The gel fuel ignition at local conductive heating

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ABSTRACT

An experimental study of ignition of a gel fuel at local conductive heating has been performed. The initial temperatures of the fuel samples were 120, 260, and 290 K. Metal particles in the shape of a sphere, a disk, and a parallelepiped with a characteristic size of 10 mm were used as ignition sources. The initial temperature of the heating sources varied in the range of 1050–1350 K. The use of software and hardware high-speed video recording (4200 frames per second at a maximum resolution of 1280×800 pixels) allowed analyzing the regularities of physical and chemical processes, occurring during the induction period. Limit conditions necessary for stable ignition of a gel fuel and dependences of ignition delay time on parameters of a local heating source have been established. A low-inertia (sampling rate of 100 Hz) measuring system based on miniature thermocouples and an oscilloscope served to establish the velocities of the gel fuel melting front motion from the contact boundary between the metal particle and the fuel in the direction of the thermal wave propagation during induction period and under stationary combustion. The mathematical model of ignition of the gel fuel has been developed within the framework of the mathematical apparatus of continuum mechanics and the theory of chemical kinetics. The results of numerical simulation are in good agreement with the experimental data obtained. The applicability limits of the developed model within which it reliably describes characteristics of ignition have been established. The mathematical model may be used to develop advanced energy-efficient technologies for ignition of new fuels in wide ranges of parameters of the system *gel fuel/local heating source*.

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1. Introduction

1.1. Gel fuel

In recent years, due to the relevance of the development of territories with extreme climatic conditions [1], near and far space [2], when the ambient temperature reaches extremely low values, a promising trend in elaboration of power engineering and rocket and space technology has been the creation of new fuels, for example, gel ones, as well as energy-efficient ways of their ignition, for example, at local conductive heating by the sources of limited heat content.

Among the wide variety of condensed substances used as fuels, it is possible to distinguish conditionally: solid, liquid, gaseous and gel fuels. The latter are less common in practice. The reason for this is the lack of a general theory of ignition and combustion of such fuels in comparison with solid, liquid and gaseous condensed substances [3–7]. Physical and chemical processes occurring during ignition and combustion of solid, liquid and gaseous fuels are well studied. The mathematical models [8–12] have been developed to reliably predict the main characteristics and to use these results in the design of engines and power plants to optimize their functioning. Developing the theoretical foundations of energy technologies at the combustion of gel fuels is impossible without basic research of ignition and combustion processes. The need for such studies is explained by the advantages of gel fuels in comparison with other types of condensed substances. Due to their semi-solid and semi-liquid state, these fuels combine the positives of both the solid as well as the liquid propellants.

Gel fuels have higher energy characteristics in comparison with composite solid propellants, in particular the specific impulse of 300–350 s at a force of 1 kg per 1 kg of fuel [13]. Replacing a composite solid propellant with a gel fuel will make the dynamic engine thrust control in time relatively easy to implement [14]. In addition, gel fuels, compared to liquid fuels, have lower fire hazard indicators due to the minimized evaporation losses and leakage during storage. Components of gel fuels and products of their combustion are characterized, as a rule, by less negative impact on the environment compared to typical liquid rocket fuels [15].

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Nomenclature

$a_p, b_p, c_p, d_p, r_p, z_p$ dimensions of hot particles (m)
C heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$
D diffusion coefficient $(m^2 \cdot s^{-1})$
E activation energy $(J \cdot mole^{-1})$
k pre-exponential factor (s^{-1})
k_γ evaporation constant
M molar mass (kg/kmole)
P vapor pressure (N/m^2)
P^n saturated vapor pressure (N/m^2)
Q_1 thermal effect of oxidation of fuel vapors $(J \cdot kg^{-1})$
Q_3 thermal effect of the gel fuel melting $(J \cdot kg^{-1})$
Q_{ef} thermal effect of fuel evaporation $(J \cdot kg^{-1})$
q_r radiant heat flux density on the surface of a hot particle $(W \cdot m^{-2})$
R_t universal gas constant $(J \cdot mole^{-1} \cdot K^{-1})$
r, z coordinates (m)
r_l, z_h dimensions of the solution domain (m)
T temperature (K)
T_0 initial temperature of air and fuel (K)
T_p initial temperature of a hot particle (K)
T_s temperature at the phase transition boundary (K)
t time (s)
t_d ignition delay time (s)
V volume (m^3)
W_1 mass flow rate of fuel vapors oxidation $(kg \cdot m^{-3} \cdot s^{-1})$
W_3 mass rate of gel fuel melting $(kg \cdot m^{-3} \cdot s^{-1})$
W_{ef} mass evaporation rate of fuel $(kg \cdot m^{-2} \cdot s^{-1})$

$z(t)$ distance from the fuel surface to the melting front at the tth time step (m)
$z(t + \Delta t)$ distance from the fuel surface to the melting front at $(t + \Delta t)^{th}$ time step (m)

Greek symbols
γ dimensionless coefficient of evaporation
$\Delta r, \Delta z$ step over the spatial coordinate (m)
Δt time step (s)
ε the degree of blackness
λ thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$
μ mass concentration
ρ density $(kg \cdot m^{-3})$
σ Stefan-Boltzmann constant $(W \cdot m^{-2} \cdot K^{-4})$
υ coefficient of kinematic viscosity (m^2/s)
φ volume concentration
ψ stream function (m^3/s)
ω vorticity vector (s^{-1})

Subscripts
1   gas-vapor mixture
2   hot particle (local heating source)
3   gel fuel
f fuel vapors
i, j the step number over coordinates r and z, respectively
o air

On the basis of the performed analysis [16–24] it has been found that the main studies on the subject of gel fuels are devoted to:

- the development of fuel compositions based on different components and study of their rheological characteristics [16–18];
- the study of the hydrodynamics of the fuel atomization process in the combustion chamber [19–21];
- the analysis of the characteristics of fuel ignition and combustion in the conditions of sputtering [22–24].

It should be noted that in practice, the gel fuel can become an alternative to a composite solid propellant. The latter consists of two main components – fuel and oxidizer. The ignition and subsequent combustion of the high-power charges of such fuel occurs at an open surface. A similar scheme of the engine operation can be realized when using gel fuel. Depending on the environmental conditions and the purpose of the gel fuel, its aggregate state can vary significantly: from liquid with high viscosity to solid (at low temperatures). In the latter case, the main difference between gel fuel and composite solid propellant is a different complex of physical and chemical processes, occurring during heating. For example, when a typical composite solid propellant (ammonium perchlorate + butyl rubber) is heated, the exothermic interaction of the combustible component and the oxidizer occurs in the heated area of the near-surface layer [25]. The processes proceeding during the induction period are well described within the framework of the mathematical model of solid-phase ignition of condensed substance [25,26]. Gas-phase ignition is typical for gel fuels. When the fuel is heated, a gas mixture is formed as a result of the fuel evaporation and mixing of volatiles with an external oxidizer [19]. In order to predict the characteristics of the gas-phase ignition of a gel fuel, appropriate mathematical models are necessary. These differ, for example, from the ignition models of solid [25,26] and liquid [27,28] con-

densed substances. The development of such predictive models is impossible without fundamental research. Experimental studies of ignition processes in the development of new fuels are quite a difficult task. Metrological support at a high level of experiments on the study of interrelated physical and chemical processes simultaneously occurring in the condensed phase and in the gas medium is often difficult to implement in practice, for example, due to the relatively small values of ignition delay times. Such significant limitations require the development of modern experimental techniques based on the use of high-speed hardware and software for recording the parameters of high-rate processes. The results of such experimental studies are the basis for the development of new ignition models, reliably describing the regularities and characteristics of the process. Practical application of the mathematical models allows:

- reducing the cost of resources for experimental studies;
- predicting and preventing potentially dangerous experimental conditions;
- intensifying fundamental and applied research to achieve the planned results in the shortest possible time.

1.2. Ignition devices

In the development of new fuels much attention is paid to solving the problem of energy efficient and stable ignition. Currently, pyrotechnic or pyrogenic igniters are used to initiate combustion of fuel charges depending on their size and weight characteristics [13,29,30]. The principle of operation of an energy-efficient ignition for gel fuel charges can be based, for example, on the local conductive heat supply to the condensed substance by a small group of sources of limited heat content. It is assumed that the main advantage of such ignition devices over the pyrogenic ones, the principle of which operation is based on the ignition of the main fuel charge by hot gaseous combustion products of the ignition