ELECTRICAL MODELING OF THE COMBUSTION PROCESS BY MEANS OF A LOW-TEMPERATURE PLASMA

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The authors discuss the possibility of modeling the process of combustion of a homogeneous gas mixture on the basis of identical temperature dependences of the reaction rate and the electrical conductivity of a low-temperature plasma.

The direct experimental study of the combustion process is associated with considerable difficulties. The analytical solution of the problem of gas combustion in a flow and its numerical calculation on a computer are seriously complicated by the nonlinearity of the basic system of differential equations (of motion, energy, and diffusion) and the presence of essentially nonlinear heat and mass sources. Moreover, the continuing lack of adequate information on the laws of turbulent transfer in flames (not to mention the fact that, in general, the system of Reynolds equations for a compressible gas is not closed) seriously detracts from the usefulness of numerical calculations.

Under these conditions the role of an effective auxiliary medium of investigation might be played by modeling with preservation of the basic physical characteristics of the problem—gas-dynamic structure of the turbulent flow—where the heat release due to combustion is simulated by the Joule heat released when an electric current is passed through a heated gas.

The mathematical basis for this analogy is the common temperature dependence of the reaction rate (Arrhenius law), on the one hand, and the electrical conductivity of a low-temperature plasma, on the other.

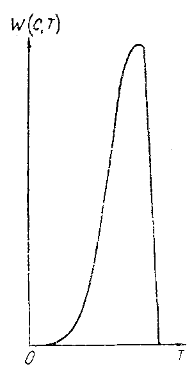

Fig. 1. Temperature dependence of chemical reaction rate W(C, T).

For both effects this law may be expressed in the form of an exponential temperature dependence:

$$f/f_0 = \exp(-A_1/T),$$

$$\sigma/\sigma_0 = \exp(-A_2/T).$$

It is important not only that the dependence is of the same type—sharp increase in the values of f and σ with temperature—but also that the values of A_1 and A_2 are of the same order magnitude. Some typical values of A_1 and A_2 are shown in the table.

The analogy between a number of effects (hysteresis, etc.) in combustion and the passage of a current through a semiconductor, based on a similar temperature dependence of the reaction rate and resistance, was noted previously in [4].

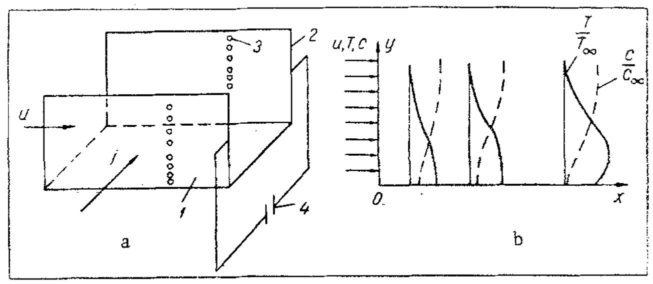

Fig. 2. Model of the process of ignition in a longitudinal flow over a hot surface: a) diagram of model (1—plate, 2—electrodes, 3—measuring electrodes (shown in section only, measuring circuit not included in the figure), 4—power sources); b) distribution of temperature and concentration in boundary layer for a reacting gas flowing over a hot surface.

In our case, however, we are concerned with a probably more effective and more natural method of modeling.

In examining the feasibility of modeling we will make the following assumptions. We assume that the electric currents passing through the low-temperature plasma are sufficiently small, so that their effect on the flow is reduced exclusively to heat release. This means the absence of a magnetic field, either applied or induced, owing to the smallness of the magnetic Reynolds number ($R_m \ll 1$).

If this condition is satisfied, the system of differential equations of motion and energy for a flow of reacting gas mixture and a flow of low-temperature plasma, through which a current is passed, will, under certain conditions, be analogous. In fact, for a viscous compressible gas the equations of motion and continuity will coincide completely in both cases. In the energy equation the specific heat release due to the chemical reaction will be replaced by the expression for the Joule heat. The equation of state (perfect gas) will also be identical.

As for the diffusion equation, which forms part of the system of equations describing the combustion process, it has no direct analog in the plasma model. Thus, in order to preserve the generality of the processes and the possibility of approximate modeling, it is necessary to ensure a dependence of the local current on resistance that, all things considered, would simulate the effect of burnup of the fuel mixture. In other words, it is necessary to ensure a temperature dependence of the square of the current analogous to the temperature dependence of the rate of heat release during the reaction.

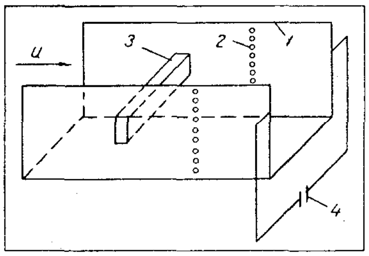

Fig. 3. Model of flame stabilization behind a bluff body: 1) electrode, 2) measuring electrodes (shown in section only, measuring circuit not included in figure), 3) bluff body, 4) power source.

For strongly exothermic reactions this dependence (Fig. 1) has the following characteristic properties: a sharp, almost exponential rise in the region close to ignition, intense burnup (heat release) close to the maximum temperature, and, finally, a very steep fall to zero as a result of burnup of the reacting components. Therefore, the simplest, qualitatively reliable approximation of this dependence on the electrogas-dynamic model will be the introduction of a limitation on the current and the switching off of the current at a given maximum value.

As for the similarity of the boundary conditions, a necessary condition of modeling, it is realized automatically by selecting a suitable, geometrically similar model system, distribution of hot and cold flows in the initial section, etc.

The plane flow analogy, with the current flowing at right angles to the plane of the velocity vector, is the simplest to realize. For axisymmetric motion, modeling, through possible in principle, is associated with a number of difficulties, and this system will not be considered here.

We now turn to several examples illustrating the proposed modeling method, confining ourselves exclusively to fundamental considerations.

We will consider the problem of the ignition of a flow of fuel mixture moving over a plate, limiting the discussion to the temperature field preceding ignition, i.e., neglecting burnup of the mixture. In this case, instead of the third equation of the system

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \frac{\partial \tau_T}{\partial y}, \quad \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0,$$

$$\rho u c_p \frac{\partial T}{\partial x} + \rho v c_p \frac{\partial T}{\partial y} = \frac{\partial q_T}{\partial y} + c_1 \exp\left(-\frac{A_1}{T}\right)$$

for the model (Fig. 2a), when current flows through the plasma, we will have

$$\rho u c_p \frac{\partial T}{\partial x} + \rho v c_p \frac{\partial T}{\partial y} = \frac{\partial q_T}{\partial y} + c_2 \exp\left(-\frac{A_2}{T}\right).$$

The nature of the temperature field corresponding to ignition is shown schematically in Fig. 2b (analogous temperature profiles determined numerically were presented in [5]).

If in the same problem it is desired to take burnup into account in the first approximation, then for conditions of similarity of the temperature and concentration fields and similar values of a and D (thermal diffusivity and diffusion coefficient) [6] it is necessary, as already mentioned, to take the coefficient of the exponential in the form $A_2(T_m - T)$ (T_m is the maximum value of the temperature), i.e., introduce a limitation on the maximum current.

In the system shown in Fig. 3, as in the previous example, the conditions of motion (averaged and fluctuational) are preserved unchanged, and the energy equation and its relation with the motion are "automatically" reproduced. Obviously, the boundary conditions for velocity and temperature are also respected.

We also note that, by using plasma as a sort of resistance thermometer, it is possible to model the mixing process in compressible gas flows. Obviously, in this case the value of the current must be the minimum necessary to permit measurements, and the heat released by the current must be neglibly small.

In practice, electrical modeling of the combustion process encounters unavoidable difficulties. In particular, it is clearly necessary to eliminate distortions associated with the potential drop adjacent to the electrodes, etc. Preliminary experiments show, however, that these difficulties can be overcome.

NOTATION

f and σ are the rate constant and electrical conductivity, respectively; T is the temperature; A_1 and

Values of Activation Energy
(Pressure 1 atm)

Type of plasma	Seeding component, %, potassium or cesium	A_2, eV	Reference	A_1 eV, for hydrocarbon fuels
Air	—	2.24	[1] calc.	1.6—2.4
Combustion Products	0—1.0 (K)	2.24	[2] expt.	
Combustion products	0.02—0.04 (K)	1.93	[1] calc.	
Argon	0.02 (Cs)	1.63	[1] calc.	

A_2 are the values of the activation energy for chemical reaction and ionization, respectively; τ_T and q_T are the turbulent friction stress and heat flux, respectively; $c_i \exp(-A_i/T)$ is the heat release due to chemical reaction and Joule heat; $c_2 = \text{const } V^2/L^2$; V is the constant voltage; L is the distance between electrodes in model.

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