CCLXXV.—*Striated Photographic Records of Explosion Waves. Part II. An Explanation of the Striæ.*

By Colin Campbell and Arthur Calvert Finch.

It has been shown (J., 1926, 3010; 1927, 1572) that when the explosion-wave in certain gaseous mixtures is photographed by means of a moving-film camera, the records are striated in appearance and the trace of the flame front is marked by regular undulations. The mixtures which showed these phenomena most clearly were those of carbon monoxide and oxygen, with or without the addition of small quantities of hydrogen. The period of the striæ and also of the undulations was approximately proportional to the diameter of the containing tube but independent of its length. In a tube of internal diameter 15 mm. the period was about 1/39,000 sec. and was apparently not affected by the method of ignition of the gases. Several suggestions were put forward as to the cause of these phenomena, such as induced vibrations in the apparatus, a periodic propagation of the explosion-wave, or (as suggested by Mr. E. F. Greig) the flame travelling along a helical path.

The experiments now recorded appear to show that the facts can be accounted for by the last suggestion, and that the vibration of the apparatus or of a column of the gaseous mixture is not responsible for the effect.

EXPERIMENTAL.

The general experimental procedure previously described (J., 1926, 3010) has again been used except that, since only one gaseous mixture was under observation in any one experiment, the diaphragm apparatus was no longer necessary. The explosion apparatus consisted simply of glass and lead tubes of the same internal diameter (usually 12·5 or 15 mm.) rigidly cemented together to form a continuous gallery, usually about 4 m. long, which was placed horizontally in front of a moving-film camera. The explosive mixture was ignited by a break-spark near the closed end of the gallery, the other end (often seen in the photographs) being opened just before firing. The photographs were obtained on Lumière paper, usually 100 mm. wide, which was fastened to a cylindrical drum capable of being rotated at peripheral speeds up to 55 m. per sec. In order to obtain the exact direction of movement of the film as it passed the focus of the camera lens, a small electric lamp, placed near the tube and giving a pin-hole illumination, was lit for several seconds just before the mixture was ignited : this produced the thin black lines seen on many of the photographs.

The " Vibration " Theory.

It was at first imagined that the striæ might have been caused by the vibration of the camera itself, but the fact already mentioned (J., 1927, 1576), that striæ of different periods in two portions of the same tube have been recorded together on the same film, would appear to disprove such an explanation. Further evidence against it can now be given. For example, striæ of gradually increasing periods were obtained when a conical, instead of a cylindrical tube was employed. This is shown in Fig. 1, which was obtained when the internal diameter of the tube increased from 10 mm., on the right, to 25 mm., on the left of the photograph. An *abrupt* change in the internal diameter of the explosion tube has a marked effect on the speed of the flame as well as on its general character (Campbell, J., 1922, **121**, 2483), but the gradual widening of the tube produced no alteration in the speed of the flame in this experiment. In two experiments where the widening was more rapid (the diameter increased from 15 mm. to 28 mm. over a distance of 31 cm.), the character of the flame was altered and its speed reduced.

Vibration of the camera being excluded, that of the explosion tube was next examined. Such vibrations, set up by the explosion itself or transmitted through the bench from the driving motor on the concrete floor, might be either (1) longitudinal vibrations similar to those in a freely supported bar after a sharp knock, or (2) transverse vibrations in the material of the tube (compare vibrations of a bell) causing alternate compression and rarefaction of the hot gases.

Longitudinal vibrations in a glass tube would have a frequency proportional to its length; they would have the same frequency in all parts of the same tube and would almost certainly show the presence of nodes and anti-nodes at fixed points in it. The striæ, however, have a frequency which is independent of the length of the tube, the frequency is not always the same in different parts of the same tube (*e.g.*, in a conical tube), and the undulations on the trace of the wave-front do not correspond to the same points in the tube in different experiments. Moreover, the frequency of the striæ in one particular tube is about 40,000 per second, whereas the fundamental frequency of the longitudinal vibrations of this tube has been calculated to be about 2,500.

The theory that the striæ are caused by *transverse* vibrations in the material of the tube would appear to gain support from the close relationship which has been found to exist between the frequency of the striæ and the diameter of the tube. On this view, it might be expected that an alteration in the thickness of the wall of the explosion tube would alter the frequency of the striæ. This change has not been observed, but as no method appears to be available for calculating the variation of frequency with wall thickness for bell-vibrations of this type, we are unable to predict whether the effect would be sufficiently great to be apparent. It seemed probable, however, that a change in the elastic properties of the tube wall would alter the frequency of vibration to a much greater extent, and rubber tubes might therefore be expected to give results different from those in glass; but experiments in which a section of the glass explosion tube was replaced by one made of (*a*) thick rubber provided with a thin glass window, and (*b*) very thin semi-transparent rubber, showed striæ of similar frequencies in the glass and rubber sections of the tube.

Since no difference in the striæ could be seen when tubes of rubber and glass were used, an attempt was made to reduce to a minimum any possible transverse vibrations in a glass tube. For this purpose, the glass explosion tube, instead of being clamped, was encased in a large block of cement (reinforced by iron bolts) except for a slit 3 cm. wide extending along the middle 60 cm. of its length. The photograph obtained through this slit showed striæ of the same intensity and frequency as those observed in a tube clamped in the ordinary way.

It would appear, therefore, that vibrations either longitudinal or transverse in the tube itself cannot explain the formation of the striæ.

A train of compression waves in the gaseous mixture, initiated at or near the open end of the tube and moving in a direction opposite to that of the flame motion, might produce striæ, but it has previously been pointed out (J., 1927, 1573) that the slope of the striæ actually observed would require the velocity of such waves to be almost infinitely great. In any case, it seems impossible to believe that the open end of the tube could be a region of high pressure several milliseconds before the flame had arrived there. That the method of ignition also is not concerned in the formation of the striæ is shown by the fact that their frequency is unchanged (*a*) when the frequency of electrical oscillations is altered by increasing the capacity of the secondary circuit, and (*b*) when the mixture is ignited by a taper, the tube, in this experiment, being open at both ends.

The " Helix " Theory.

If a flame is travelling along a helical path in a cylindrical tube, it should appear at two windows separated by an arc of 90° at a time interval which is one fourth of that required for consecutive appearances at the same window. To test this by viewing the flame through

Fig. 1.

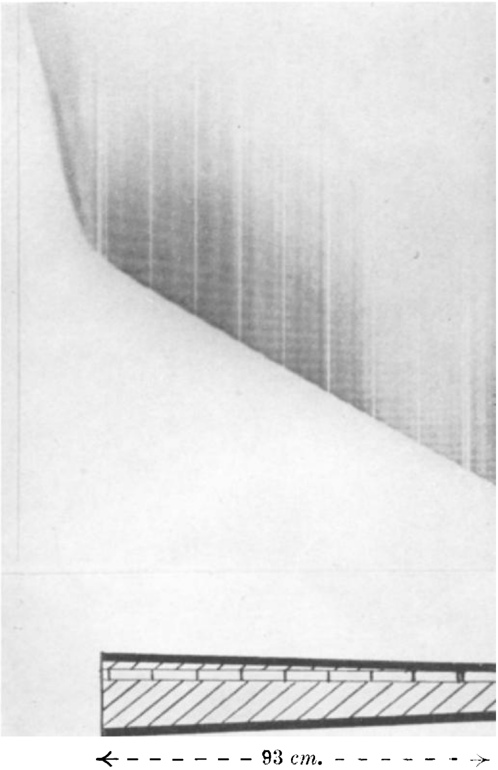

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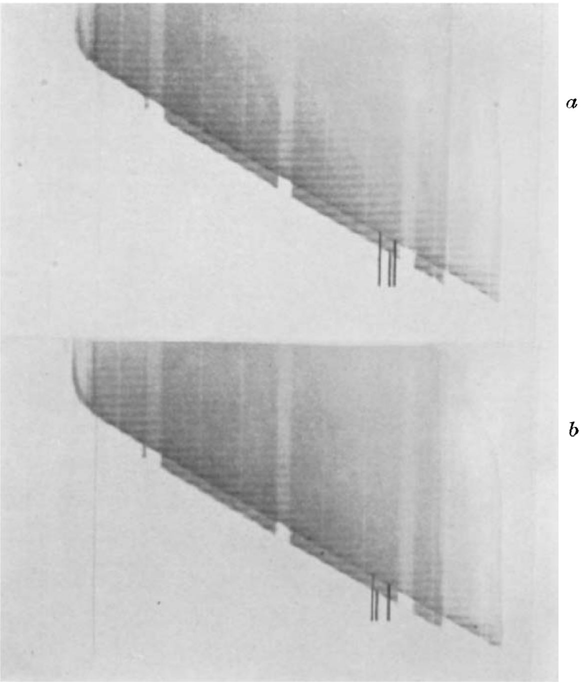
Fig. 2.



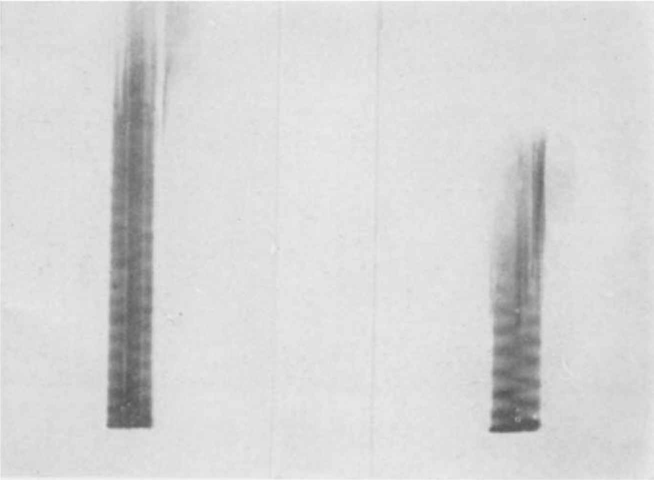
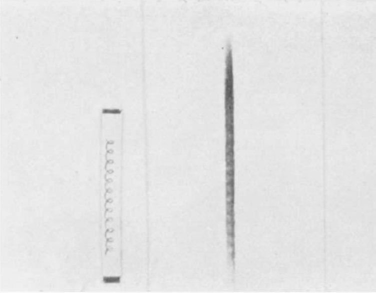
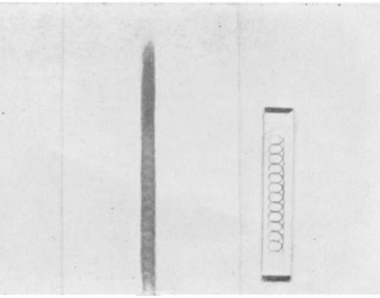


Fig. 8.



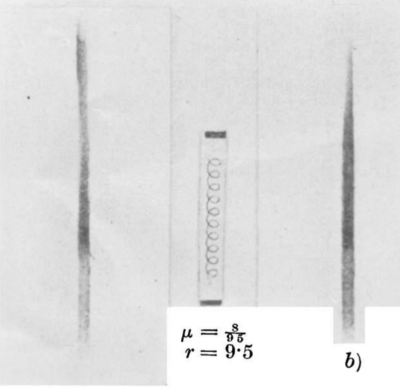
$\mu = \frac{1}{15}$
$r = 7{\cdot}5$

FIG. 3.



$\mu = \frac{2}{15}$
$r = 7{\cdot}5$

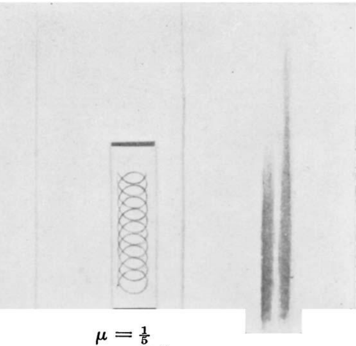
FIG. 4.



$\mu = \frac{8}{95}$
$r = 9{\cdot}5$

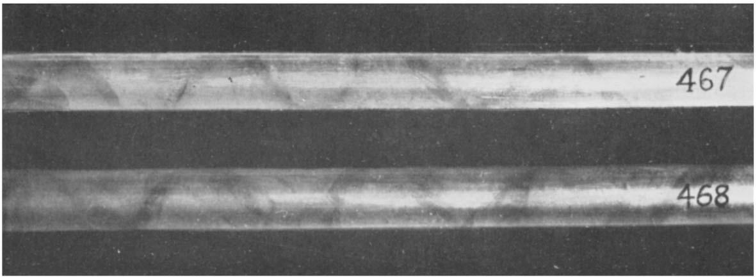
b)

(a) FIG. 5.



$\mu = \frac{1}{5}$
$r = 9{\cdot}5$

FIG. 6.



← *Direction of propagation of explosion-wave.*

FIG. 7.

FIG. 11.

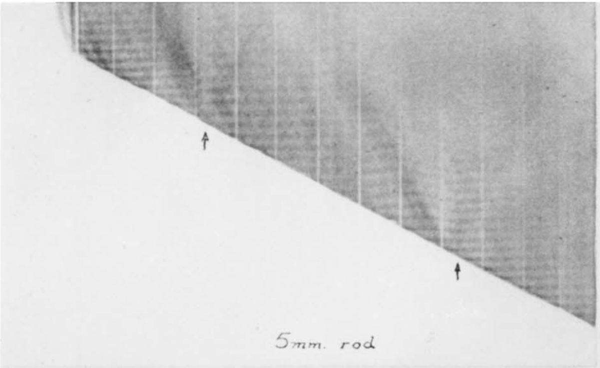
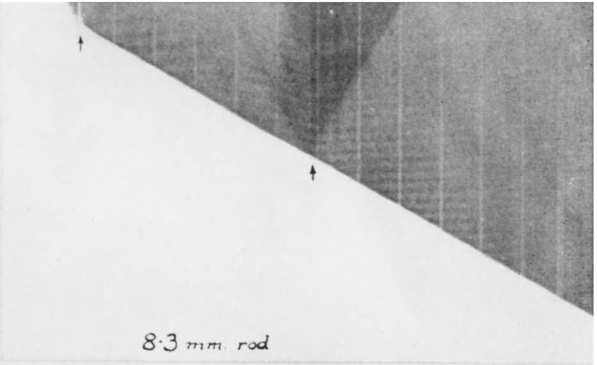


FIG. 12.



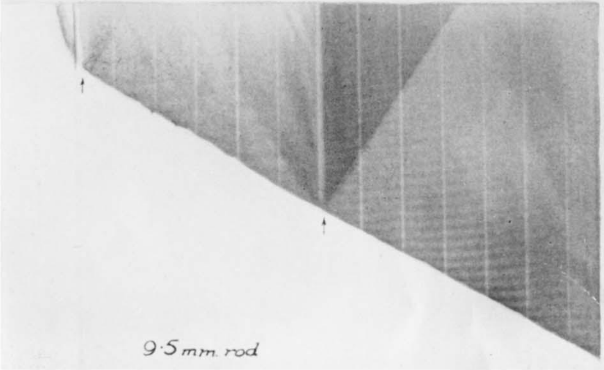


FIG. 13.

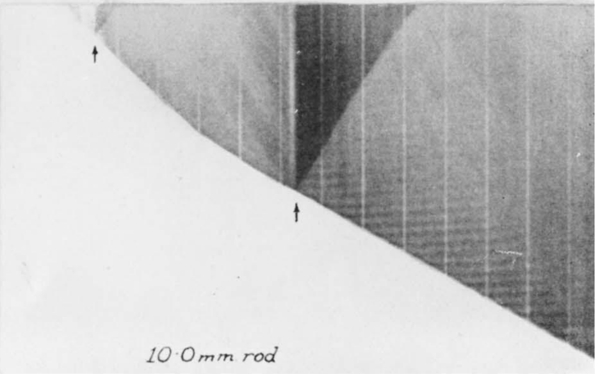


FIG. 14.

Vertical reference lines 10 *cm. apart.*

" top " and " front " windows was not satisfactory, because the aspects relative to the camera were not quite similar, one being normal and the other tangential to the tube. Moreover, through a window at the front of the tube, the flame would be visible both at the front and the back of the tube and the consequent doubling of the frequency of the striæ causes a loss of photographic resolution.

Both difficulties were overcome and two tangential views obtained by the use of a plate-glass mirror placed behind the tube and parallel to it. One image on the film record was made directly by the light from the flame as it passed a window near the top of the tube; the other image was produced by the light, after reflexion from the mirror, from the flame as it passed a window at the back. To prevent undesirable reflexions, the tube and the mirror were carefully screened, and in order that both images should be in focus, the aperture of the lens was considerably reduced. In spite of these precautions, a slight confusion on the film was caused by the unavoidable overlapping of the two images. Although this confusion was reduced by using a mixture (*e.g.*, $CH_4 + 6O_2$) which gave clear undulations on the trace of the flame front and very slight luminosity behind it, it was found that such mixtures often gave slightly irregular striations : for this reason carbon monoxide–oxygen mixtures were almost always used. The undulations were further apart and therefore easier to measure when wide tubes were used, but the size was limited by the fact that with tubes wider than 15 mm. the undulations and striæ were less regular.

Two negatives obtained when a 12·5 mm. tube, provided with windows 3·5 mm. wide, was used are reproduced in Fig. 2 (*a*) and (*b*). In each case the upper trace is the direct one, and the lower is that obtained by reflexion from the mirror. It is evident that the periodic character of the photograph is the same through whichever window the flame is seen. If a line is drawn parallel to the direction of motion of the film through each undulation, it is clear that in (*a*) each undulation in the direct image is distant $L/4$ (where L is the distance between successive undulations seen through one window) from the next on its left in the mirror image, whereas in (*b*) the phase difference is $3L/4$. The difference between the two records can be explained by assuming that in (*a*) the flame has passed round the tube in a clockwise direction, appearing first at the top window and then at the back window, whereas in (*b*) the direction has been counter-clockwise. The sense of the rotation is, in this case, apparently fortuitous and the same has been observed when other gaseous mixtures have been employed.

End-on Photographs.—Additional information regarding the rotary motion of the flame has been obtained by taking photographs with the tube pointing directly towards the camera. Preliminary experiments had shown that the explosion tube could be placed within 80 cm. of the lens without the latter being damaged or displaced even though the tube itself was completely shattered. The explosion tube was clamped as rigidly as possible, and complete alinement between the axis of the tube and the axis of the lens was secured by the use of a spirit-level and by accurately placed sights similar to those used on a rifle. In order to reduce the amount of extraneous light that reached the camera, the explosion tube was made of copper instead of glass, and on the open end was placed a cap of black paper with an annular aperture (2 mm. wide), the outer edge of which coincided with the inner surface of the tube. With this arrangement, a disc of flame of uniform luminosity moving regularly towards the open end of the tube would produce, on the moving film, a continuous band; any periodic change of the luminosity of the flame—owing to periodicity, chemical or physical, in its propagation—would result in its being recorded as a series of rings. If, however, the foremost actinic portion of the combustion is small in size compared with the diameter of the tube and is rotating regularly about the axis of the latter, it should produce a record which is cycloidal in form. The type of cycloid produced would depend on the *apparent* peripheral rate of rotation of the flame, and this rate would be altered by changing the distance of the tube from the camera, other conditions remaining the same.

Figs. 3, 4, 5, and 6 are reproductions of some of the records obtained by the above method. They are clearly cycloids, and when compared with one another, show the alteration of type as the distance of the tube from the camera is altered. Since different parts of the terminal tube of the explosion gallery could not be at the same distance from the lens, there is a slight variation in type even in a single record, but as the length of the terminal tube was usually short compared with its distance from the camera, the variation is in most cases inappreciable.

The form of cycloids to be expected when the tube is at various positions in front of the camera can be calculated from the known velocity of the explosion-wave (V), the tube radius (r), and the distance L (see above). If the flame is travelling round the circumference of the tube, the arc traversed in time t will subtend an angle α at the centre such that $t = L\alpha/2\pi V$. It has been shown (J., 1927, 1575) that $L = 6r$ (approx.), and therefore $t = 3r\alpha/\pi V$. If the wheel had remained stationary during this period, the position of the flame image would be given by $x = \mu r \cos \alpha$; $y = \mu r \sin \alpha$, where μ is the magnification. But, since the film is moving vertically at a velocity W (the peripheral wheel velocity), each point on it has moved forward, in time t, a distance $3r\alpha W/\pi V$. The trace of the flame image on the moving film is therefore the cycloid in which the above value of y is replaced by $y = \mu r \sin \alpha + 3r\alpha W/\pi V$. An example illustrates the method employed in plotting the theoretical cycloids :

Experiment 456. Mixture $CH_4 + 5\frac{1}{2}O_2$. Velocity of explosion taken as 1900 m./sec.; $r = 7{\cdot}5$ mm.; $\mu = 1/15$; $W = 53{\cdot}83$ m./sec. Hence the cycloid is $x = 0{\cdot}5 \cos \alpha$; $y = 0{\cdot}5 \sin \alpha + 0{\cdot}2030\alpha$. By taking different values for α, corresponding values for x and y were obtained. A curve was plotted from these values : it was then photographed and reduced in size for comparison with the record obtained in this experiment. Similar cycloids were plotted for each magnification and tube radius, and the reduced reproductions placed alongside the actual photographic records in Figs. 3—6. In each case, the value of μ taken is that which corresponds with the middle point of the horizontal part of the explosion tube : the theoretical and recorded cycloids, therefore, correspond most closely over the central portions of the latter.

The agreement between the theoretical and the observed results appears to point conclusively to a rotational movement of the flame. That the rotation may be in either direction seems clear from Figs. 5 (*a*) and (*b*), for in (*a*) the cycloid corresponds to a clockwise rotation, whilst in (*b*) it is in the opposite direction.

Helical Traces on the Walls of the Tube.—The " helix " theory is also supported by evidence of a nature quite different from that hitherto described. The inner surface of the terminal glass tube of a gallery of lead and glass sections was found, after several explosions, to be coated with a light deposit of lead dust in which was discernible a very incomplete network of markings apparently consisting of portions of clockwise and counter-clockwise helices. During attempts to repeat this observation and to obtain perfect records of this type, many different incombustible powders were tried as coatings for the interiors of the tubes. A light deposit of French chalk, which adhered fairly readily to the glass surface, was found to be most suitable. Two of the tubes so coated, and used each for one experiment only, have been photographed for us by Messrs. Flatters and Garnett of Manchester and are reproduced in Fig. 7. In both cases the mixture $2CO + O_2$ (containing $0{\cdot}7\%$ H_2) was used. The helical trace is, in each case, clearly marked; in Expt. 467 it is clockwise with respect to the forward movement of the flame, whilst in Expt. 468 it is counter-clockwise.

Both tubes were of 14·7 mm. bore and the average pitch of the helical trace, whose direct measurement is rendered easy by its uniformity and completeness, is very nearly 44 mm. This distance may, with very small error, be considered identical with that between points in the tube corresponding to successive undulations in the photographic record of the foremost actinic portions of the flame associated with the explosion in a tube of the same diameter. It may be, indeed, that the dust trace shows the actual path traversed by this part of the flame but, on the other hand, it is conceivable that it is due to some invisible disturbance travelling ahead of the flame.

There are several other points of agreement between the photographic records and these helical dust traces. For example, the dust trace produced when the mixture $2CO + O_2$ (containing 1% H_2) was used showed greater regularity than that formed with the mixture $CH_4 + 6O_2$, just as the undulations obtained in the photographs of the flame in the carbon monoxide mixture were more regular than those in the methane mixture. Again, a slow (pre-detonation) flame in the same carbon monoxide mixture was found to give neither striæ in the photographs nor traces in the French chalk, and the well-established explosion-wave in electrolytic gas also gave negative results in both cases.

That the first luminous portion or " head " of the explosion traverses a helical path gives no explanation of the long striæ which are a striking feature of many of the photographs taken on a moving film. Such a luminous " head " to the combustion as it traversed a helical path in a tube provided with only a narrow window would be recorded on the film as a chain of well-marked points or short arcs, whilst the combustion behind the head, if uniformly distributed across the tube section, would produce a uniform background in the photograph. The record, therefore, although probably showing an undulated trace, would be devoid of striæ, and quite unlike any actually obtained.

The production of striæ can, however, be explained by making the further assumption that the most luminous portion of the gas behind the flame front forms a long slender " tail," which lies close to the wall of the tube and rotates with a frequency almost identical with that of the head. Such a rotation of the tail explains the observation that the frequency of the striæ photographed through a middle window is double that recorded through a top window, just as the frequency of the undulations in the photographic record produced by the head was doubled under similar conditions. Through a middle window, the tail is visible twice (at the front and the back of the tube) during each revolution, but with a top window, only once.

Photographs of the Flame in a Vertical Tube.—That this long tail is a reality, and that it rotates in the tube, is evident from the following experiments. A vertical glass tube, 30 cm. long and of 28 mm. bore (2 mm. wall), was completely covered with black paper except for a 1 mm. horizontal slit round the semi-circumference on the optical axis of the camera lens. The lower end of the tube was rigidly joined, by a conical copper tube (expansion 15—28 mm. over a length of 63 cm.), to a 15 mm.-bore lead tube about 6 m. long. The whole gallery was filled with the mixture $2CO_2 + O_2$ (containing about 1% of H_2) and firing was effected, as usual, by a spark near the closed end of the lead tube. The photograph of the flame, as it passed up the tube, was taken on a film moving at 50 m./sec. Two typical records are shown in Figs. 8 and 9. It is clear that, although the tube was invariably shattered by the explosion, the most luminous part of the burning gases had passed the slit before this occurred.

If the head only of the flame had been rotating, the first recorded portion of the photograph would have been a well-defined point or short line followed by a general greyness of diminishing photographic intensity. The records, however, show a considerable number of well-defined lines of alternate positive and negative slope, and these are evidently produced by the passage of successive portions of a long slender tail first across the front and then across the back of the tube. The regularity of the zig-zag lines also suggests that the whole length of the highly luminous gas is moving round the tube at a velocity which is approximately constant.

The form of the tail. Since the head and the tail of the combustion are rotating in the tube with the same frequency, it seems probable that the tail is the still-luminous track of the head, a very intense local burning near the wall of the tube. The tail, therefore, may occupy the exact position of the path traversed by the head, or its position and form may be modified by the movement of the gases of which it is the most luminous part.

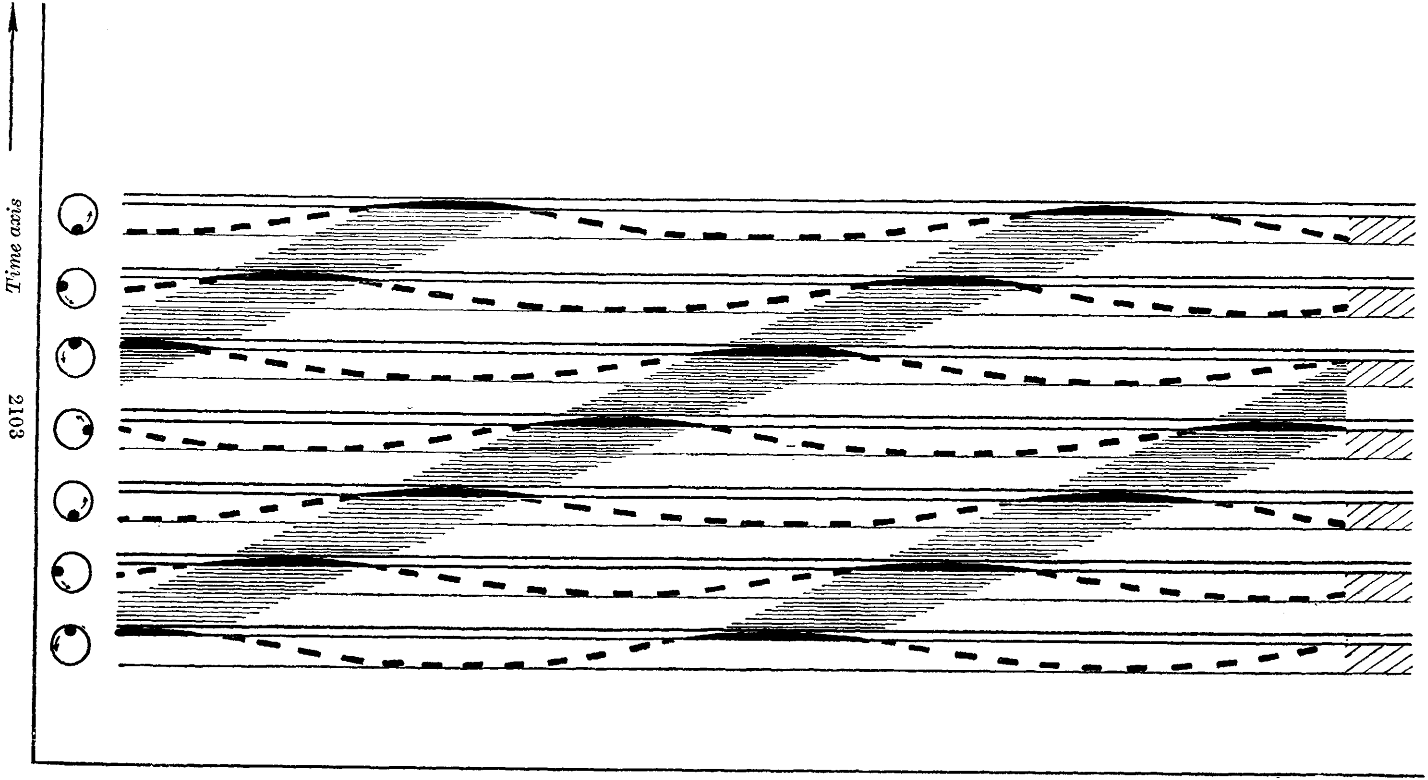
If, during an explosion, the gaseous mixture is, for the moment, assumed to remain at rest, and the head of the flame is traversing a helical path, the luminous tail would, at any instant, be helical in form—like a helical coil of wire lying in the tube. At a narrow horizontal window certain fixed points would be illuminated and should appear as *vertical* bars or striæ in the photographs. It is, however, almost certain that the gaseous mixture is being carried forward in the same direction as the explosion wave, for incandescent dust particles are, in many experiments, apparently carried forward at velocities approaching 1000 m./sec. If this be the case, the helical path of the tail should also be carried forward and produce striæ sloping in the *same* direction as the trace of the flame front. The records, however, show striæ which are never vertical but are either horizontal or have a slight slope in the opposite direction, and it appears most improbable that a backward movement of the gases, sufficiently rapid to produce striæ of this type and starting from the wave front, could take place. The hypothesis that the tail occupies the helical track of the head in gas which is at rest or moving parallel to the tube axis appears, therefore, to be untenable.

We are inclined to the view that, if the gaseous mixture were at rest or moving only forwards or backwards in the tube, the track of the head would be parallel to and probably near the wall of the tube, and that the tail would be a long narrow pencil of burning gas also parallel, or nearly parallel, to the axis of the tube. This would cause a uniform exposure of the photographic film. If now, the gaseous mixture were set in rotation, the head and tail would both appear intermittently at a horizontal window; the photographic trace of the head of the flame would be undulated, and each appearance of the tail would be recorded as a stria.

If the luminous pencil remained parallel to the axis of the tube whilst the whole mixture was rotating at constant velocity, it should produce horizontal striæ, and these have, in some cases, been observed. The striæ are, however, more frequently slightly inclined to the horizontal, and their slope may be accounted for in one of two ways : either (*a*) the pencil of luminous combustion is inclined to the tube axis, or (*b*) the rates of rotation of different parts of the burning gases are not identical.

Some information on this point may be obtained by comparing the vertical distance on the film between the ends of a single stria with the width of a strip of film which would be affected by a luminous inclined rectilinear tail as it passed once across a narrow window. Each point on a rectilinear tail must, in rotating, pass a window at the same angular velocity as the head of the flame : the time of exposure t is therefore equal to $La/2\pi rV$, where a is the length of arc visible through the window. Using a 3 mm. upper window in a 15 mm. tube, and neglecting the optical effects of the tube wall (which would still further restrict the field of vision), it is safe to assume that not more than one-quarter of the internal circumference is visible. Hence $a/2\pi r < 0{\cdot}25$ and therefore $t < 0{\cdot}25 \times 45/1750 \times 10^{-3}$, *i.e.*, $< 6{\cdot}4 \times 10^{-6}$ sec. During this time a film travelling at 50 m./sec. will be exposed over a vertical distance of $6{\cdot}4 \times 10^{-6} \times 5 \times 10^{4} = 0{\cdot}32$ mm. If, in addition, the tail should, at any moment, appear as a line inclined across the full width of the window, an additional strip of film, whose maximum width is that of the image of the window, will be exposed. In a typical experiment, where $\mu = 0{\cdot}06$ and the window is 3 mm. wide, the additional strip will be 0·18 mm. wide, and the total maximum width of film

Fig. 10.



affected during the recording of each stria will be 0·32 + 0·18 = 0·50 mm. The vertical distance on the film between the ends of a single stria usually measures 1·2—1·5 mm., and it would therefore appear that, under the conditions of our experiments, a rectilinear tail of any possible slope cannot account for the production of striæ having both great length and appreciable inclination.

An alternative suggestion is that the pencil of luminous gas forming the tail is not rectilinear but is regularly distorted along its length so that it tends to assume the form of a helix. This distortion might be produced by a constantly diminishing speed of rotation of the gaseous medium as its distance from the head increased. Successive portions of this tail, therefore, would not appear at a horizontal window simultaneously but at successive time intervals, and would be recorded as sloping striæ (Fig. 10). The smallness of the slope suggests that the deviation of the tail from a straight-line form is slight, *i.e.*, that the helix is of great pitch. In those mixtures which do not allow of the formation of a long tail, the pitch of the tail helix may be so great that a complete turn may never occur. In other cases, the tail may be long enough for several turns of the helix to be luminous at the same time, and, through a narrow upper window, the corresponding points on each turn of the helix should be visible at any instant. The pitch of the helix, in these cases, may be estimated, therefore, by drawing a horizontal line—representing an instant of time—across one of the records so that it cuts two or more striæ; the length of the line thus intercepted is a measure of the pitch of the helix. Because of the lack of definition of the striæ, the measurement is only approximate, but in one case the pitch so estimated was found to be 46 cm., or about 10 times the pitch of the path of the head of the flame.

Insertion of a Coaxial Rod.—It was thought that some further information on the movements of the gases might result from experiments in which a glass rod was inserted into the tube coaxially with it, so as to offer to gaseous rotation an increased frictional resistance, while having a minimum effect upon any helical motion of flame in a still medium, if a propagation of this type took place.

The tube was 15 mm. in diameter, and the rods were 50—60 cm. long and 5—10 mm. thick. A rod was supported centrally by short, thin copper vanes attached at each end; these vanes offered only a slight resistance to the forward movement of the explosion. The mixture used was, in every case, $2CO + O_2$ (containing about 1% of H_2), and some of the records are reproduced in Figs. 11—14. When a 5 mm. rod was inserted, the forward velocity of the explosion-wave was quite unaffected, but, in the neighbourhood of the rod, the frequency of the striæ was appreciably decreased. Before and beyond the rod, the undulations and the striæ had the normal frequency. When a rod of 8·3 mm. was used, its effect as an obstacle to the flame became evident, a strong pressure wave being reflected back through the burning gases from the end of the rod first encountered by the explosion wave : the striæ were not so well marked, and the flame velocity was not quite constant. A 9·5 mm. rod accentuated these effects, and the rod was shot from the tube, even though the end of the rod first encountered by the flame had been tapered to a point. A 10 mm. rod appeared to offer an insurmountable obstacle to the normal propagation of the flame. The pressure wave was very intense, and the rod was ejected from the tube : the flame velocity fell to about three-fifths of its former value, and the striæ were hardly visible.

TABLE I.

Effect of an Inserted Rod on the Pitch of the Undulations.
Diameter of Tube (*D*) = 14·7 *mm.*

Diameter of rod, mm.	—	5·0	8·3	9·5	10·0
Distance between undulations, *L*, mm.	44	53	55	61	indeterminate
L/*D*	2·99	3·61	3·73	4·16	—

The change in frequency of the striæ at the point where the rod was originally placed is not very abrupt; this may be due, in part at least, to the movement of the rod along the tube, for it was found difficult to make it very secure without using supports which were themselves obstacles to the explosion wave. The frequency of the striæ, however, becomes quite constant within a few centimetres, and is, in each experiment, much smaller in that part of the tube occupied by the glass rod than in the unobstructed portions of the tube. As the thickness of the rod is increased, the frequency of the striæ diminishes and the pitch (*L*) of the undulations undergoes a corresponding increase as shown in Table I. It appears reasonable to suppose that the narrower the annular space the greater will be the retarding effect of the viscous, frictional, or other forces on the speed of rotation of the gases, and the change in pitch of the undulations may indicate that such retardation has taken place.

Effect of Tube Form on the Rotation of the Gases.—It has been shown (J., 1927, 1575) that in uniform cylindrical tubes having diameters of 8—19 mm. the distance between successive undulations is approximately proportional to the tube diameter. This distance, which may be identified with the pitch of the helical path traversed by the head of the combustion, depends on the period of rotation of the gases and on the forward velocity of the flame. For any given mixture the latter is constant, and therefore the period of rotation of the gases is proportional to the diameter, and hence to the circumference of the tube. That is to say, the *peripheral* velocity of rotation of the gases in the flame front is approximately constant in tubes of different diameters. This explains the gradual decrease in frequency of the undulations observed when a flame travels towards the wider end of a conical tube (Fig. 1).

The head, during each rotation in the wider part of the tube, traverses a longer path than the tail, which is still rotating in the narrower part : it will therefore appear at a horizontal window less frequently than points on the tail, and the end of the latter may become visible before the head passes across the window at a point nearer the wider end. Intermediate points on the tail will be similarly affected to a degree corresponding to the distance from the head, and the photographic records should show striæ sloping in the same direction as the trace of the flame front; such striæ are seen in Fig. 1.

The hypothesis of gaseous rotation may also explain the record (Fig. 7 of the previous paper; J., 1927, 1572) obtained when an explosion wave passes from a wide to a narrow tube. The velocity of the explosion wave remained unchanged, but the period of the undulations very rapidly became that characteristic of the narrow tube. The striæ in the two sections of the tube are not independent, as would be the case if the flame travelled along a helical path in a quiescent medium. If the gases are rotating at constant peripheral velocity in the two sections of the tube, as has been suggested above, the angular velocity of rotation will be greater in the narrow section. The change of velocity at the junction will, of necessity, be a gradual one, and the period of rotation of the tail will therefore be unequal at various points along its length, decreasing towards the flame front. This would account for the great increase in backward slope of the striæ in the first few cm. of the narrow section of the tube.

Although the rotation of the medium would appear to account for the striæ, certain questions still remain unanswered. It is, for instance, not yet clear how such rotation is initiated, what conditions are necessary for its continued existence, and whether the absence of striæ when certain gaseous mixtures are employed is due to the absence of rotation or to the predominant effect of other factors. Such problems as these are at present under investigation.

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