IGNITION LIMITS IN TURBULIZED GAS MIXTURES

![Figure 1](image)

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Figure 1

Figure 1: Figure 1

Abstract

Full Text

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IGNITION LIMITS IN TURBULIZED GAS MIXTURES

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Ignition of a gas mixture by a spark is one of the types of thermal explosion, the critical conditions of which are determined by equality between the rates of heat release from the reaction in the volume heated by the spark and heat removal from the outer surface of the reaction kernel into the surrounding gas (see (^{1}), § 15). The method of artificial turbulization of a gas under conditions of a closed volume (^{2}) makes possible a quantitative investigation of the influence of turbulence on the ignition of gases by a spark. The data shown in Fig. 1 indicate that, at a constant energy of the capacitor spark, with an increase in the absolute intensity of turbulence (U'_Σ) created in the bomb, the concentration limits narrow, or the lower pressure limit rises. The concentration limits also narrow as the spark energy is decreased, and the more strongly, the higher the turbulence intensity (see the dash-dot curve in Fig. 1 II). Qualitatively, these results agree with observations in a turbulent flow of a gas-air mixture: an increase in the limiting ignition current as the flow velocity increases (^{3}). However, the significance of the observations presented is not exhausted by the demonstration of the, at first sight, trivial fact that intensification of turbulent heat removal from the initial reaction kernel makes ignition by a spark more difficult. Indeed, in the case of a turbulent mechanism of heat exchange there should have been no influence whatever on heat transfer and, consequently, on the ignition limit, from the thermal conductivity of the gas. It is precisely for this reason that the rate of turbulent combustion, directly determined by turbulent diffusion, does not depend on the thermal conductivity of the gas mixture and, hence, on the laminar burning velocity (at unchanged partial pressures of the reacting components and combustion temperature).

Fig. 1. Ignition limits of a propane-air mixture: **I** —by pressure at various compositions of the mixture; **II** —by concentration at $P_0 = 1$ atm and at constant spark energy; *a* —when the spark energy is reduced by a factor of 20; *b* — ignition limits of a methane-air mixture.

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

Fig. 2. Ignition limits of stoichiometric mixtures with oxygen of propane and hydrogen, diluted with argon (*a*) or helium (*b*).

This fact, which constitutes one of the decisive proofs of the incompatibility of the mechanism of turbulent combustion with the so-called "surface-laminar model," is clearly demonstrated by experiments for stoichiometric mixtures with oxygen of propane and hydrogen, diluted with helium or argon and having, respectively, the same combustion temperature (Fig. 2). The rates of turbulent combustion coincide over wide ranges of variation of the turbulence intensity when the laminar burning velocities differ by approximately a factor of 2. But, as is evident from the same Fig. 2, the ignition limit upon dilution with helium occurs at a significantly lower turbulence intensity than upon dilution with argon (for the propane mixture with argon, the available maximum turbulence is altogether insufficient to reach the ignition limit). The data obtained show that even with a 20-fold increase in the spark energy the ignition limit in mixtures with helium remains considerably lower than with argon. It must therefore be acknowledged that turbulent mixing of the gas hampers spark ignition, while the conductive mechanism of heat removal from the initial reaction kernel is preserved. This can be explained by the fact that heat transfer into the fresh gas is determined by the thermal resistance of the boundary layer surrounding the kernel. In the case of weak turbulence, under its action the surface of the initial reaction kernel is curved, as is evident from the series of frames in Fig. 3*b*, obtained by the schlieren cinematography method. Only after 1.5 msec from the moment of spark breakdown, beginning with frame No. 8, does visible fragmentation of the kernel appear, indicating the entry into play of the turbulent transport mechanism proper. Conductive heat removal through the boundary layer of the curved surface exceeds heat removal from the surface of a laminar flame, which leads to a slowing of flame formation in the turbulent gas (cf. the series of frames *a*, *b*) and to a narrowing of the ignition limits.

At strong turbulence, extinction of the initial kernel occurs after it is torn from the electrodes, as can be seen from Fig. 3 . The higher the turbulence intensity, the earlier, in the course of formation, the tear-off occurs, and the greater is the ratio of the surface area to the volume of the reaction kernel. Heat removal from a unit surface is still determined by the thermal conductivity of the gas. Of particular interest are the limits of turbulent ignition of hydrogen–air mixtures. As can be seen from Fig. 4, the ignition limit

Fig. 3. Series of motion-picture frames for hydrogen–air flames with $\alpha = 0.2$:

a —laminar flame, —initial stage of propagation of a turbulent flame at $U'_\Sigma = 2.8$ m/sec,
—tear-off of the initial kernel at $U'_\Sigma = 7$ m/sec, —propagation limit

with an excess of hydrogen occurs at lower turbulence intensities than with an excess of air, despite the higher combustion temperature of rich mixtures; thus, at $\alpha = 0.17$ (comb. temp. 1300° K) the limit is $U'_\Sigma = 2$ m/sec, whereas at $\alpha = 5.6$ (comb. temp. 860° K) the limit is $U'_\Sigma > 5$ m/sec.

In addition to the increased thermal conductivity, the reduction of the limit for rich hydrogen-air mixtures is also substantially influenced by the fact that the reaction rate increases with the ratio O_2/H_2. Thus, according to experimental data (^{4}) and calculations (^{5}), the maximum width of the chain-ignition region corresponds to the composition $H_2 + 4O_2$, i.e. $\alpha = 8$ (see (^{5}), p. 76). The increased reaction rate in mixtures of hydrogen with excess air is also manifested when comparing the rates of turbulent combustion far from the ignition limits. Thus, U_T is considerably higher for a mixture with $\alpha = 4.25$ at a combustion temperature of 1030° K than for $\alpha = 0.2$ and a combustion temperature of 1400° K. Here again the discrepancy between the rates of turbulent and laminar combustion is confirmed: the latter are considerably higher in rich mixtures with an increased coefficient of molecular transport. From the data presented in Fig. 1 it follows that, at the same turbulence intensity, the lean ignition limit for methane mixtures is wider than for propane mixtures, despite the higher thermal conductivity of methane mixtures. This difference should also be attributed to the increase in the reaction rate in lean methane mixtures as compared with higher alkanes, as was shown in our work (^{6}). As can be seen from Figs. 2 and 4,

the increase of the turbulent burning velocity with the intensity of turbulence slows down as the ignition limit is approached, deviating from the linear law $u_T \sim u'_\Sigma \dfrac{t_0}{\tau_i}$ (1). However, a study of the corresponding motion-picture frames, for example Fig. 3b, shows that this deviation cannot be attributed simply to a slowing of the turbulent propagation of the flame. In reality it is connected with a profound change in the very character of flame propagation, namely with the fact that, at high turbulence intensities, the flame propagates in separate tongues and does not fill the entire volume corresponding to the radius of ejection. Calculating, from the total projection of the ejections, the equivalent area of a circle, we naturally obtain an underestimated visible flame velocity $U_\mathrm{v} = dr/dt$. The ratio of the actual volume V_ϕ, encompassed by separate flame ejections, to the volume of a sphere with the radius of the maximum ejection V_M characterizes the incompleteness of filling of the volume by the free turbulent flame and, for the investigated flames of air mixtures of methane, propane, and hydrogen immediately near the ignition limits, has the constant value: $V_\phi/V_M \approx 0.35$.

Fig. 4

Fig. 4

Figure 4: Fig. 4

This quantity is a quantitative characteristic of the probability of extinction of a turbulent flame in the course of its propagation.

As can be seen from the series of frames in Fig. 3a, at a sufficiently high turbulence intensity complete extinction of the turbulent flame occurs after it has encompassed a considerable volume. Here we are dealing with a true limit of propagation of the turbulent flame before the spark-ignition limit is reached. The fact that an intensification of turbulence, together with acceleration of combustion, leads, beginning with some U'_Σ, first to an increase in the probability of extinction and then to complete extinction of the developed center of turbulent combustion follows directly from the ideas of the new model—namely, from the fact that pulsating ignition becomes impossible when the mixing time becomes less than the ignition induction period: $t_0 = l_1/U' < \tau_i$. This reduction of $t_0 = l_1/U'$ below the critical level corresponds to an increase in U' and, together with the pulsation velocity, has a statistical character. With an increase in the root-mean-square value of the turbulence intensity U'_Σ, the probability of realization of the above inequality increases.

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CITED LITERATURE

1. A. S. Sokolik, *Self-Ignition, Flame, and Detonation in Gases*, Publishing House of the Academy of Sciences of the USSR, 1960.
2. A. S. Sokolik, V. P. Karpov, DAN, 129, No. 1, 168 (1959).
3. Kimura Itsuro, Kumagai Seiichiro, J. Phys. Soc. Japan, No. 5, 599 (1956).
4. N. M. Chirkov, *Acta Physicochimica URSS*, 6, 915 (1937).
5. A. B. Nalbandyan, V. V. Voevodskii, *The Mechanism of Oxidation and Combustion of Hydrogen*, Publishing House of the Academy of Sciences of the USSR, 1949.
6. V. P. Karpov, A. S. Sokolik, DAN, 138, No. 4 (1961).

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