TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 668✓

COMBUSTION VELOCITY OF BENZINE-BENZOL-AIR MIXTURES IN HIGH-SPEED INTERNAL-COMBUSTION ENGINES

By Kurt Schnauffer

VDI-Verlag G.m.b.H., Berlin, 1931

Washington
April, 1932

30 P.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 668

COMBUSTION VELOCITY OF BENZINE-BENZOL-AIR MIXTURES IN HIGH-SPEED INTERNAL-COMBUSTION ENGINES*

By Kurt Schnauffer

The present paper describes a device whereby rapid flame movement within an internal-combustion engine cylinder may be recorded and determined. By the aid of a simple cylindrical contact and an oscillograph the rate of combustion within the cylinder of an airplane engine during its normal operation may be measured for gas intake velocities of from 30 to 35 m/s and for velocities within the cylinder of from 20 to 25 m/s. With it the influence of mixture ratios, of turbulence, of compression ratio and kind of fuel on combustion velocity may be determined. Besides the determination of the influence of the above factors on combustion velocity, the degree of turbulence may also be estimated. As a unit of reference in estimating the degree of turbulence, the intake velocity of the charge is chosen.

The combustion of gases or of power fuels is so important for the entire technic that the problem of just how the burning proceeds has often been attacked. While the combustion processes under atmospheric conditions may be taken as fairly well understood (Passauer), the processes occurring within the cylinder of an internal combustion engine still remain to a large extent unknown, although the theory of chain reactions has thrown much light on many of the phenomena observed. The principal difficulties met with in either experimental or theoretical studies of the problems raised by the engine lie in

---

*Dissertation submitted in partial fulfillment of the requirements for the Diploma in Engineering of the Technical Institute of Berlin.

estimating the influence of the many undetermined factors introduced by the engine itself while in actual operation. Along with the thermal and chemical characteristics of the fuel mixtures, as autoignition temperature, specific heat, heat conductivity, reaction rate and heat of combustion, there are also the effects to be taken into account of intake temperature and pressure, mixture ratio, compression ratio, engine speed, ratio of piston arms, form of combustion chamber, position of ignition, degree of turbulence present, cooling system - all of which play important roles. Although these factors may not be of equal importance, it is very difficult in any study of the engine's problems to determine which of the factors are of major, which of minor importance on combustion processes.

The experimental side of the investigation is rendered especially difficult owing to the high velocity of explosive reaction processes. There are engines in practical use in which the entire work cycle, involving charging, compression, ignition, burning, expansion and discharge of burned products, all occur within 0.01 second. Due to this short interval it is difficult indeed to differentiate, study and measure with some degree of precision and satisfaction the processes of combustion.

In order to clear up some of the obscure points, the D.V.L. (Deutsche Versuchsanstalt für Luftfahrt) have developed an electrical recording and measuring device that permits in a simple way the determination of combustion velocities of fuel-air mixtures within the cylinder of a normally working airplane engine. By the term "combustion velocity," as here used is meant the total combustion velocity which is made up of the transfer of activating energy, the localized temperature rise connected with the rate of molecular transformation, which is in part made up of the turbulence (mass movement) of the reacting gases. The average rate at which these processes, as indicated by the flame front in passing from one end of the combustion chamber to the other, is here termed the combustion velocity. Along with the determination of this total combustion velocity, necessary for an estimate of the relation between heat and work of the engine, there has also been determined the relation of this velocity to mixture ratio, engine speed, degree of turbulence, compression ratio and quality of fuel.

Previous investigations.- Among the numerous investigations that have been carried out with a view to determine the rate of combustion and to gain further knowledge of the processes involved in a working engine, the work of the following investigators should be especially mentioned: Mallard and Le Chatelier, Dixon, Nägel, Neumann, Clerk, Hopkinson, Nusselt, Herzfeld, Stevens, Ricardo, Klüsener, Maxwell and Wheeler, Endres, Janeway and Lindner. (See Bibliography, page 15.) Most of these investigators have confined their studies, whether experimental or theoretical, to the reaction as it occurs in closed bombs. For benzine-benzol-air mixtures, the lower value of about 2 m/s had been obtained. After Clerk and Hopkinson had called attention to the effect of turbulence on the rate of burning, experiments were carried out in closed bombs provided with rotating fans to simulate as closely as possible the turbulence occurring in the cylinder of a working engine. By the use of indicator diagrams, by samples of the engine's working fluid withdrawn during its operation and chemically analyzed, it was found that these results did not agree with velocities occurring in the working engine. Furthermore, the results obtained by different observers working with closed bombs and rotating fans varied so greatly as not to be comparable. Even successive results with the same fuel, bomb and observer showed similar variations.

A later mode of investigating combustion velocity in engine cylinders, introduced by Ricardo, makes use of stroboscopic methods. The method is applicable only to experimental engines provided with windows easily fouled by soot. Besides, the progressive appearance of light at the windows depends for its registry on the observer's eye, so that, owing to unavoidable light diffusion throughout the cylinder, errors in registration could easily occur.

Experimental procedure.- In the present investigation the electrical device, referred to above, was employed. With this device it was possible to follow the spread of the flame through the cylinder. The principle underlying the use of the apparatus is the well-known one that a flame is a good conductor. The electrical potential across the electrodes of an air gap produces a current when connected by a flame conductor. This fact was made use of to deflect the recording beam in an oscillograph. Investigations concerning the conductivity of an air gap ionized by flames were carried out as early as 1857, by W. Hankel. He found a close relation to exist between flame temperature and conductivity, and between size of terminals and their condition of incandescence. In spite of much further investigation of the phenomenon the physical principles underlying it still remain obscure. The opinion is that the conductivity is effected by ions, without knowing whether the ionization results from chemical action or is purely a thermal characteristic.

A number of measuring electrodes were inserted in the cylinder head of the engine. The instant at which a flame filled the gap between the electrodes of a measuring plug was photographically recorded by the displacement of the oscillograph beam. By accurately measuring the distance between the gaps of the different plugs it is easy to determine the period occupied by the flame in passing from the ignition gap to each of the other plugs.

These measurements were made with a six-record oscillograph made by Siemens and Halske, Berlin. Figure 1 shows the ignition chamber of an air-cooled cylinder of the Siemens and Halske Sh 13 airplane engine used in this investigation: a is the ignition plug; b, c and d are the measuring plugs placed in line along the diameter of the head. The flame originating at the ignition gap a, passes successively in its spread through the cylinder, the gaps b, c and d of the measuring plugs. The instant of its arrival at each gap is recorded by the oscillograph. From this record the rate of displacement of the flame front and the combustion velocity may be determined.

Figure 2 is a reproduction of an oscillogram so secured. The instant of ignition and the arrival of the flame at each measuring gap is indicated in the oscillogram by a deviation in its light trace. The first deflection a, is the beginning of the flame spread at the point of ignition; the second, third and fourth deflections b, c, d register the instant of the flame's arrival at the other measuring gaps. The record shows plainly the spread of the flame front over the course marked by the measuring plugs. The distance between the recorded deflections on the record indicates, in reference to the time record e, the period occupied by the flame front in passing from the point of ignition to any particular measuring gap. All these records are simultaneously accompanied by the time record of a calibrated tuning fork shown on the line e. Since both the distance traversed by the flame and the time occupied in its passing are recorded on the gram, then by division of the length by the time and the assumption of uniform rectilinear displacement, there is obtained the combustion velocity.

The minute deflections; not indicated by letters, on the lines c and d, are induction effects due to the ignition current. These records may be made more prominent or be made to disappear entirely, as in the case of line b, by changing the position of the ignition cable. It will be noticed that their position on the film record is naturally perpendicular to the ignition record on a.

In making the records here offered those obtainable at the points b and c were neglected and only those used between the point of ignition and d, at the further end of the cylinder head. The distance between these two points was 130 mm (5.1 in.). Figure 3 shows two oscillograms obtained over this distance.

Three different forms of set-up were experimented with in making these measurements. The last and simplest arrangement, with which practically all of the work was done is shown in Figure 4 with the exception of the oscillograph. Besides the oscillograph there was also employed one R.E. 134 radio tube, a thermal battery of 4 volts, an anode battery of 200 volts, a resistance of about 40,000 Ω and a measuring electrode (spark plug). Since measuring electrodes may easily be obtained anywhere, the combustion processes may be investigated with this arrangement on any engine desired.

Figure 5 shows the first arrangement and wiring scheme used. In this arrangement, the current supplying the circuit involving the gap ionized by the flame, was obtained from a short-circuited generator. The current set up in this circuit when the gap is closed by the ionizing flame was stepped up by a three-coil transformer so as to be strong enough to be recorded sharply by the oscillograph O.

Figure 6 shows two oscillograms obtained by this arrangement. As may be seen in the figure, the ionization current across the gap has still imposed upon it the impress of an alternating current. This prevents a satisfactory record of the flame's arrival at B. For this reason the connections shown in Figure 7 were developed. Figures 2 and 3 show oscillograms obtained with this arrangement. These figures show a sharply defined deviation on the arrival of the flame at the gap B. Now since the record of the ignition spark A is also sharply marked, it is possible to determine with accuracy the distance AB and from it find the mean combustion velocity between these points. In this simplified arrangement only one radio tube is required. When the gap J, is ionized by the arrival of the flame front, the battery circuit B, is closed and across the resistance of the lattice of the tube, a fall of potential takes place. This changes the initial potential of the tube's lattice and also the anode current. The anode current will again be normally recorded when its trace returns to its point of rest.

The above scheme may even be further simplified by doing away with the battery B, the ammeter in the anode circuit, the compensation battery and compensation resistance. Figure 8 shows this further simplified arrangement. In making the final adjustments in this arrangement, it is convenient to use temporarily an ammeter in the anode circuit. It was with this last arrangement that the present investigation was largely carried out. It was used also in studies made of "knocking" tendencies in fuels and in estimation of combustion temperatures in the working engine. The device is practically free from inertia.

The magnitude of the current passing the ignition gap and its relation to the gap's temperature, has been investigated by Lusby. As may be seen by referring to Figure 9, at about 1200° C, flame temperature, a current of 50×10^{-9} A was flowing. At about 2000° C, a current of about 1900×10^{-9} A was passing. These magnitudes in current strength varying with temperature, permit, by suitable adjustments in the apparatus, to arrive at approximate estimates of combustion temperatures. In Figure 6 an abrupt flattening of the ionization current record at d may possibly be due to temperature change resulting from turbulence. It is not yet possible, due to disturbing influences of many undetermined factors, to determine by this means the true temperature; yet it is possible in many cases to arrive at approximate estimates of temperatures affecting the conductivity of the ionization gap.

A somewhat modified Bosch spark plug and a measuring electrode of 5 mm diameter (fig. 4) have proved very satisfactory as ionization gaps. That one terminal of the gap must be earthed because only the middle conductor is insulated, is of no effect upon the oscillogram records. As a source of ignition current, a Bosch magnet generator driven by a motor was used.

In carrying out measurements as here described, it is necessary to have the instant of ignition sharply recorded. In the preliminary trials made, the oscillograph was connected up with the primary current of the transformer in order that the interruption in this low potential current might be recorded. This arrangement was found unsatisfactory. A trial was then made to use the high voltage current direct from the ignition plug. A specially made double pole plug was used for this purpose, but this was soon found to cause ignition from its incandescent temperature. Finally a Liliput plug completely insulated from the cylinder head was made use of. This gave entirely satisfactory results. The high voltage current, after it had leaped the ignition gap and ignited the mixture, had in part passed through the oscillograph connections and gave on the oscillogram a sharp impression of the instant of ignition. The K.L.G. Liliput plug No. 267 functioned throughout the investigation without influence on other parts of the explosion record.

Procedure and results.- The influence of mixture ratios, of engine speed, of turbulence, of compression ratio and of fuel composition on combustion velocity, were determined under various working conditions of the engine. Measurements of the effect of compression ratios $\epsilon = 5:1$ at 1900, 1600, 1000 and 800 r.p.m. as well as compression ratios $\epsilon = 6:1$, $5:1$, and $4:1$ at 1600 r.p.m. were carried out. The above seven sets of records were further carried out with three different fuels. These 21 series of observations covered the entire range, by short progressive steps, from the lower to the upper ignition limits of the fuels used. For every mixture ratio, the engine speed and fuel-air proportion were measured and the combustion velocity determined. From 12 to 15 oscillogram records were obtained in each case. In this way an extensive range of observations on the influence of the above-named factors on combustion velocity was secured.

The results of this series of experiments are represented in diagram (figs. 10 to 16) in such a way that the combustion velocity for each work cycle is written over the corresponding ratio value of air excess in the charge. From these figures it will be seen that the combustion velocities from the oscillograph records scatter badly. For instance, in Figure 10 the velocity for one work cycle is recorded at about 15 m/s. In the cycle immediately following, for the same conditions and for the same charge, it is about 25 m/s. Mean values from these results which might be of value from some standpoint of the investigation, were not obtained, since the scattering shown gives a good idea of the influence of turbulence on combustion rate as represented on the oscillogram. Besides, a fewer representations of velocity positions in the figures could easily lead to wrong conclusions. But in spite of pronounced scattering Figures 10 to 16 show that all points lie within rather well-defined limits designated in the figures by limiting curves.

FACTORS INFLUENCING COMBUSTION VELOCITY

Mixture ratios.- Since in all of the 21 series of observations made the mixture ratios of the charges recorded varied between the lower and upper ignition limits, the records so obtained provide a good basis for estimating the effect of mixture ratio on combustion velocity. All the results obtained in this series of observations agree in following a curve resembling a parabola that has its apex on the figure between the values $\upsilon = .85$ and $\upsilon = .90$, that is, for a fuel excess between 10 and 15 per cent. This parabola-like curve expresses then the influence of mixture ratio on combustion velocity. This effect is profound; small changes in mixture ratios produce wide differences in combustion rate. All the diagrams show the well-known sharp falling off in rate with mixtures poor in fuel content. With air excess ratios from $\upsilon = .6$ to $\upsilon = 1.2$ the enclosing curves of the figures may be calculated with fair approximation to their abscissas and show then the same ignition limits as already obtained by closed bomb methods.

The profound influence exerted on combustion velocity by the mixture ratio may be interpreted somewhat as follows: The combustion velocity in an engine reaches its maximum for the most favorable mixture ratio. With the fuels used and with fuel-air mixtures this occurs for an air excess ratio between $\upsilon = .85$ and $\upsilon = .90$. Any change in this mixture ratio value decreases the number of reacting molecules and thereby the temperature and energy liberated. Moreover, with an excess of fuel present, endothermic side reactions may occur that still further lower the reaction energy, temperature and energy of activation. The effect of all this is to decrease the velocity of combustion. To these factors must be added also the unburned fuel; it must be heated, which requires a further decrease in available energy.

A lack of fuel in the mixture ratio likewise results in a decrease of combustion velocity due to a decrease in the number of reacting molecules and to energy withdrawn for the heating up of inert components. It would seem also that the energy transport from one fuel molecule to another may be reduced due to the bad heat conductivity of the air content of the mixture. If so, ignition would thereby be retarded. This appears to be the case in greater degree for all benzol-air mixtures than for benzine-air mixtures.

This view, however, is not in agreement with the experimental results of Stevens that indicate that under conditions of constant pressure, the heat conductivity of the gaseous mixtures are without influence on the rate of combustion. Results described in the following paragraphs dealing with the influence of different fuels on combustion velocity (compression ratio, presence of inert gases, preheating by contact with hot cylinder walls, etc.) show indirectly that the effect of heat conductivity on combustion velocity must be very small. It seems established that so far as their use in engines is concerned, that ignition limits are somewhat smaller in the case of benzol-air mixtures than in benzine-air mixtures. This might lend some weight to the first viewpoint offered above. A definite conclusion, however, cannot be drawn from the results of the present investigation with a working engine.

Turbulence.- The possibility of changing the degree of turbulence in a mixture ratio introduced into the cylinder of a working engine seemed possible of realization by changing, at full throttle, the engine's speed; for, by so doing the intake period, and with open throttle, the charge for one filling stroke would remain practically constant, while the intake velocity would change, thus changing the degree of turbulence in the cylinder. This feature of the investigation was so carried out that at open throttle, constant compression ratio, $\epsilon = 5:1$ and constant spark advance, at 34°, the load and speed of the engine were varied by steps between 1900 and 800 r.p.m.

As unit of reference by which to express the degree of turbulence, the average velocity of the entering charge at the intake value was chosen. Turbulence in the cylinder is a function also of the period between the inflow of the charge and its ignition. This period, however, is small relative to engine speed. To be very accurate, it must be taken into account that the turbulence depends, not on the average rate of inflow, but on its instant rate. This value changes with the diameter of the intake opening as well as with the speed of piston movement.

Figures 10 to 14 give the results of the observations made of the effect of turbulence on combustion velocity. If average values from these diagrams are compared, it will be seen that increasing turbulence corresponds to increased intake velocity. The mean combustion velocity increases with increased turbulence. It increases from 14 to 21 (ν = .85) when the intake velocity is increased from 20 to 30 m/s. These values exceed those found by closed bomb methods without turbulence by about 2 m/s at most. Figure 17 shows that mean combustion velocity increases very nearly linearly with increased intake velocity.

Figures 10 to 14 show further that the scattering in combustion velocity values increases with increased intake velocity. For example, it increases from 6 to 12 m/s when the intake velocity increases from 20 to 30 m/s. The diagrams that show the least scattering are those of low combustion and low intake velocities. The following may be offered by way of explanation to account for the marked scattering of combustion velocity values at different intake velocities. Turbulence in an engine cylinder is entirely haphazard. In consequence the advance of the flame front in the cylinder is always some component of the direction of the turbulent motion, which may have the effect of increasing or decreasing the advance of the flame front in the cylinder. Since the velocity of turbulence is always much greater than the combustion velocity, these upper and lower combustion velocity values may lie wide apart. Somewhere between these limiting values all other velocity values must lie. The difference in the widths of the scatter-value zones may be accounted for by the difference in engine speeds corresponding to the different turbulence values.

Some examples may be given: Figure 10 at ±6 m/s turbulence velocity, gives a combustion velocity of 21 m/s; Figure 11 at ±4.5 m/s turbulence velocity, a combustion velocity of 19 m/s; Figure 12 at ±3.75 m/s turbulence velocity, a combustion velocity of 14 m/s; and Figure 14 at ±6 m/s, a combustion velocity of 22.5 m/s. These values represent the relation between degree of turbulence as estimated and combustion velocity. (See fig. 18.) The dominating effect of turbulence is not apparent in these results.

In passing judgment on the results here presented, it must be borne in mind that they are obtained directly from a working engine and that the limiting curves approximately outlining the region of scattering combustion velocity values from which turbulence values were drawn is, at best only an approximation. This may differ widely from actual values, since it may not be known whether or not, between the two limits given, the turbulence was always in one direction. Curves drawn reducing the limits of variation would reduce the accuracy of the measurements given. It would seem that the deviations cannot be very great since they agree fairly well with those obtained by Endres from engine investigations. Those obtained by him from the experiments of Hintz on the velocity of turbulence give for the highest engine speeds ±5 to ±6 m/s.

The further question arises as to whether or not the difference observed in combustion velocity (for example, in fig. 12 it amounts to 12 m/s) is really due to the influence of turbulence alone. A time-pressure record was obtained synchronously with that of the combustion velocity record. A comparison of the two showed that the time-pressure record remained constant while the combustion velocity record obtained at the same time showed great variations. It was not probable that these variations were due to changes in temperature or to differences in mixture ratios, since in that case corresponding differences would occur in the time-pressure record also. It seems the more probable therefore that the scattering in combustion velocity records is to be attributed to the effect of turbulence.

The records obtained in this line of the investigation offer evidence as to what degree the intake velocity may serve as a unit of reference in expressing the degree of turbulence; Figure 19 shows no real proportionality to exist. Rather, the figure shows equality, the agreement between the two being very close. It is the closest over the shortest measuring distances.

With increase of engine speed, intake velocity as well as combustion velocity, increases. The limit of this increase would evidently be reached when intake velocity reaches the velocity of sound. In its present form this limit could not be reached without great loss to the engine's volumetric efficiency. On the other hand, by the use of explosive charges the required pressure ratio might be obtained. Also in the case of engines furnished with compression pistons, turbulence velocities even above the velocity of sound could be reached.

In practice the velocity of combustion as well as degree of turbulence is determined by the limiting speed at which the engine runs smoothly. If the combustion velocity becomes too great, then the rate of energy transformation becomes so high that "knocking" develops, resulting in too rapid pressure increase. These limitations to turbulence do not occur when combustion and energy transformation in the engine are independent of each other, as for instance, in the gas turbine or where the working fluid of the engine is separately heated. Otherwise the relation between power output of the engine and turbulence are very close.

A schematic figure illustrating the intimate relation between combustion velocity, mixture ratios and turbulence is given in Figure 20. In this figure, along with a limiting value obtained by Neumann in a closed spherical bomb with no turbulence, there are represented the values obtained in the present investigation. There is represented in the figure the relation between turbulence and combustion velocity over the entire range from the lowest to the highest velocities obtained with the working engine. Neumann's value, although obtained from a closed bomb and with benzine-air as fuel, nevertheless fits very well in this series of other values.

The lower and upper enclosing curves in Figures 10 to 16 were extended to the abscissas. They all give with the line joining their maximum values, the value $\upsilon = .85$. The entire figure gives a clear conception as to how mixture ratios, combustion velocities and turbulence are related in a working engine. Without including Neumann's value, the width of the turbulence bands, and with it combustion velocities increase very nearly linearly. Only for the highest intake velocities are deviations shown.

Compression ratio.- The single-cylinder experimental engine made use of in investigating the effect of compression ratios on combustion velocity, was provided with a device whereby the ratio could be changed. Observations with this engine included compression ratios 4:1, 5:1, and 6:1 while other conditions of engine operation, open throttle, fuel, spark advance and engine speed remained unchanged. By this arrangement only the final pressure and temperature of the compression were changed. Since at higher compression the fuels, benzine and benzine-benzol-air mixtures, had a tendency to "knock" badly, the fuel benzol only was used.

Figures 10, 15 and 16 contain the compression ratio results. Combustion velocities increased by increasing the compression ratio from 4:1 to 5:1, from 19 to 21 m/s; and from 5:1 to 6:1, from 21 to 22 m/s. The small increase noted may be attributed to a small change in turbulence or to the reduced volume of the compression chamber and resulting increased final temperature. The difference, when scattering is considered, is very small - of about the same order as the change in energy output of the engine. Figure 20 would therefore be imperceptibly altered from the effect of a change in compression ratio.

Kind of fuel used.- The fuels used in the investigation were benzene, benzol, and a mixture 1:1, of them both. The results obtained with these three kinds of fuel differed very little. That seemed to be what might be expected from the combustion characteristics of benzine. It has a lower boiling point than benzol and gives a higher combustion temperature. Its ignition temperature is lower than benzol. The heat of reaction of the two fuels is the same. Counter to this is the retarding influence of the specific heat of benzine. It is about 20 per cent greater than that of benzol. For these reasons apparently and possibly owing to stronger radiation, its combustion velocity does not rise above that of benzol. A conclusive proof of this, however, cannot be drawn from the results with the working engine. The investigation with these fuels yielded no new results outside the fact that presence of benzine somewhat extends the limits of ignition of the other gas.

Other influences.- In flow pressure, inflow temperature and spark advance all influence markedly the rate of combustion. Intake pressure influences the potential of the cylinders' charge and the combustion temperature. Besides these influences the intake velocity, influenced by throttling, affects the turbulence. As already pointed out the intake velocity influences only to a slight degree the combustion velocity and that these influences derive principally from form and operation of the engine. With the explosive mixture initially at rest and with combustion taking place at constant pressure, Stevens has established the fact that the rate of flame movement is independent of pressure.

Intake temperature is of significance especially for cases where the charge is necessarily weak in fuel content. Increased intake temperature increases ignition limit, and in that way allows the use of fuel combinations that otherwise would be unavailable. Limitation to the extent that preheating may be carried lie in the fall of potential of the charge and in the tendency to "knock" in the case of benzine-air mixtures.

SUMMARY

If it is held in mind that to ignite a fuel molecule, a definite activation energy is required and that the time required for this energy transfer determines the rate of transformation, then for any fuel there is offered two possibilities whereby the rate of transformation may be influenced: by influencing the intensity of the energy source, and by influencing the period of energy transfer.

Under these two viewpoints arrange themselves all those influences affecting combustion velocity, together with the fundamentals on which an explanation of the processes observed, rests. Investigations with closed bombs have shown that changes in the intensity of the energy of the initial source have but little influence on combustion rate, while on the other hand, a shortening of the period of activation has a profound influence on combustion rate. Results of the investigation here presented show the marked influence exerted on the velocity of combustion by turbulence. Whether one favors the older viewpoint concerning the kinetic energy of the molecule or accepts the explanation offered by the theory of chain reactions, in either case the influence of turbulence, by increasing flame area, operates to accelerate the velocity of combustion.

These facts would not be greatly modified by considering that the velocity values given contain also the velocity rate of molecular transformation. Rates of molecular transformation are influenced in exactly the same way as combustion velocities, namely, by temperature and turbulence. It may be justifiable then, as a first approximation, to consider combustion velocity to depend directly on the rate of transfer of the energy of activation.

From the standpoint of molecular transformation the results here given would apply to combustion chambers only of cylindrical form with ignition at the side as shown in Figure 1. They do not apply to cylinders with stationary valves, as in the Ricardo form. They do provide, however, the basis of understanding of the processes occurring in those forms of containers.

Translation by F. W. Stevens,
Bureau of Standards,
Washington, D. C., March 30, 1932.

BIBLIOGRAPHY

Passauer, H.: Verbrennungsgeschwindigkeit stickstoffreicher Gase. Feuerungstechnik, Vol. 17, 1929, p. 7.

Passauer, H.: Verbrennungsgeschwindigkeit und Verbrennungstemperatur bei Vorwärmung von Gas und Luft. Das Gas- und Wasserfach, Vol. 73, 1930, p. 313.

Mallard und Le Chatelier: Recherches expérimentales et théoriques sur la combustion des mélanges gazeux explosifs. Ann. des Mines, Vol. 8, 1883, p. 274.

Dixon; On the Movement of the Flame in the Explosion of Gases. Phil. Trans., london, Vol. 200, 1903, p. 315.

Nägel, A.: Versuche über die Zündgeschwindigkeit explosibler Gasgemische. Forschungsarb. Ing.-Wes., No. 54, Berlin, 1908.

Neumann, K.: Untersuchung des Arbeitsprozesses im Fahrzeugmotor. Forschungsarb. Ing.-Wes., No. 79, Berlin, 1909.

Clerk, D.: Report of the Gaseous Explosions Committee of the British Association for the Advancement of Science. London, 1912, p. 202. Also, The Working Fluid of Internal Combustion Engines. Engineering, Vol. 96, I, 1913, pp. 28, 58.

Hopkinson, B.: Report of the Gaseous Explosions Committee of the British Association for the Advancement of Science. London, 1912, p. 203. Engineering, Vol. 96, I, 1913, p. 62.

Nusselt, W.: Die Zündgeschwindigkeit brennbarer Gasgemische. Z.V.D.I., Vol. 59, 1915, p. 872.

Herzfeld, A.: Der Wärmeübergang und die thermodynamische Berechnung der Leistung bei Verpuffungsmaschinen, insbesondere bei Kraftfahrzeugmotoren, Berlin, 1925.

Stevens, F. W.: A Constant Pressure Bomb. T.R. No. 176, N.A.C.A., 1923.

Stevens, F. W.: The Gaseous Explosive Reaction - The Effect of Inert Gases. T.R. No. 280, N.A.C.A., 1927.

Stevens, F. W.: The Gaseous Explosive Reaction - A Study of the Kinetics of Composite Fuels. T.R. No. 305, N.A.C.A., 1929.

Stevens, F. W.: The Gaseous Explosive Reaction at Constant Pressure - The Reaction Order and Reaction Rate. T.R. No. 337, N.A.C.A., 1929.

Stevens, F. W.: The Gaseous Explosive Reaction - The Effect of Pressure on the Rate of Propagation of the Reaction Zone and upon the Rate of Molecular Transformation. T.R. No. 372, N.A.C.A., 1930.

Ricardo, H. R.: Some Notes on Gasoline-Engine Development. T.M. No. 420, N.A.C.A., 1927.

Klüsener, O.: Untersuchungen zur Dynamik des Zundvorganges. Forschungsarbeiten Ing.-Wes., No. 309, Berlin, 1928.

Maxwell, G. B., and Wheeler, R. V.: Flame Characteristics of "Pinking" and "Not-Pinking" Fuels. Jour. Inst. Petroleum Technologists, Vol. 14, 1928, p. 175; Vol. 15, 1929, p. 408.

Endres, W.: Der Verbrennungsvorgang im Gas- und Vergasermotor. Berlin, 1928.

Janeway, R. N.: Detonation is Laid to High Temperature Attained by Unburnt Gas. Aut. Ind., Vol. 59, 1928, p. 623.

Lindner, W.: Mehrfachfunkenaufnahmen von Explosionsvorgängen nach der Toeplerschen Sehlierenmethode. Forschungsarb. Ing.-Wes., No. 326, Berlin, 1930.

Klüsener, O.: Das Arbeitsverfahren raschlaufender. Zweitakt-Vergasermaschinen. Forschungsarb. Ing.-Wes., No. 334, Berlin, 1930.

Hanke, W.: Über das Verhalten der Weingeistflamme in Elektrischer Beziehung. Pogg. Ann. Physik und Chemie, Vol. 108, 1859, p. 146.

Schnauffer, K.: Das Klopfen von Zündermotoren. Z.V.D.I., Vol. 75, 1931, p. 455. Extended in D.V.L. Jahrbuch, 1931, p. 375.

Lusby, S. G.: The Mobility of the Positive Ion in Flames. Phil. Mag., Vol. 22, 1911, p. 775.

Hintz, H.: Mittel und Wege zur Beeinflussung der Verbrennung beim Strahlzerstaubungsverfahren. Z.V.D.I., Vol. 69, 1925, p. 673.

Schnauffer, K.: Aufzeichnung rasch verlaufender Druckvorgänge mittels des Verfahrens der halben Resonanzkurve. Luftfahrtforschung, Vol. 6, 1930, p. 126. D.V.L.-Jahrbuch, 1930, p. 304.

a, Ignition gap
b,c and d,
Ionization gaps

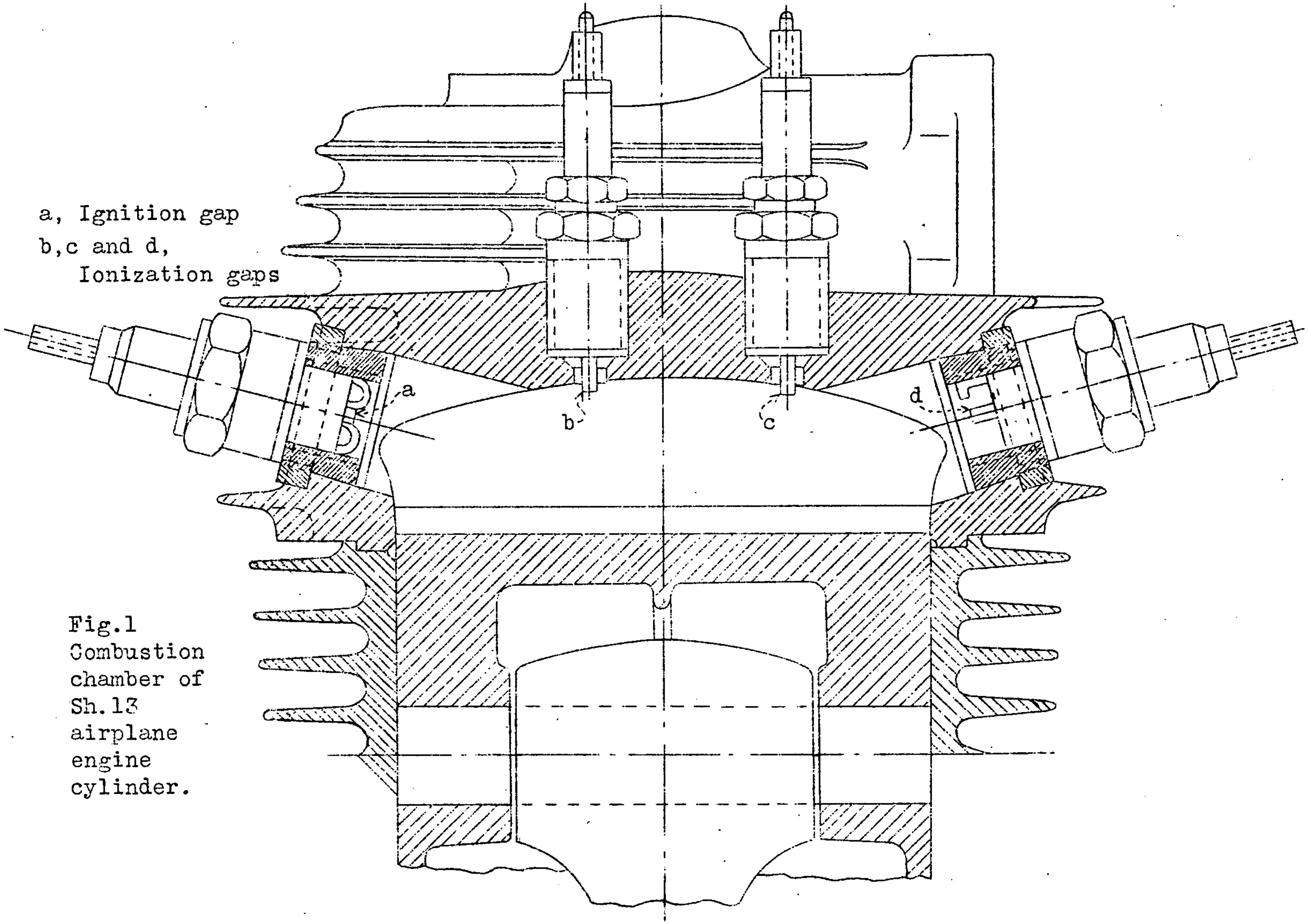


Fig.1
Combustion
chamber of
Sh.13
airplane
engine
cylinder.

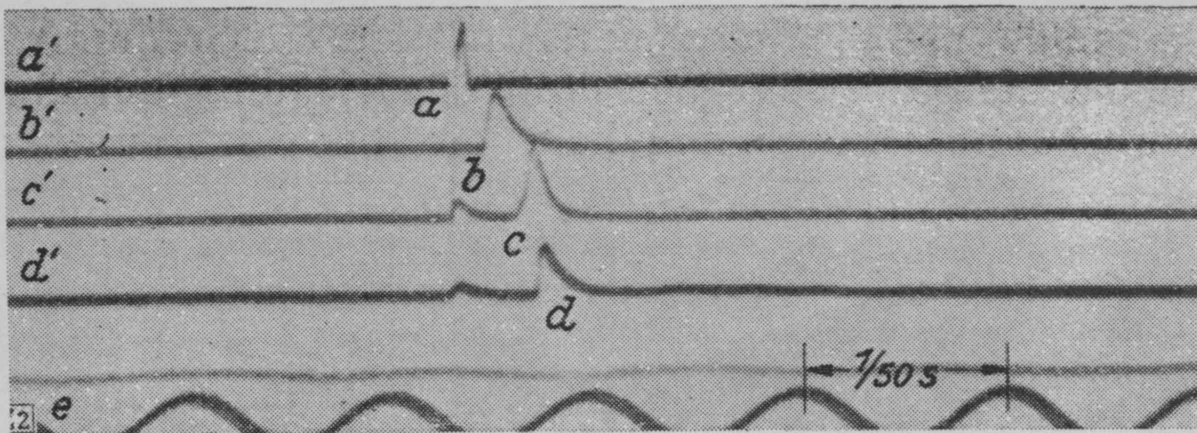


Fig.2 Oscillogram for determining combustion velocity.a', ignition current. b',c' and d',ionization currents. e, time record. a, ignition point. b,c and d,instants of flame arrivals.

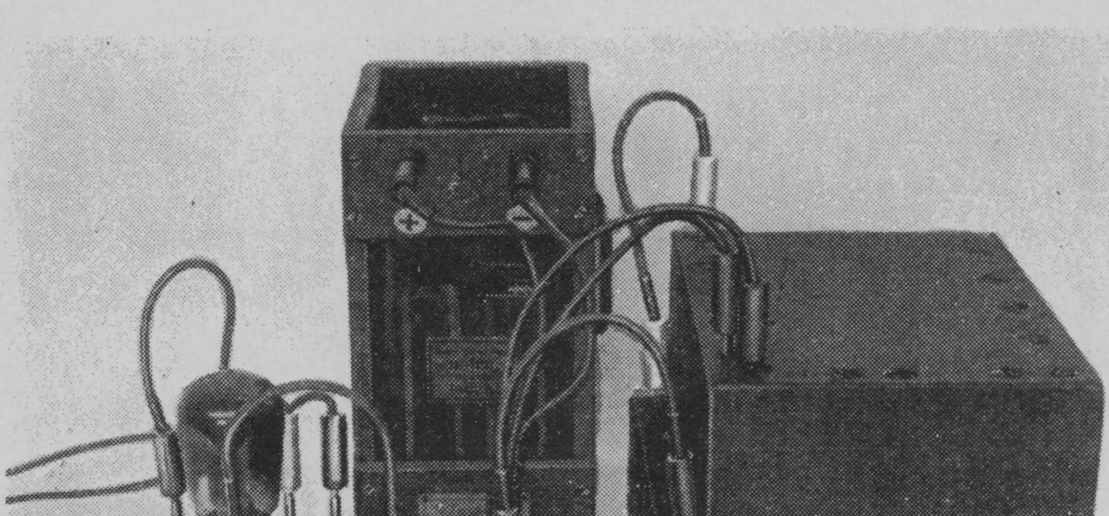


Fig.4 Recording outfit.

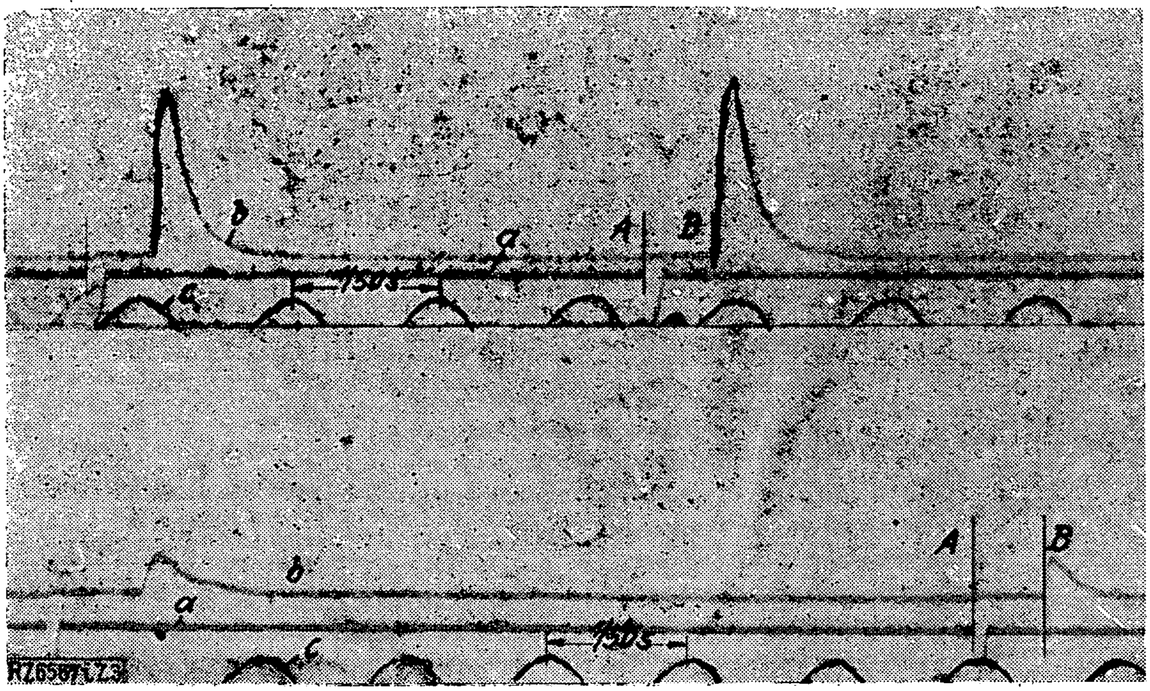


Fig.3 Oscillogram for determining combustion velocity(direct current method). Above,1600 r.p.m.,below,930 r.p.m. a, ignition current. b, ionization current. c, time record. A, ignition point. B, instant of flame arrival.

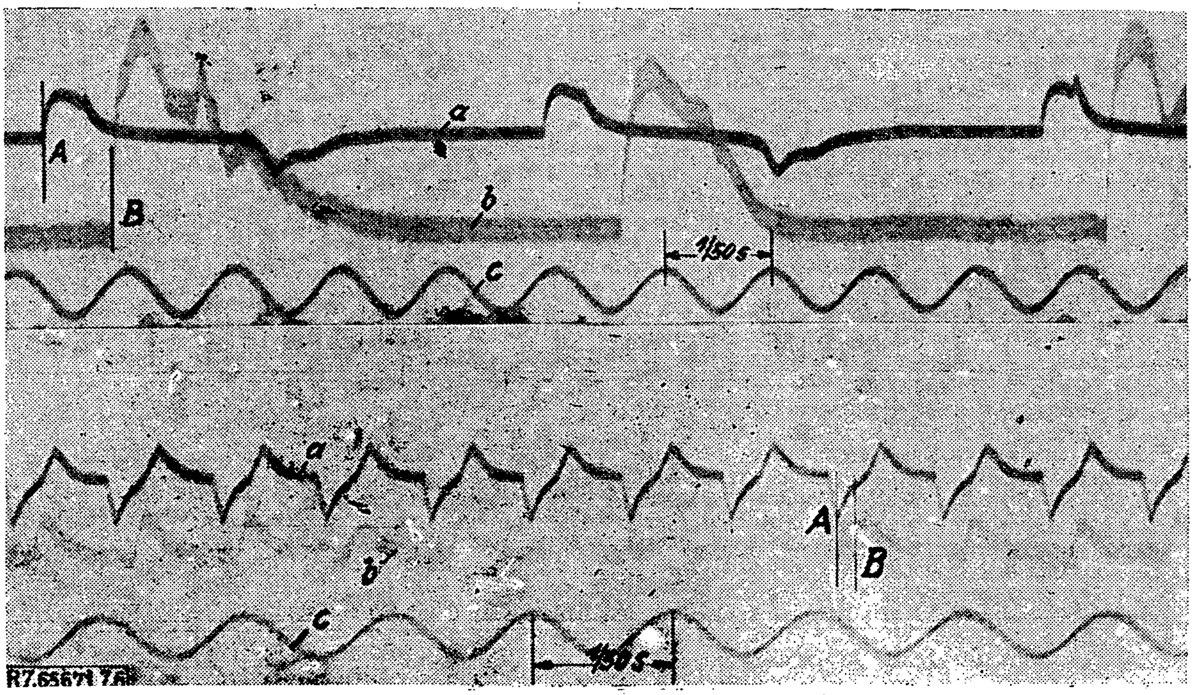


Fig.6 Oscillogram for determining combustion velocity(alternating current method). Above,4-cycle engine 1275 r.p.m. Below,2-cycle engine,4180 r.p.m. a, ignition current. b, ionization current. c, time record. A, ignition instant. B, instant of flame arrival.

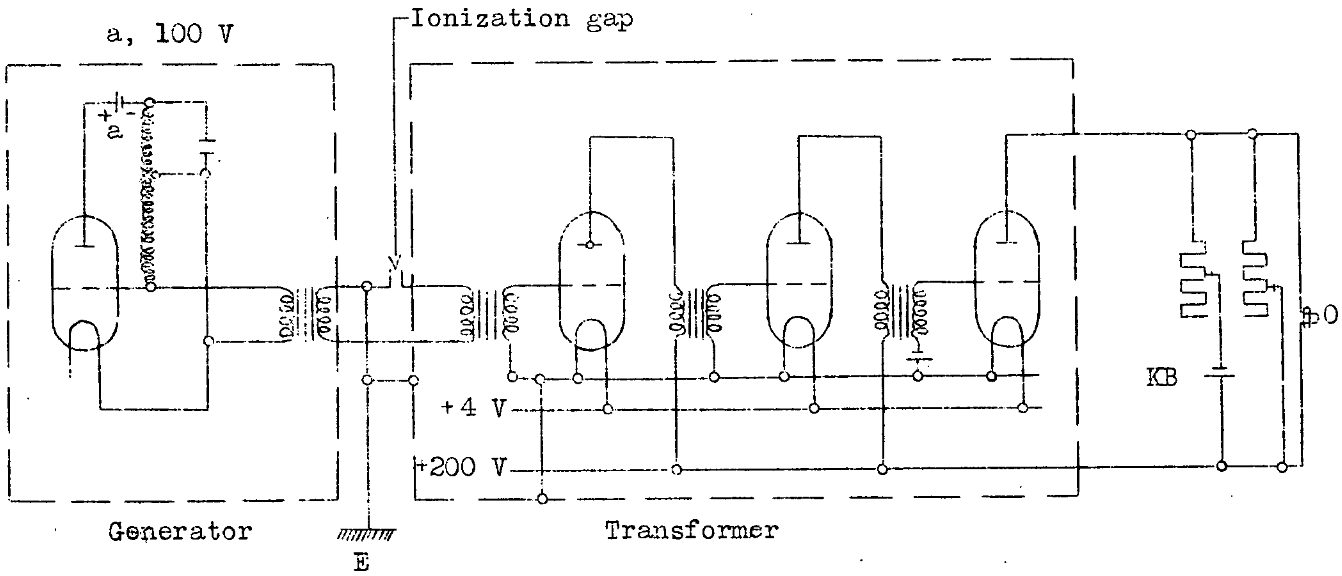
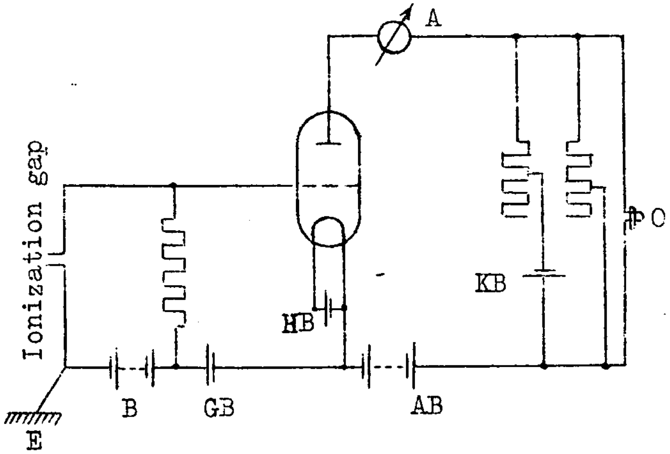
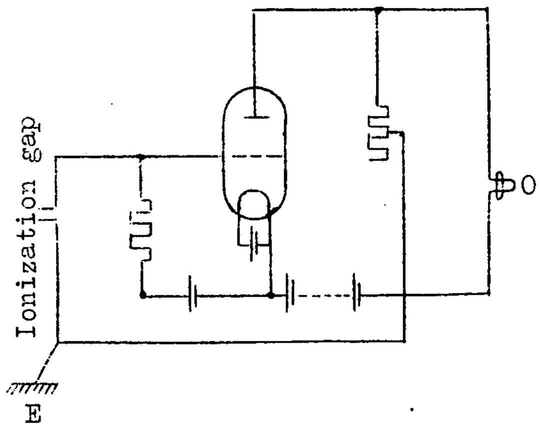


Fig.5 Wiring for alternating current. O, Oscillograph. E, Earth. KB, Compensation battery.



O, Oscillograph
A, Ampere meter
E, Earth
B, Supply battery
AB, Anode battery
GB, Lattice battery
HB, Thermal battery
KB, Compensation battery

Fig. 7 Connections for direct current.



E, Earth
O, Oscillograph

Fig. 8 Simplified connections for direct current.

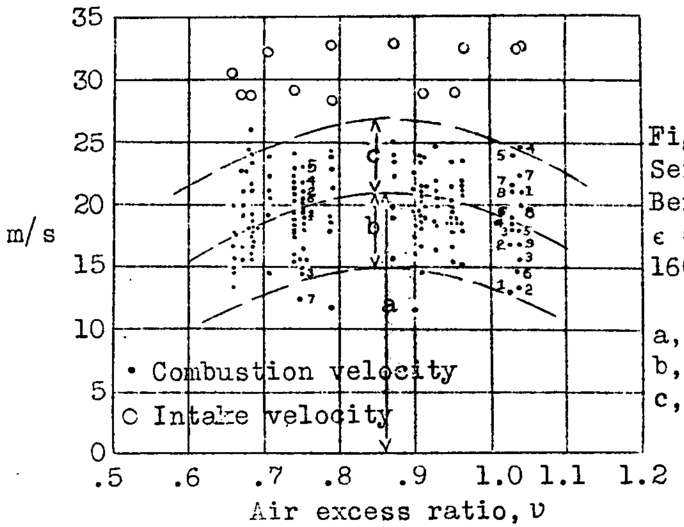


Fig.10
Series 1
Benzol,
ϵ = 5:1
1600 r.p.m.

a, Intake
b, -Turbulence
c, + "

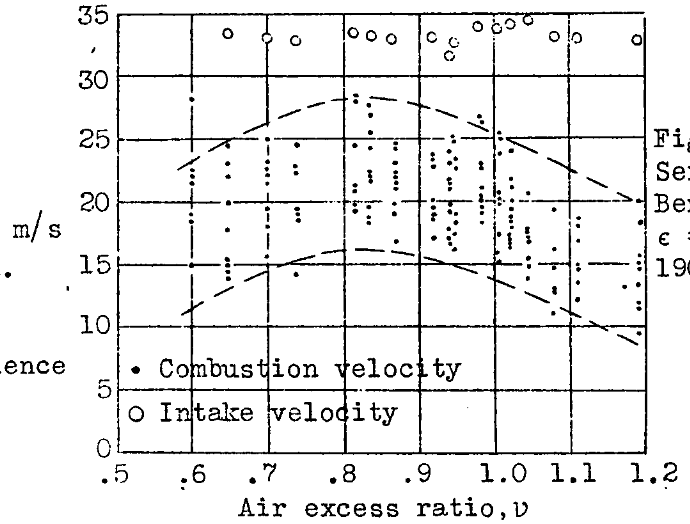


Fig.14
Series 5
Benzol,
ϵ = 5:1
1900 r.p.m.

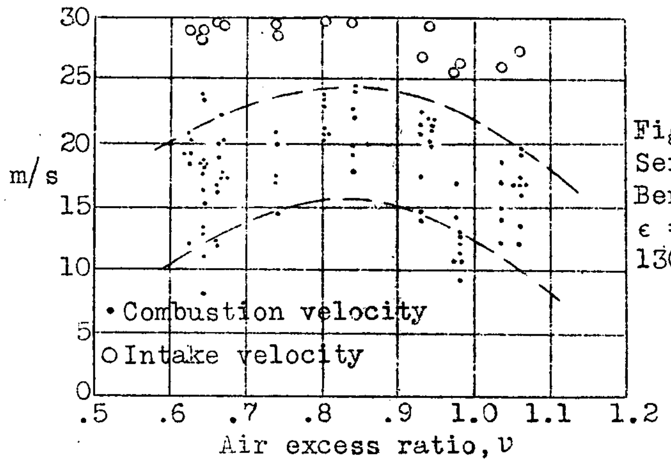


Fig.11
Series 2
Benzol,
ϵ = 5:1
1300 r.p.m.

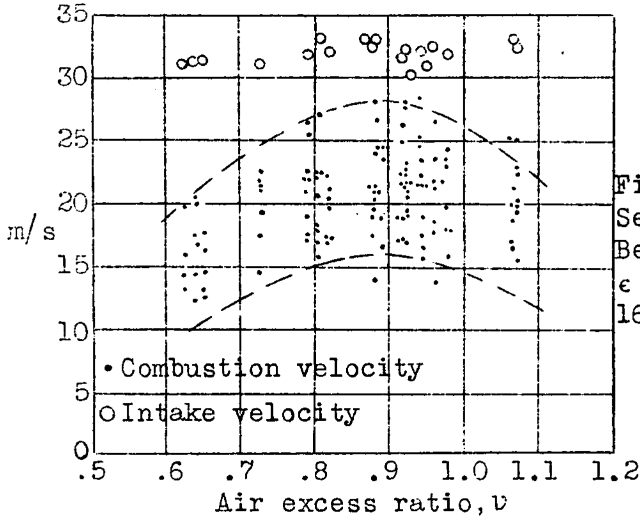


Fig.15
Series 6
Benzol,
ϵ = 6:1
1600 r.p.m.

Relation between combustion velocity and excess air ratio, ν

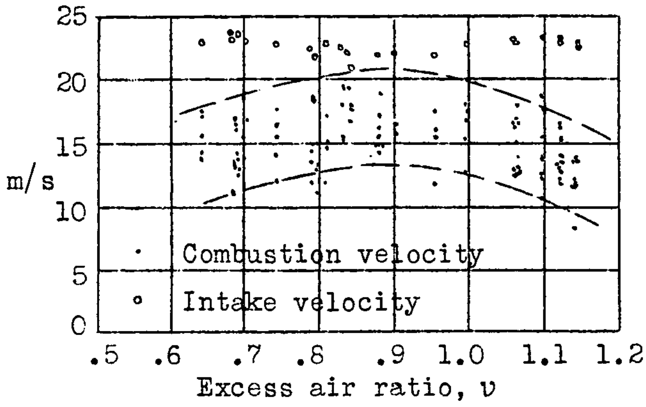


Fig. 12 Series 3 Benzol, ε = 5 : 1 1000 r.p.m.

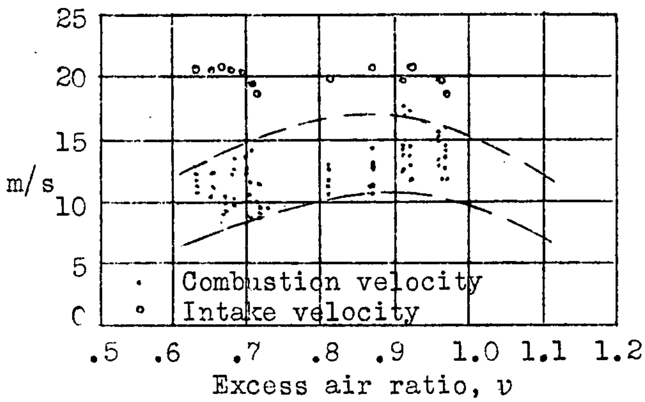


Fig. 13 Series 4 Benzol, ε = 5 : 1 800 r.p.m.

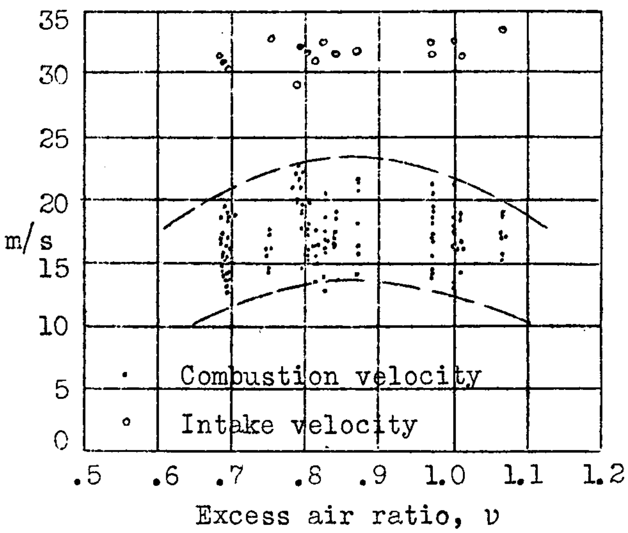


Fig. 16 Series 7 Benzol, ε = 4 : 1 1600 r.p.m.

Figs. 12,13,16, Relation between combustion velocity and excess air ratio, ν