The conditions under which combustion of unitary solid fuels occurs in a liquid (water) medium are discussed. The physical prerequisites for maintaining stable combustion are determined. The necessary conditions and constraints, which, when satisfied, ensure underwater combustion along a flat surface of fuel, are formulated. Possible combustion regimes, differing by direction and rate of displacement of the boundary of the surface of gas formation, are analyzed as a function of the orientation of a semi-infinite flat sample. Experimental results confirming the existence of stable combustion of solid fuel directly in a water medium are presented.

Technical equipment with autonomous sources of a working body is required in rescue, underwater-technical, and ship-raising work. Under the indicated conditions the most suitable sources are condensed materials in the solid state — unitary solid fuels (USF) — which are capable of burning without access to air.

The desire for using USF in the unloaded state led to the development of gas generators, in which a well casing is used as the body [1, 2]. Margolin et al. investigated the combustion of water-filled porous explosives [3]. Underwater combustion of miniature cylindrical fuel samples due to localization of a heater by gluing of a paper membrane is mentioned in [4]. As far as analysis of the conditions under which combustion of USF is maintained in a liquid medium is concerned, there are evidently no such data in the literature.

The aim of the present paper is to substantiate the possibility and conditions of existence of stable combustion regimes on the flat surface of unitary solid fuels directly in a liquid (water) medium in the absence of wave formation.

1. FUNDAMENTAL POSSIBILITY OF UNDERWATER COMBUSTION OF USF

In order to determine the conditions of underwater combustion it is necessary to know the admissible amounts of water that can penetrate into the chemical-reaction zone. A quantitative estimate can be given using the influence function $f(x)$ introduced in [5, 6]:

$$f(x) = \exp\left(-\frac{\rho u c_2}{\lambda_2} x\right).$$

where $u$ is the combustion velocity, $\rho$ is the fuel density, $c_2$ and $\lambda_2$ are the heat capacity and thermal conductivity of the products of combustion, and $x$ is the coordinate of the reaction zone (the origin of the coordinates corresponds to the onset of exothermal reactions, and the combustion zone is located on the right-hand side).

As is well known [5], the value of the influence function at each point determines the fraction of the released heat that is expended on heating of fresh material, thereby ensuring advancement of the combustion front (a kind of efficiency of the reaction layer $dx$). At the point $x = 0$ this function is equal to 1 and it decreases monotonically with increasing $x$. At some
distance from the front of onset of chemical reactions the release of heat has virtually no effect on the combustion velocity (the influence function is close to zero). Therefore, for combustion it is not important that heat be released to the right of this region. In particular, a liquid medium, for example, water, can be located in this region. We shall assume that for standard unitary compositions exothermal reactions stop completely in the region of the water surface. For this reason, penetration of liquid into the reaction zone without significant effect on the combustion velocity is admissible at distances $\delta_T$ where the influence function has a negligible value. Taking a 1% value of the influence function

$$f(\delta_{79}) = 0.01 = \exp\left(-\frac{\rho u c_s}{\lambda_2} \delta_{199}\right),$$

we obtain

$$\delta_{79} \approx \frac{4.60 \rho_c^2}{\rho u c_s^2}.$$  

This is the first condition for stable combustion. When this condition is satisfied, the combustion velocity is at least 99% of the initial velocity.

The numerical value of the minimum gap between the water surface and the combustion surface of the fuel at pressures of 0.1 MPa, calculated from Eq. (3), is 1.1 mm. As the pressure increases, this quantity decreases as the inverse $\nu$-th power of the pressure ($\nu$ is the exponent in the combustion law).

There arises the question of possible regimes of underwater combustion. Consider a semi-infinite block of USF positioned with its flat surface oriented upward (Fig. 1, left). Suppose that the fuel is ignited by some method along half of the surface above which, as a result, there will be a gaseous medium. Since under the conditions of fuel combustion the arrival of gas undergoes pulsations, it is obvious that oscillations of the liquid will appear at the boundary. The boundary zone will then be periodically alternately filled with water and dried.

In order to determine the behavior of the boundary of the surface under these conditions, the degree to which the water and the gaseous medium act on the USF must be compared. For this, it is desirable to compare for the indicated media the thermal activity defined by the relation [7]

$$\varepsilon = \frac{\gamma \lambda c_p}{\sqrt{P}},$$

which is virtually constant for water and proportional to $\sqrt{P}$ for gas. The dependence of the initial temperature of the surface on the thermal activities can be expressed by the relation

$$T_s = \frac{K_s}{1 + K_s} (T_{s1} - T_{s0}) + T_{s0},$$

where $K_s$ is the thermal activity, equal to $\sqrt{\lambda_1 c_p \rho_1/\lambda_0 c_p \rho_0}$ and the index 1 refers to the high-temperature medium.

The thermal activity is equal to 1531 for water, 143 for products of combustion under a pressure of 10 MPa, and 738 J/(sec$^{0.5}$m$^2$K) for fuel H. For this reason, the thermal effect of the water on the combustion surface under these conditions is an order of magnitude stronger than that of the gaseous medium. At lower pressures this difference is even larger.