

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

No. 1110

FEB 25 1947

ON COMBUSTION IN A TURBULENT FLOW

By K. I. Shelkin

Journal of Technical Physics (USSR)
Vol. XIII, Nos. 9-10, 1943



Washington
February 1947

NACA LIBRARY
LANGLEY MEMORIAL AERONAUTICAL
LABORATORY
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 1110

ON COMBUSTION IN A TURBULENT FLOW¹

By K. I. Shelkin

The characteristics introduced by the turbulence in the process of the flame propagation are considered. On the basis of geometrical and dimensional considerations an expression is obtained for the velocity of the flame propagation in a flow of large scale of turbulence.

INTRODUCTION

It has long been a well-known fact that the motion of a gas very greatly increases the rate of combustion of the gas mixture. The combustion of fuel mixtures under practical conditions always occurs in a flow existing either before the combustion (furnaces, internal-combustion engines) or arising in the process of combustion process as a result of the propagation of the burning gases (the inflammation of mixtures at rest in pipes, gas reservoirs, inflammation of methane in mines, etc.). For this reason, it is very essential to study the laws of increase in the rate of combustion as a function of the properties of the gas flow.

In connection with this problem, it is necessary to distinguish the effect of the motion of the gas mass with a certain definite velocity whereby the combustion surface is expanded and thereby the combustion rate increased, from the effect of the turbulent fluctuations, the velocity irregularities of smaller scale.

In a gas at rest or in a laminar flow the velocity of propagation of the flame in a direction perpendicular to the surface of combustion is constant. This velocity is denoted as the normal or fundamental flame velocity; it depends only on the physicochemical properties of the mixture, and does not depend on the motion of the gas. The total rate of combustion, the volume of gas burned per unit of time, is equal to the product of the flame area by the normal combustion velocity. In a turbulent flow; for example, in a burner or pipe, the combustion surface is not smooth as in a laminar flow, but there appear on it small disturbances of the flame front produced by the turbulent fluctuations.

¹Jour. Tech. Phys. (USSR), vol. XIII, nos. 9-10, 1943, pp.520-530.

If there is considered a sufficiently large surface, the dimensions of which are large in comparison with the scale of turbulence, the rate of combustion per unit surface will no longer be constant as in the case of the laminar flow, but will increase and will depend on the velocity of the fluctuations. In this sense it is as though the normal velocity of combustion increased. In this paper an attempt will be made to arrive at a quantitative estimate of this increase.

Qualitatively, the effect of turbulence on combustion has been known for 60 years. Mallard and Le Chatelier (reference 1) wrote in 1883 that turbulence (agitation) increases the heat transfer, increases the surface of the flame, and forms new centers of inflammation. The turbulence may increase the velocity of the flame 100 times compared with its velocity in a medium at rest. The fact that the ignition of slowly burning mixtures in mines may lead to catastrophic explosions was explained by Mallard and Le Chatelier as due to the effect of the turbulence.

Unfortunately, since the publication of the work of Mallard and Le Chatelier 60 years ago, the concepts with regard to this phenomenon have undergone no essential change. The authors know of only one work (reference 2) in which an attempt is made at a quantitative approach to the study of this phenomenon; this work will be discussed in the presentation which follows.

Recall the fundamental characteristics of turbulent flow. The latter is characterized by the degree, scale, and frequency of the turbulence. The degree of turbulence, or simply the turbulence, is quantitatively determined by the Karman number K given by

$$K = \frac{\sqrt{v^2}}{W}$$

where $\sqrt{v^2}$ is the mean square value of the fluctuating component of the velocity, denoted in what follows by v' , and W is the mean velocity of the flow. The turbulence depends on the geometric dimensions, the configuration and degree of roughness of the pipe through which the gas moves, and does not depend on the velocity of the flow and the Reynolds number Re when the latter is above the critical and the turbulence is measured at a sufficiently large distance from the entrance or turbulence-producing screen. This assertion is based on turbulence measurements in aerodynamic wind tunnels. It possibly is also valid for chambers of other shape as the combustion chamber of an engine. Thus the fluctuating velocity, at least in pipes, increases proportionately with the mean flow velocity.

The scale of turbulence may be determined by the expression

$$\lambda = \int_0^{\infty} R dx$$

where

$$R = \frac{|v_1| |v_1'|}{\sqrt{v_1^2} \sqrt{(v_1')^2}}$$

is the coefficient of correlation and x the distance between two points in the space in which there are simultaneously measured the fluctuating components v_1 and v_1' . In the physical sense the scale of turbulence is the distance for which there exists a relation between the fluctuations. Roughly speaking, it is the distance penetrated by a turbulent gas element in which the element mixes with those surrounding it. In a flow there is always observed an entire spectrum of scales starting with the largest.

The frequency of the fluctuations may be thought of as connected with the scale and the velocity of the fluctuations, and hence is not an independent magnitude characterizing the turbulence.

In all cases of combustion in turbulent flow, the most essential property of the flow as regards combustion is the forced mixing of the elementary volumes of the gas. The intensity of the turbulent mixing is determined by the coefficient of the turbulent exchange $\lambda v'$ which has the dimensions of temperature conductivity, coefficient of diffusion or of kinematic viscosity.

The turbulent exchange affects the process of the mixing of air with the fuel if the latter were not previously mixed. This process, however, will not be considered in what follows. The combustion of a homogeneous fuel mixture leaving aside the stage of mixture formation will be considered.

ELEMENTARY THEORY

In considering combustion in a turbulent flow, it is necessary to compare a magnitude having the dimensions of length and characterizing the turbulence (i.e., the degree of turbulence) with a magnitude of the same dimensions characterizing the combustion: namely, the width of the flame front. On the ratio of the scale of turbulence to the width of the front of the normal flame depends the nature of the effect of the turbulence on the speed of propagation of the combustion. Two cases may be considered: namely, when the scale is respectively small and large as compared with the width of the flame front.

The scale of the turbulence is small with respect to the width of the zone of normal combustion. This case was considered by Damköhler (reference 2) who for the speed of the turbulent propagation obtained the relation

$$u_T = u_N \sqrt{\frac{\chi_T}{\chi_M}}$$

where u_N is the speed of normal combustion (according to Damköhler, the speed in the laminar flow), χ_T the coefficient of turbulent exchange, and χ_M the temperature conductivity.

A similar result was arrived at independently by Y. B. Zeldovich (private communication to the author). This type of relation is obtained, since it is assumed that the reaction time in the flame front is determined by the speed of the chemical reaction but the process of mixing in the flame front takes so little time in comparison with the reaction time that the mixing time may be neglected. This actually occurs when the scale of fluctuations l is small in comparison with the width of the front, and the coefficient of turbulent exchange cannot be neglected in comparison with the temperature conductivity.

Consider the flame front under these conditions. On figure 1 is shown schematically the temperature distribution in the flame. According to the theory of normal flame propagation (reference 2) the velocity of the flame, independent of the mechanism of the reaction, is of the order of the square root of the temperature conductivity divided by the reaction time:

$$u \sim \sqrt{\frac{\chi}{\tau}}$$

The reaction time τ_x in the normal flame is determined for a temperature near the combustion temperature and depends on it according to the law of Arrhenius:

$$\tau_x \sim e^{E/RT}$$

where τ_x is given with an accuracy up to a factor having the dimensions of time.

Let the temperature T at the section B determine the reaction time. In the case of the absence of turbulence the temperature will be the same at all points of the section. It is assumed that the same

temperature distribution is also established in the presence of turbulent exchange. In that case, at a mean temperature T in section B the temperature at various points of this section will be different; it will vary approximately from $T - \lambda \frac{dT}{dx}$ to $T + \lambda \frac{dT}{dx}$. It is recalled that λ is the scale of turbulence. The turbulent fluctuations will bring the gas into section B from the neighboring layers included between sections A and C and at a distance from B equal to the scale of turbulence. It is evident that the scale of the elementary areas lying in section B the temperature of which differs from T will be of the order of λ^2 . In such a distribution of the temperature over the section the reaction time over the entire section will no longer be determined by the mean temperature T . To a rough approximation it will be of the order

$$\tau_x \sim \frac{e^{\frac{E}{R\left(T + \lambda \frac{dT}{dx}\right)}} + e^{\frac{E}{R\left(T - \lambda \frac{dT}{dx}\right)}}}{2} \quad (2)$$

The order of magnitude of the temperature gradient is $\frac{T_c - T_0}{\lambda}$, where T_c and T_0 are the combustion temperature and the initial temperature, respectively, and λ is the width of the flame front. In the case where $\lambda \frac{dT}{dx} < T$ or $\lambda \left(T_c - T_0 \right) < T$, there is obtained on neglecting second-order quantities

$$\tau \sim e^{\frac{E}{RT}} = \tau_x$$

This condition is realized if $\lambda \ll \lambda$.

Suppose that λ increases for a constant turbulence exchange coefficient $\lambda v'$. The temperature distribution and the gradient depend on $\lambda v'$ and hence remain unchanged, and λ likewise does not change. The ratio λ/λ , however, increases and in the end $\lambda \frac{dT}{dx}$ cannot be neglected in comparison with T . The reaction time in section B for the same mean temperature T will be determined by the exponential curve

$$\tau \sim e^{\frac{E}{R\left[T - \lambda/\lambda (T_c - T_0)\right]}}$$

For some value of λ it will become so large that an element of the gas with a temperature $T - \lambda/\lambda (T_c - T_0)$ mixes with the neighboring elements rather than reacts. The combustion will be determined by the rate of mixing of the element of gas (with subsequent rapid combustion

at a higher temperature and a corresponding concentration of reaction products). For large values of l therefore the determining factor will be the mixing time of an order of magnitude to l/v . It may be noted that for constant lv' , l/λ increases with l but the reaction time depends on the temperature exponentially, and therefore increases more rapidly.

Thus it may be stated that for scales of turbulence of the order of the width of the combustion zone the reaction time will be determined not by the speed of the reaction at a given section but by the speed of mixing of the elementary volumes of the gas. This is what constitutes the new factor introduced by the turbulence in the mechanism of the propagation.

Bearing in mind what has been said previously, the following resume may be made. For turbulence of small scale ($l < \lambda$), the speed of propagation of the turbulent flame depends on the ratio of the coefficient of turbulent exchange to the temperature conductivity. If it is assumed that the molecular and turbulent (diffusive) flows combine ($\chi = \chi_T + \chi_M$)

$$u_T \sim \sqrt{\frac{\chi_M \chi_T}{\tau_x}} = u_N \sqrt{1 + \frac{\chi_T}{\chi_M}} \quad (1a)$$

The above formula has the advantage as compared with (1) that in the limit for $\chi_T = 0$ it gives $u_T = u_N$.

In a flow of small scale of turbulence the flame propagation is determined by the coefficient of turbulent exchange. Hence, within certain limits (as long as $l < \lambda$) it depends on the scale of turbulence.

For turbulence of large scale, as will be seen later, the scale of turbulence does not affect the flame speed; the determining factors are only the velocity of the fluctuations, the degree of turbulence and the Karman number. In the intermediate range ($l \sim \lambda$) a transition occurs when, at least for strong turbulence ($v > u_N$), the mixing being begins to affect not only the heat transfer (as for small scales) but also the time of chemical reaction in the flame. Thus are presented the laws of flame propagation at a small scale of turbulence, and the properties that appear as the scale increases are showed.

It should be pointed out that the case where the scale of turbulence is small by comparison with the width of the flame front is rarely met with in pure form. Under normal conditions for homogeneous gas mixtures the width of the flame front is of the order of 0.1 millimeter. Under real conditions (gas furnaces, engine combustion chamber) scales of order of magnitude less than 0.1 millimeter can only accompany larger scales and occupy only a certain extreme position in the scale spectrum. However,

immediately on passing to slowly burning mixtures (e.g., lean mixtures) the width of the front may considerably exceed the above-mentioned order of magnitude, and the probability of existence of the case discussed increases.

Next, consider the case where the scale of turbulence is large in comparison with the width of normal combustion zone. An analysis of this case in its general form on the basis of dimensionality considerations permitted Y. Zeldovich to conclude (unpublished work) that the speed of turbulent propagation of the flame does not depend on the scale of turbulence and can be represented by a formula of the type

$$u_T = u_N f(u_N/v')$$

where $f(u_N/v')$ is a function of the ratio of the velocities to be determined. In the case of large-scale turbulence the flame surface is curved. As the velocity of the fluctuating components increases the curvature increases, and finally the flame front begins to break away. At strong turbulence the elementary volumes of gas, both burning and fresh, move chaotically with respect to one another. In the flame there remain "islands," centers of unburned mixture, broken off by the fluctuations into parts and annihilated by the flame. If the effect of the curvature on the speed of flame propagation is neglected, the normal flame speed may be considered as constant. The surface of combustion, however, increases and hence also the total rate of combustion.

Before determining the speed of turbulent combustion over the flame surface, consider the limiting case of a strong large-scale turbulence when the combustion zone is filled with islands of unburned mixture.

In figure 2 the space between the sections AA and BB may be considered as the reaction zone of the turbulent combustion. In front of the plane AA is the fresh mixture, and behind the plane BB are the products of combustion. From A to B the mean concentration over the cross-sectional areas of the products of combustion increases, and the concentration of the fresh gas decreases. The distance between the sections may be considered as the width of the turbulent flame front. As was mentioned previously, the speed of the flame, from dimensional considerations independent of the mechanism of the reaction is a magnitude of the order of

$$u \sim \sqrt{\chi/\tau} \quad (3)$$

In a turbulent flame the part of the temperature conductivity is taken by the coefficient of exchange lv' and the part of the reaction time by the mixing time l/v' , and this gives for the velocity:

$$u_T \sim \sqrt{\frac{\lambda v'}{\lambda/v'}} = v' \quad (4)$$

Thus the conclusion is reached: for large turbulence when the velocity of fluctuation v' is large by comparison with the normal velocity u_N (only in this case will the combustion front have a form like that in fig. 2), the velocity of turbulent flame propagation is proportional to the mean fluctuating velocity and does not depend on the chemical nature of the gas mixture.

The reaction time in a turbulent flame may be computed in a different manner. The combustion time of an elementary volume λ^3 may be determined as

$$\tau \sim \frac{\lambda^3}{\bar{S}_S u_N} \quad (5)$$

where $\bar{S}_S u_N$ is the volume rate of combustion, the product of the flame area by the normal velocity. It should be taken into account that an elementary volume with area of the order λ^2 on entering the combustion front is broken up into parts by the fluctuations. The breaking up will continue as long as the flame with normal velocity u_N passes over a distance equal to the scale of turbulence λ , this time is equal to λ/u_N . During this time the total path traversed with the fluctuating velocity reaches the value $L = \lambda/u_N v'$.

The ratio L/λ shows how many times during the combustion of the volume λ^3 the latter is traversed by fluctuations. Each such traversal leads to the formation of a new flame area of the order to λ^2 . The mean area of combustion of an element λ^3 will be proportional to the magnitude

$$\lambda^2 v'/u_N \quad (6)$$

The averaging of this quantity with respect to the combustion time affects only the constant factor. The time required for burning the volume λ^3 is found equal to

$$\tau \sim \frac{\lambda^3}{\lambda^2 \frac{v'}{u_N} u_N} = \frac{\lambda}{v'} \quad (7)$$

The same result is attained; namely, that the combustion time is proportional to the mixing time.

The case where $v' \gg u_N$ has been considered. The case of small turbulence may be approached only geometrically. It is in this manner that the problem is considered by Damköhler. Rightly seeing the reason for the increase in velocity of combustion in the increased area of the flame surface, he schematically represents the flame surface as consisting of conical surfaces with their bases at right angles to the direction of flame propagation (fig. 3). Taking the areas of the cones proportional to v' he arrives at the expression

$$u_T \sim v'$$

The considerations of Damköhler are not accurate and for small v' are not true. According to Damköhler, the absence of turbulence ($v'=0$) leads to zero velocity of the flame. Actually a relation like (4) as shown above is obtained only for strong turbulence $v' > u_N$, and not for weak turbulence which is the case considered by Damköhler.

Consider this problem more in detail. The ratio of the speed of turbulent propagation of the flame to the normal speed will be equal to the ratio of the lateral area of the figure a (fig. 3) to its base. The height of the figure, which is assumed as a cone, will be of the order lv'/u_N . For an element of the flame front will be carried away by the fluctuation from the general flame front only during the time required for the normal of the flame to traverse the distance l . This time is equal to l/u_N . The height of the cone will therefore be of the order of lv'/u_N . The lateral area is

$$S_{lat} \sim Al^2 \sqrt{1 + B(v'/u_N)^2}$$

where A and B are nondimensional coefficients of the order of unity. The ratio of the velocities of propagation is

$$\frac{u_T}{u_N} = \frac{S_{lat}}{S_{base}} = A_1 \sqrt{1 + B(v'/u_N)^2} \quad (8)$$

For strong turbulence $v' > u_N$ (equation (8)) leads to the known relation

$$u_T \sim v'$$

The absence of turbulence $v' = 0$ should lead to the condition $u_T = u_N$. This gives the value $A_1 = 1$.

For any turbulence, including small turbulence, the criterion should hold

$$\left(\frac{u_T}{u}\right)^2 = 1 + B \left(\frac{v'}{u_N}\right)^2 \quad (9)$$

The value of the fluctuating component of the velocity is thus found to vary hyperbolically with the velocity of turbulent flame propagation (fig. 4). If v' is replaced by the product of the Karman number by the mean flow velocity, the formula is obtained

$$\left(\frac{u_T}{u_N}\right)^2 = 1 + BK^2 \frac{W^2}{U^2 N} \quad (10)$$

in which all magnitudes are subject to direct measurement.

It is of importance to note that in the finite expression (9) or (10) the scale of turbulence does not enter. Hence, the obtained relation will be valid for any scale, provided the latter does not exceed the width of the normal combustion front.

SOME PRACTICAL REMARKS

From formula (9) it follows that for large ratios v'/u_N (or by formula (10) KW/u_N) unit y may be neglected under the root sign. The combustion velocity is then independent of the normal flame velocity and therefore of the physicochemical properties of the mixture, and is proportional to the fluctuating velocity. For a given value of the latter (large in comparison with u_N) different fuels will burn at the same rate. If the ratio v'/u (KW/u_N) is of the order of 1 or less, the rate of combustion will depend on u_N . Within increasing fluctuating velocity the rate of combustion increases hyperbolically. For very small v' the effect of the turbulence may be neglected as a second-order magnitude. By comparing v'/u_N with unity, it should be remembered that the value of B is equal to 1 only in order of magnitude. Furthermore, it will evidently depend on the structure of the turbulence. For example, in pipes with roughness of various shapes determining the structure of the turbulence, different values of B may be expected.

Examination of formula (9) permits drawing the conclusion that if the velocity of fluctuation is not very large in comparison with u_N the effect of the turbulence on the speed of propagation characterized by the relative increase in the combustion velocity (u_T/u_N) will be greater the slower the combustion of the mixture of the same composition at rest. The lower the value of u_N the greater the given v' (given turbulence), the numerical value of the root in formula (9).

This conclusion is confirmed by the published tests on the effect of swirling and turbulence on the speed of combustion (reference 3). Swirling always more greatly increases the speed of combustion of lean and rich mixtures than stoichiometric mixtures. The conditions of the experiment do not permit a quantitative analysis of these data but qualitatively they correspond in any case to these results. To evaluate the possible effect of turbulence on the flame propagation, it is necessary first of all to know the normal speed of combustion u_N and, of course, the speed of the fluctuations or, if the turbulence is known (the Karman number), the mean flow velocity. In table 1 are given the normal flame speeds for certain fuel-air mixtures taken from the book of Jost (reference 4) (the speeds correspond to the composition of the mixture of maximum combustion rate). As an example, there are also given the mean flow speeds for 5-percent turbulence ($K = 0.05$), the mean fluctuating speed of which is equal to the corresponding normal speed of the flame.

Table 1

| Fuel | u_N (cm/sec) | W (m/sec) |
|--|-------------------|--------------|
| Hydrogen | 267 | 53.4 |
| Acetylene | 131 | 26.2 |
| Ethylene | 63 | 12.6 |
| Propylene | 43.5 | 8.7 |
| Methane | 37.0 | 7.4 |
| n-pentane | 35.0 | 7.0 |
| n-hexane | 32.0 | 6.4 |
| Benzol + 0.5 per- cent H_2 | 38.5 | 7.7 |
| Carbon monoxide + 1.2 percent water | 41.5 | 8.3 |

Table 1 gives an indication of the order of flame speed at 5-percent turbulence when there is to be expected a hyperbolic dependence of u_T on W or when this dependence may be considered as linear. Thus, for hydrogen-air mixtures of stoichiometric composition a linear

dependence (and independence of the speed of propagation on the normal flame speed) may be expected at flow speeds exceeding approximately seven to eight times the speed giving this dependence in pentane or benzol - air mixtures. For hydrogen these will be speeds of the order of hundreds of meters per second; for benzol, methane, pentane, hexane, of the order of tens of meters per second. If the turbulence is increased two times, up to 10 percent, then to attain the same result half the flow speed would be required, and so forth.

The practical independence of the speed of flame propagation on the physicochemical properties of the fuel in the engine was also observed by Marvin (reference 5). On figure 5 are given the curves of the flame path against the crank angle degrees obtained at constant engine speed. The slope of the curves gives the flame speed. In the center part of the combustion chamber where the flame front is sufficiently developed the flame speed changes little over a large distance of the chamber, and for various fuels is approximately the same while the normal combustion speeds of these fuels differ considerably from one another (table 1). Different speeds in the engine are observed only in the initial stage of the flame propagation.

The results of Marvin can readily be explained. The velocities of the fluctuations of the gas in the engine are large in comparison with the normal velocities so that the flame propagation is described by expression (4), that is, the rate of combustion is proportional to the speed of the fluctuation, and does not depend on the normal flame speed. It is very probable that under the same conditions for hydrogen or acetylene the speeds would be different. It is possible that for these gases the same speed of the fluctuations would not be large by comparison with u_{fl} . These considerations are in the nature of suppositions since the true value of the speed of the fluctuations under the test conditions of Marvin is not known.

The absence of an accelerating effect of the turbulence in the initial phase of the combustion (well known from the engine literature) may from the author's point of view be explained by the fact that at the start of combustion when the dimensions of the flame are small in comparison with the scale of the turbulence the latter does not affect the rate of combustion. A center of combustion is displaced as a whole by the fluctuation, and its surface therefore does not become branched. The rate of combustion is determined only by the normal flame speed. In this way it is assumed that the turbulence in the engine is of relatively large scale.

Certain results for comparison of the theory with experiment are given also by other investigations conducted on engines. There are, however, fundamental difficulties, in applying the theory previously presented, to combustion in the engine. Consider a few of these.

In the first place, with regard to the effect of the rotational speed on the combustion rate, it is not known whether the Karman number remains constant when the speed changes. This can only be assumed on analogy with pipes and special determinations of K , for engines are lacking. In the second place, the true effect of the motion of the entire mass of the gas in the engine chamber on the combustion rate is not clear. It may be supposed that owing to the small length and the strong turbulence-producing effect of the intake valve, the degree of turbulence of the flow during intake and then in the chamber will be very strong, and the part played by the regular motion of the gas is small. Finally, photographs give the flame speed with respect to the walls of the chamber and not with respect to the gas, which is of interest in the latter speed. In the latter case, however, the picture is not clear. It may, moreover, be supposed that rotational flows are predominant in the engine. This is indicated, for example, by Marvin's photographs in which a curving of the flame front is noted, explained by the circular motion of the gas in the cylinder head. These considerations are confirmed also by the fact that generally over a considerable distance of the combustion chamber the photographs of the flame in the engine show an only slightly varying flame speed. In the case of the presence of a strong flow along the chamber (from one end to the other) there should exist also a return flow. It would then be possible to expect large irregularities in the flame propagation. There is, therefore, some basis for supposing that the principal cause for the increased rate of combustion in the engine is the turbulence and not a mass movement of the gas in the engine head. In this respect the opinion of engine specialists may be subscribed to: for example, Bouchard, F. Taylor, and E. Taylor, who write, "the rapid increase in the maximum combustion rate with rotational speed is due primarily to an increase in the small-scale in contrast to the organized motion of the gas in the engine head but not in the sense of comparison with the width of the flame front of normal combustion, of higher gas velocities through the intake system." (See reference 6.) The same authors investigated the dependence of the flame speed on the rotational speed. The curve of flame speed against rotational speed is given in figure 6. The speed of the mixture on intake, and therefore the speed of the gas in the chamber, increases in proportion to the rotational speed. Hence, in figure 6 on the axis of abscissas instead of the rotational speed there may be laid off a magnitude proportional to the speed of the gas or under the assumptions made to the speed of the fluctuations. The shape of the curve corresponds strongly to the theoretical relation obtained (fig. 4). Unfortunately, for small rotational speeds the experimental curve is extrapolated (dotted). Bouchard, F. Taylor, and E. Taylor drew this part of the curve on the basis of measurement of the time of combustion of 95 percent of the charge. The tests of these authors confirm (though indirectly with account taken of the assumptions made) the conclusions as to the effect of the speed of the flame propagation. An accurate check of the theory requires, of course, special tests with parallel measurement of the speed of combustion, Karman number and flow speed.

CONCLUSIONS

1. With strong turbulence as the scale of the turbulence increases to a value comparable with the width of front of normal combustion, the rate of the combustion reaction begins to depend on the mixing.
2. For turbulence the scale of which exceeds the width of the front of normal combustion ($l > \lambda$), the speed of the flame propagation increases hyperbolically with the speed of the fluctuations. For large fluctuation speeds ($v' > u_N$) the dependence may be considered linear, and for small values ($v' < u_N$) the effect of the turbulence is of second-order smallness.
3. The data presented in the literature on the measurement of the flame speeds of various fuels in the engine and the measurement of the dependence of the flame speed on the rotational speed confirm the theoretical conclusions, if it is assumed that the increase in the combustion rate in the engine is determined by the turbulence.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

REFERENCES

1. Mallard and Le Chatelier: Ann. de Mines, 1883.
2. Danköhler, G.: Zeitschr. für Elektrochemie, vol. 46, no. 11, Nov. 1940, pp. 601-626.
3. Lafitte, P.: La Propagation des Flammes dans les Melanges Gaseux. Paris, 1939, p. 72.
Lewis, B., and von Elbe, G.: Combustion, Flames, and Explosions of Gases. 1938, p. 192.
4. Yost, W.: Explosions and Verbrennungs Vorgänge in Gasen. Julius Springer (Berlin), 1939.
5. Marvin, Charles F. Jr.: Observations of Flame in an Engine. SAE Jour., 1934, p. 391.
6. Bouchard, C. L., Taylor, C. F., and Taylor, E. S.: Variables Affecting Flame Speed in the Otto-Cycle Engine. SAE Jour., vol. 41, 1937, p. 515.

BIBLIOGRAPHY

1. Zeldovich, Y. B.: Jour. Experimental and Theoretical Physics. (USSR), vol. 11, 1941, p. 159.

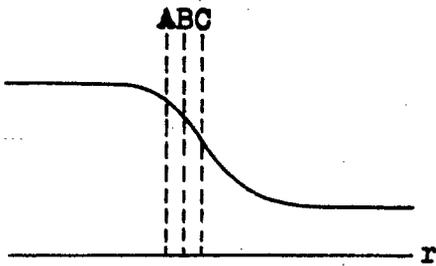


Figure 1.

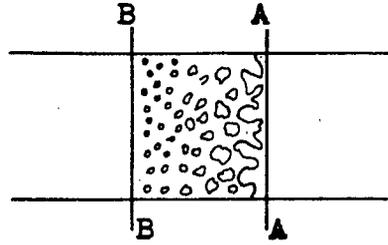


Figure 2.

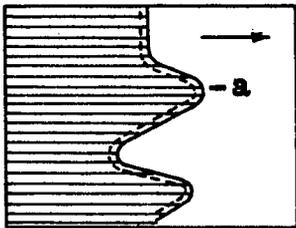


Figure 3.

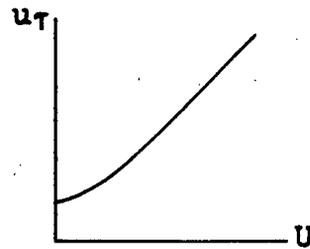


Figure 4.

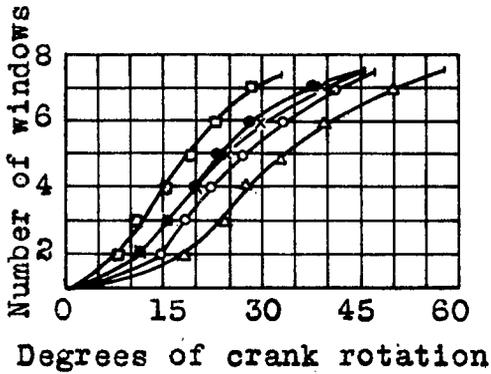


Figure 5.- □ Ethylene
 ● Ethane × Propylene
 ○ Propane △ Methane

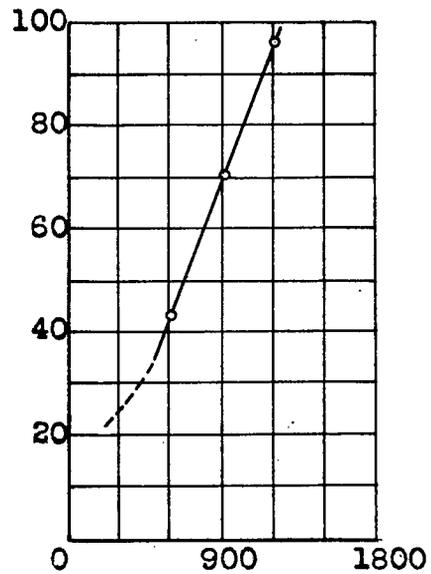


Figure 6.

Author



Flow of gas

Flame propagation
Effect of turbulent flow
Combustion
Effect of turbulent flow