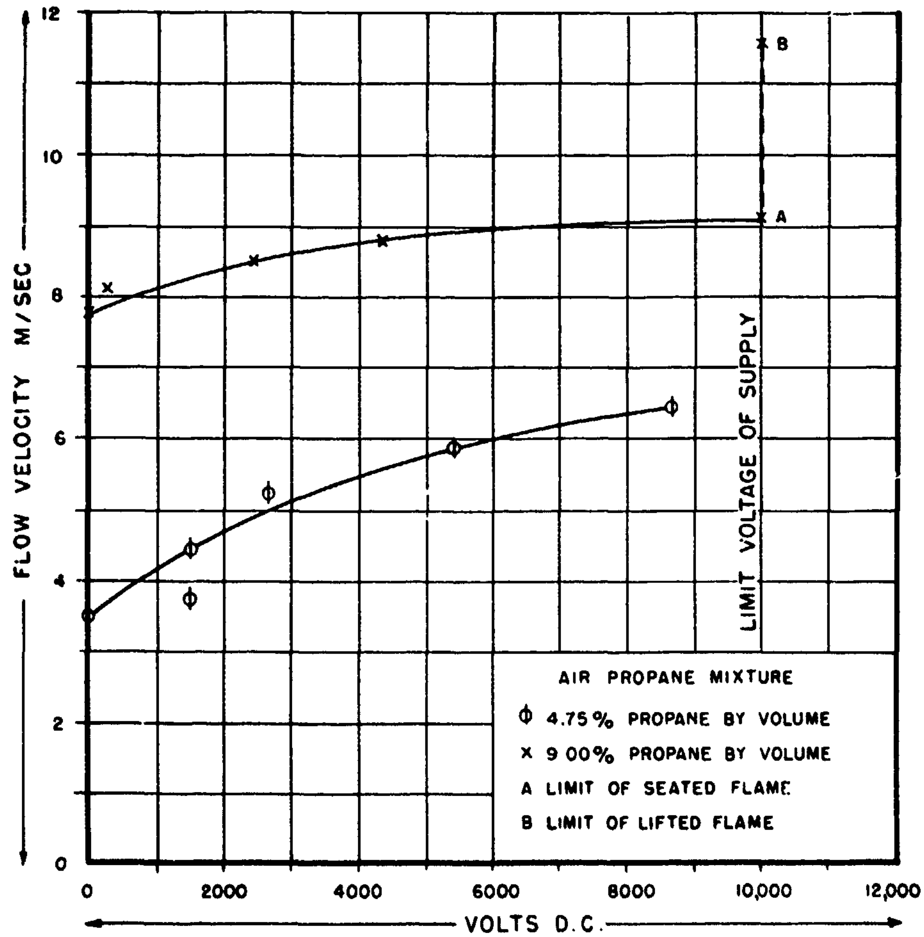


Fig. 20

ELECTRIC FLAME HOLDING EFFECT

NOZZLE OF Fig 4

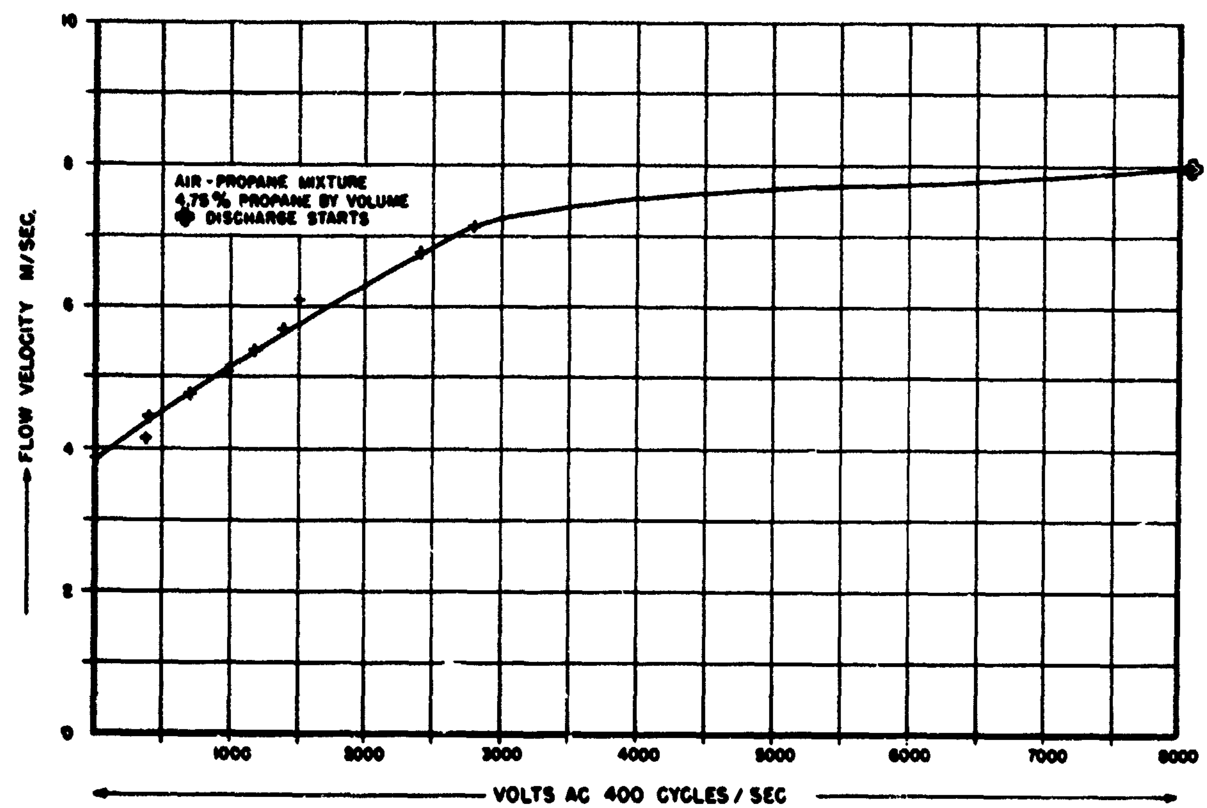


Figs. 19 to 23 show the dependence of the blow-off limit on d-c and a-c potential for various mixture compositions and nozzle diameters and designs. The data of Fig. 20 were obtained with the nozzle shown in Fig. 4; those of Fig. 23 with the glass pipe nozzle shown in Fig. 3. Curves I and II of Fig. 23 refer to the arrangement of Fig. 3a, and curves III and IV to the arrangement of Fig. 3b. The reasons for trying these special arrangements will be mentioned later.

The data presented in Figs. 19 to 23 were obtained by decreasing the field slowly while gas flow and composition were maintained constant, and noting the voltage at which the flame just started to lift. Because of unavoidable slight asymmetries of the nozzles, the flames always lifted asymmetrically, and if the field was decreased slightly below the blow-off value, the flame remained in a partially lifted position. In order to bring a partially lifted flame back to the stable position, the voltage had to be increased somewhat above the blow-off value obtained with decreasing field. This hysteresis phenomenon is, however, not peculiar to the electrical flame-holding effect; similar phenomena have been observed when increasing and decreasing the flow at the blow-off limit, without field.[10, 11]

It is obvious that the data presented here do not have an absolute significance, since the effect depends to a certain degree on the position and configuration of the electrodes. However, the position and shape of the upper electrode has surprisingly little influence on the flame-holding effect as long as it is located within the ionized burnt gas. On the other hand, it was found that the position and shape of the lower electrode is very critical. If the nozzle tip does not act as lower electrode, as in the case of the glass pipe in Fig. 3, the lower electrode must be located very

Fig. 21
ELECTRIC FLAME HOLDING EFFECT
MACHE TYPE NOZZLE, TIP I.D. 1.02 CM



close to it and must have a similar configuration, so that the dark space is always located between the two electrodes.

Excepting the data given in Fig. 20, an upper limit of electrical flame stabilization was reached at about twice the flow corresponding to blow-off without field. This limit is due to the appearance of sparking (visible discharge) at the electrodes, when a certain potential is reached. At these limits, which are indicated in Figs. 19 to 23, the current through the flame, which was found to be normally of the order of 10μA, increased roughly by a factor of 10, the potential dropped to a considerably lower value, and the flame blew off. The sparking potential depends on the shape and the temperature of electrodes. As is well known, sparking starts preferably at points of high field concentration caused by sharp points and edges of the electrode surface. This is the reason for the use in this work of spherical or ring-shaped upper electrodes with smoothly rounded surfaces. To eliminate also the sharp edge of the nozzle tip as a source of sparking, a special type (Fig. 4) was tested. With this design no sparking occurred up to 10,000 V, d-c, the limit attainable with our high voltage supply. The results obtained with this nozzle are shown in Fig. 20. In this case, above a certain flow value (point A, Fig. 20) a completely lifted flame could be prevented from blowing off by the electrical field (dotted part of curve). This effect has not been observed with the other nozzles. The arrangement of Fig. 3a was also tried in an effort to increase the sparking potential. It is believed that the improvement over the arrangement in Fig. 3b is due to a decrease of ion current density since the effective surface of the lower electrode is increased.

It should be noted that for equal flame-holding effect the required a-c potential (r.m.s. value) is roughly twice the required d-c potential (see Figs. 19 and 21).

Fig. 22

ELECTRIC FLAME HOLDING EFFECT

MACHE TYPE NOZZLE, TIP I.D. .5 CM.

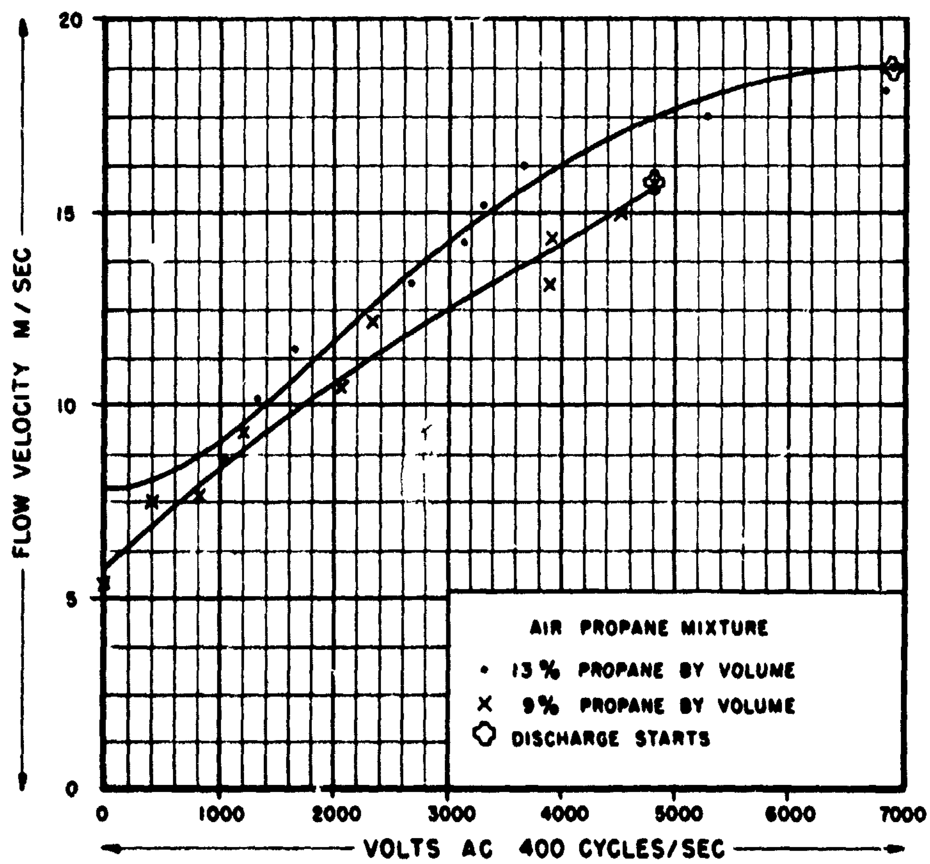
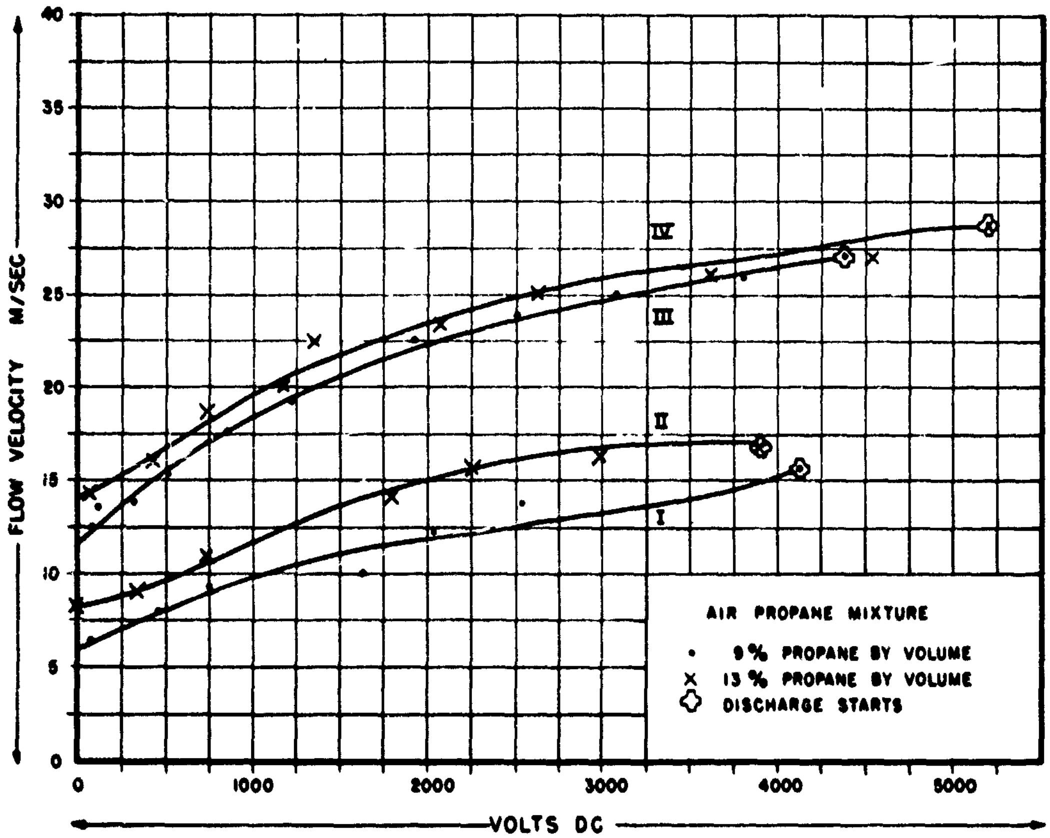


Fig. 23

ELECTRIC FLAME HOLDING EFFECT

NOZZLE AND ELECTRODE ARRANGEMENT Fig. 3(a) & 3(b)



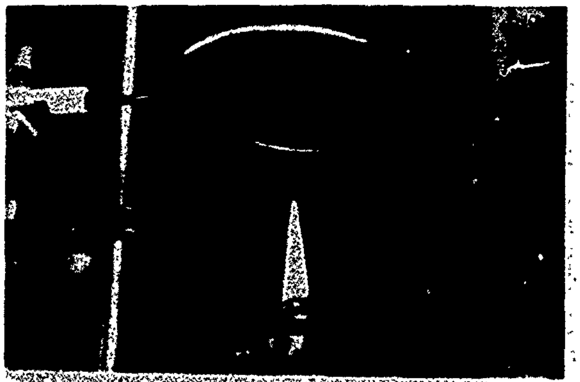


FIG. 24 a. FLAME AT BLOW-OFF LIMIT, WITHOUT FIELD.

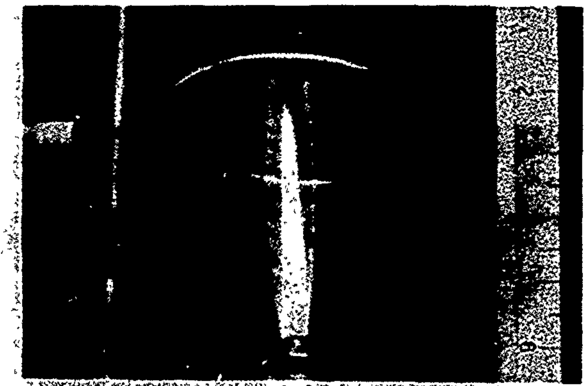


FIG. 24 b FLAME AT BLOW-OFF LIMIT, WITH FIELD. MIXTURE COMPOSITION SAME AS FOR FIG. 24 a.

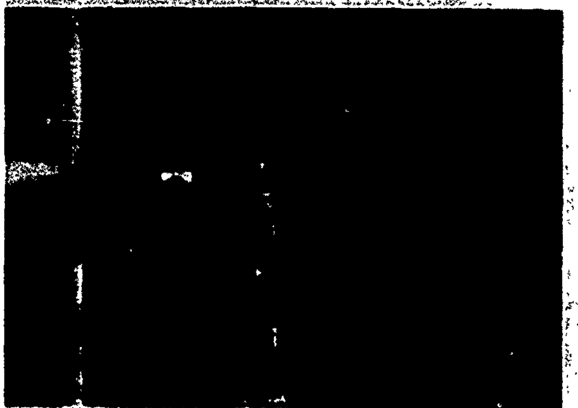


FIG. 25 a. PARTIALLY LIFTED FLAME WITHOUT FIELD.

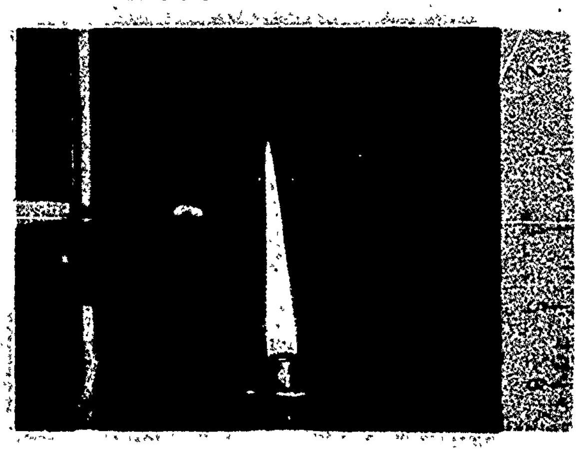


FIG 25 b FLAME STABILIZED BY FIELD. GAS FLOW AND COMPOSITION SAME AS FOR FIG. 25 a

An illustration of these effects is given in Figs. 24 and 25. Fig. 24a shows a flame just below blow-off without field. By applying a field, the flow could be increased, with constant mixture composition, until the considerably larger flame in Fig. 24b was obtained. Figs. 25a and 25b were taken with the same flow and mixture composition. It is seen that without field the flame is partially lifted (Fig. 25a), while after applying the field it returns to a stable position (Fig. 25b).

Preliminary experiments concerned with establishing an electrical flame stabilization at a flame holder in a pipe have not yet given conclusive results.

(b) *Areas of Flame Surfaces*

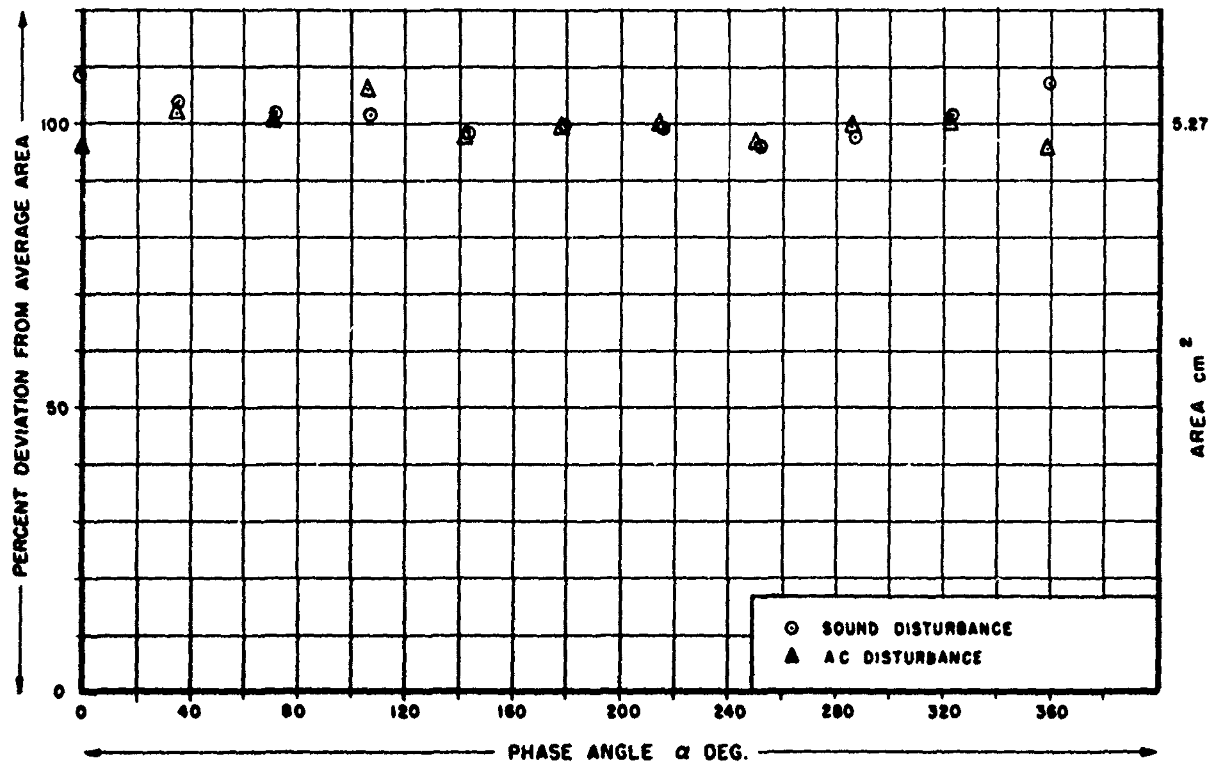
In order to check the independence of the burning velocity with respect to flow disturbances, areas of the flame surfaces were determined for the series of photographs shown in Figs. 9, 10, 12, 13, and 15. Since gas flow and composition were maintained constant throughout this series, the surface should also remain constant if the burning velocity is not altered by the influence of the disturbance applied to the flame. The flow data of this series were 180 cc/s. air, 8 cc/s. gas (4.25% gas by volume), Mache nozzle 1.00 cm. inner diameter. The frequency was 253 c.p.s. A stroboscopic disc with three holes was used. The computations were based on enlarged prints of the photographs, with a linear magnification factor of about 8.3. The contours of the flame surfaces were approximated by polygons and the areas calculated by evaluating the expression $\frac{2\pi}{m^2}\Sigma\, s_i r_i$ where s_i are the sides of the polygon contour and r_i the corresponding radii, measured on the enlarged prints, and m is the linear magnification factor. Because of the slight asymmetry of the contours, the computations were carried out for both sides of each photograph and averaged. Table 1 shows the results of these calculations.

Table 1. Areas of flame surfaces in cm². (180 cm³/s. air, 8 cm³/s. Natoxalene, Mache nozzle, 1.00 cm. inner diameter.)
Undisturbed flame (Fig. 9) — 5.65 cm².
With d-c field applied (Fig. 10) — 5.15 cm².

Phase angle, degrees (arbitrary zero)	Flame disturbed by a-c field (Fig. 12)	Flame disturbed by sound (Fig. 13)	Remarks
0	5.03	5.69	—
36	5.38	5.47	—
72	5.32	5.38	—
108	5.61	5.36	—
144	5.13	5.17	—
180	5.29	5.28	—
216	5.29	5.25	—
252	5.08	5.10	—
288	5.21	5.15	—
324	5.27	5.34	—
360	5.10	—	—
288	—	(Fig. 15) 5.35	High Intensity sound
average	5.25	5.32	—

Fig. 26

PERCENT DEVIATION OF SURFACE AREA OF FLAME vs PHASE ANGLE α



The variation of surface area with phase angle appears to be quite irregular and does not show any periodicity, as can be seen from Fig. 26. It seems reasonable to assume that these variations are caused, apart from the influence of other experimental errors, by slight changes in flow and composition, which are too small to be observed on the flow meters. The values for the undistorted flame, and for the flame with d-c field applied, lie within the range of the values for the series of distorted flames. The differences among these values, and the averages for the two series, seemed to be too large to be accounted for by experimental errors. A second series of photographs was therefore taken.

In this second series, photographs of the undisturbed flame were made at the beginning and at the end, and twice between those of the disturbed flame in order to minimize the effect of gradual changes of flow parameters. The flow data are approximately the same as for the first series. The results are shown in Table 2.

Table 2. Areas of flame surfaces in cm^2.

Undisturbed	d-c field	a-c field
4.61	4.46	4.63
4.67	4.42	4.66
4.58	—	—
4.58	—	—
Av. 4.62	4.44	4.64

Both Table 1 and Table 2 indicate a decrease of flame surface under the influence of a d-c field. In the case of a-c fields, the evidence is not conclusive, as Table 1 shows a decrease and Table 2 a very small increase of surface area. It can be concluded, however, that, if any effect due to a-c fields should exist, it would be much smaller than the one observed with d-c.

In addition, the data of Table 1 do not allow a definite conclusion about the effect of sound on surface area. But if it is present at all, the effect would be very small; it should be noted particularly that the highly distorted surface for high intensity sound (Fig. 15) gave a value very close to the average for sound of smaller intensity.

Thus, while a 5% (approx.) decrease of surface area due to d-c fields could be detected, no measurable effect of a-c fields or sound could be found, but the accuracy of the method does not exclude entirely the possibility of effects of a smaller order (say 1%). This seems to be of no consequence as far as the application of this method to the study of disturbed flame fronts is concerned.

The fact that the surface area is independent of amplitude and phase of the disturbance leads to the conclusion that the burning velocity is also independent of these parameters. While this conclusion is strictly valid only for the average of the burning velocity taken over the whole flame surface, it seems highly improbable that variations of burning velocity due to the distortion of the flame front could be present without causing some variation of the average value.

From the data of Table 1, an average value of 35.6 cm/s. for the burning velocity of the mixture of 4.25% Propane by volume in air is obtained. This value is in good agreement with the data given by other authors.[6,8] Some caution must be exercised, however, in ascribing too high an accuracy to the absolute values of the burning velocity calculated from areas of flame surfaces determined from photographs of the luminous flame cone. It has been shown theoretically[12] that the apparent thickness of the luminous zone does not bear a simple relation to the thickness of the combustion zone, so that it is not clear where the contour should be traced on the photographs in order to give the "true" flame surface. It seems that shadow and striae methods[11,13,14] should give more nearly correct values, but the possibility of errors caused by refraction of the light rays in the hot burnt gas surrounding the flame[14] cannot be excluded.

(c) *Propagation of Disturbances*

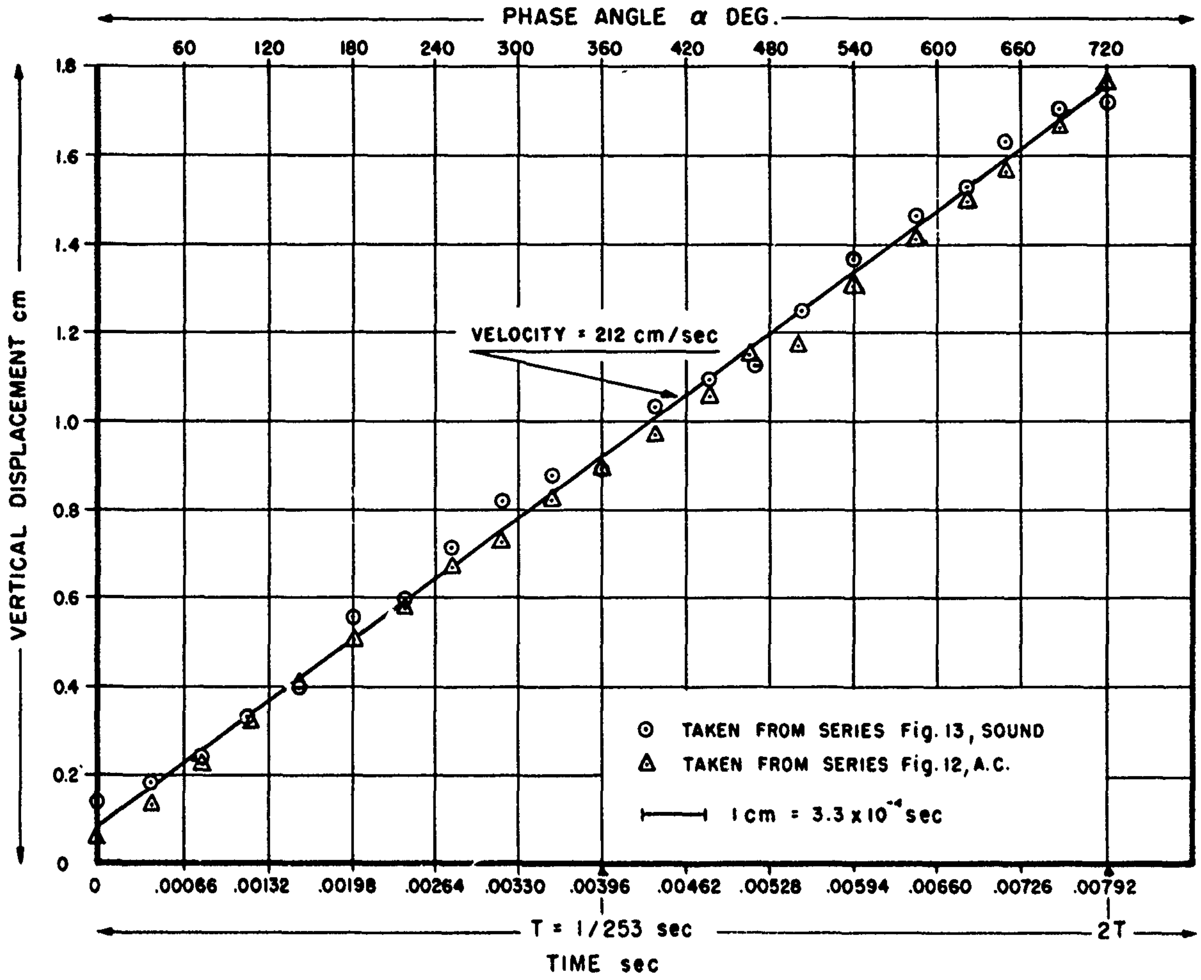
The velocity of propagation of disturbances was determined from the series on Figs. 12 and 13. The difference in phase between consecutive pictures is 36° or one-tenth of a period. The point selected as representative of the velocity of disturbance was the point of contact between a given wave and the inside envelope of the wave pattern.

Fig. 27 is a plot of displacement vs. time for this movement. For reason of comparison with the streaming velocity, the vertical displacement of the representative point and not the displacement along the envelope is given on this diagram. The average vertical propagation velocity for series 12 and 13 is found to be 212 cm/sec.

It would be desirable to compare this velocity with a value of the gas flow velocity obtained by a reliable direct measurement, e.g. by the method of intermittently illuminated dust particles.[9] Such measurements have not yet been performed in the course of this work. Only the total volume flow has been meas-

Fig. 27

VERTICAL VELOCITY OF DISTORTION



ured, and there exists some doubt about what cross section should be used to calculate the actual flow velocity. Referred to the inside diameter of the nozzle-tip, a maximum possible value of 240 cm/sec. is obtained; while the diameter of the base of the flame cone, measured on the photograph, leads to a value of 190 cm/sec. as a possible minimum. The velocity of propagation of the disturbance waves is seen to lie between these extreme values. It is not possible to decide whether it is exactly equal to the flow velocity until an accurate measurement of the latter has been performed.

E. DISCUSSION

(a) *Electrical Flame Stabilization*

Although the stabilizing effect of electrical fields on flames has not been reported previously, a number of related phenomena have been investigated by various workers. The general subject of electrical phenomena in flames has been reviewed by Wilson.[15] Effects of electrical fields on flame shapes and propagation have been reported by various authors. A fairly complete bibliography of this field can be found in the texts by Lewis and von Elbe[17] and Jost.[18] Both increase and decrease of flame velocities under the influence of electrical fields have been observed; in most cases these changes in apparent flame speed are likely to be due to changes in flame surface area, not to a change in

FIG. 28 UNDISTURBED FLAME

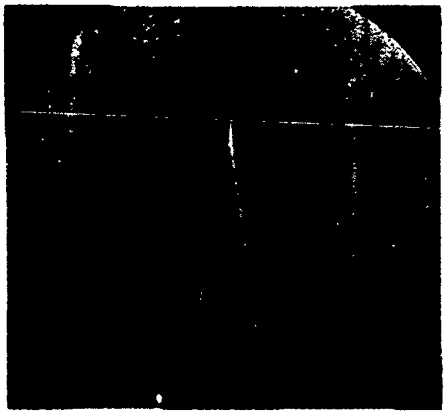


FIG. 29 FLAME WITH D.C. FIELD APPLIED.

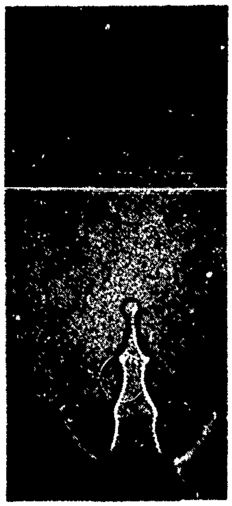


FIG. 30

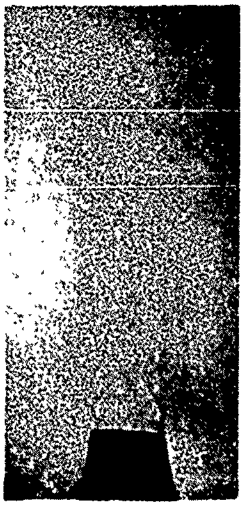


FIG. 31

FIG 32

FIG. 33

FIG. 34 FLAME DISTURBED ELECTRICALLY BY 180° OUT-OF-PHASE VOLTAGES ON ELECTRODES OF PORCELAIN NOZZLE FIG. 5

STROBOSCOPIC SHADOWGRAPHS

FIG. 30 ACOUSTICALLY DISTURBED FLAME, LEAN MIXTURE.
FIG. 31 GAS JET, CONDITIONS OF FLOW AND DISTURBANCE SAME AS FOR FIG. 30
FIG. 32 ACOUSTICALLY DISTURBED FLAME, RICH MIXTURE.
FIG. 33 GAS JET CORRESPONDING TO FIG 32.

burning velocity.[7,16] With few exceptions it has been found that the flame is attracted by the negative electrode, but the conclusion drawn by some authors, that the bulk of the flame carries a positive charge, must be considered erroneous. As discussed in reference 15, a positive space charge appears only in the vicinity of the cathode, owing to the large difference of the mobilities of the negative and positive ions. This space charge causes also a large potential drop near the cathode. If the nozzle acts as cathode, this drop is still more increased, because the concentration of ions in the dark space is much lower than in the flame, so that the dark space acts like a large series resistance. It is therefore reasonable to assume that practically all of the applied potential drop is concentrated across the dark space, while only a small fraction occurs in the body of the flame. Two facts suggest that the potential drop across the dark space is responsible for the stabilizing effect:

1. The effect is not materially altered by changes of position and shape of the upper electrode.
2. If in an electrically stabilized flame the dark space is bridged with a short piece of wire, the flame blows off immediately

The mechanism by which the potential drop causes stabilization has not yet been established conclusively. The most likely explanation appears to be the following: The current in the vicinity of the nozzle is carried exclusively by the positive ions, which collide with the molecules of the hot gas in the outer cone, creating in this way an "ion wind." The deformation of the outer cone brought about by this ion wind is not visible on the flame photographs, Figs. 9 and 10. The effect can be made visible, however, by means of the shadowgraph technique. Figs. 28 and 29, showing a flame without and with a d-c field applied (nozzle negative), were obtained by this method, using a Western Union 100W Zirconium lamp and projecting the shadow directly on the film without intermediate lenses. Fig. 29 shows that the burnt gas is pulled down by the ion wind and surrounds the nozzle tip completely. (It should be noted that the boundary of hot gas visible in the shadowgraphs lies outside the boundary of the faintly luminous "outer cone.") It is well known that the surrounding atmosphere has a profound influence on flame stability (cf. ref. 9, Fig. 16; and ref. 10, p. 3); a plausible explanation of the electrical flame-holding effect would then be that the hot gas surrounding the nozzle supplies heat and chain carriers and impedes the entrainment of cold air, thus increasing the *local* burning velocity at the base of the flame cone sufficiently to make it equal to the local flow velocity. This view is confirmed by the decrease of thickness of the dark space under the influence of the d-c field (see Figs. 9 and 10) and by the slight decrease of surface area (Tables 1 and 2), which would indicate a slight increase of average burning velocity corresponding to the larger increase of local burning velocity close to the nozzle.

That a similarly strong stabilizing effect cannot be observed with reversed polarity (nozzle positive) can be understood from the fact[15] that the negative ions in a flame are for the most part free electrons, which, owing to their high mobility and small mass, cause neither a high potential drop nor an ion wind near the anode.

In the case of the a-c potential, the high mobility of the negative ions will enable the establishment of the positive space charge during the half cycle when the nozzle is negative and the disappearance of this space charge during the other half cycle. The movement of the positive ions will therefore be directed towards the nozzle during one half cycle, and will disappear during the other half. Application of the shadow technique has shown that a similar deformation of the outer cone, though not quite as strong as with d-c fields, takes place under the influence of an a-c field. Stroboscopic observation of the shadow image did not reveal any periodicity of this deformation with the frequency of the applied field. This seems to indicate that the ion wind persists during the unfavorable half cycle, owing to inertia effects.

In accordance with the explanation of the electrical flame-holding effect given above, the disappearance of the effect at the point where sparking sets in can be understood as follows. Sparking at the cathode indicates emission of electrons caused by ion impact. These electrons carry now a large fraction of the current and remove the positive space charge, and therefore the cathode potential drop and the ion wind disappear.

(b) *Observations on Disturbed Flames, and their Significance for the Theory of Flame Propagation in a Turbulent Medium*

The following discussion is concerned primarily with those observations on distorted flames which are of importance for the original aim of this work, namely, the study of flame propagation under turbulent conditions. It should be understood in this connection that the work carried out so far leaves many problems still unsolved. In the last Section plans for future work intended to clarify these problems will be discussed.

At first it would appear that there is a fundamental difference between the type of distorted flame fronts investigated here and a flame front in a truly turbulent medium. As has been said before, the shapes of the flames observed here indicate that the disturbance acts on the flame only in a small region immediately above the burner tip. In a turbulent flow, on the other hand, disturbances act everywhere and continuously on the flame front. But the fact that the artificially created disturbances have an effect only in the vicinity of the burner tip points to a peculiar instability of the flame in this region. Similar instabilities might always be present in flames in the vicinity of flame holders or other obstacles located in the gas flow, so that also in the case of true turbulence the effect of the disturbances on the flame front might be much larger in certain unstable parts of the flame than elsewhere. Furthermore, the observations reported here suggest that a small distortion of a flame front does not persist unchanged or die out gradually, as has been assumed tacitly by the authors of the existing theories on the subject;[1,2] instead, a gradual increase for moderate intensities and an increase followed by a decrease for higher intensities, have been observed. These effects will have to be incorporated in some way in the theory of turbulent flames. Recent observations by Nicholson and Probert (ref. 19, pp. 7 and 8) on flames held by a rodshaped flame holder in a rectangular duct confirm this viewpoint. These authors observed a wave movement of the flame front originating at or near the flame holder, propagating along the flame front and in some cases increasing in amplitude. They suggest that this type of disturbance may be more significant for the increase in flame velocity than the low intensity turbulence present in the unburnt gas.

The nature of the instability of the flame at the burner tip and the mechanism by which the disturbance acts on the flame have not yet been established. Extensive researches on similar phenomena in diffusion flames and gas jets have been carried out by Brown and Zickendraht.[4,5] These authors agree that the seat of the instability is the boundary layer of the emerging jet; they do not agree on other points, particularly on the nature of the resonance effects observed by Brown, and their discussions indicate that an adequate theory of the problem is still lacking. Qualitatively, the situation can be described as follows: even in the absence of a disturbance, unlit gas jets have a tendency to develop vortices originating periodically at the exit port and traveling up along the boundary with the surrounding air. Shadow photographs showing this phenomenon are given in ref. 11, p. 183. In the presence of an acoustical disturbance the generation of the vortices falls into synchronism with the frequency of the sound. It is not certain, but it appears plausible, that the mechanism of generation of the disturbance in the case of the flame is of the same nature as in the case of the unlit gas jet. A comparison of the two cases is shown in the stroboscopic shadowgraphs, Figs. 30 to 33. The frequency of the acoustical disturbance was in all cases the higher resonance frequency of the burner pipe, approximately 250 c.p.s. Figures 30 and 31 show a flame and the corresponding gas jet for flow and mixture conditions approximately equal to those in the series of Figs. 9-15. Figures 32 and 33 correspond to a richer, slow burning mixture, other conditions being approximately the same as for Figs. 30 and 31. It should be noted that the spacing of the vortices along the jet is only approximately half the wave length of the pattern of the flame, so that the vortices travel with approximately half the flow velocity. Thus, while the mechanism of generation of the disturbance might be the same, the propagation proceeds differently in the flame and in the jet. It is to be noted, however, that in both cases the velocity of propagation of the disturbances corresponds approximately to the mean value of the tangential components of the flow velocity at both sides of the boundary. In the case of the unlit jet, the surrounding air is at rest, and accordingly the propagation velocity is roughly half the flow velocity. In the case of the flame no discontinuity of the tangential component of the flow velocity across the flame front is present, and the propagation velocity was found to be equal to the flow velocity within experimental accuracy. Preliminary experiments on gas jets surrounded by flowing air have confirmed the view that the propagation velocity is given roughly by the mean value of the flow velocities.

Since the appearance of fully developed vortices is caused by the discontinuity of the tangential velocity, none are present in Bunsen flames. However, incipient vortices can be observed in disturbed rich-mixture flames (Figs. 17, 18, and 32), which are a transition toward diffusion flames. In true diffusion flames, fully developed vortices have been observed.[4]

Of course, no analogous effect on the gas jet exists for electrical disturbance, since the electrical field is ineffective without the ionization present in the flame. From the fact that the electrical field is concentrated at the nozzle (at least for one half cycle), one would expect the electrical disturbance to act on the flame only in the vicinity of the nozzle tip, even if the instability of the flame in this region were not present.

A priori, any one, or any combination, of the following three mechanisms could be responsible for creating the distortion of the flame front:

1. A pulsation of the flow through the nozzle tip.

2. A small flow disturbance localized at the nozzle rim and causing the lighting region of the flame formed at the base of the cone to expand and contract periodically.

3. A periodical variation of the local burning velocity at the nozzle tip. The following experimental facts indicate that a pulsation of the flow is not present:

   (a) A determination of the volumes of the flame cones has been made for the series Figs. 12 and 13. As with the surface areas (Table 1), no periodical variation of volume could be detected; only an irregular scattering of the values was found. Since the out-flow through the flame surface must be constant, as it is equal to the product of surface area and burning velocity, which were found to be constant, the constancy of the volume, apart from irregular variations, indicates that no periodical variation of in-flow takes place.

   (b) An experiment was performed which showed that distortions which are not in phase with respect to each other could be created electrically on opposite sides of a flame. For this purpose the nozzle shown in Fig. 5, consisting of a porcelain tube fitted to the Mache type nozzle and provided with two aluminum foil electrodes on opposite sides of the tip, was used. 180° phase shift is obtained if the two electrodes are connected to the terminals of the secondary winding of the high voltage transformer, with the center tap of this winding grounded. (No upper electrode is needed in this particular case.) The flame appears in the stroboscope as shown in Fig. 34. It is also possible, by means of two transformers and a phase-shifting network in one of the primaries, to generate distortions on opposite sides of the flame with any phase difference desired. This shows clearly that a pulsation of the flow through the nozzle cannot be responsible for the distortion of the flame front. Out-of-phase distortions on opposite sides of a flame were also observed with acoustical disturbance off resonance.

   (c) Finally, the flow inside the flame cone was explored by injecting from the inside of the nozzle a jet of pure gas of small diameter (approximately .4 mm) into the disturbed flame, and observing the deflection of this jet stroboscopically by means of the shadow technique. No deflection could be detected inside the flame cone except very close to the flame front. This confirms the result that no disturbance of the flow in the unburnt gas is present, except close to the cone surface.

Regarding the other possible causes of the distortion of the flame front, the presence of a periodical expansion and contraction of the cone base has been detected by measurement on enlarged prints of the series shown in Figs. 12 and 13. The amplitude of pulsation of the diameter was found to be roughly .015 cm. for both the a-c and sound series.

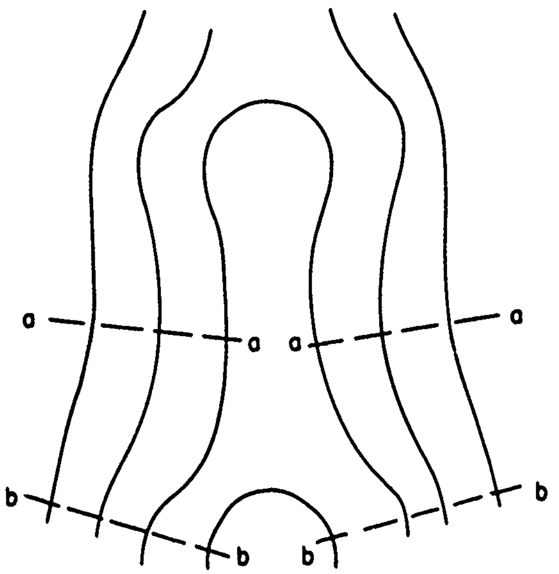
Finally, it seems very difficult to find out experimentally whether a periodical variation of local burning velocity is also present. At least for the case of electrical disturbance such a variation appears probable, in view of what has been said in the discussion of electrical flame stabilization.

Equally important for the theory of flame propagation under turbulent conditions is the mechanism by which the distortion propagates along the flame front. One result of fundamental significance which has been obtained during this investigation is the constancy of flame surface area, independent of intensity and phase angle of the disturbance. From this result it has been concluded that the burning velocity is also constant and independent of the distortion of the flame front. This is in agreement with theory; as long as the radius of curvature of the flame front is large compared with the thicknesses of the heating and reaction zones, the thermal theory predicts constant burning velocity. For small radii, the theory predicts a larger burning velocity if the flame front is concave toward the unburnt gas and a smaller one if it is convex.

Under the assumption of constant burning velocity, and assuming further that no flow disturbance is present in the unburnt gas, the shape of a flame front generated by a lighting source describing a periodical movement in a gas stream can be determined by applying Huygens' principle. (A periodical change of local burning velocity near the lighting source could be treated in the same way.) This leads to a wave-shaped flame front with an initial amplitude of the same magnitude as the amplitude of motion of the lighting source and a gradual decrease of amplitude during propagation. In sharp contrast to this result, the observed shapes show either a continuous increase of amplitude (Figs. 11, 12, and 13) or for higher intensities an initial increase followed by a decrease (Figs. 14 and 15). Since it appears unreasonable to abandon the assumption of constant burning velocity, the presence of a flow disturbance in the unburned gas must be assumed in order to account for the observed shape. This flow disturbance can be determined by finding out how the flame front appears to propagate

Fig. 35

MOVEMENT OF THE FLAME FRONT RELATIVE TO THE UNBURNT GAS. ENLARGED APPRO. 8:1 FROM Fig. 12-108°. ALONG a-a THE RELATIVE VELOCITY IS LARGER THAN THE BURNING VELOCITY, ALONG b-b IT IS SMALLER THAN THE BURNING VELOCITY.



to an observer moving with the flow velocity of the unburnt gas. This can be done easily using a single stroboscopic flame photograph, by superposing the flame pattern several times with a vertical displacement equal to the distance traveled by the gas stream in one period. Fig. 35 shows the results obtained by this procedure from an enlarged print of the photograph, Fig. 12, 108° phase angle. If propagation had proceeded according to Huygens' principle, the traces would have to be equidistant, the distance being equal to the product of burning velocity, time interval ($\frac{1}{253}$ sec.), and magnification factor. From the actual, variable, distance of the lines, the apparent propagation velocity of the flame front in each point can be calculated. The extreme values of this velocity are found to be 24.3 cm/s. and 44.1 cm/s. Their arithmetic mean value is 34.2 cm/s., which is in reasonably close agreement with the value of the burning velocity, 35.6 cm/s., found from volumetric rate of flow and surface area (see p. 14). The disturbance velocity is thus of the order of 10 cm/s.; it is directed outward where the flame front is concave toward the unburnt gas and inward where the flame front is convex. Obviously this flow disturbance is responsible for the observed increase of amplitude. (It should be noted that the influence of flame front curvature on burning velocity predicted by the thermal theory, if present, would counteract the effect of the flow disturbance.)

The presence of this flow disturbance points to a certain degree of instability of the flame front. Such an instability, causing an initially small disturbance to increase in time, has been predicted theoretically by L. Landau.[20] Landau's treatment, however, leads to an exponential increase, while the observed increase is only roughly linear. Qualitatively, the instability can be explained as follows: The distortion of the flame front will cause a disturbance of the flow in the burnt gas such that the flow lines converge where the flame front is convex toward the unburnt gas and diverge where it is concave. The pressure gradients resulting from the convergence and divergence of the flow are of opposite sign, and cause an inflow to occur where the flame is convex and an outflow where it is concave toward the unburnt gas.

Experimental proof of the existence of this flow disturbance in the burnt gas was obtained by the technique of the exploratory gas jet mentioned earlier. While the jet, observed stroboscopically by the shadow method, was not deflected in the unburnt gas, except very close to the flame front, it assumed a wave shape after emerging into the burnt gas. The shape was roughly a mirror image of the shape of the flame front. Therefore, in accordance with the above explanation, the jet was blown away where the flow lines converged and attracted where they diverged. In the unburnt gas the jet followed the shape of the flame front when it came close to it, which should be the case if the postulated flow disturbance is present.

No explanation has yet been found for the rather abrupt change from amplitude increase to decrease in the case of high intensity disturbance.

F. CONCLUSION AND PLANS FOR FUTURE WORK

The preceding discussion indicates that the method which constitutes the subject of this report has already led to some results of considerable importance for an understanding of flame propagation under turbulent conditions. It also shows, however, that numerous problems arise which can be solved only by modifying and refining the experimental methods.

In order to investigate further the mechanisms of generation and propagation of distortions on a flame front, a systematic evaluation of the influence of amplitude and frequency of the disturbance on the flame pattern is planned. It is particularly intended to extend the range of frequencies to values which correspond to wave lengths of order equal to or smaller than the thickness of the combustion zone. In this connection it is also planned to check the results of Hahnemann and Ehret.[6] These authors applied high intensity sound disturbances of approximately 5,000 c.p.s. to Bunsen flames and observed, without stroboscope, a "steel-helmet shaped" flame, the surface area of which was equal to the area of the undisturbed flame cone. The creation of flame front distortions at regions other than the base of the cone, by means of local hydrodynamic disturbances, will be also attempted.

In order to vary the burning velocity, which is considered to be an important parameter, the use of other gas mixtures besides propane-air is contemplated.

A theoretical treatment of propagation of disturbances in flame fronts, based on the qualitative description given on page 20, has been initiated.

In addition to the work on the Bunsen flame, investigation of flames lifted from the burner, either held by a flame holder or burning freely in the gas stream, is planned. Preliminary work on flames held by a wire introduced perpendicularly into the gas stream showed that these flames always vibrate spontaneously. The fundamental frequency of this vibration is identical with one of the resonance frequencies of the burner pipe. Synchronization within a small frequency range is possible by means of sound. It was also found that the motion of the flame front is not strictly periodical, apparently owing to the presence of high frequency components which are not integral multiples of the fundamental. Flames burning freely in the gas jet show an even more violent and irregular spontaneous motion. Because of the long exposure times needed for direct flame photography, this technique is not well suited for the investigation of these flames. It is therefore planned to use high-speed photography or high-speed motion pictures combined with the shadow and striae techniques for the study of these types of flames.

A quantitative evaluation of the flow in disturbed flames would be of fundamental importance for an understanding of the observed phenomena. It is planned to apply the powder method described by Lewis and von Elbe[9] for this purpose, since the introduction of an exploratory gas jet, mentioned in the discussion, gives only qualitative results and creates additional distortions of the flame front.

Finally, modifications of the stroboscopic technique are planned which would make it more adaptable to work at high frequencies and for synchronization with spontaneously vibrating systems. Rotating discs are not well suited for these cases. The introduction into the light path of a vibrating reed actuated electromagnetically, or of a mirror galvanometer deflecting the light beam of the shadow or striae system is proposed instead. These devices would work well at high frequencies. They could be synchronized with the sound generated by the self-vibrating system by means of a microphone. This technique would also be suited for stroboscopic work on pulse jets.

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