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V. P. Karpov and A. S. Sokolik

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Abstract

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V. P. Karpov and A. S. Sokolik

On the Influence of Pressure on the Velocity of Laminar and Turbulent Combustion

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The difference in the mechanism of propagation of laminar and turbulent flames should be reflected in a different dependence of the corresponding combustion velocities on pressure. For laminar combustion this dependence is given by the approximate thermal theory (^{1}), according to which:

$$u_r \sim p_0^{n/2-1}. \tag{1}$$

where n is the order of the gross reaction in the flame.

Measurements carried out in a Bunsen flame cone for a number of air mixtures at pressures below atmospheric led to values $k = n/2 - 1 < 0$: according to (^{2}), for benzene, n-heptane, and iso-octane $k = -0.33$; according to (^{3}), for propane $k = -0.3$; finally, in the summary of measurement results for propane given in (^{4}), $k = -(0.19 \div 0.3)$.

Measurements of the combustion velocity of propane-air mixtures in the initial stage of combustion in a spherical bomb (^{5}) gave $k = -0.05$. The same dependence on pressure was also obtained in our experiments, carried out in the bomb described in (^{6}), for a stoichiometric propane-air mixture over the pressure-measurement range from 0.4 to 1.76 ata. The propagation velocity of a spherical laminar flame was determined over the range of variation of the flame radius from $R \approx 10$ mm (i.e., excluding the ignition stage) to $R \approx 40$ mm (i.e., less than 55% of the bomb radius), when the pressure increase due to combustion does not exceed 3-4% of the maximum pressure increase.

Let us consider the source of such a significant difference in the dependence of u_r on pressure under burner-flame conditions and during propagation in a closed volume. In the latter case the combustion velocity is determined from the visible flame-propagation velocity dr/dt by the relation

$$u_r = \frac{[(dr/dt)]}{\varepsilon}. \tag{2}$$

In determining the degree of expansion due to combustion, ε, the width of the combustion zone is neglected, and the mean temperature of the gas enclosed in

Fig. 1

Figure 1: Fig. 1

the spherical flame is taken equal to the adiabatic combustion temperature, so that

$$\varepsilon = \frac{T_{\text{ad}}}{T_0} \frac{m}{m_0}, \tag{3}$$

where $\frac{m}{m_0}$ is the change in the number of molecules during combustion. However, this assumption is justified only at pressures sufficiently close to atmospheric; as the pressure is lowered and the combustion zone broadens, the mean gas temperature in the flame differs increasingly from the adiabatic temperature; the degree of expansion determined from (3) increasingly exceeds the actual one, and the combustion velocity calculated from (2) proves to be increasingly underestimated in comparison with the true value. A comparison in Fig. 1 of the combustion velocities of a propane-air mixture measured in a burner according to the data of work (^{4}) and of our results in the bomb shows that a noticeable discrepancy between them is found at $p_0 < 0.5$ ata and increases with further lowering of the pressure. Since measurement of the combustion velocity in a flame

the burner is not related to the magnitude of the expansion ratio; the dependence $u_r \sim p^{-(0.2 \div 0.3)}$ should be regarded as the most reliable.

A decrease in pressure is associated with a decrease in the combustion temperature T_r, owing to an increase in the degree of dissociation. The increase of this factor in the dependence of u_r on pressure can be estimated approximately by means of the formula

$$u_r \sim T_r^{2.7} (T_r - T_0)^{-1.5} \exp(-E/2RT_r), \tag{4}$$

which combines all the temperature-dependent factors in the formula of the thermal theory for a flame with a bimolecular reaction. According to the data of (^{7}), for a stoichiometric propane-air mixture within the pressure range studied, T_r changes from 2242 to 2277° K. Taking, on the basis of modern experimental data for hydrocarbon-air mixtures, $E \approx 20$ kcal/mole, we obtain, according to (4), a change in u_r of no more than 1%.

Thus, the entire observed change in the laminar burning velocity within these pressure limits should be attributed wholly to the change in pressure itself. According to (1), this corresponds to a reaction order in the flame of $n \approx 1.4 \div 1.6$.

Fig. 1

The influence of pressure on the turbulent burning velocity in a stream was studied in works (^{4}) and (^{8}) in an open flame, and in the works of Doroshenko and Nikitskii (see (^{9}), p. 32) and (^{10}) in a chamber behind turbulence-generating grids (everywhere within the subatmospheric-pressure range).

In experiments with an open flame carried out at constant Reynolds number, either constancy of the turbulent burning velocity u_t was observed (^{4}), or its increase with decreasing pressure: $u_t \sim p^{-0.25}$ (^{8}). However, the condition $\mathrm{Re} = wd\rho/\mu = \mathrm{const}$ at an unchanged burner diameter means that, as the pressure is lowered, the flow velocity increases as $w \sim p^{-1}$, and with it the level of turbulent pulsations directly acting on the turbulent burning velocity also increases. Indeed, in experiments (^{10}) it was shown that the relative intensity of turbulence $u'/w \sim p^{0.34}$. This means that the absolute turbulence intensity changes as $u' \sim p^{-0.66}$, which should lead to an acceleration of turbulent burning as pressure is lowered, as under the conditions of experiments (^{8}).

Conversely, when a constant flow velocity is maintained, a direct dependence of u_t on pressure is observed, for example $u_t \sim p^{0.4}$ for a propane–air mixture in (^{10}), or with an exponent of 0.25 and 0.5 in the experiments described in (^{9}). In studying the influence of pressure on the turbulent burning velocity in a closed volume, it had first been established that the absolute turbulence intensity u'_Σ (see (^{6})) remains constant at a given voltage on the electric motors of the stirrers over the pressure range from 100 to 760 mm Hg. In the experiments performed, the value $u'_\Sigma = 4.2$ m/sec was chosen, so that for the stoichiometric propane–air mixture $u'_\Sigma/u_r > 10$. The results of these experiments, shown in Fig. 1, within the pressure range 1.76–0.5 ata, correspond to the dependence $u_t \sim p^{0.3}$.

The closeness of the values of the pressure exponent obtained under bomb and flow conditions indicates a fundamental similarity of the mechanism

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1.35 atm

0.4 atm

Fig. 2

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Fig. 2. Luminescence spectra of anthraquinone and its α-derivatives at 77°K in heptane:
1 —anthraquinone; 2 —α-methylanthraquinone; 3 —α-phenylanthraquinone;
4 —α-methoxyanthraquinone; 5 —α-hydroxyanthraquinone.

turbulent combustion, regardless of the way in which the turbulence itself is produced. On the other hand, the observed increase of u_t with increasing pressure at an unchanged turbulence intensity cannot be reconciled with the surface-laminar model in any of its variants, since the laminar and turbulent burning velocities vary with pressure in opposite directions.

From the point of view of the model of pulsating ignition (11) and the general relation

$$u_{\mathrm{t}} \sim u'_{\Sigma} \frac{t_0}{\tau_i} \tag{5}$$

the observed change of u_{t} with pressure, under the condition $u'_{\Sigma} = \mathrm{const}$, represents the combined effect due to the influence of pressure both on the ignition induction period τ_i and on the characteristic diffusion time t_0. According to (10), the turbulence scale l_1 does not depend on pressure; therefore

$$t_0 = \frac{l_1}{u'} \sim p^{-0.34}. \tag{6}$$

This means that u_{t} decreases when the pressure is lowered as a result of an increase in τ_i and a shortening of t_0.

Under the conditions of the bomb experiments, however, i.e., at $u'_{\Sigma} = \mathrm{const}$, one should also assume $t_0 = \mathrm{const}$. Under this assumption the observed change of u_{t} with pressure must be attributed entirely to the change of the ignition induction period with pressure, i.e., $\tau_i \sim p^{-0.3}$. The small value of the pressure exponent indicates that in the present case the kinetic part of the total induction period is comparable with the time of mixing of fresh gas with combustion products.

When the pressure is reduced below 0.5 ata, a sharper decrease of u_{t} is observed than corresponds to the pressure exponent (0.3). As is seen from the series of motion-picture frames shown in Fig. 2, the decrease in this pressure range of the mean propagation velocity of the spherical flame is due to the fact that the flame does not uniformly embrace the whole volume of the sphere, but propagates in separate tongues, analogously to the propagation of a turbulent flame at the concentration limits (see Fig. 3 in (11)). This reflects the increasing difficulty of turbulent ignition as the pressure is lowered, since τ_i increases and t_0 decreases. Under the given experimental conditions turbulent ignition becomes altogether impossible at pressures below 0.4 ata. In terms of the model of pulsating ignition, turbulent ignition is impossible when the ignition induction period exceeds the time allotted to it for diffusive mixing, i.e., when

$$\tau_i > t_0. \tag{7}$$

This is a general condition for the limits of turbulent ignition, whether with respect to pressure or to mixture composition. It should be noted that the hydrodynamic factor enters this condition not only through the magnitude t_0, but also through the magnitude of the induction period, which depends on the conditions of turbulent mixing.

Institute of Chemical Physics
Academy of Sciences of the USSR

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CITED LITERATURE

1. Ya. B. Zel' dovich, D. A. Frank-Kamenetskii, *ZhFKh*, **12**, No. 1, 100 (1938).

2. F. H. Garner, G. K. Ashforth, K. Long, *Fuel*, **30**, 17 (1951).

3. A. Egerton, IV Symposium on Combustion, 1953, p. 321.

4. B. Fine, *Combustion and Flame*, **2**, No. 2, 109 (1958).

5. J. Manton, B. B. Milliken, Proceedings of the Gasdynamic Symposium on Aerothermochemistry, Northwest Univers., Evanston, 1956, p. 157.

6. V. P. Karpov, E. S. Semenov, A. S. Sokolik, *DAN*, **128**, No. 6, 1220 (1959).

7. D. Simon, F. Bells, A. Sprakowski, IV Symposium on Combustion, 1953, p. 100.

8. S. A. Gol' denberg, V. S. Pelevin, VII Symposium on Combustion, 1957, p. 590; *Izv. AN SSSR, OTN, Energet. i avtomat.*, No. 2 (1959).

9. E. S. Shchetinkov, *Sb. Combustion in a Turbulent Flow*, 5, Izd. AN SSSR, 1959.

10. A. V. Khramtsov, VII Symposium on Combustion, 1957, p. 609.

11. A. S. Sokolik, V. P. Karpov, *DAN*, **129**, No. 1, 168 (1959).

Note: Figure translations are in progress. See original paper for figures.