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Simulation of Ignition of a Supersonic Flow of a Propane–Air Mixture by Electric Discharge

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Abstract—The numerical simulation of the ignition process of a supersonic flow of a preliminary mixed propane–air mixture by electric discharge, with respect to power, geometry, and the duration of energy input, was carried out via a two-dimensional thermo–chemical model. The ignition thresholds evaluated in the framework of this model were in agreement with the experimental values of power density and induction duration.

Key words: supersonic flow, propane–air mixture, electric discharge, ignition.

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INTRODUCTION

Decreases in induction duration and development of volumetric ignition of fuel–air flows are among the fundamental problems of supersonic combustion demanding physical solutions. Presently, the most promising approach to solving these problems consists in the creation of some type of electrical discharge in the supersonic flow [1, 2]. In particular, the efficiency of direct and pulse–periodic current discharges has been experimentally demonstrated for supersonic propane–air flows [3, 4]. However, the experimental determination of the optimal conditions of ignition, namely, the choice of discharge geometry and the main discharge characteristics, such as current, pulse duration, relative pulse duration, etc. under the variation of flow parameters, involves large material and time expenses. Therefore, the development of appropriate theoretical models is of interest for these purposes.

A gas dynamic model, describing the influence of an electrode discharge on supersonic air flows, was developed in [5, 6] within the framework of the model of a thermal source [7, 8]. It turned out that from the gas dynamic point of view it is sufficient to describe a discharge as a short elliptical region of energy release located close to the head electrode, while the main discharge element, which is an extensive positive column, can be ignored. With respect to physics, this means that electrode discharges in a flow, both transverse [9], longitudinal [10] or longitudinal–transverse [11], at currents of 1 A or higher combust in the regime of the cathode or anode spots. Such a regime, where the current spot (or several current spots) occupies only a very small part of a cathode or anode, frequently arises in the discharge existing in an immobile gas with electrodes made of low-melting-point metals [12]. In the case of a supersonic flow, this regime becomes dominant. At least for the cathode region, this can be explained by the fact that under strong cooling of the cathode by a gas flow it is more advantageous from the energy point of view (due to the exponential dependence of thermoemission current versus temperature) to heat, only a small part of the cathode to a higher temperature and not the entire cathode. For discharge in a supersonic flow due to high temperature and electron density in the spot, rapid and basic gas heating, to a temperature higher than 1000 K [13], along with appropriate reconstruction of the flow did in fact occur in the short near-electrode region. As a result, the most extensive part of the discharge, that is, the positive column, simply represents the trail of this source, from the gas dynamic point of view.

For flows of combustible mixtures with air the presence of the spot in the head part of the discharge results in the intense behavior of chemical reactions in this part, with heat release and formation of active species. A detailed description of the influence of an electrode discharge on the ignition process of the supersonic flow of a fuel–air mixture based on the joint solution of electro–dynamic and kinetic equations requires huge computer recourses. Accounting that theories on cathode spots number more than 20 [12], such an approach is impracticable indeed.

The simplest approximation can be a model based on agas dynamic model [6] with allowance for the kinetics of thermal-equilibrium combustion. The thermodynamic description of heat release due to chemical reactions supposes an infinite rate of their behavior, which is in agreement with the model of a heat source, assuming a infinite rate of transformation of electrical energy into heat. The availability of experimental data on the ignition of a supersonic flow of a preliminary mixed propane–air mixture by a transverse pulsed electrical discharge published in [3] allows the estimation of the possibility of such a simple approach.

THE MODEL OF A DISCHARGE IN A SUPERSONIC FLOW AS A SOURCE OF HEAT

A two-dimensional axially symmetric model describing the influence of a discharge on a supersonic air flow [6], proceeds from the description of a laminar flow by the Navier-Stokes equations with an additional source of heat in the energy equation with a given configuration of the energy input zone. However, in contrast to the purely gas dynamic problem [6], in the ignition problem the rapid transit of reacting particles through a short cathode region (in comparison with induction duration) does not allow us to ignore the extensive region of PS discharge. Therefore, in the proposed model, the zone of heat release was divided into two parts: (i) a short and narrow head region with an intensive energy input, and (ii) an extensive, weakly expanding plasma region with a low value of specific energy input.

Distribution of the power of heat dissipation per unit square in the source was described by the following equation:

$$\omega_h = c_h(z)\exp[-(r/\beta_h(z))^2],$$

where z and r are the axial and radial coordinates, $\beta_h(z)$ and $c_h(z)$ are the given functions of z. The function $c_h(z)$ was determined using the linear power of heat dissipation $P_h(z)$ in the section $z = \text{const}$:

$$P_h(z) = 2\pi\int_0^\infty \omega_h r dr.$$

The $P_h(z)$ values were assigned in the computations indeed. In the initial part of discharge $z_{cb} < z \le z_{ce}$, which modeled the narrow “cathode” region of the discharge, $P_h(z) = P_c$ and $\beta_h(z) = \beta_c$. In the discharging region $z_{ce} < z \le z_{de}$ these functions are $P_h(z) = P_s$ and $\beta(z) = a_h\sqrt{z + b_h}$. The factors a_h and b_h are determined by the conditions $\beta(z_{ce}) = \beta_c$, $\beta(z_e) = \beta_e$, where z_e and β_e are the characteristic parameters.

In accordance with the experimental data, the region of the simulation was confined within $0 \le z \le 14$ cm and $0 \le r \le 2$ cm. We used a nonuniform structured grid, with the number of cells being 300×75. In the region of the source of heat dissipation the cells were concentrated in the axial direction and close to the axis they were concentrated in the radial direction.

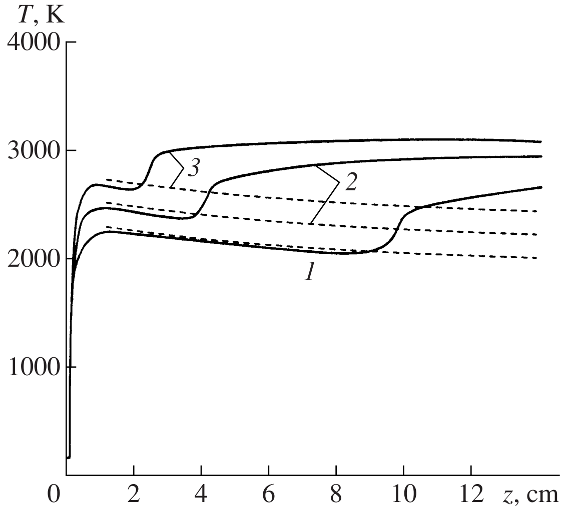

Fig. 1. Distribution of the axial gas temperature along the flow for several values of the linear power P_s in the discharging region: (*1*)–50 W cm^{-1}, (*2*)–55 W cm^{-1}, (*3*)–60 W cm^{-1}. The ratio between linear powers in the cathode and anode regions is $P_c/P_s = 10$, the factor $\beta_c = 0.02$ cm. Solid lines represent the reacting gas mixture, dotted lines show the nonreactive mixture.

A total of three thermally equilibrium models were used for the description of ignition of propane–air mixture and its subsequent combustion, namely:

- a global model [14] considering 5 species (C_3H_8, O_2, N_2, H_2O, and CO_2) with only the global reaction $C_3H_8 + 5O_2 \Rightarrow 3CO_2 + 4H_2O$;
- the quasi-global model [14] considering 11 species (C_3H_8, O_2, N_2, H_2O, CO_2, H_2O_2, CO, H_2, OH, O, and H) with only the global reaction and several detailed reactions;
- a detailed model [15] considering 30 species (C_3H_8, O, H, O_2, N_2, H_2, CO, OH, H_2O, HO_2, H_2O_2, HCO, CO_2, CH, CH_2, CH_3, CH_4, C_2H, C_2H_2, C_2H_3, C_2H_4, C_2H_5, C_2H_6, C_3H_5, C_3H_6, $i C_3H_7$, $n C_3H_7$, CH_2O, CH_2OH, and CH_3OH) with 70 chemical reactions.

RESULTS OF THE SIMULATION

The simulation was carried out for the following experimental conditions [3]: the total pressure $P_0 = 4$ atm, the temperature of deceleration $T_0 = 300$ K, the Mach number of the flow $M = 2$, and a stochiometric composition of the mixture is used.

We studied the influence of the power and geometry of energy input on the ignition process. In this case, we varied the linear power in the cathode P_c and discharging P_s regions, the extension of the discharging region and the characteristic size of the cathode region. The main computations were fulfilled for the following geometry of the energy input region: $z_{cb} = 0.1$ cm, $z_{ce} = 0.2$ cm, $z_{de} = 14$ cm. The characteristic parameters were chosen to be equal $z_e = 12$ cm, $\beta_c = 0.2$ mm, and $\beta_e = 0.15$ cm.

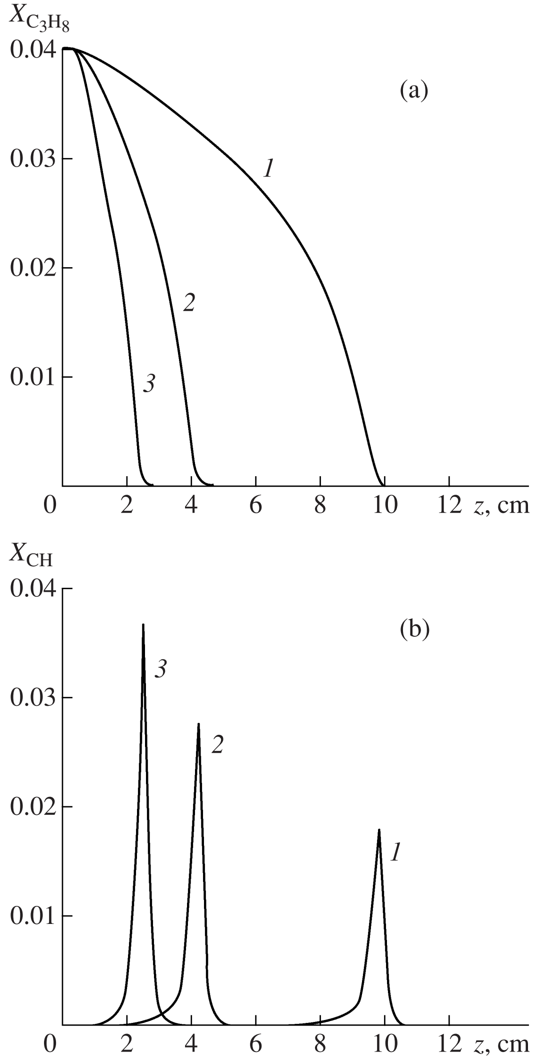

Fig. 2. Axial distribution of the mole fraction of propane (a) and CH radical (b) in the supersonic flow of a propane–air mixture downstream on the flow obtained for different linear powers in the discharging region z_{de} = 14 cm. The designations are the same as in Fig. 1.

Preliminarily, we compared the results obtained in the framework of all the above proposed models. Below we present the data obtained via the detailed model [15].

Figure 1 shows the influence of the linear power of the energy input on the axial distribution of gas temperature. One experimentally determined feature of a discharge in an air flow is rapid gas heating at a small distance from the electrodes and weak temperature variation downstream on the flow [12]. It is evident that for a nonreactive mixture the proposed model describes this feature. However, if in the head part of the energy input region a difference in temperatures between the reacting and nonreactive mixtures is practically lacking for all values of the linear power, for the reacting mixture downstream on the flow we have observed a substantially smaller amplitude but a sudden change in temperature, which undoubtedly indicates ignition of the flow. This fact is visually confirmed by the corresponding axial distributions (Fig. 2 a, b) of the mole fractions of the fuel, namely, propane and the intermediate combustion product, that is, the CH radical. The mole fraction the x_i of i-component represents the ratio between the mole number n_i of the i-component and total mole number $n = \Sigma n_i$ of the mixture, i.e., $x_i = n_i/n$. For a preliminary mixed stoichiometric propane–air mixture. its value is 0.00403. An increase in the power density of the energy input results in an increase of the gas temperature and leads to faster ignition of the flow; at lower powers ignition does not occur. The given power density corresponds with the characteristic length (or delay time) of ignition. The delay times change within the range from 200 to 60 μs; this range conforms qualitatively and quantitatively with the range of experimentally observed pulse durations needed for ignition.

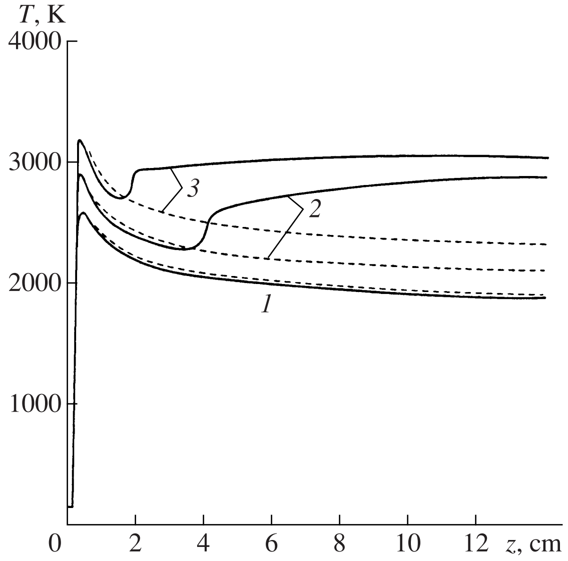

Fig. 3. Distribution of the axial gas temperature for several values of the linear power P_s in the discharging region. The parameters are $P_c/P_s = 2.5$, $\beta_c = 0.01$ cm, and z_{de} = 14 cm. The designations are the same as in Fig. 1.

The variation of the parameters of the cathode region, namely, a twofold decrease of its radial size with a simultaneous decrease in the ratio between specific energy inputs in the cathode and discharging regions by a factor of four, results in a change of the axial distribution of the gas temperature (Fig. 3). In this case, the initial temperature jump exhibits an increase in value; however, in the head part the temperature slumps in the axial direction. As a result, in contrast to the situation presented in Fig. 1 the ignition of flow at P_s = 50 W cm^{-1} does not occur. However, already at P_s = 55 W cm^{-1} and at higher powers, the qualitative and quantitative difference from the results presented in Fig. 1 is not too large.

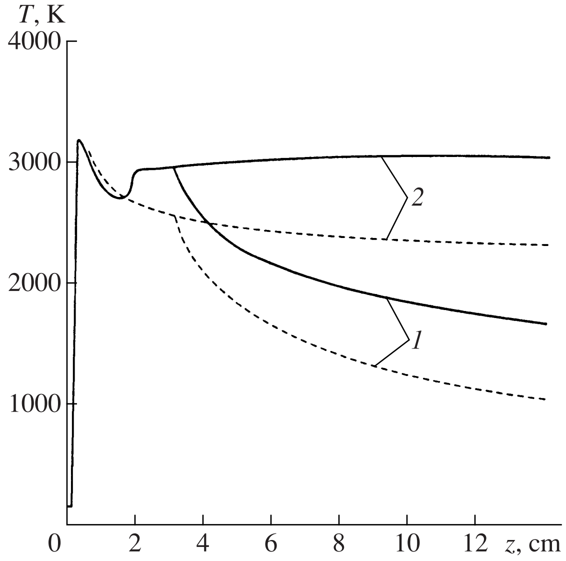

Fig. 4. Distribution of the axial gas temperature for two values of the extensive region of energy input z_{de}: (*1*) 3 cm, (*2*) 14 cm. The parameters are P_s = 60 W cm^{-1}, P_c = 150 W cm^{-1}, and β_c = 0.01 cm.

The modeling computations show that with a decrease of power to the critical value, ≈40 W cm^{-1}, the ignition is not observed at any variation of the parameters β_c, P_c and P_s within the examined limits. Thus, in agreement with the experimental data, a threshold limit of enclosed specific power, which determines the ignition process, exists. For the examined conditions the threshold limit of electrical power was found experimentally [3] to be ≈500 W cm^{-1}. The typical part of the electrical power spent on rapid gas heating amounts to ≈10% of the electrical power [16], i.e., the evaluated threshold limit correlates with the experimental data.

We also studied the role of the dimension z_{de} of the energy input region. Figure 4 shows the axial distribution of gas temperature for two substantially differing z_{de} numbers equals 3 cm and 14 cm (at identical values of P_c and P_s). The temperature distribution in the flow exhibits a jump from 2700 to 3000 K, which indicates ignition of the flow. However, downstream on the flow, at $z > 3$ cm, a substantial difference in the temperature behavior is observed, namely, it monotonically decreases after the end of the energy input region (short source), and for an extensive source it remains practically constant. It is significant that when the length of the energy input region is less than 2–3 cm (depending on the P_s value) the ignition of flow is not observed, which points to the existence of an ignition threshold limit for length. This is in agreement with the results of experiments carried out with a longitudinal discharge [17], in which the ignition does not occur with a decrease of the distance between electrodes below 4 cm. The corresponding induction time of about 50 μs agrees with an abrupt increase in linear power with a decrease in the duration of the discharge pulse.

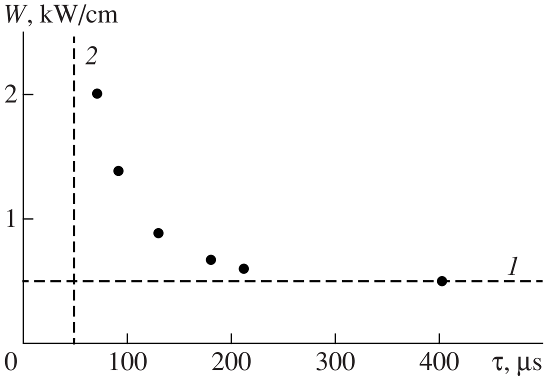

Fig. 5. Pulse duration τ versus linear power *W* needed for the ignition of a supersonic flow of a propane–air mixture. The points indicate the experimental data [3]. The estimated threshold of ignition under the assumption that 10% of the electrical power is spent on rapid gas heating is shown at the panel as (*1*); the threshold of ignition estimated from the data on the induction duration, which were obtained for minimal dimension of the energy input region, is shown at the panel as (*2*).

Thus, the relatively simple model proposed here provides results that qualitatively, and to a certain degree, quantitatively match the experiments (Fig. 5). This means that when using electrode discharges in a flow, the heat mechanism of ignition can play an appreciable role.

The combustion of the flow takes place in the radial direction as well. In this case, the ignition occurs on the axis of the heat source, where the gas temperature is maximal. This process is accompanied by the radial expansion of the region of propane combustion with an increase in z value. The radial rate of propagation of the combustion front amounts to ≈10 m s^{-1}. As a result, for the velocity of a supersonic flow, the combustion zone in a laminar stream will represent a cone with a half opening angle of several degrees. In practice, the rapid motion of the cathode spot provides a wider zone of combustion. Nevertheless, a multi-electrode structure, including a number of transverse discharges, is needed for volumetric ignition. Such a system was in fact used for ignition in the experiments described in [18].

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