THERMAL MECHANISM OF THE INCREASE IN THE NORMAL RATE OF PROPAGATION OF A FLAME IN A PRECONDUCTION ELECTRIC FIELD

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§1. The action of preconduction electric fields on flames attracted the attention of investigators long ago in connection with the problem of creating simple physical methods for controlling combustion processes [1-3]. In a number of communications, an experimental investigation was made of the effect of direct and alternating electric currents on the rate of propagation of flames (see, for example, [4, 5]).

However, three principal mechanisms of the action of an electric field on flames are usually distinguished, proposed by various authors to explain the observed effects: gasdynamic ("ion wind"), kinetic, and thermal [2].

Each of these mechanisms assumes that the effect of an electric field is above all the result of its action on charged particles, formed due to ionization processes in the flame front.

In the case of a gasdynamic mechanism [3, 5-8], it is assumed that the electric field, acting on the charged regions of the gas, arising as a result of the diffusion of ions and electrons, brings the hot mixture into convective motion, which, as with the propagation of a flame in a gravity field [9], brings about a considerable extension of the front of the flame and an increase in the velocity of its uniform motion, with an unchanged value of the normal velocity. This mechanism of the action appears in constant and low-frequency electric fields, in which the period of the vibrations is far greater than the time of the formation of a gasdynamic structure of the flow at the flame front.

In [2, 3], the increase in the rate of propagation of flames was explained by the action of the electric field on the kinetics of the chemical reactions, as a result of the activation of the reactive particles by the hot electrodes (the kinetic mechanism).

Another possible reason for the increase in the velocity of a flame in an electric field is a rise in the temperature of the reaction mixture due to Joule heat (the thermal mechanism): electrons forming in the combustion zone diffuse into the heating zone and into the zone of the reaction products and, heated up in the electric field, give up their energy to molecules, further heating the gas. As a result, as with the kinetic mechanism, there is an increase in the normal velocity of the propagation of the flame. The role of the thermal mechanism is considerable for highly ionized (hydrocarbon) flames, under conditions assuring the passage of sufficiently large currents with a density of ~ 0.1-1 A/cm^2 through the front of the flame.

To clarify the actual mechanism of a preconduction electric field on the propagation of a flame under these or other experimental conditions, a theoretical study of each of the above-mentioned processes is needed. Below, an investigation is made of the thermal mechanism of the effect of a preconduction electric field on the propagation of a flame in a mixture of previously mixed gases.

Let us consider in more detail the relationship between the kinetic and thermal mechanisms from the point of view of the elementary processes taking place at the flame front.

Electrons, heated up by the electric field, colliding with heavy particles, bring about the ionization and dissociation of molecules, and the excitation of electronic, vibrational, rotational, and translational degrees of freedom.

The first three of the above processes have a high energy barrier in comparison with the rest and, therefore, take place in rather strong fields. As a result of these processes, active particles are formed (ions

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and radicals), whose presence can change the mechanism of the chemical conversion, i.e., can lead to a kinetic mechanism of the action of an electric field on the combustion rate.

It is natural to understand the thermal mechanism of the action as an acceleration of the chemical reactions as a result of an increase in the temperature of the reagents (and not due to the appearance of new stages of the chemical conversion). From this point of view, the thermal mechanism comes about as the result of the excitation of vibrational, rotational, and translational degrees of freedom of the molecules by electron impact.

Starting from existing literature data on the kinetics of reactions with the participation of excited particles and data on the exchange of energies in molecular collisions, it must be borne in mind that an increase in the temperature of translational and, of course, rotational (rotational–translational relaxation takes place very rapidly [10]) motion leads to the acceleration of exothermic chemical reactions. Vibrational excitation of the molecules generally increases the rate of endothermic reactions, which can limit the rate of the overall chemical process [5], while, at the same time, endothermic reactions are frequently not very sensitive to a change in the temperature of the translational motion [11, 12]. By virtue of what has been said, in a consideration of the thermal mechanism, it is necessary to take account of the difference between the translational and vibrational temperatures, on which depend the rates of the different stages of the chemical conversion. However, if vibrational–translational relaxation takes place rapidly in comparison with the characteristic residence time of a particle of the gas at the front of the flame, as is assumed in what follows, the vibrational and translational temperatures can be assumed identical.

Below, we consider fields with a maximal value of the intensity several times less than the threshold for breakdown. With such fields, processes of dissociation and ionization by electron impact are insignificant in comparison with thermal dissociation and chemical ionization, respectively. It is obvious that the excitation of the electronic states of the molecules also does not have a large value, since, in molecular gases, the energy of the electrons is expended above all for the excitation of vibrational degrees of freedom. Thus, the change in the normal velocity of the propagation of the flame, which can be observed in such fields, must be explained from the point of view of a thermal mechanism.

In combustion, and in the plasma of a gas discharge, physically allied phenomena are frequently encountered [13]. For example (similarly to combustion waves in a burning mixture [14]), ionization waves can be propagated [15], and detonational conditions of the combustion of explosives [16] can be compared to the phenomenon of detonation in optical discharges [17]. The analogy between processes of the propagation of discharges and combustion, developed in [18, 19], should considerably promote a deeper understanding of the overall laws governing the propagation of ionization waves, characterized by different mechanisms of the propagation [15, 18, 20, 21].

The phenomenon investigated in the present work essentially combines processes of combustion and processes taking place in the plasma of a gas discharge. It consists in the simultaneous propagation of the wave of a chemical reaction, maintained by the chemical energy evolved with combustion, and the wave of a dependent (the electrons originate during the process of chemical ionization) discharge, which exerts an effect on the combustion rate.

§2. To eliminate from the discussion the convective motion of the gas, arising under the action of the force of gravity and the electric field (taking account of which considerably complicates the calculation), we turn to the following scheme of the process.

Let there be a vertically arranged tube of rectangular cross section, with uninsulated electrodes mounted on its side walls, and let a flame be propagated over a hydrocarbon combustible mixture from the top downward, so that the force of gravity cannot bring about convective motion of the gas. If, to the electrodes, there is applied, not a direct voltage, but a voltage varying with a sufficiently high frequency, then the mass electric forces also cannot bring the gas into motion. Then, with solution of the problem of the velocity of the propagation of a combustion wave, the front of the flame can be assumed to be flat, arranged perpendicular to the axis of the tube.

In a system of coordinates connected with the front of the flame, the equations for determining the gas temperature T, the relative concentration of the reagent in deficit a (for definiteness, the combustible), and the electron density N_e in a one-dimensional approximation have the form

$$\rho u c_p \frac{dT}{dx} = \frac{d}{dx} \lambda \frac{dT}{dx} + QW(a, T) + \delta \overline{\mathrm{E}}^2; \tag{2.1}$$

$$\rho u \frac{da}{dx} = \frac{d}{dx} \rho D \frac{da}{dx} - W(a, T), \quad W = k_0 \rho^n a^n \mathrm{e}^{-E/RT}; \tag{2.2}$$

$$\rho u \frac{d}{dx}\frac{N_e}{\rho} = \frac{d}{dx} D_a \frac{dN_e}{dx} + W_e + (\nu_i - \nu_a) N_e - k_d N_e^2, \tag{2.3}$$

where ρ is the density of the gas, g/cm^3; $\rho u = \mathrm{const}$ is the mass velocity of the gas flow; c_p is the heat capacity; λ is the coefficient of thermal conductivity; Q is the heat effect of the chemical reaction; W is the rate of a chemical reaction of n-th order, with a preexponent k_0 and an activation energy E; $\sigma = e^2 N_e / m\nu_m$ is the conductivity of the plasma (e and m are the charge and mass of an electron, ν_m is the effective frequency of collisions between electrons and neutrals); **E** is the intensity of the electrical field [the line above $\mathbf{E}^2$ indicates averaging over the period of the vibrations of the field, which is assumed to be small in comparison with the characteristic time $\lambda/\rho c_p u^2 \sim 10^{-5}$ sec ($p \sim 1$ atm) of the change in the distribution of all the quantities in a stationary combustion wave]; D is the diffusion coefficient of the reagent a; D_a is the coefficient of ambipolar diffusion of the electrons; W_e is the rate of generation of electrons as the result of chemical ionization processes; ν_i and ν_a are the frequencies of ionization by electron impact and by adhesion of the electrodes; and the term $k_d N_e^2$ describes the "destruction" of electrons as a result of electron–ion recombination.

The first two equations are the equations of the diffusional–thermal theory of combustion [14], with the difference that the equation of the thermal conductivity includes a term describing the Joule heat. To take account of this additional source of heat, we must find the distribution of the concentration of electrons from the third equation.

Equation (2.3) is written under the assumption of the ambipolar character of the diffusion of the electrons, valid with the condition that the Debye radius is far smaller than the characteristic length of electron diffusion. Let us confirm this assumption by an evaluation.

With a temperature of the electrons $T_e \lessapprox 1$ eV, and with a concentration in the reaction zone $N_m = N_e|_{x=0} = 10^{12}$ cm^{-3} [3], the Debye radius $\tilde{d} \le 6.9 (T_e/N_m)^{1/2} \simeq 7 \cdot 10^{-4}$ cm (T_e, K). The characteristic length of electron diffusion [evaluation using formula (3.3)] with $D_a \simeq 20$ cm^2/sec, $\nu_a \approx 10^5$ 1/sec, $k_d \approx 5 \cdot 10^{-8}$ cm^3/sec [3, 22, 23] (p = 1 atm; data on adhesion to molecules of O_2 and CO_2), and $u \approx 10^2$ cm/sec is approximately 10^{-2} cm, which is far greater than the Debye radius. The effect of negative ions on the character of the electron diffusion is not taken into consideration, which is permissible at distances less than the length of the "destruction" of electrons as a result of adhesion, at which there is mainly the evolution of Joule heat. To simplify the calculations, thermal diffusion of the electrons is also left out of consideration.

The rate of formation of electrons W_e as a result of chemical ionization processes accompanying the combustion of hydrocarbons is described by a very complicated kinetic scheme [3]. However, within the framework of the theory of the normal propagation of a flame, generally using the assumption of a one-stage chemical reaction, we can set $W_e = \gamma W$, where the coefficient γ determines the number of electrons formed per unit mass of the reacting hydrocarbon molecules. The value of γ can be determined using the experimental data systematized in the monograph [3].

Having in view an investigation of a process of the type of the propagation of a combustion wave (in high-intensity fields, the discharge will take place simultaneously over the whole volume), we shall consider preconduction fields. (We recall that the threshold fields for breakdown in air in the case of direct and alternating voltages with frequencies of ≤ 1 MHz, with a distance between the electrodes on the order of a few centimeters, differ only slightly from one another and, under normal conditions, are equal to approximately 25-30 kV/cm [24], decreasing with a decrease in the density of the gas.)

In addition, let us consider conditions, corresponding to a dependent discharge, under which the decisive role in the generation of electrons is that of processes of chemical ionization at the flame front, and not that of ionization by electronic impact. For this purpose, even in the reaction products, where the density of the particles is minimal, the inequality $\nu_i(\sqrt{\overline{\mathbf{E}^2}}/N) \ll \nu_a(\sqrt{\overline{\mathbf{E}^2}}/N) + k_r N_m$ (N is the density of the gas) is satisfied, which imposes a limit on the value of the similarity parameter in the discharge $\sqrt{\overline{\mathbf{E}^2}}/N$. According to the data of [25], the condition $\nu_i < \nu_a$ for air is satisfied with $\sqrt{\overline{\mathbf{E}^2}}/N \lessapprox 9 \cdot 10^{-16}$ V · cm^2. With the conditions under consideration, the discharge is concentrated only in the combustion zone, and the current flows through a region with a width on the order of the length of the destruction of the electrons. The boundary conditions for the system (2.1)-(2.3) are

$$\begin{gathered} x = -\infty, \ T = T_0, \ a = a_0, \ N_e = 0, \\ x = +\infty, \ dT/dx = 0, \ da/dx = 0, \ dN_e/dx = 0, \end{gathered} \tag{2.4}$$

where a_0 and T_0 are the initial values of the concentration of the reagent and the temperature; in what follows, the subscript 0 relates to values characterizing the initial mixture. The problem (2.1)-(2.4) is indeterminate, since one boundary condition is unnecessary by virtue of invariancy of the equations and the boundary conditions with respect to a shift along the coordinate. This makes it possible to determine the normal rate of propagation of the flame, which is an eigen number of the problem.

We note the profound analogy between the phenomenon under consideration here and the propagation of a flame in the case of a chain mechanism of the chemical conversion. In such flames, during the process of the main reaction of the consumption of the substance a, intermediate products are formed, i.e., active radicals, which, recombining, give off heat, accelerating the main reaction [26]. In the present case, the role of the intermediate products is played by electrons, formed as a result of a chemical reaction, and the Joule heat which they give up to the gas, like the heat evolved with recombination of active centers in flames with chain reactions, promotes an increase in the combustion rate.

The analogy extends to the degree to which the process of the motion of the wave of the chemical reaction in both cases is described by similar systems of equations. (If we set $Q=0$, $D=D_a$, and $k_d N_e \gg \nu_a$, the system of equations (2.1)-(2.3) with the boundary conditions (2.4) goes over into a system of equations for determining the rate of propagation of a flame in mixtures with strong branching of the chains, investigated in [26].) This furnishes a basis for solving the system (2.1)-(2.3) using a method employed in [26] for determining the normal rate of propagation of a flame in accordance with a chain mechanism. This method is based on the postulation of an infinitely narrow zone of the chemical conversion, which can be used to obtain solutions outside the reaction zone. Then, by extrapolation of the distributions of the temperature and the concentration, obtained in the heating zone, to the zone of the chemical conversion, the structure of the zone of the chemical reaction itself is considered approximately, and the rate of propagation of the flame is determined.

For simplicity in the exposition, we shall assume that the density of the gas and the coefficients $D=\varkappa=\lambda/\rho c_p$, D_a, ν, ν_m, as well as the velocity u, are constant and equal to their values in the reaction zone. (The calculation over to the normal velocity of the propagation of the flame $u_n=u_\rho/\rho_0$). Since the processes near this zone determine the normal rate of propagation of the flame, the postulation made can have no effect on the qualitative aspect of the results obtained or significantly distort the quantitative conclusions. The same applies to the procedure of linearization of the recombination term, proposed in [26]; further, we set $k_d N_e^2 \approx k_d N_m N_e$.

We now make use of the fact that the chemical reaction is concentrated in a region which is narrow in comparison to all the diffusion dimensions. In actuality, with $p=1$ atm, the width of the heating zone $\sim \varkappa/u \approx 10^{-3}-10^{-2}$ cm, the width of the diffusion zone of the electrons $\gtrsim \varkappa/u$, and the dimension of the zone of the chemical conversion $(\varkappa/u)(RT_1/E) \approx 10^{-1}\varkappa/u$ (T_1 is the temperature in the zone of the reaction). We note that these relationships between diffusional dimensions and the width of the zone are practically independent of the pressure, where the destruction of the electrons is determined by the mechanism of adhesion, i.e., with $p \gtrsim 1$ atm (see the evaluation below).

§3. Integrating Eq. (2.2) with respect to x from $-\infty$ to $+\infty$, and taking account of the boundary conditions, we obtain

$$\int_{-\infty}^{+\infty} W(a, T)\, dx = \rho u a_0. \tag{3.1}$$

Since the reaction is concentrated in a narrow zone, it can be assumed that $W \sim \delta(x)$. Then from (3.1) it follows that

$$W = \rho u a_0 \delta(x). \tag{3.2}$$

Using (3.2), from Eq. (2.3), taking account of $\nu_i \ll \nu_a + k_d N_m$, the distribution of the electron concentration to the right and left of the reaction zone can be determined.

Taking account of the boundary conditions, the solutions have the form

$$\begin{gathered} x<0, \quad N_e = N_m e^{\alpha_1 x}, \quad x>0, \quad N_e = N_m e^{-\alpha_2 x}, \\ \alpha_{1,2} = (u/2D_a)(s+1), \quad s=\sqrt{1+4\nu D_a/u^2}, \quad \nu=\nu_a+k_d N_m. \end{gathered} \tag{3.3}$$

Now, calculating the diffusional fluxes from the reaction zone and substituting them into the relationship $D_a\,[dN_e/dx]_{-0}^{+0} = -\gamma u A_0$ $(A_0=\rho a_0)$, which takes account of a δ-shaped source of electrons, we obtain

$$\gamma u A_0 = N_m \sqrt{u^2 + 4\nu D_a}. \tag{3.4}$$

Eliminating N_e and W from (2.3) using (2.1), (2.2), and integrating the equation obtained with respect to x from $-\infty$ to $+\infty$, taking account of conditions (2.4), we determine the final temperature of the gas:

$$T_2 = T_0 + (A_0/\rho c_p)(Q + Q_e),\ Q_e = \gamma e^2 \overline{\mathbf{E}}^2/m\nu\nu_m \tag{3.5}$$

(Q_e is an additive to the heat effect of the chemical reaction, connected with heating of the gas by the electrons).

We find the solutions of Eqs. (2.2), (2.3) using the procedure employed above with determination of the profile of the electron density. Using (3.2), (3.5), and taking account of (2.4), we obtain

$$x < 0,\ A = A_0(1 - e^{ux/\varkappa}),\ x > 0,\ A = 0; \tag{3.6}$$

$$x < 0, \quad T = T_0 + (T_1 - T_0)\,e^{ux/\varkappa} + \frac{\nu Q_e N_m}{\gamma \rho c_p \alpha_1 (u - \varkappa\alpha_1)}\,(e^{\alpha_1 x} - e^{ux/\varkappa});$$

$$x > 0, \quad T = T_2 - \frac{\nu Q_e N_m}{\gamma \rho c_p \alpha_2 (u + \varkappa\alpha_2)}\,e^{-\alpha_2 x}, \tag{3.7}$$

where T_1 is the temperature in the reaction zone, connected with the temperature T_2 by the relationship

$$T_1 = T_2 - \nu Q_e N_m/\gamma\rho c_p \alpha_2(u + \varkappa\alpha_2). \tag{3.8}$$

The temperature T_1 exceeds the adiabatic combustion temperature in the absence of a field $T_a = T_0 + (QA_0/\rho c_p)$.

Equations (3.4), (3.5), and (3.8) permit determining the values of N_m and T_1 as a function of the velocity u. Still one more equation (required for solution of the problem) is obtained from relationship (3.1), in which the distributions of a (x) and T(x) in the reaction zone are given, extrapolating the "external" solutions (3.6), (3.7) to the reaction zone. Taking into consideration that in the reaction zone the temperature differs only slightly from T_1 and introducing an expansion with respect to the small difference $T - T_1$ into the Arrhenius exponent [26], we obtain (we assume that n = 1)

$$u = \sqrt{k_0 \varkappa}\,\frac{RT_1^2}{E(T_1 - T_0)}\,e^{-E/2RT_1} + \frac{\alpha_2(\varkappa\alpha_2 + u)}{\alpha_1}\,\frac{T_2 - T_1}{T_1 - T_0}. \tag{3.9}$$

If the Joule heat is small ($\overline{\mathbf{E}}^2 \to 0$), then $T_1 \to T_2 \to T_a$, and the rate of propagation coincides with the velocity of the combustion wave in the absence of a field;

$$u_a = \sqrt{k_0\varkappa}\,(RT_a^2/E(T_a - T_0))\exp(-E/2RT_a).$$

Calculating the derivative $\partial u/\partial \overline{\mathbf{E}}^2$ from (3.9), and taking account of relationships (3.4), (3.5), (3.8), it can be shown that the velocity of the flame rises with an increase in the intensity of the electrical field.

We now find the connection between the velocity of the flame and the temperature in the reaction zone T_1, assuming that the increase in the final temperature, brought about by the imposition of the electrical field, is small in comparison with the temperature T_a, i.e., $T_2 - T_a - T_a \ll T_a$. In this case, the second term in the right-hand side of Eq. (3.9) can be neglected, and the effect of the field on the temperature in the combustion zone is taken into account only in the Arrhenius exponent. As a result, we obtain

$$u = \sqrt{k_0\varkappa}\,\frac{RT_a^2}{E(T_a - T_0)}\,e^{-E/2RT_1} \cong u_a e^{E(T_1 - T_a)/2RT_a^2}, \tag{3.10}$$

Formula (3.10) shows that the increase in the rate of propagation of the flame with the imposition of an external electrical field is brought about by a rise in the temperature in the reaction zone in comparison with its value in the absence of a field. This rise is due to dissipation of the Joule heat, i.e., to the action of an additional source of energy, whose intensity is proportional to the concentration of electrons and which, in distinction from a "chemical" source of heat, concentrated in a narrow zone, is distributed over the space and brings about an increase in the temperature T_1 by heating of the gas on both sides of the reaction zone. Here a great role in the increase of u is played by heat evolved in the region ahead of the reaction zone (x < 0). In actuality, integrating the equation of thermal conductivity (2.1) from $-\infty$ to $+\infty$, and taking account of (3.2), (3.3), (3.8), we obtain

$$T_1 - T_a = \frac{\nu Q_e N_m}{\gamma\rho c_p u}\left(\frac{1}{\alpha_1} + \frac{\varkappa}{u + \varkappa\alpha_1}\right),$$

where the first term in the right-hand side corresponds to the contribution from the region x < 0 to the increase in T_1 and the second term, to the contribution from the region x > 0. Their ratio, equal to

$$(2(D_a/\varkappa) + s - 1)/(1 + s),$$

is always greater than unity ($D_a > \varkappa$). The less significant effect of the region $x > 0$ on the increase in T_1 can be explained by the fact that part of the heat evolved in this region is entrained by the convective flow of gas and does not arrive in the reaction zone.

Let us make a further analysis for conditions where the principal mechanism of the destruction of the electrons is their adhesion to electrically negative molecules of the type of O_2 and CO_2, present in excess in hydrocarbon flames, i.e., we shall assume that $\nu = \nu_a$.

The recombination mechanism of the destruction of electrons is insignificant if $\nu_a > k_d N_e$. Taking into account that $\nu_a = k_a \eta N$ (η is the number of particles of electrically conducting gas), and setting $k_a \approx 10^{-13}$ cm³/sec, $\eta \approx 0.2$, $N_e \approx 10^{12}$ cm^{-3} (see evaluations below), and $k_d \approx 5 \cdot 10^{-8}$ cm³/sec [23], we obtain the result that this condition is satisfied with a concentration of particles $N > 2.5 \cdot 10^{18}$ cm^{-3}, i.e., with a pressure on the order of atmospheric or above.

Eliminating N_m and T_2 from Eqs. (3.4), (3.5), (3.8), and (3.9), we obtain a system of equations for determining u and T_1, which, in the variables

$$u' = u/u_a, \quad \nu' = 4\nu_a \varkappa / u_a^2, \quad \varkappa' = \varkappa / D_a, \quad \theta_1 = T_1/T_a,$$
$$\theta_0 = T_0/T_a, \quad \beta = E/2RT_a, \quad \theta_k = Q_e A_0/\rho c_p T_a, \quad s'^2 = \varkappa' u' + \nu'$$

has the form

$$u' + \theta_k \frac{u'(u' - s')}{2s'(\theta_1 - \theta_0)} = \theta_1^2 \frac{1 - \theta_0}{\theta_1 - \theta_0} e^{\beta\left(1 - \theta_1^{-1}\right)}; \tag{3.11}$$

$$\theta_1 = 1 + \theta_k \left[1 - \frac{u'(\sqrt{\varkappa'}\, u' + s')}{s'(2u' - \varkappa' u' + \sqrt{\varkappa'}\, s')}\right]. \tag{3.12}$$

Let us evaluate the value of θ_k for the concrete case of a mixture of 10% CH_4+air. For the evaluations, we shall assume that $T_0 \ll T_0$; then the value of $\theta_k \approx Q_e/Q$ is determined by the ratio of the corresponding heat effects.

According to the experimental data of [3, 4], over a wide range of pressures, with the combustion of stoichiometric mixtures, one electron–ion pair is formed for approximately 10^5 atoms of carbon, entering into the reaction, so that, in the case of methane, we can set $\gamma \approx 10^{18}$ g^{-1}. For such a value of γ, the concentration of charged particles in the zone of the chemical reaction in the absence of an electrical field, according to formula (3.4), gives a value of $\sim 10^{12}$ cm^{-3} for N_m, which is in agreement with experimental data [3].

For an approximate determination of ν_m and ν, use can be made of the data of [27] for the energy distribution function of the electrons in molecular nitrogen. It is found that, with $\sqrt{\overline{E^2}}/N \approx 3 \cdot 10^{-16}$ V·cm² (this value corresponds, for example, to an intensity of the electrical field in the reaction zone of ~ 1 kV/cm at atmospheric pressure), the rate constant of the adhesion $k_a = \nu_a/\eta N$ is approximately equal to 10^{-13} cm³/sec [3, 22], and $\nu_m/N \approx 5 \cdot 10^{-8}$ cm³/sec [28]; under these circumstances, the electron temperature $T_e \approx 0.8$ eV. The values given are in reasonable agreement with existing experimental data for air [25].

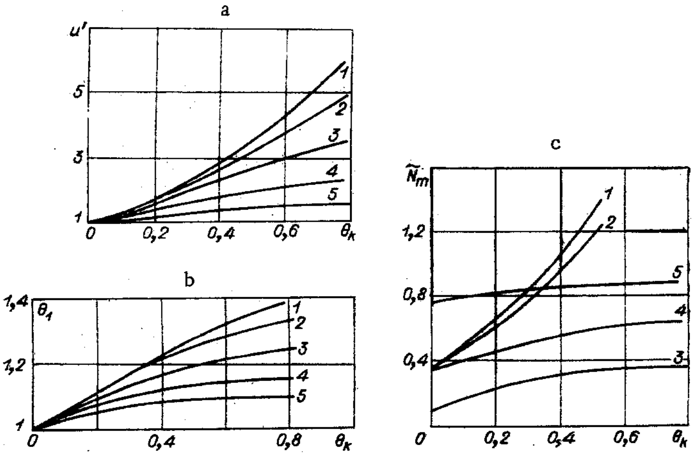

Fig. 1

Setting $\eta = 0.2$ we obtain $Q_e = 6.8 \cdot 10^{31} \overline{\mathrm{E}^2}/N^2 (\sqrt{\overline{\mathrm{E}^2}}$, V/cm, N, 1/cm^3). For $\sqrt{\overline{\mathrm{E}^2}}/N = 3 \cdot 10^{-16}$ V·cm^2 — $Q_e \approx 6$ kcal/g. The heat-removing capacity of methane $Q \approx 13$ kcal/g, so that $\theta_k \approx 0.4$. Thus, Q_e can attain values comparable with the value of Q, i.e., with sufficiently large intensities of the electrical field, Joule heating leads to a considerable increase in the temperature of the gas.

For the example given, the conductivity of the flame $\sigma \sim 10^9$ sec^{-1}, which, with an intensity of the field $\sqrt{\overline{\mathrm{E}^2}} \sim 1$ kV/cm, for the density of the current passing through the flame gives a value of $j \sim 1$ A/cm^2.

Figure 1a–c gives the dependences, calculated using Eqs. (3.4), (3.11), and (3.12), of u', θ_1, and $N'_m = N_m/\gamma A_0 = u'/s'$ (for the mixture under consideration at atmospheric pressure $\gamma A_0 \simeq 7 \cdot 10^{12}$ cm^{-3}) on the final temperature with $\nu' = 0.7$, $\varkappa' = 0$; 10^{-3}, 10^{-2}, 10^{-1}, 1 (curves 1–5), $\beta = 4$, and $\theta_0 = 0.125$.

The curves show that, under the effect of an electrical field, the rate of propagation of the flame can increase by several times. An increase in the parameter $\varkappa'$ (a decrease in D_a for a fixed value of $\varkappa$) leads to a decrease in the rate of propagation, of the temperature of the reaction zone, and to an increase in N_m (in Fig. 1c, for curve 1 the values of the ordinate must be multiplied by 10^{-2} and, for curve 2, by 10^{-1}).

For the example given above, with $\nu'/\varkappa' \approx 70$ and $\theta_k = 0.4$, the velocity of the flame increases by 2.3 times (curve 3).

At low pressures, the principal mechanism of the destruction of electrons is recombination. For calculation of the normal combustion rate with $p < 1$ atm, the system of equations (3.4), (3.5), (3.9), and (3.8) must be used, in which we must set $\nu = k_d N_m$. We note that, by virtue of the above analogy between the phenomenon under consideration here and the propagation of a flame in systems with chain reactions, this system of equations with $\varkappa = D_a$ can be used for determining the normal velocity in a system with the following reaction mechanism: $A + B \rightarrow 2B + Q$, $B + B + X \rightarrow C + X + Q_e$) (A is the starting substance; C is the reaction product; B is an active center; and X is a given particle), which is a generalization of the case discussed in [26] (in distinction from [26], even with $Q_e = 0$, the velocity of the flame does not revert to zero, since, in the reaction of the formation of active centers, the heat Q is evolved, maintaining the propagating combustion wave).

The scheme described in Sec. 1 for the observed effect of an increase in the normal rate of propagation of a flame in a preconduction electric field was verified experimentally in [5]. It was found that the normal velocity of the flame in a methane–air mixture at atmospheric pressure and an effective intensity of the electrical field $\sqrt{\overline{\mathrm{E}^2}} = 440$ V/cm, varying with the frequency 4 MHz, rises by approximately 15% in comparison with its value in the absence of a field. This fact is in good agreement with our results (compare the value of the velocity in Fig. 1a with $\theta_k \approx 0.08$), and can be regarded as an experimental confirmation of the results obtained.

The mechanism proposed in [5] for the increase in the normal velocity as a result of excitation of the vibrational degrees of freedom of oxygen molecules is obviously described within the framework of the approach developed here, since it makes use of the assumption of the existence of thermodynamic equilibrium with respect to the vibrational–translational degrees of freedom of the molecules, excited by vibrations; it is therefore taken into account automatically.

The assertion of the authors of [5] that, in their experiments, the translational temperature of the molecules cannot be changed in any significant way due to the small value of the Joule heat, is doubtful. It contradicts the calculation made in the present work, according to which the vibrational temperature of molecules of oxygen increases by 150°C with the imposition of an electrical field; such an increase in the vibrational temperature requires a considerable amount of Joule heating, which can also change the translational temperature significantly (the total heat capacity of the translational and rotational degrees of freedom of a diatomic molecule is only 2.5 times greater than the heat capacity calculated for the vibrational degree of freedom).

In actual fact, the possible breakaway of the vibrational temperature of the molecules from the translational can be explained if the finite nature of the time of vibrational–translational relaxation is taken into consideration. It is well known that in combustible gases consisting of a mixture of molecular gases with a large amount of air, the energy of the electrons is mainly expended for excitation of vibrations of the molecules; then, during the relaxation process, it is transmitted to the translational degrees of freedom. As has already been remarked above, taking account of this circumstance is bound up with the need to consider a two-temperature model of the combustion process, and with a more detailed analysis of the kinetics of chemical conversion, requiring, specifically, presently lacking data with respect to the effect of excitation of the molecules on the rate of the elementary acts of the chemical reaction.

In an experimental study of the phenomenon under consideration, it can be found useful to measure the value of the effect as a function of the concentration of easily ionized additives added to the combustible mixture, which can be used to considerably change the conductivity of the flame. A comparison of these data with our conclusions will promote a refinement of the results obtained above.

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