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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 399

FLAME MOVEMENT AND PRESSURE DEVELOPMENT IN AN ENGINE CYLINDER

By CHARLES F. MARVIN, Jr., and ROBERT D. BEST

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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	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s$^2 = 32.1740$ ft./sec.^{2}

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

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 750 mm $= 0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3 = 0.07651$ lb./ft.^{3}.

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

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

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

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

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

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

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

R, Resultant force.

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

i_t, Angle of stabilizer setting (relative to thrust line).

Q, Resultant moment.

Ω, Resultant angular velocity.

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

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.

C_p, Center of pressure coefficient (ratio of distance of *c. p.* from leading edge to chord length).

α, Angle of attack.

ϵ, Angle of downwash.

α_o, Angle of attack, infinite aspect ratio.

α_i, Angle of attack, induced.

α_a, Angle of attack, absolute. (Measured from zero lift position.)

γ, Flight path angle.

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By CHARLES F. MARVIN, Jr., and ROBERT D. BEST
Bureau of Standards

65742—31

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By Charles F. Marvin, jr., and Robert D. Best

SUMMARY

This investigation, which was carried out at the Bureau of Standards at the request and with the financial assistance of the National Advisory Committee for Aeronautics, describes a visual method for making stroboscopic observations, through a large number of small windows, of the spread of flame throughout the combustion chamber of a gasoline engine. Data, secured by this method on a small engine burning gaseous fuels, are given to show the effects of mixture ratio, spark advance, engine speed, charge density, degree of dilution, compression ratio, and fuel composition on flame movement in the cylinder. Partial indicator diagrams showing pressure development during the combustion period are included. Although present knowledge is not sufficient to permit qualitative evaluation of the separate effects on flame movement of chemical reaction velocity, thermal expansion of burned gases, resonance, turbulence, and piston movement, the qualitative influence of certain of these factors on some of the diagrams is indicated.

INTRODUCTION

Much research by many investigators has been undertaken during the past 30 years or more in attempts to discover and formulate the laws governing flame movement and pressure development during gaseous explosions in containers of various sorts. Most of the fundamental information which has been secured regarding the phenomena of combustion has resulted from those studies which strove toward simplicity in the experimental process, the composition of the charge, and the symmetry of the container. While some information has been obtained regarding the profound and complex effects on flame movement of resonance, turbulence, and combustion chamber geometry, it is not sufficient to permit the calculation, from fundamentals, of either flame movement or pressure development in engine cylinders. Such data, therefore, must be secured experimentally by observations on an actual engine. Some such observations have been made by Ricardo (reference 1) and Glyde (reference 2), using a single row of windows across the engine head for following flame travel and an engine indicator for measuring cylinder pressures, and by Withrow and Boyd (reference 3). The purpose of the present investigation was to make similar stroboscopic observations of flame movement and simultaneous measurements of pressure development, using a larger number of windows so distributed as to permit examination of the whole combustion chamber. Although the investigation is not yet complete, considerable material has been collected, and the present report is mainly a presentation of these data.

APPARATUS AND PROCEDURE

A small, 4-cycle, single-cylinder, L-head engine, coupled to an electric dynamometer, is being used in the experiments. The engine is equipped with a special head in which 31 windows are symmetrically distributed over the combustion space. Each cycle these windows are illuminated, one after another, by the flame in the cylinder as it spreads from the point of ignition. The head is observed through a stroboscope which permits a momentary view of the windows at the same point in successive cycles. Viewed in this manner, windows over the unburned portion of the charge ahead of the flame front appear dark, while the inflamed gases over which the reaction zone has passed appear luminous and remain so until far down on the expansion stroke. By varying the timing of the "view," the progress of the flame may be followed and corresponding values of crank angle and flame position noted.

Figure 1 shows the apparatus diagrammatically. The windows in the engine head are constructed as shown in the enlarged detail at A. The small deep hole below each glass prevents the flame from being seen in a given window until it has reached a point in the combustion chamber directly below that window. The flat steel head in which the windows are mounted according to the pattern shown at B is separated from the top of the cylinder block by a steel collar which forms the walls of the combustion chamber. For the first series of runs, the depth of this collar was such as to give a compression ratio of 3.6 to 1, and the spark plug was screwed into the collar so that its points came flush with the combustion chamber wall just between the valves. Later the collar was planed down to give a compression ratio of 5 to 1. It was then too thin to take the spark plug, and a special plug was mounted in the window hole nearest to the previous location, its point coming flush with the inner surface of the head.

A large lens C is placed just above the head, and light from the windows after passing through the lens is turned through an angle of 90° by the mirror D and projected through the stroboscope E.

The stroboscope consists of two rotating disks driven from the engine crankshaft. The disk nearest the eyepiece rotates at one-fourth crankshaft speed, and once each cycle one of the two sight holes drilled near its outer rim comes opposite a similar hole in the eyepiece. The other disk rotates at 3.75 times crankshaft speed; and while the holes in the slow-moving disk and the eyepiece are in line, a third hole in the high-speed disk moves past, restricting the view to less than 4° of crank angle. The timing of this brief view can be varied over a range of about 300° of crank angle by means of a phase-changing device at F.

An observer at the stroboscope eyepiece sees a reflection of the whole head with its 31 windows in the mirror. Due to the properties of the lens, each window appears as it would if the eye of the observer were directly above and looking straight down through the window.

The procedure in making a run is to adjust the phase-changing device, for each window in turn, to the point where the flame first becomes visible in that window and record the corresponding position of the engine crank as indicated on a graduated scale. Since there is some variation in the progress of the flame from cycle to cycle, the operator adjusts for the "average" flame. Such settings are generally reproducible within 1° or 2° of crank angle. It might be noted that these observations do not distinguish between flame and incandescent reaction products; nor in the term "flame" is it possible to distinguish between diffusion flames, which may predominate, and the sharply defined zone of reaction that characterizes the explosive process in homogeneous mixtures only.

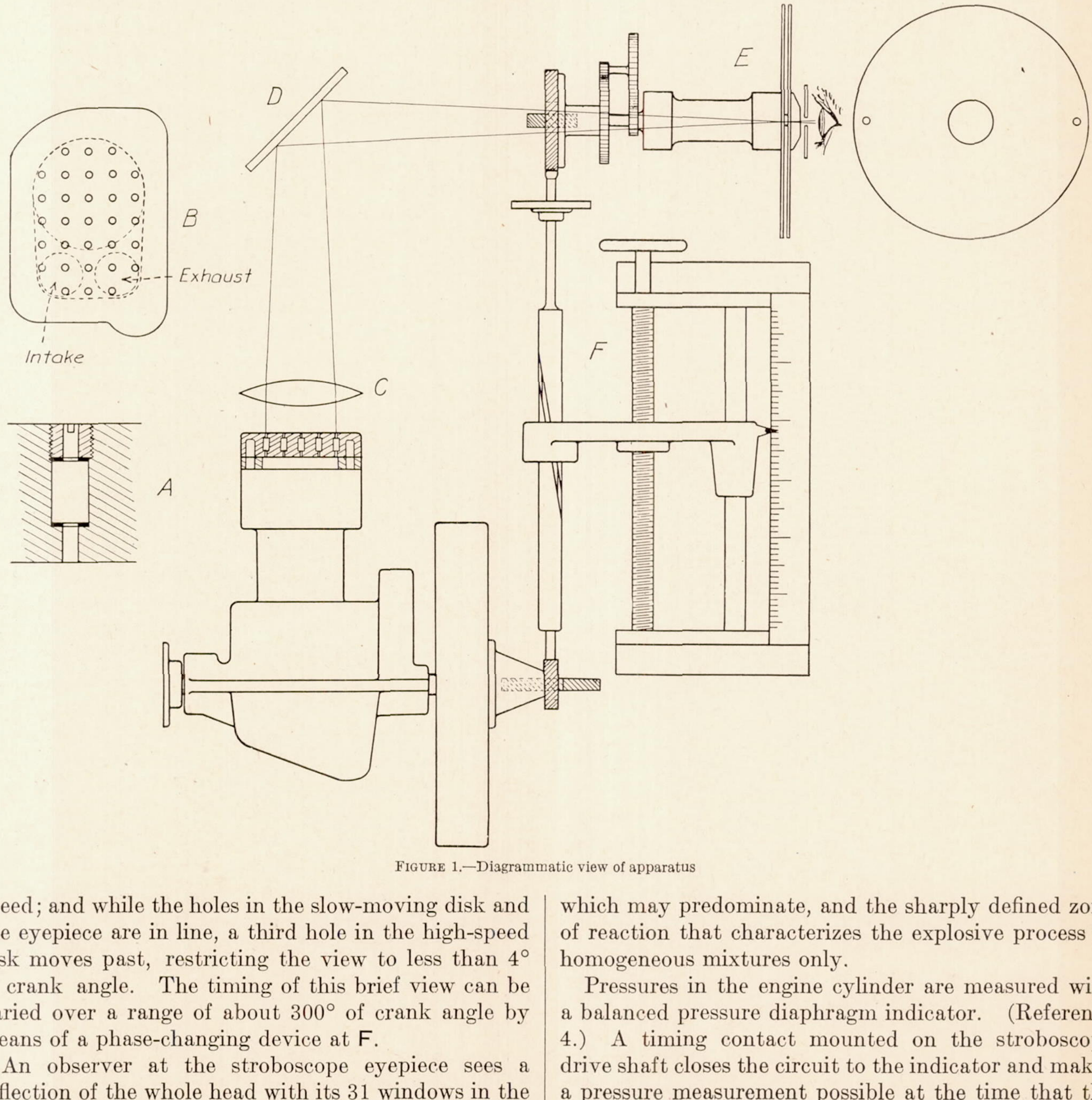

FIGURE 1.—Diagrammatic view of apparatus

Pressures in the engine cylinder are measured with a balanced pressure diaphragm indicator. (Reference 4.) A timing contact mounted on the stroboscope drive shaft closes the circuit to the indicator and makes a pressure measurement possible at the time that the sight holes of the stroboscope are in line for the "view." Pressure is read each time a setting is made on a window and also at several points before the spark occurs and during the expansion period.

Pressure, like flame position, varies from cycle to cycle. Three readings are therefore taken for each stroboscope setting: (1) a "maximum" pressure which is rarely exceeded, (2) an "average" pressure, and (3) a "minimum" pressure which is exceeded by nearly every explosion. The rare occurrence of a cycle with excessively high or low pressure is ignored.

About an hour and a half is required to make observations on all of the windows, check four or five of these observations, and take the 150 or more pressure readings comprising a run. During this time a dozen or so measurements of air and fuel flow, torque, engine speed, and exhaust gas temperature are taken and any necessary adjustments made to maintain constant engine operating conditions. Friction torque and compression pressure are measured after each run.

Gaseous fuels were used throughout the tests reported here. The fuel gases are mixed with the desired proportions of air at a metering valve and the charge is passed through a reservoir containing fans and baffles to ensure thorough mixing before delivery to the engine. A flame trap is installed near the intake port to prevent possible back fires from igniting the charge in the mixer.

Finely powdered sodium bicarbonate is introduced in small amounts into the charge in the mixer. Carried through by the charge into the engine, this powder brightens the flame and makes it readily visible in spite of the very brief view afforded by the stroboscope. No effect of the sodium salt on the propagation of the flame or the operation of the engine has been detected.

For comparison with the engine test results a number of photographic records were made of the progress of the flame down the center of a closed bomb similar in shape to the combustion chamber of the engine. The bomb was constructed by mounting the steel collar previously mentioned between two steel plates, one of which was provided with a thick glass window running the length of the chamber and corresponding to the middle row of windows in the engine head. A spark plug was mounted in the other plate, its position relative to the combustion chamber being the same as in the engine. Photographs of individual explosions in the bomb, taken on a rotating drum, gave time-displacement diagrams comparable with those plotted from the engine test results.

RESULTS

Table I summarizes 18 runs which show the effects of a wide range of operating conditions and a number of gaseous fuels on flame movement and pressure developement in the engine cylinder.

Flame diagrams.—Figure 2 is the flame diagram for the "normal" run at the lower compression ratio. Circles on the plan view of the combustion chamber show the locations of the windows. The stroboscope reading within each circle indicates the position of the engine crank in degrees from upper dead center when the flame first becomes visible under the corresponding window. The curved lines, representing successive positions of the flame front at 5° intervals after the occurrence of the spark, were obtained by plotting the stroboscope readings against the positions of the corresponding windows as regards both "row" and "column," drawing curves through the points so plotted as shown in Figure 3, then replotting points at 5° intervals on these curves back onto the plan view of the head. A vertical section through the center of the combustion chamber is also drawn. In the absence of any information as to the curvature of the flame front in this view, it has been represented by circular arcs drawn about the point of ignition. The horizontal dashes show the level of the top of the piston for successive positions of the flame and indicate the extent of piston movement during a normal explosion.

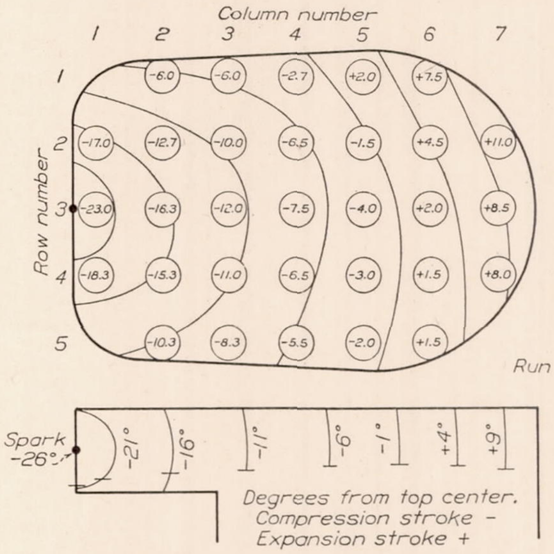

FIGURE 2.—Flame diagram. Normal run. Compression ration 3.6 to 1

Diagrams such as Figure 2 picture the resultant movement of the flame under the simultaneous influence of a variety of distinct factors. (1) After the occurrence of the spark, the flame advances into the unburned mixture at a rate determined by the rapidity of the chemical reactions occurring. (2) Expansion of the heated products of combustion and their rejection behind the zone of reaction pushes the flame front forward and compresses the unburned charge ahead. (3) Resonance and wave effects, such as are noted in photographs of explosions in glass bombs, possibly influence the movement of the flame in individual explosions in the engine cylinder, although such effects may not be distinguishable in the average flame for many cycles as it is observed through the stroboscope. (4) These motions, orderly and regular themselves, are superimposed upon general and local turbulent movements, lingering in the charge from the intake and compression strokes, or initiated by the mass movements described under (2). (5) During combustion the piston continues to move, modifying the turbulence and changing the volume and shape of the combustion chamber with consequent effects on flame movement.

Present knowledge of the fundamental relations between these various factors and flame movement is not sufficient to permit quantitative predictions of the progress of the flame under given conditions in the engine. Nor is it possible, having observed the resultant movement in the engine, to accurately resolve this resultant into its components. While the diagrams are thus not susceptible to quantitative analysis, the effects of some of the above-mentioned factors may be recognized in certain of the diagrams.

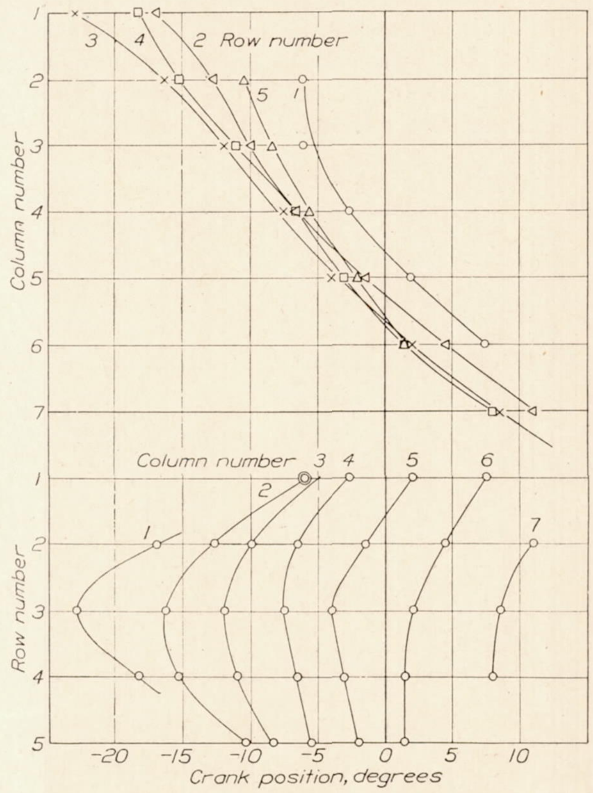

FIGURE 3.—Curves for constructing flame diagram

In the nonturbulent form of head so far used, the only outward indication of turbulence in the flame travel diagrams at the 3.6 compression ratio is a slight general counterclockwise swirl which retards the motion of the flame on the inlet valve side of the engine and advances it on the exhaust side. For some unknown reason this swirl appears consistently in the opposite direction but to about the same extent in most of the diagrams for the 5:1 compression ratio.

In view of the fact that the flame diagrams for the various operating conditions are generally quite similar in appearance and differ chiefly in the time required for the flame to pass across the head, only a few full diagrams are reproduced here. (Figs. 4 through 7.) Instead flame travel across the center row of windows has been plotted in Figures 8 through 14. These time-displacement diagrams afford a convenient basis for comparing the effects of the various operating conditions on flame travel and show directly the "inflammation time" or the time required for the flame to traverse the combustion chamber completely.

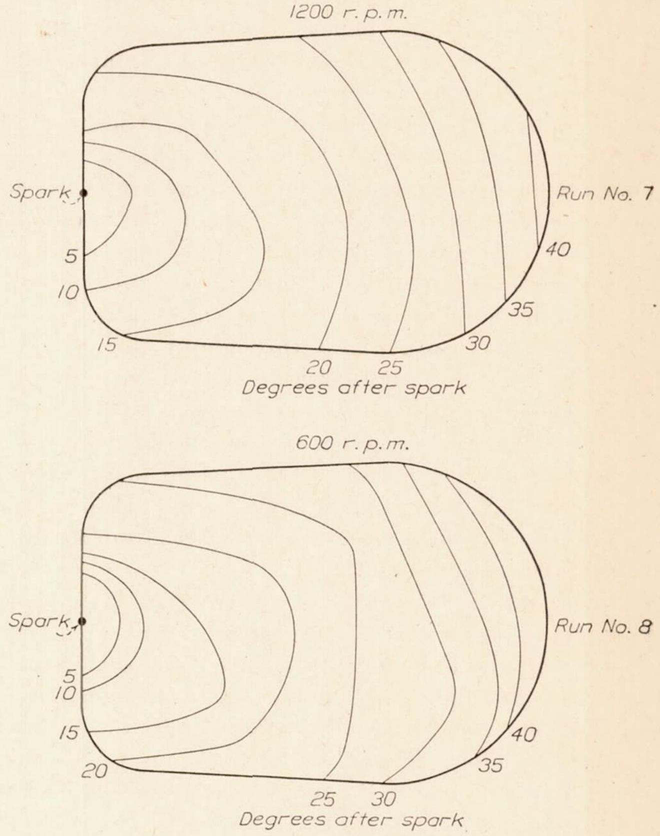

FIGURE 4.—Flame diagrams

Conditions at the instant the spark occurs are different in one or more respects for each of the runs made. While these initial conditions are solely responsible for the progress of the flame in the early stages, pressure, temperature, and piston movement may vary differently in the several runs as combustion progresses, and these variations may modify the effects of the initial conditions on the subsequent movement of the flame.

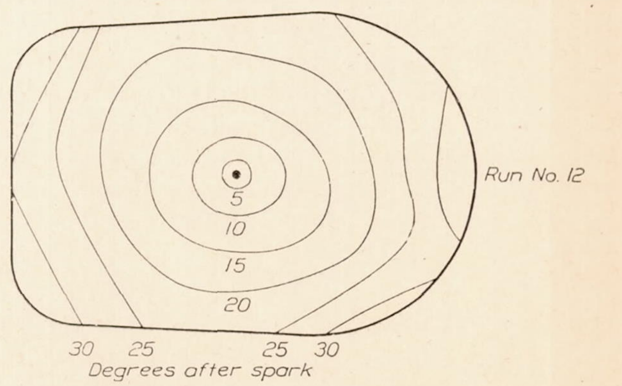

FIGURE 5.—Flame diagram. Spark plug in center of head

In Figure 8, showing the effect of mixture ratio on flame travel, the slower reaction velocities and smaller

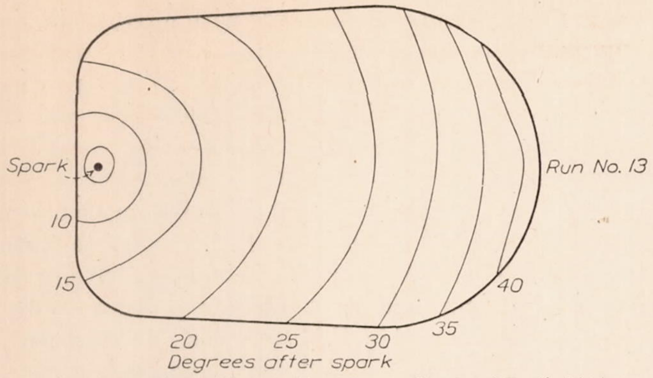

FIGURE 6.—Flame diagram. Normal run. Compression ratio 5 to 1

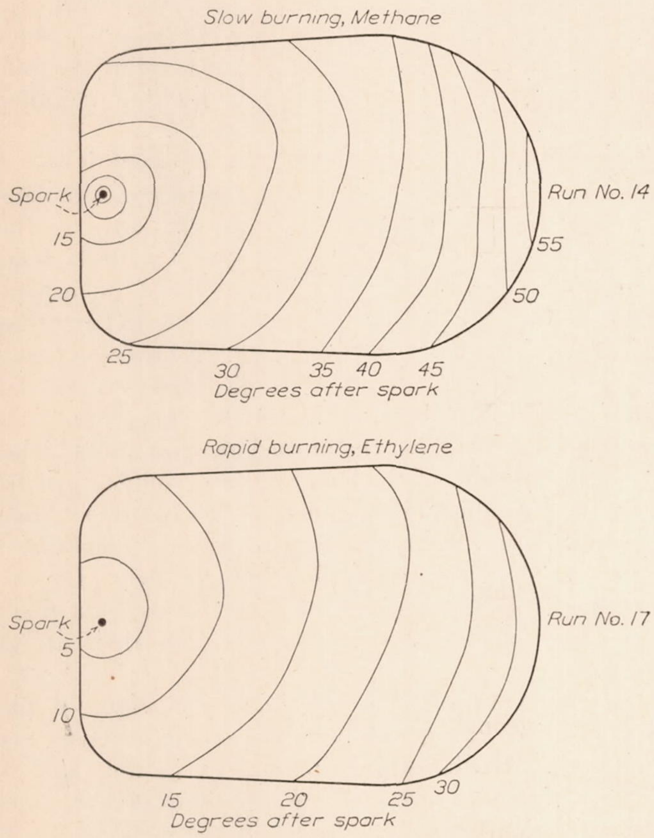

FIGURE 7.—Flame diagrams

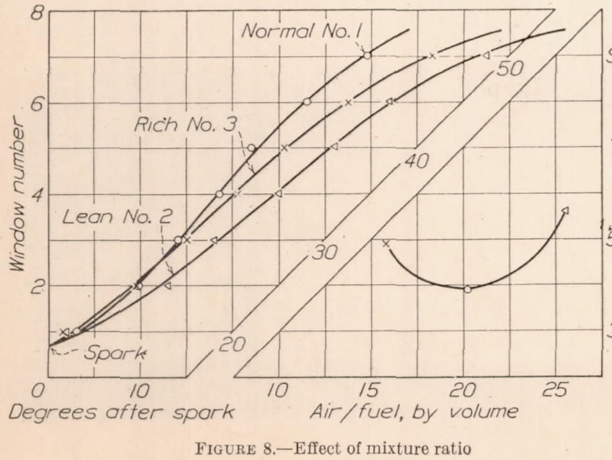

FIGURE 8.—Effect of mixture ratio

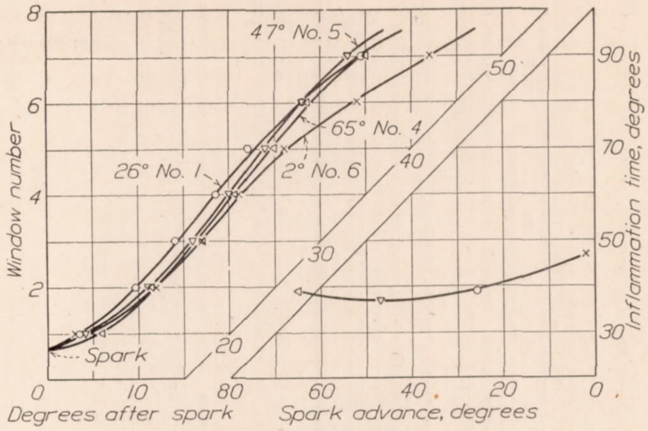

FIGURE 9.—Effect of spark advance

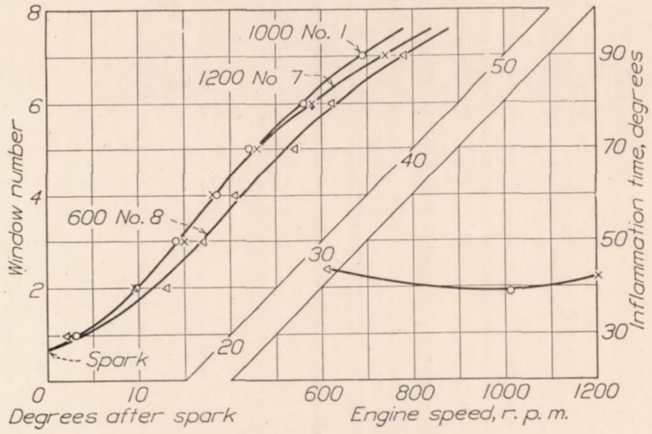

FIGURE 10.—Effect of engine speed

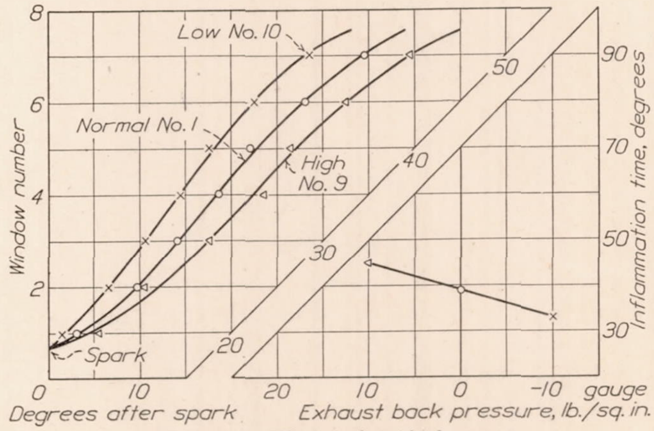

FIGURE 11.—Effect of exhaust back pressure

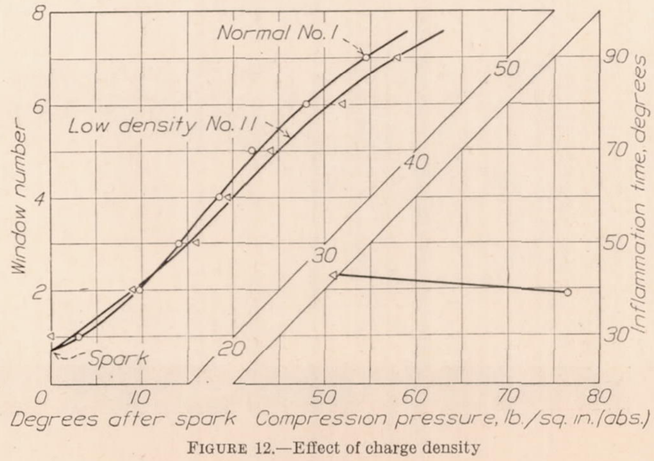

FIGURE 12.—Effect of charge density

expansion tendencies of the rich and lean mixtures are reflected in longer inflammation times as compared to the maximum power mixture. Differences in chemical reaction velocities and in the amount of expansion

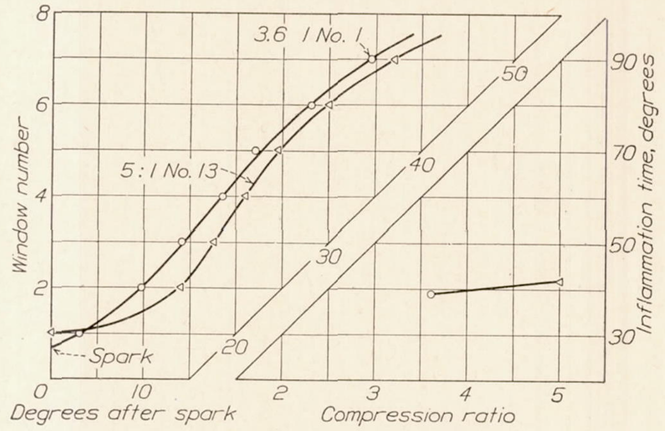

FIGURE 13.—Effect of compression ratio

which takes place behind the flame front are also largely responsible for the differences in flame travel shown in Figure 11, where the proportions of fresh charge and residual were varied, and in Figure 14

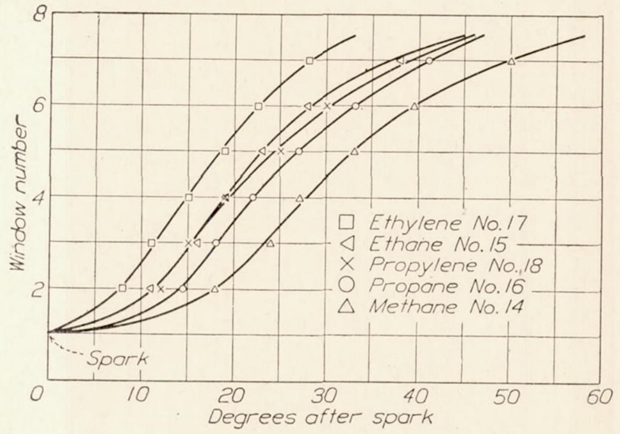

FIGURE 14.—Effect of fuel

where "correct" mixtures of different fuels with air were used. In general, when the composition and proportions of the charge are varied, other operating conditions being maintained as nearly constant as possible, chemical reaction velocity and the extent of the expansion behind the flame front are the primary sources of any variations noted in flame travel.

Figure 12 compares runs made with mixtures having approximately the same proportions of air, fuel, and residual gases but different densities at the point of ignition. The close similarity in the curves and the small difference between the inflammation times is in general agreement with results derived from experiments made in the bomb, where inflammation time shows no significant variation with change in initial pressure. That flame velocity is independent of pressure is also indicated by "constant-pressure bomb" experiments reported by F. W. Stevens. (Reference 5.)

In the two runs at different compression ratios shown in Figure 13, spark-plug location, combustion chamber depth, per cent residual, and pressure and temperature at the time of ignition are different.

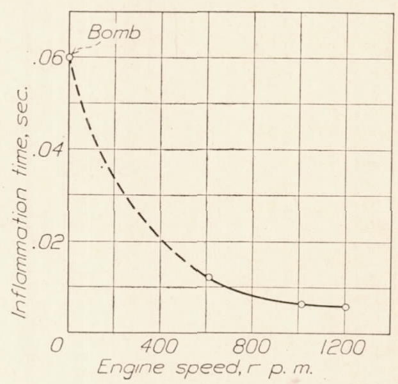

FIGURE 15

Pressure, it seems, has no effect on flame speed; low residual (as at 5 to 1) tends toward high-flame speeds; and high temperature (as at 5 to 1) has been suspected of having a similar influence. On the other hand, the greater heat loss from the burned gas, due to its higher temperature and to the larger surface-volume ratio for the 5 to 1 combustion chamber, tends toward low-flame speeds. Other more obscure effects of combustion chamber geometry may also be involved. The net result is that flame speeds at 5 to 1 are at first much less, and on the average slightly less than at 3.6 to 1.

In the spark-advance series shown in Figure 9, piston position, charge temperature, charge pressure and probably turbulence are different at ignition and at all subsequent corresponding positions of the flame front in the four runs. Thus, in the comparision of these runs, any possible effect of temperature is so confused with indeterminate effects of combustion chamber proportions and turbulence as to render interpretation impossible.

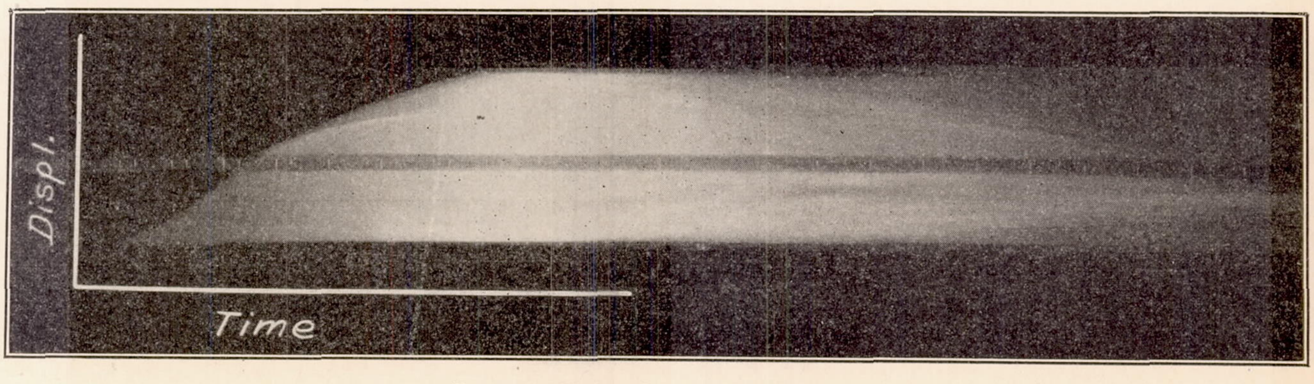

FIGURE 16.—Photographic record of explosion in bomb

The outstanding effect noted in this investigation is the pronounced influence of engine speed on flame speed. At 1,200 r. p. m. the flame crosses the head in about the same number of degrees of crank angle, or in about one-half the time, required at 600 r. p. m. This is in spite of the fact that all conditions in the combustion chamber with the exception of turbulence are believed to be closely similar throughout the combustion periods in the two runs. Also general turbulence, as indicated by the lack of symmetry of the flame diagrams about the point of ignition, is roughly the same at both speeds, and in neither case is the nature of the general movement such as would be expected to affect the inflammation time materially. (See fig. 4.) A possible explanation is that increasing engine speed greatly increases the raggedness of the flame front, and consequently its effective area, which permits it to ignite a given volume of charge in a much shorter time. That this effect becomes even more pronounced at slower speeds is suggested by the fact that the flame takes more than ten times as long to traverse the bomb (in which there in no initial turbulence) as the engine head at 1,200 r. p. m. Inflammation times for three engine speeds and for the bomb (zero engine speed) are shown in Figure 15.

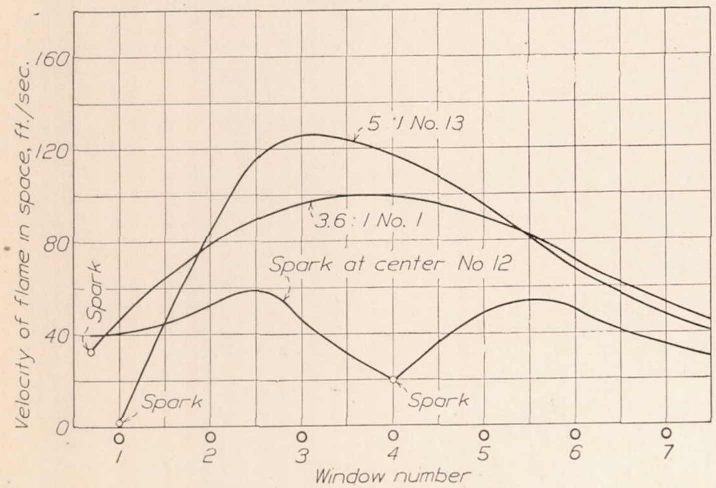

FIGURE 17.—Velocity-displacement diagrams

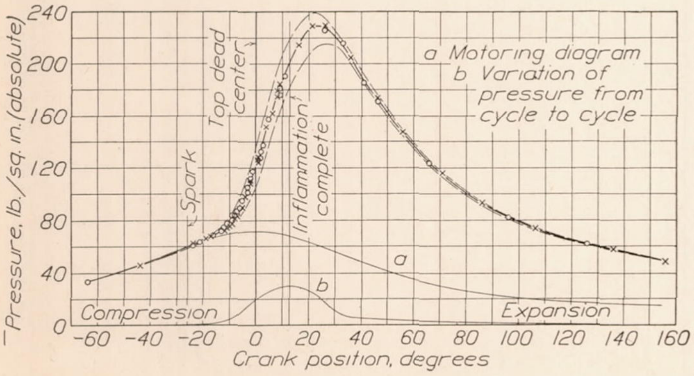

FIGURE 18.—"Normal" run No. 1

Figure 16, a typical photographic time-displacement record for the bomb, shows the slow start of the flame, its acceleration to a maximum speed near the center of the combustion chamber, and its decreasing speed during the later portion of its travel. A similiar variation in slope is characteristic of all of the time-displacement diagrams for both the bomb and the engine. Even in run 12, where the spark plug was at the center of the head, the flame exhibits this rise and fall in velocity in both directions along the middle row of windows, as shown in the velocity-displacement

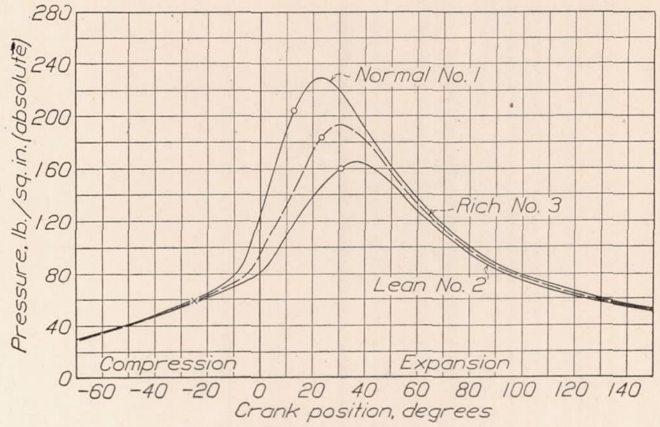

FIGURE 19.—Effect of mixture ratio

curve for this run in Figure 17. Curves for the "normal" runs at the two compression ratios are plotted in the same figure. Although entirely satisfactory explanations for the general form of these curves and for the differences between them have not been formed it is believed that the effects of combustion chamber geometry on heat losses and on the mass movement of the gases carrying the flame are major factors.

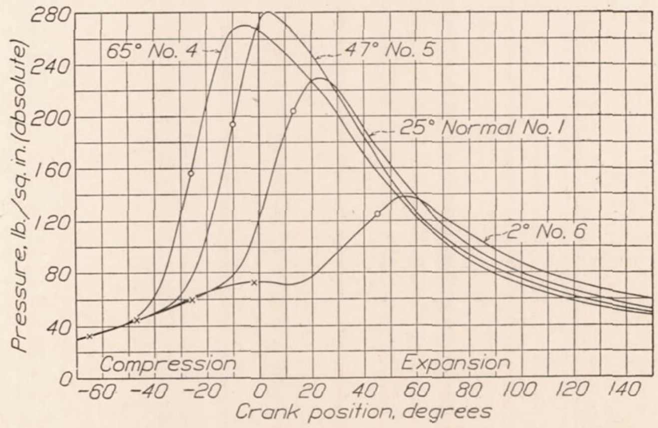

FIGURE 20.—Effect of spark advance

Indicator diagrams.—Figure 18 is a partial indicator diagram for the "normal" run at the lower compression ratio. (This "normal" run incorporates the data taken during two runs made under similar conditions about one month apart. "Average" pressures measured on the earlier run are indicated by circles and those for the later run by crosses, to show the excellent agreement obtained.) The solid line shows pressures for the average cycle and the enveloping dash lines show the range of variation in pressure from cycle to cycle. During compression this variation is very small, amounting to only a few tenths of a pound per square inch. After the spark occurs the variation increases, reaching a maximum at about the point where inflammation is complete, thereafter diminishing rapidly to a relatively small value along the expansion line. The variations shown in Figure 18 are typical of those recorded for all of the runs, and only the "average" cycles are therefore

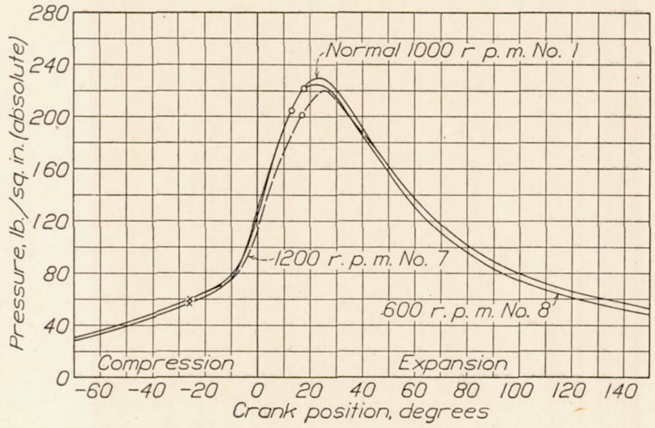

FIGURE 21.—Effect of engine speed

shown in Figures 19 through 26. On each pressure diagram, the occurrence of the spark is denoted by a cross, while complete inflammation, as estimated from the flame diagrams, is indicated by a circle. Without exception, inflammation appears to be complete a considerable time before maximum pressure is reached at the lower compression ratio. It is not known whether this is due to heat liberation from continuing reaction within the luminous gases; to the ex-

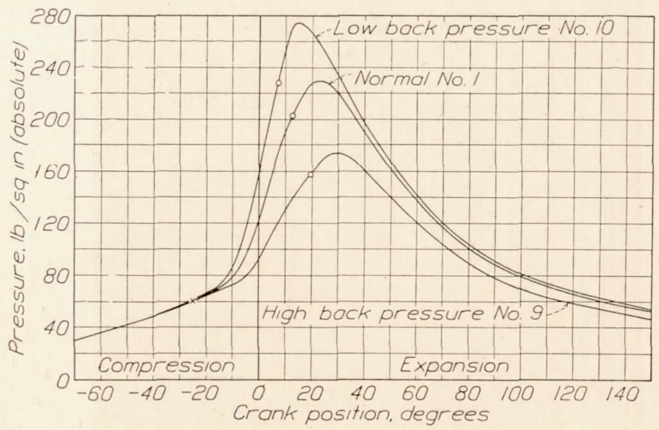

FIGURE 22.—Effect of exhaust back pressure

istence, after inflammation is estimated to be complete, of layers of highly compressed but unignited charge close to the combustion chamber walls; or to a combination of these conditions. In any case, the runs at the higher compression ratio do not show this large and consistent time lag between the point of "complete inflammation" and the attainment of maximum pressure. This would be expected, since heat loss is greater and piston movement near top center has a more pronounced influence on pressure at high than at low compression ratios, both effects tending toward earlier attainment of maximum pressure at higher compression ratios.

CONCLUSIONS

The method described for observing flame movement in the engine cylinder provides a reproducible and apparently satisfactory means of obtaining experimental data regarding a phenomenon so complex in

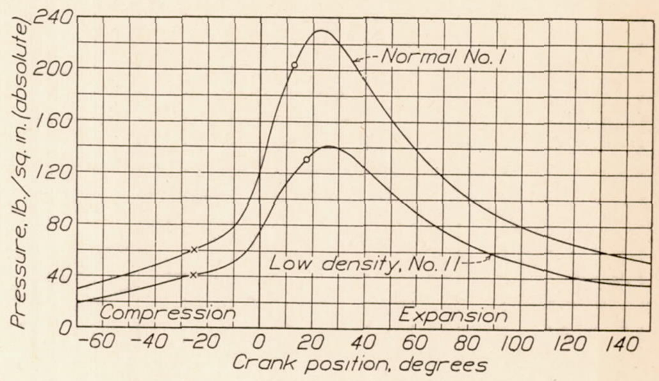

FIGURE 23.—Effect of charge density

its nature that adequate theoretical analysis is not possible on the basis of existing knowledge.

Data so far obtained indicate that normal combustion in the engine progresses from the spark plug throughout the combustion chamber according to a more or less definite pattern, determined by the geometry of the combustion chamber and by turbulence. In all of the tests (in the bomb as well as in the engine) the movement is characterized by an increase in the

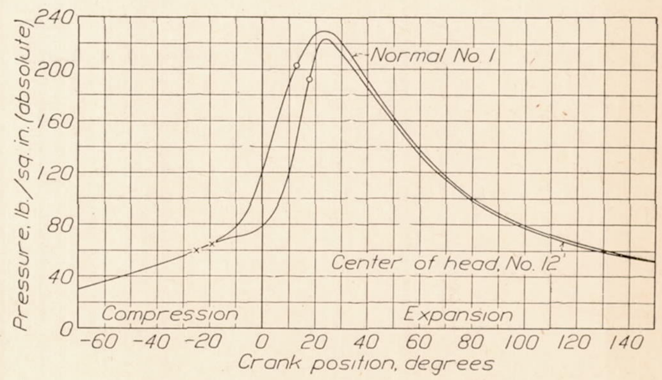

FIGURE 24.—Effect of spark-plug location

velocity of the flame during the first portion of its travel followed by a decrease thereafter.

Observed flame velocities in space varied from a few feet to about 125 feet per second, with an average velocity of about 67 feet per second for the normal runs.

In the low turbulence head so far used, progress of the flame is roughly the same in all directions from the point of ignition, except for some lack of symmetry in the pattern such as might be caused by a general swirl of the charge about the vertical axis of the combustion chamber.

Decreasing the engine speed appears to have little effect on this distortion of the flame diagram but results in a rapid reduction in flame speed, which suggests that if turbulence affects flame travel it does so mainly by local action in the neighborhood of the flame front rather than by disturbance of the general pattern of spread.

A decrease in flame speed is also caused by increasing the ratio of residual to fresh charge or by using a mixture richer or leaner than that giving maximum power. Flame speed is apparently independent of pressure, and if there is an effect of temperature, it is masked in the tests by simultaneous effects of turbulence or combustion chamber shape.

The results suggest that the shorter "combustion" periods generally believed to result from increased compression ratio are merely the earlier attainment of

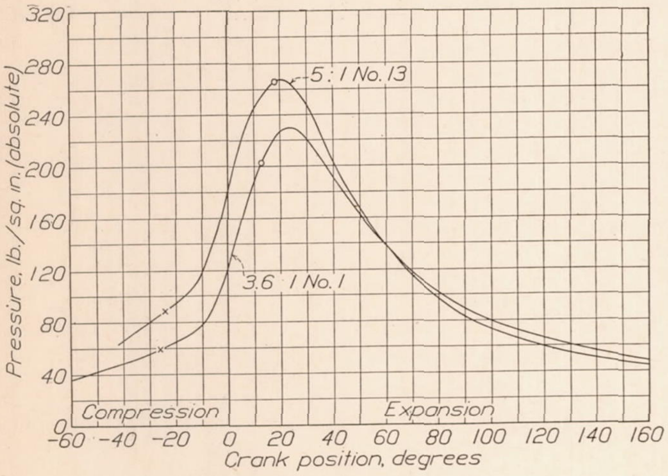

FIGURE 25.—Effect of compression ratio

maximum pressure, caused by greater heat loss and more pronounced effect of piston movement away from top center, rather than by greater flame velocities at the higher compression ratios.

Qualitatively the indicator diagrams support the conclusions drawn from the flame diagrams. However, attempts at closer correlation between flame movement and pressure development are of doubtful value in view of the questionable reliability of flame position as a measure of volume burned. The considerable amount of heat liberation which occurs after the charge is apparently completely inflamed further complicates such attempts.

It is believed that a method could be devised for estimating, from theoretical considerations, flame diagrams for the normal explosion of given mixtures in given combustion chambers. Such estimated diagrams would involve the chemical reaction velocity and the thermal properties of the charge, and perhaps to a certain extent the geometry of the combustion chamber, but would assume no turbulence, piston movement, or resonance effects. Basic data for such an analysis, experimental tests of the validity of the method, and perhaps some insight as to the effects

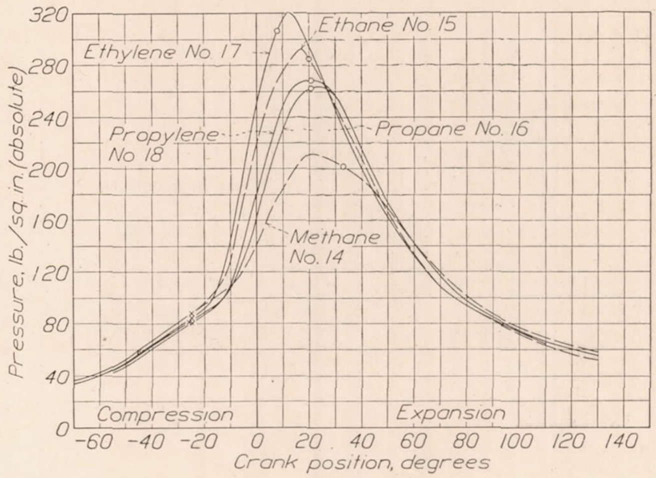

FIGURE 26.—Effect of fuel

of resonance could best be obtained from studies with bombs. However, direct experiments in an engine seem best for investigating the effect of turbulence and the additional effect of piston movement on flame travel and pressure development in actual engines. Both lines of attack appear promising and necessary.

BUREAU OF STANDARDS,
WASHINGTON, D. C., *May 1, 1931.*

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TABLE I.—SUMMARY OF RUNS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Run No.	Purpose: To show effect of—	Fuel	Spark-plug location	Compression ratio	$\frac{Air}{Fuel}$, by volume	Spark advance	Engine speed (r. p. m.)	Volumetric efficiency (per cent)	Exhaust back pressure (lbs./sq. in.)	B.M.E.P. (lbs./sq. in.)	I.M.E.P. (lbs./sq. in.)	Fuel consumption (lb./i. hp-hr.)	Indicated thermal efficiency (per cent)	Exhaust-gas temperature (°C.)	Inflammation time (degrees)	Inflammation time (seconds)	Compression pressure (lbs./sq. in. abs.)	Explosion pressure (lbs./sq. in. abs.)
1	Normal run—3.6 to 1	Propane		3.6	20.2	26	1,010	74.1	(1)	70.6	87.5	0.632	20.0	684	39	0.0064	76.5	230
2	Lean mixture	do		3.6	25.5	25	1,006	75.5	(1)	59.0	74.2	.605	21.0	661	56	.0093	74.1	165
3	Rich mixture	do		3.6	15.8	25½	1,008	74.7	(1)	63.4	80.4	.872	14.6	622	49	.0081	76.4	194
4	Excessive spark advance	do		3.6	20.3	65	1,009	71.8	(1)	47.9	64.9	.818	15.5	640	39	.0064	75.8	270
5	Excessive spark advance	do		3.6	19.7	47	1,009	77.9	(1)	63.4	78.0	.758	16.8	630	37	.0061	76.8	281
6	Excessive spark retard	do	Collar between valves	3.6	19.7	2	1,011	72.1	(1)	53.5	70.2	.781	16.3	759	47	.0075	75.5	138
7	High speed	do		3.6	20.2	25	1,204	74.4	(1)	67.8	85.4	.646	19.7	722	42	.0058	76.2	220
8	Low speed	do		3.6	19.8	26	610	75.2	(1)	65.9	79.3	.705	18.0	575	44	.0120	72.0	225
9	High back pressure	do		3.6	20.2	25½	1,009	65.5	10.45	40.3	62.4	.776	16.4	710	45	.0074	78.5	174
10	Low back pressure	do		3.6	20.1	25½	1,010	84.7	−9.96	82.5	90.3	.694	18.3	605	33	.0054	73.9	275
11	Low charge density	do		3.6	19.8	25	1,010	49.3	−4.27	39.7	54.4	.687	18.5	601	43	.0071	51.0	141
12	Spark in center of head	do	Center window	3.6	20.3	19	1,013	73.4	(1)	67.0	84.0	.648	19.6	684	37	.0061	74.9	224
13	Normal run—5 to 1	do		5.0	20.4	24	1,010	73.5	(1)	71.7	89.3	.602	21.1	615	42	.0069	110.8	268
14	Methane	Methane		5.0	9.6	25	1,011	75.3	(1)	65.0	83.5	.487	24.2	658	58	.0096	112.4	232
15	Ethane	Ethane	First window, third row.	5.0	16.4	25	1,010	72.9	(1)	69.7	88.0	.511	24.3	612	45	.0074	114.0	293
16	Propane	Propane		5.0	24.0	26	1,007	74.2	(1)	73.4	91.0	.512	24.8	648	47	.0078	108.5	264
17	Ethylene	Ethylene		5.0	14.2	25	1,006	73.4	(1)	70.1	86.5	.558	22.1	638	33	.0055	108.4	322
18	Propylene	Propylene		5.0	22.0	25	1,010	75.2	(1)	73.1	90.3	.542	23.5	------	46	.0076	106.2	269

[1] Atmospheric.

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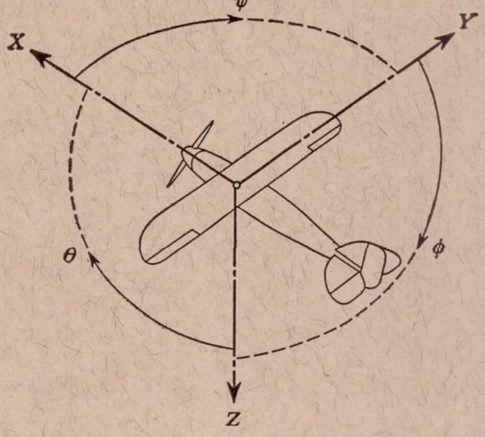

Positive directions of axes and angles (forces and moments) are shown by arrows

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

$$C_l=\frac{L}{qbS} \qquad C_m=\frac{M}{qcS} \qquad C_n=\frac{N}{qbS}$$

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

4. PROPELLER SYMBOLS

D, Diameter.
p, Geometric pitch.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slipstream velocity.
T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$.
C_s, Speed power coefficient $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$.
η, Efficiency.
n, Revolutions per second, r. p. s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

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

1 lb. = 0.4535924277 kg
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.