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REPORT No. 187

FLAME SPEED AND SPARK INTENSITY

By D. W. RANDOLPH and F. B. SILSBEE

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AERONAUTICAL SYMBOLS.

1. FUNDAMENTAL AND DERIVED UNITS.

	Symbol.	Metric.		English.	
		Unit.	Symbol.	Unit.	Symbol.
Length	l	meter	m.	foot (or mile)	ft. (or mi.).
Time	t	second	sec.	second (or hour)	sec. (or hr.).
Force	F	weight of one kilogram	kg.	weight of one pound	lb.
Power	P	kg.m/sec		horsepower	IP
Speed		m/sec	m. p. s.	mi/hr	M. P. H.

2. GENERAL SYMBOLS, ETC.

Weight, $W = mg$.

Standard acceleration of gravity, $g = 9.806\text{m/sec.}^2 = 32.172\text{ft/sec.}^2$

Mass, $m = \frac{W}{g}$

Density (mass per unit volume), ρ

Standard density of dry air, 0.1247 (kg.-m.-sec.) at 15.6°C. and 760 mm. = 0.00237 (lb.-ft.-sec.)

Specific weight of "standard" air, 1.223 kg/m.^{3} = 0.07635 lb/ft.^{3}

Moment of inertia, mk^2 (indicate axis of the radius of gyration, k, by proper subscript).

Area, S; wing area, S_w, etc.

Gap, G

Span, b; chord length, c.

Aspect ratio = b/c

Distance from $c.\ g.$ to elevator hinge, f.

Coefficient of viscosity, μ.

3. AERODYNAMICAL SYMBOLS.

True airspeed, V

Dynamic (or impact) pressure, $q = \frac{1}{2}\rho V^2$

Lift, L; absolute coefficient $C_L = \frac{L}{qS}$

Drag, D; absolute coefficient $C_D = \frac{D}{qS}$

Cross-wind force, C; absolute coefficient $C_C = \frac{C}{qS}$.

Resultant force, R

(Note that these coefficients are twice as large as the old coefficients L_c, D_c.)

Angle of setting of wings (relative to thrust line), i_w

Angle of stabilizer setting with reference to thrust line i_t

Dihedral angle, γ

Reynolds Number $= \rho\frac{Vl}{\mu}$, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi/hr., normal pressure, 0°C: 255,000 and at 15.6°C, 230,000;

or for a model of 10 cm. chord, 40 m/sec., corresponding numbers are 299,000 and 270,000.

Center of pressure coefficient (ratio of distance of $C.P.$ from leading edge to chord length), C_p.

Angle of stabilizer setting with reference to lower wing. $(i_t - i_w) = \beta$

Angle of attack, α

Angle of downwash, ϵ

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Bureau of Standards

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FLAME SPEED AND SPARK INTENSITY.

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SUMMARY.

This report describes a series of experiments undertaken to determine whether or not the electrical characteristics of the igniting spark have any effect on the rapidity of flame spread in the explosive gas mixtures which it ignites. The results show very clearly that no such effect exists. The flame velocity in carbon-monoxide-oxygen, acetylene-oxygen, and gasoline-air mixtures was found to be unaffected by changes in spark intensity from sparks which were barely able to ignite the mixture up to intense condenser discharge sparks having 50 times this energy.

INTRODUCTION.

The experiments described in this report were performed at the Bureau of Standards as a part of the general investigation of problems connected with the phenomena of combustion in internal-combustion engines, which is being carried on under the auspices of the National Advisory Committee for Aeronautics. The object of the experiments was to detect the effect, if any, of the character of an igniting spark on the speed of the flame which it produces in explosive gaseous mixtures.

The time required for the flame to spread and for combustion to take place within the engine cylinder is an appreciable fraction of a cycle in high-speed engines, and therefore any change in the rate of flame propagation might be expected to affect the engine power. It should be noted, however, that such effects would be expected to be relatively small since the additional power obtained with high rates of combustion would be measured by the difference in area between the actual indicator card and one in which the corners at upper dead center were sharp instead of rounded. Detonation or knocking is also in all probability very directly connected with the rate of the combustion of the fuel, and any effect of the manner of ignition upon this rate might be expected to affect the tendency to detonate.

The belief seems to be general among automotive engineers that there is a very definite effect of the kind suggested above, and a "fat" or "hot" spark is considered desirable as giving more complete combustion and greater power, as well as more certain ignition. On the other hand, when it is considered that the actual energy content of even a relatively strong magneto spark (0.1 joule) is equivalent to the heat of combustion of only two millionths of a cubic centimeter of liquid gasoline, or of three thousandths of a cubic centimeter of the compressed-gas mixture within the engine cylinder, it appears unlikely that any change in this infinitesimal amount of energy would affect the progress of the chemical reaction which, after the very first moment, liberates a very much greater amount of heat.

If the effect did exist it would have a very direct bearing on the design of ignition systems, since the latter should, of course, be so arranged as to give the type of spark which is most suited to give rapid combustion without detonation. Devices for attachment to ignition apparatus are now on the market which claim to be able to produce effects of this character.

The fuel mixtures used in this investigation were mainly carbon monoxide and oxygen, and acetylene and oxygen. These fixed gases were chosen because they insured uniform mixture of the constituents and did not require the complicated heating apparatus which would be necessitated by experiments on liquid fuels. The data obtained in this way are therefore more accurate than those on gasoline, but corroborative experiments were also performed using mixtures of X-gasoline and air at about 90° C. and such initial pressure as to correspond to the density conditions met with in automotive engines. The carbon monoxide has a relatively slow rate of flame propagation, while the acetylene mixtures burnt with extreme rapidity, and the results can therefore be considered as applicable over an extreme range of flame speeds. The types of ignition sparks are described below and were all within the range which it might be commercially practicable to obtain in regular automotive equipment.

PREVIOUS WORK.

Relatively little information is available in the literature bearing directly on the particular problem which was the subject of these experiments. A very considerable amount of work, however, has been done in mixtures of fixed gases by Thornton,[1] Wheeler,[2] Morgan [3] and others on the related question, "What intensity of spark is required to produce ignition in a given explosive mixture?" At the British National Physical Laboratory [4] an extensive study was made of this latter question, using gasoline-air mixtures and sparks obtained by the discharge of a small condenser. In general, an increase in either the parallel capacity or in the sparking voltage increased the igniting power of the spark. The effect of voltage was found to be much more important than that of capacity, so that at a high sparking voltage the capacity which had to be discharged at the spark to produce ignition was found to be materially less even than that which would store the same energy at the higher voltage. Although their experiments, therefore, show that energy is not a complete measure of igniting power, energy may serve as a basis of comparison of different condenser sparks provided these have the same sparking voltage.

Experiments have also been made by operating internal-combustion engines with ignition systems delivering sparks of different characteristics. Thus Borth [5] obtained indicator cards on a gas engine ignited by several different types of spark and found no difference in the pressure-time diagrams so long as the spark ignited the mixture at all. This work, though very carefully done, was mainly on types of spark now nearly obsolete. Most experiments in engines are not very conclusive, however, since the power output of the engine is subject to variations from such a large number of factors other than the quality of the spark, and also because, as pointed out previously, a relatively considerable change in the rate of combustion would be expected to affect the engine power only slightly.[6] Tests made both in England and at the Bureau of Standards, however, have shown no detectable difference in the engine power when a given engine under identical conditions was operated alternately on a normal magneto spark, and on condenser discharge sparks containing either very much less or very much greater amounts of energy.

BUBBLE APPARATUS.

The velocity of the flame produced by the various sparks was measured by the device invented and developed by Stevens [7] in his studies of combustion phenomena. See Figure 1. In this apparatus the explosive mixture of gases to be investigated is confined in a soap bubble. An opening at the rear of the pipe, from which the bubble is blown, permits the insertion of a pair of electrodes which are arranged so that the igniting spark occurs at the center of the spherical bubble. By the passage of the spark the gases are ignited and the flame surface spreads outward as a luminous spherical wave of continuously increasing diameter.

The progress of the flame is recorded photographically by focusing an image of the burning bubble upon a photographic film which is mounted on a drum which can be revolved about a horizontal axis perpendicular to the axis of the lens. A horizontal slit is placed just in front of the film so that the image of only a narrow equatorial strip of the spherical flame surface

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1 Thornton, W. M., Phil. Mag., Vol. 40, p. 345, 1920 (and earlier papers).
2 Wheeler, R. V., Chem. Soc. Journ. Trans., Vol. 117, p. 903, 1920 (and other papers).
3 Morgan, J. D., Chem. Soc. Journ. Trans., Vol. 115, p. 94, 1919.
4 Paterson and Campbell, Physical Society (London) Proceedings, Vol. 31, p. 168, 1919:—"Some Characteristics of Spark Discharge and its Effect on Igniting Explosive Mixtures." This paper also contains reference to other work on this problem.
5 Borth, W., Mitt. über Forschungsarbeiten Verein Deut. Ing., Vol. 55, p. 70 et. seq., 1908.
6 Air Service Information Circular, Vol. I, No. 17, McCook Field Serial No. 1172, Feb., 1920.
7 Stevens, F. W., N. A. C. A. Report No. 168, A Constant Pressure Bomb.

can fall on the film. As the sphere of flame expands, the length of the luminous strip at the equator increases continuously while the motion of the film on the drum at right angles to the motion of the flame serves to impress the flame image on successively different portions of the film, and draws out the image into a wedge, as shown in Figure 2. This figure shows at the apex of the wedge the bright image of the igniting spark which, it may be noted, lasts for an appreciable time interval after the instant of ignition. The burnt gases often remain incandescent for an appreciable time after combustion has been completed, and consequently the photographic image retains its final width for some distance at the end of the wedge. The original size of the bubble and the identity of the particular experiment were obtained in each case by taking a preliminary exposure with the film stationary, as shown in Figure 2.

A time scale for the record was obtained in the earlier work by photographing on the film simultaneously with the exposure an image of a second spark supplied from a 60-cycle alternating source. This method, however, was not very satisfactory and in the later films the time record was obtained by photographing a beam of light which was interrupted by shutters attached to the prongs of a tuning fork which was driven electrically by being coupled with the oscillating circuit of a three electrode electron tube.[8] Forks having periods of 100 cycles and 250 cycles per second were used, according to the speed of the explosions under observation.

The gas mixture from which the bubbles were blown was obtained from supply tanks or (in the case of carbon monoxide) from a small generator using the decomposition of formic acid by heated sulphuric acid. Each constituent gas passed through a calibrated orifice, the pressure drop through which could be measured on an inclined water manometer. The gases were then united in a mixing tube and passed to the bubble pipe, and thence to an exhaust chimney.

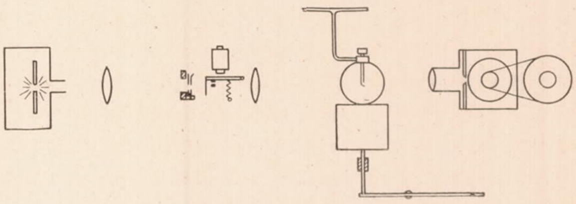

FIG. 1.—Schematic diagram of apparatus.

The procedure in the experiments was to establish a steady flow of gases through the apparatus, then to place a soap film across the opening of the bubble pipe, and by throttling the flow of gas through the exhaust chimney to form the bubble. The electrodes were then pushed down to the center of the bubble and automatically cut off the bubble from the gas supply. The stationary picture with the identifying number was then taken, Figure 2. The camera and magneto motors were started, the tuning fork was set in motion, and the bubble was fired. A contact on the shaft of the film drum served to simultaneously remove the short circuit from the magneto and to open the shutters which normally cut off the timing light. This insured the simultaneity of the time record and the explosion. Several exposures were taken on each film without altering the setting of the gas valves, but with different types of spark. In spite of this precaution, however, it is probable that the principal cause of the deviations in the results was fluctuation in the mixture ratio rather than in the other parts of the measurements.

BULB APPARATUS.

In order to extend the observations to conditions more closely resembling those in automotive engines, a further series of runs was made, using mixtures of X-gasoline and air. In these experiments the mixtures were contained in a thin glas bulb instead of in a soap bubble, and an initial pressure of about 60 lb. per sq. in. (gage) was used instead of atmospheric pressure. The known volume of gasoline was extruded from a calibrated syringe on to a small piece of filter paper placed in the bulb. The bulb was then quickly connected to the piping system through an automatic connector which gave a pressure-tight connection with the compressed air system. Compressed air was run into the bulb to an initial pressure of about 45 lbs. (gage), and the whole system isolated by a valve. During this process there was very little opportunity for the gasoline vapor to escape. A water bath maintained at nearly 100° C. was then raised to surround the bulb and left in position for about two minutes. The resulting rise in temper-

[8] Eckhardt, E. A., Karcher, J. C., Keiser, F.—Jour. Optical Society, vol. 6, p. 949, Nov., 1922.

ature served to vaporize the gasoline, and also raised the pressure within the bulb to a value of about 60 lbs. per sq. in. The water bath was then removed and the gas fired in the same manner as with the soap bubbles.

The combustion of these mixtures, even when the amount of gasoline was such as to give the most powerful explosion, was relatively slow and unfortunately gave very little light so that the records of which Figure 5 is an example do not admit of satisfactory reproduction. The original negatives, however, show very clearly that the flame proceeds regularly in a manner similar to the other materials for a definite interval, after which the photographic image abruptly ceases. This instant marks the time at which the bulb burst and permitted the luminous material to expand and cool to such an extent as to no longer affect the film. During the initial burning, as recorded, in most instances there was a definite tendency of the flame to slow down with the progress of the combustion. This presumably results from the accumulation of unburnt fuel ahead of the flame so as to retard the expansion of the products of combustion. The free expansion at the beginning contributes materially to the relatively high initial velocity of the flame in space. As the bulbs were fragile it is probable that the pressure did not rise very much above its initial value before the bulb burst.

During the later portions of the explosion the record shows a marked though gradual brightening of the flame, which may be due to the increase of pressure in the burnt gases but which suggests, at least, the possibility of combustion by successive stages.

SPARKS USED.

An electric spark is the result of the sudden passage of electricity through the gas in a gap between two electrodes. The electric charge is carried in this case largely by charged particles of the gas called ions, and to a lesser extent by particles of the metal electrodes which have been vaporized by the intense local heating. A complete description of the character of a spark, therefore, involves a very considerable number of variables, some of which it is difficult to control experimentally.

A spark will pass across a given gap only when there is applied to the terminals of the gap a voltage having a value V (known as the breakdown voltage of the gap) which depends among other things upon the length of the gap, the shape of the electrodes, and the density of the gas between them.

When the spark is obtained by the discharge of a condenser of capacity C connected in parallel with the spark gap, the energy which was initially stored in the plates of the condenser is equal to $1/2\ C\ V^2$, and this energy is ultimately dissipated as heat in the gap and at the electrodes. The current through the gas at any instant during the passage of such a spark is determined by the voltage at which the discharge took place, and by the resistance and inductance of the leads connecting the condenser with the spark gap. This current usually oscillates in direction with a frequency depending upon the capacity and inductance of the circuit. In the case of most ignition systems this frequency is exceedingly high (of the order of one million cycles per second), and the oscillations are rapidly damped.

In the case of sparks obtained by the discharge of an induction coil or magneto, which are the usual sources of current in jump spark ignition systems, the resulting spark is more complex than the simple condenser spark just described. After the primary circuit of the induction coil is broken, a high voltage is induced in the secondary winding, and an electric charge accumulates on the outer layers of this winding and on the leads connecting the coil with the spark gap. When this charge has built up a voltage equal to the breakdown voltage of the gap, the first phenomenon which takes place is a discharge of this accumulated charge in a condenser spark of the type just described. This is known as the capacity component of the entire spark and the energy contained in it can be computed by the formula given above, using for C the capacity of the outer layers of the secondary winding of the coil together with that of the secondary leads, and of the electrodes themselves. It should be noted that the part of the secondary capacity which is thus discharged is only a small part of what is usually referred to as the "secondary capacity" of the coil and that its numerical magnitude can be estimated only by indirect and

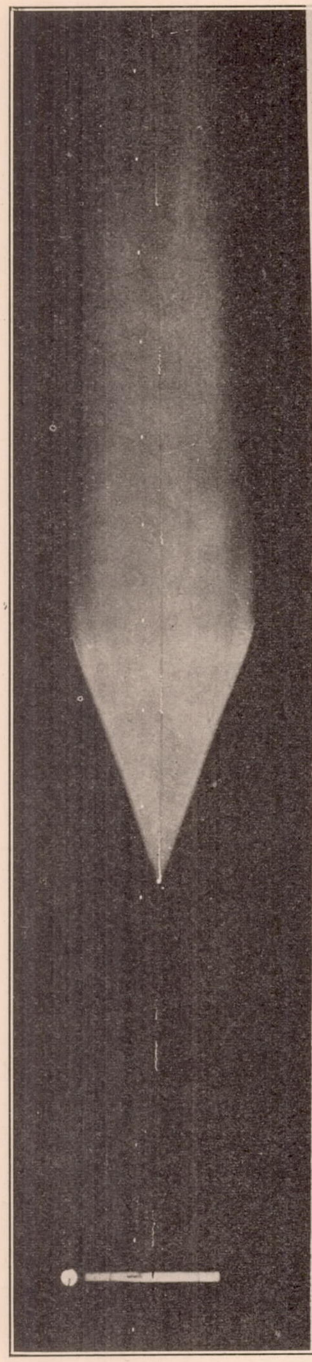

FIG. 2.—Typical record of burning of CO and O_2 mixture, showing stationary picture of bubble and electrodes, wedge record of combustion, ignition spark at apex of wedge, timing sparks at left of center line.

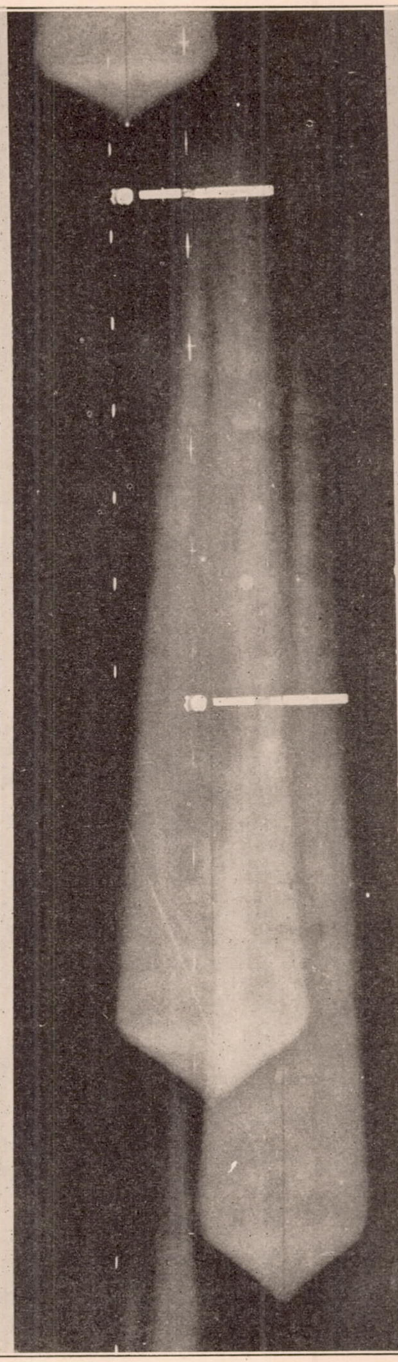

FIG. 4.—Typical record of burning of C_2H_2 and O_2 mixture. The concave faces of the wedge indicate a progressive speeding up of the flame.

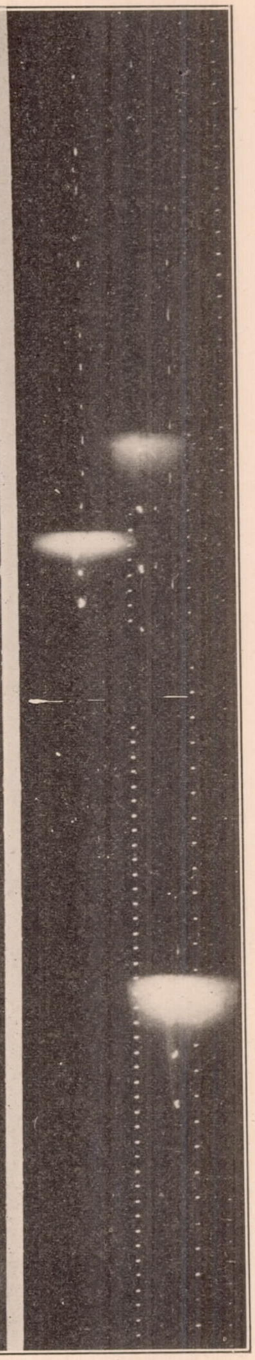

FIG. 5.—Typical record of burning of gasoline-air mixture in closed bulb. Convex sides of wedges show a slowing down of the flame. Note: Wedges extend from first igniting spark in each case but the light was very faint at the beginning of the process.

approximate methods. After this first discharge has been completed, however, the flow of current across the gap is maintained as a result of the voltage produced by the decrease of magnetic flux in the core of the coil. The energy which was initially stored in this core is given by the expression $1/2\ L\ I^2$ where L is the self-inductance of the primary winding and I is the current flowing in this winding at the instant of "break." Part of this energy is wasted as loss in the coil, and a further part is temporarily stored in the secondary capacity and dissipated in the spark gap by the capacity components of the spark described. The remainder, however, which is usually much larger than the capacity component is later dissipated in the spark gap by the steady flow of current which follows after the capacity component has ceased, and is known as the inductive component of the spark. The value of the current during this latter period is relatively small (of the order of 0.05 ampere), and gradually decreases until it reaches zero at the time when the supply of magnetic energy is exhausted. The duration of this inductive component of the spark is of the order of 0.005 second. During the time that this inductive component of current is flowing, the voltage across the terminals of the spark gap is much less than the initial breakdown voltage and has a fairly constant value which is called the "sustaining voltage" of the spark. In the case of ignition sparks the sustaining voltage is of the order of 800 volts.

In the present work the sparks were obtained in most cases from a magneto or coil, and were modified so as to give five distinct types of discharge. Necessary changes in the apparatus also caused slight changes in the electrical constants of the circuit in two other cases, so that altogether there were used eleven different combinations of circuit. The resulting sparks are distinguished in Table I by the letters A to K, inclusive. Sparks A, D, and J were normal magneto sparks delivered by Dixie or Bosch magnetos. These machines give sparks of the kind just described, and have a relatively large energy content. Spark G was similar, but was obtained with the magneto at higher speed and with a different spark gap. Spark E was obtained from a small induction coil of the type regularly used on automobiles. This was operated with a six-volt battery and with a considerable series resistance so as to deliberately weaken the spark to the utmost extent which could occur in practice.

Sparks B, H, and K were obtained by connecting condensers of 3,400 or 1,700 micro-microfarads in parallel with the spark gap. If a condenser is thus connected to the secondary of the induction coil in parallel with a spark gap, the capacity component of the spark is greatly increased at the expense of the inductive component, and if the condenser is so large that the coil is barely able to produce a spark at all, then the spark consists almost entirely of the capacity component.

To insure certain firing, however, the condensers used in these experiments were not made so large as to absorb the entire energy of the magneto, consequently after the first intensive capacity spark a current continued to flow through the gap, and the total duration of the spark as indicated by the photographs was quite appreciable. The tenth line of Table I gives this spark duration in seconds. From the photographs it appears probable that in many instances some slight agitation of the gas extinguished the spark after the first condenser discharge, so that the voltage across the electrodes again built up to a high value, thus causing a succession of capacity sparks rather than the continuous flow of current which was obtained with the normal type of spark.

Spark C was obtained by connecting a resistance of 10 megohms in series with the wire between the magneto and the spark gap. With this arrangement the capacity component of the spark consists merely of the discharge of the condenser formed by those portions of the wiring between the high resistance and the spark gap. The discharge from the rest of the circuit and the inductive component of the spark are held back by the high resistance and limited to an exceedingly small value of current.

Spark F was quite different in character from the preceding, and was obtained by interrupting the flow of current through an inductive circuit. The inductance consisted of the primary winding of a spark coil which had an inductance of about 0.0039 henries. Current was obtained from a 6-volt battery and was allowed to build up to a value of 5 amperes. The contacts at the center of the bubble could be separated at a moderate speed by the motion of an external handle. The current in the circuit persisted across the gap as an arc for a short interval, about 0.0009 second, which could be measured from the photographic record or from oscillograms. It is difficult to estimate the actual energy dissipated in a "break" spark of this type, but it is probably 0.06 joule.

Figure 3 indicates the arrangement and dimensions of the electrodes used in the several igniting gaps. The letters in the fourth line of Table I correspond with those of Figure 3.

RESULTS.

The data obtained by this method consist of a collection of photographs of which Figures 2 and 4 to 7, inclusive, are typical examples. These all show a progressive burning of the flame at a definite rate which, in the case of carbon monoxide, appears to be very strictly constant from the instant of ignition until all of the explosive material is consumed. In the case of acetylene the rate of burning accelerates quite appreciably (fig. 4), while in the case of gasoline in the closed bulbs (fig. 5) there is a definite slowing down of the rate of flame movement as the combustion progresses. The primary object of the investigation is obtained by measuring this rate of combustion and correlating it with the character of the igniting spark. In cases where the rate was not constant, an average value was taken; that is, the total distance traveled by the flame divided by the total time from the instant of ignition until the end of combustion. Such an average rate is at least approximately what is of most importance in engine operation and forms a reasonable basis for comparing the effects of different types of spark. It may be noted that the photographic record gives directly the velocity of the flame in space. Since the unburnt gases are pushed out ahead of the flame by the expansion of the heated products of combustion inside the spherical flame surface, the fuel just ahead of the flame has an outward velocity which is quite appreciable, and the true speed of the flame with respect to the gas which it is overtaking is less than that indicated by the film. While the factor connecting the velocity of the flame with respect to the gas with that of the flame in space can be obtained, if desired, from the initial and final diameters of the bubble, the results in this work were based upon the space velocities directly, and no computations were made of the velocity with respect to the gas.

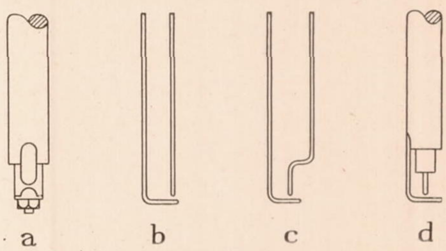

FIG. 3.—Types of electrodes used.

The data obtained is given in Table II. For convenience in analysis the observations have been grouped into eight series. The data on each series were obtained with substantially the same mixture ratio and with the same fuel, but with two or three different types of spark. The second column in Table II gives the fuel used, and the third column the mixture ratio. This ratio is expressed in parts by volume in the case of the mixtures of carbon monoxide and oxygen and acetylene and oxygen, but is expressed in parts by weight in the case of the gasoline-air mixture. The fourth column gives the number of separate explosions (bubbles or bulbs) on which the average flame velocity, as given in column 6, is based. In column 5 is indicated the type of ignition spark used. The letters in this column refer to Table I, in which quantitative data on the various electrical characteristics of the igniting sparks are given. This column also indicates roughly by the use of the words "normal," "condenser," or "weak" the principal characteristics of the spark. Column 7 gives the average deviation of a single measurement of flame velocity from the mean value given in the preceding column. The last column in the table gives the per cent difference between the results obtained with the two types of spark under comparison. A plus sign in this column indicates a greater value for the flame velocity for the type of spark which might be expected to be more intense, this expectation being such as to rank the sparks in the order of decreasing intensity as condenser, normal, weak, and "break." The mixture ratio used in Series I was that corresponding to complete combustion and gave the highest flame speed for carbon monoxide. In Series II and III the fuel mixtures were respectively about as lean and about as rich in carbon monoxide as could be ignited by the "weak" spark. With mixtures slightly beyond these limits the "weak" spark could be seen to pass inside the bubble without producing ignition. The mixtures used in Series IV and V were only slightly richer than in Series II and, therefore, the experiments would be expected to bring out any tendency of the flame to slow down as the mixtures approached that which a given spark could not ignite, if such a tendency existed. In Series VI the mixture was well toward the lean end of the inflammable range, while in Series VII the mixture was slightly richer than that giving maximum flame speed. In Series VIII, using gasoline, pairs of observations were made at a number of mixture ratios. Only the average of such pairs is given in Table II.

Table II shows that the differences in the observed flame velocities are in all cases less than what might well be expected from the magnitude of the experimental errors. We may therefore conclude that the fundamental question raised in this investigation is very definitely answered by the statement that the rate of normal burning of quiescent explosive gas mixtures is independent of the character of the igniting spark over a very large range of spark intensity.

A number of minor points observed in analyzing the records may be of interest. A definite difference was found in the records depending upon whether or not the speed of the film was sufficiently great to make the half-angle of the wedge less than 45°. This effect is shown by a comparison of Figures 2 and 6, and is due to the finite width of the slit placed in front of the film. At film speeds faster than this critical value, the diameter of the circular image of the ever-increasing sphere of flame is displaced on the film by an amount greater than the increase in its radius, consequently no light from the flame can reach the film at a point ahead of the image of the igniting spark, and the resulting record consists of a sharp-pointed wedge as in Figure 2. For slow film speeds, however, the displacement of the circular image of the flame is less than the increase in its radius, consequently light from the flame shortly after its initiation will fall upon parts of the film ahead of the image of the igniting spark. With the further increase in the diameter of the flame, the edge of the slit cuts off the light from more advanced portions of the film, and from this point onward the photographic image is drawn out continuously in one direction. The result of the first rapid enlargement of the flame image, however, causes the complete record (fig. 6) to have the shape of a wedge with a rounded tip in which the image of the spark is imbedded to a depth depending upon the width of the slit and the position in the slit of the image of the spark gap. This effect, however, does not introduce any error in the observation since the slope of a line tangent to the main face of the wedge gives correctly the rate of the burning of the fuel.

Another effect shown in Figure 6 is the dark space which was sometimes noted between the image of the spark and the beginning of the flame. This was observed only with weak sparks and in such cases the photographic record had the shape of a wedge with a rounded point. Prolongations of the straight portions of the wedge passed through the image of the spark. It is probable that the explanation of this effect is that the temperature of the small sphere of gas first ignited by the spark is so low that the gas is not luminous enough to affect the photographic film, although it is heated above its ignition temperature. As the tiny sphere of flame enlarges, its temperature increases to the normal temperature of combustion of the fuel, and the entire sphere suddenly becomes luminous enough to impress its image on the film.

In considering the duration of the igniting sparks, care must be taken to allow for the great range of film speed used. Even in the case of the relatively slow carbon monoxide films the brightness of the inductive component of the normal magneto sparks is too faint to affect the film, and only the capacity component of the sparks is visible as a single bright spot. The condenser sparks, however, since they usually consisted of a succession of capacity discharges distributed over an appreciable length of time, were of sufficient intensity to show on the film, and apparently lasted longer than the normal sparks. In the acetylene records, the later portions of the capacity spark, since they occurred in the highly heated products of combustion of the fuel, were relatively weak in luminosity and were too feeble to give an image on the

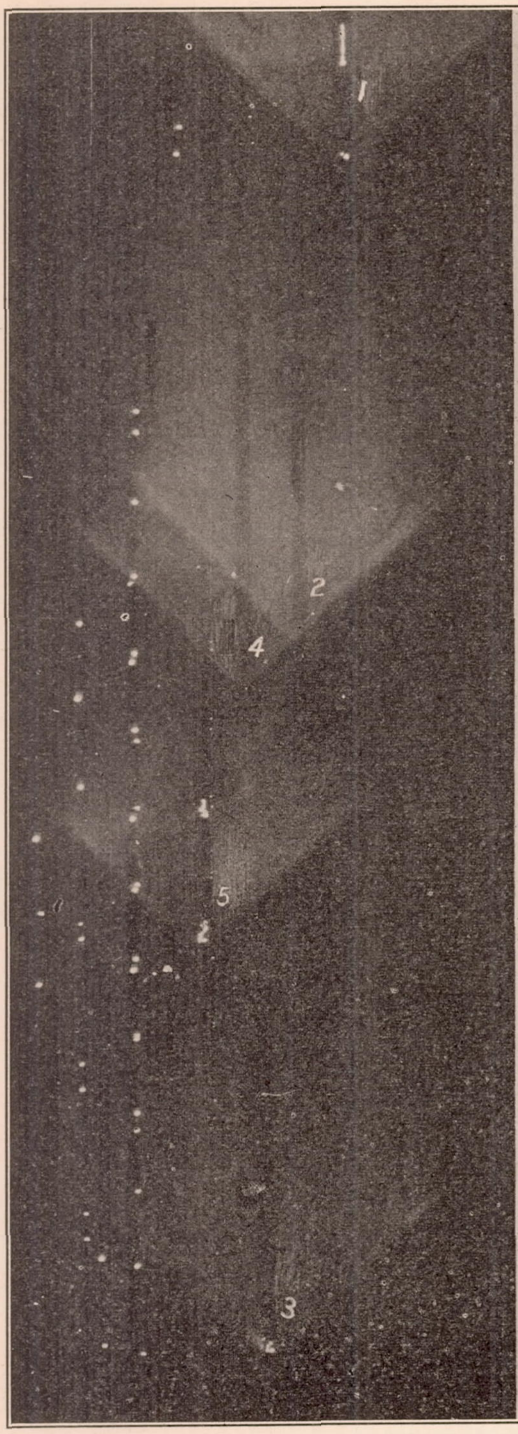

Fig. 6.—Showing at "1" and "2" the apparent imbedding of the image of the igniting spark in the blunt tip of the wedge record; and at "2" and "4" the dark space between the spark image and the flame record.

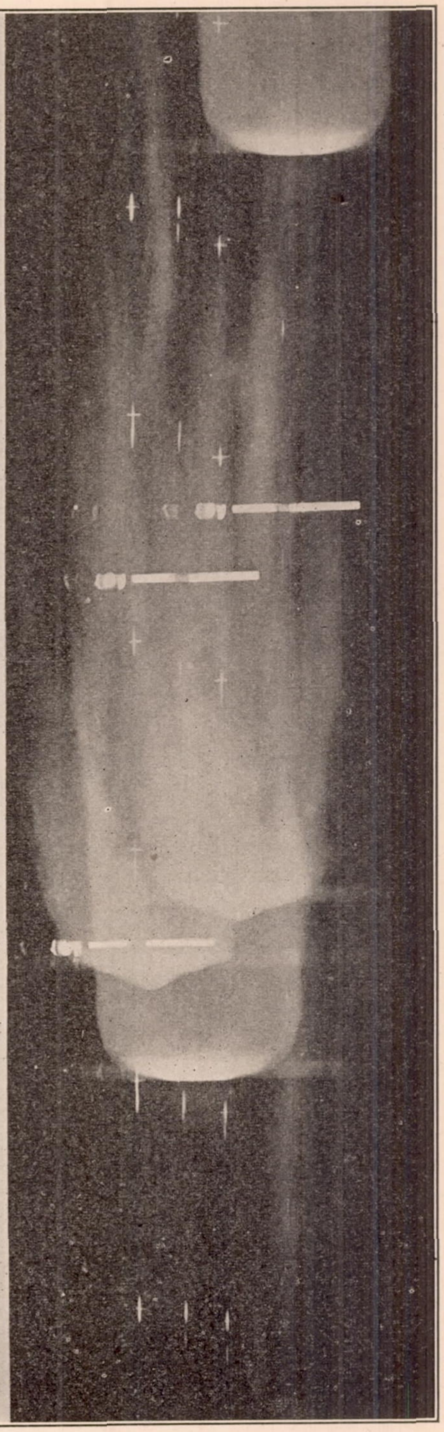

Fig. 7.—Showing detonation of C_2 and O_2 mixtures as indicated by the blunt records.

very rapidly moving film, consequently only the first condenser discharge appears on these films. The initial capacity component of the normal sparks was so faint as to be entirely invisible in the faster acetylene films. The data which are given in Table I on the duration of the various sparks are therefore based mainly on measurements obtained by the oscillograph in which the actual time during which the current flowed through the spark gap could be obtained by a method which was unaffected by the intensity of the light emitted by the spark.

A very interesting by-product of this investigation is the information which was obtained in the case of the most powerful acetylene-oxygen mixtures. In these mixtures the normal rate of burning is very high and comparable with the velocity of sound. It was found that very frequently the combustion of these mixtures occurred not by a normal burning process, as in the case of other materials, but by a very much faster type of burning. This effect is shown in Figure 7. It can be seen that the photographic records show a blunt pointed figure indicating that the entire mass of explosive gas reacted at a speed which was very great compared with the speed of the film. At the highest speed at which it was feasible to operate (7,000 R. P. M.), there was no suggestion of any definite wedge shape to these records, and a lower limit of at least 150,000 cm. per sec. may be set to the velocity of the flame. After the bubble had thus burnt "all at once" the products of combustion expanded rapidly but with an easily measurable speed shown by the curved contour of the records, to the final size corresponding to their temperature and atmospheric pressure. Explosions of this character of course produced a very sharp loud noise and at times were destructive to the apparatus in the neighborhood.

As will be seen from Figure 7 there is no very direct correlation between the presence of this abnormal burning and the character of the igniting spark. On this film one of the abnormal and one of the normal burnings were produced with the normal spark, while the other abnormal and the other normal burning were produced in substantially the same mixture by a condenser type of spark. A considerable number of such records were obtained using equal parts by volume of acetylene and oxygen. This mixture is somewhat richer than that which gives most complete chemical combustion, but was chosen because it gave such a very intense light as to make good photographic records, while at the same time under favorable conditions it showed the abnormally rapid combustion. The results of these trials are summarized in Table III which indicates which type of combustion occurred under various conditions of spark, gap length, and electrode diameter. While the results obtained are not entirely conclusive, it appears that the reaction is more likely to occur abnormally in cases where the spark gap is long, or the secondary capacity is large. It will be noted that these two conditions are such as to increase the energy of the capacity component, and hence the intensity of the sound wave produced by the spark. There are some theoretical grounds for expecting that if this sound wave is sufficiently intense, the reaction within it will be correspondingly accelerated. If the reaction velocity is sufficiently great to keep pace with the progress of the sound wave, it might be expected that the phenomenon would become unstable and that greater and greater pressures would be rapidly built up in the wave front, thus producing a different régime. These conclusions seem to be consistent with the present observations since this abnormal burning was not observed in the other fuels, or with the leaner mixtures of acetylene in which the normal rate of burning was much slower than the velocity of sound so that there was no possibility of the reaction keeping up with any initial compression wave which might have been started by the electric spark.

It seems quite possible that the abnormally rapid burning observed in these experiments is a case of detonation, and may be related to the source of "fuel knock" in automotive engines.

A careful distinction should be made, however, between detonation of the kind shown in these records which is produced immediately at the instant of ignition, and the type of detonation which is met with in internal combustion engines. In this latter case we are dealing with combustion within a closed volume under conditions where the progress of the burning increases the pressure and density of the unburnt fuel in the cylinder slowly at first, but more and more rapidly as the reaction goes on. Under such conditions it is probable that combustion proceeds at first by normal burning, and that detonation does not occur until a later instant when a considerable fraction of the fuel has already burned and has compressed the remainder of the charge to a condition where it is capable of detonating. If this view of the situation is correct, one would expect no correlation between the character of the spark or of the spark gap and the presence of detonation in an engine.

Many of the records with the fast acetylene mixtures, which have the wedge shape characteristics of normal burning, also show near the end of combustion a sharp bright streak which appears to be an image of the slit produced by a sudden increase of luminosity. Two possible explanations may account for this. One explanation is that the building up of pressure ahead of the advancing flame surface progresses to such an extent during the burning that finally the reaction changes to the abnormal type, and the remainder of the charge then burns practically instantaneously. The concave shape of the faces of the wedge indicates just such an acceleration of the flame. A second possible explanation is that the sound wave produced by the spark is partially reflected at the surface of the bubble and returns toward the center. As this returning wave of compression meets the advancing flame surface it might be expected that a sudden increase in rate of combustion and luminosity would result. Measurements of the time intervals involved are consistent with this hypothesis.

CONCLUSIONS.

The experiments described in this report seem to justify the following conclusions:

1. The ignition of explosive gas mixtures by jump sparks from an induction coil is produced by the initial or capacity component.

2. The normal rate of spread of the flame through initially quiescent gas mixtures is not affected by any change in the intensity or duration of the spark. This has been tried over the range of from 0.008 to 0.0003 second in duration; from 0.11 to less than 0.002 joule in total energy, and from 0.02 to 0.0004 joule in the energy of the capacity component, and for flame speeds ranging from 200 cm. per sec. to 20,000 cm. per sec.

3. The flame speed produced by a "break spark" or arc in which the capacity component is absent is the same as for a jump spark.

4. In mixtures having normal rates of burning comparable with the velocity of sound, an abnormally rapid burning may be set up at the instant of ignition.

5. The tendency to burn in this manner is greater with long spark gaps and with increased secondary capacity.

TABLE I.

Type.	A	B	C	D	E	F	G	H	I	J	K
	Normal.	Condenser.	Weak.	Normal.	Weak.	Break.	Normal.	Condenser.	Weak.	Normal.	Condenser.
Source	Dixie "800" magneto at 700 R. P. M.			American Bosch magneto at 1,000 R. P. M.	Ford coil 0.2[a] input.	Breaking 5.0[a] through primary of Philbrin coil.	Dixie "800" magneto at 2,000 R. P. M.			Dixie "800" magneto at 700 R. P. M.	
Electrodes	a	a	a	a	a		b–c	b–c	b–c	d	d
Gap (mm)	0.45	0.45	0.45	0.45	0.45	...	0.45	0.45	0.45	0.45	0.45
Sparking voltage	3,300	3,300	3,300	3,300	3,300	...	4,000	4,000	4,000	10,400	10,400
Condenser on secondary ($\mu.\ \mu.$ f.)	...	3,400	3,400	...	...	...	...	1,700	...	...	1,700
Resistance in series with gap (megohms)	...	...	10	...	...	...	...	...	10	...	...
Total energy per spark (joules)	0.110	0.110	0.002	0.095	0.004	0.06	0.110	0.110	0.002	0.110	0.110
Duration (sec.)	0.0072	0.0056	0.0009	0.0055	0.00067	0.0009	0.0028	0.0025	0.0003	0.0078	0.005
Effective capacity ($\mu.\ \mu.$ f.)	138	3,538	128	138	138	...	60	1,760	50	60	1,760
Electrostatic energy (joules)	0.00075	0.020	0.0007	0.00075	0.00075	...	0.00048	0.014	0.0004	0.00326	0.096

TABLE II.

Series.	Fuel.	Mixture per cent fuel.	Number of explosions.	Type of spark.	Average flame speed (cm. per sec.).	Per cent deviation.	Per cent difference.
I	$CO-O_2$	67	5	A normal	1,197	±4.2	
			5	B condenser	1,279	±3.7	+6.4
II	$CO-O_2$	31	13	B condenser	347	±7.7	
			10	C weak	343	±5.7	+1.2
III	$CO-O_2$	90	4	B condenser	649	±4.7	
			5	C weak	652	±2.0	−0.6
IV	$CO-O_2$	34	5	D magneto	451	±3.8	
			5	E battery	454	±4.2	− .7
V	$CO-O_2$	35	7	D magneto	500	±4.1	
			7	F "break"	482	±4.1	+3.6
VI	$C_2H_2-O_2$	15	3	G normal	7,150	±8.8	
			4	H condenser	7,550	±5.3	−5.3
			4	I weak	7,750	±3.9	−8.4
VII	$C_2H_2-O_2$	54	5	G normal	22,760	±3.8	
			4	H condenser	23,750	±12.3	+4.2
VIII	X-gasoline-air	7	4	J normal	196	±10.0	
			4	K condenser	187	±3.2	−4.6

TABLE III.

	Total explosions.	Number abnormal.	Percentage abnormal.
Condenser spark	34	20	59
Normal spark	42	16	38
Thick (1.6 mm.) electrode	20	12	60
Thin (0.13 mm.) electrode	22	14	64
Short (0.25 mm.) gap	21	6	29
Long (1 mm.) gap	21	20	95

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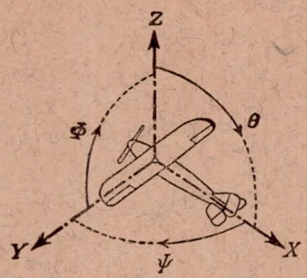

Positive directions of axes and angles (forces and moments) are shown by arrows.

Axis.		Force (parallel to axis) symbol.	Moment about axis.			Angle.		Velocities.	
Designation.	Symbol.		Designation.	Symbol.	Positive direction.	Designation.	Symbol.	Linear (component along axis).	Angular.
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_l=\frac{L}{q\,b\,S} \quad C_m=\frac{M}{q\,c\,S} \quad C_n=\frac{N}{q\,f\,S}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS.

Diameter, D
Pitch (a) Aerodynamic pitch, p_a
(b) Effective pitch, p_e
(c) Mean geometric pitch, p_g
(d) Virtual pitch, p_v
(e) Standard pitch, p_s
Pitch ratio, p/D
Inflow velocity, V'
Slipstream velocity, V_s

Thrust, T
Torque, Q
Power, P
(If "coefficients" are introduced all units used must be consistent.)
Efficiency $\eta = T\,V/P$
Revolutions per sec., n; per min., N
Effective helix angle $\Phi = \tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS.

1 HP = 76.04 kg. m/sec. = 550 lb. ft/sec.
1 kg. m/sec. = 0.01315 HP
1 mi/hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi/hr.

1 lb. = 0.45359 kg.
1 kg. = 2.20462 lb.
1 mi. = 1609.35 m. = 5280 ft.
1 m. = 3.28083 ft.