Curve 3 in Fig. 2 corresponds to the limiting case ($\lambda = 0.5$) with no stemming. Existing recommendations for elongated charges assume a ratio of $1/3$ between the stemming length and the total depth of the borehole ($\lambda = 1$). This corresponds to curve 2 in Fig. 2, from which it is evident that the best discharge conditions for borehole charges with $\lambda = 1$ are only realized for charges with $l > 30d$, which does not correspond to the optimal elongation in terms of obtaining maximum discharge volume (Figs. 1 and 3). It follows from curve 1 in Fig. 2, for a ratio of the stemming length to the borehole depth of $1/2$ ($\lambda = 1.5$), that the result of the explosion is significantly better.

Thus, the laboratory data for sandy earth agree overall with the results of large-scale in-situ explosions in loess-like loam. However, the conclusions of the present work evidently cannot be extended to disintegrating earth, since in this case the strength characteristics may have a considerable influence on the (optimal) stemming length, other conditions being equal.

**LITERATURE CITED**


**MODEL OF BUBBLE DETONATION**

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A model of detonation in a two-phase heterogeneous mixture consisting of bubbles of chemically reacting gas in a chemically inert liquid is proposed. The model takes account of the compressibility and viscosity of the liquid, the presence of an induction period of the chemical reaction, and shift of the chemical equilibrium. The initiation of the wave and its approach to steady conditions are calculated. The calculation results agree with experiment. It is shown for the first time that wave propagation at supersonic (relative to the frozen sound velocity) velocity is possible with large initial pressures in the mixture. The structure of the wave in sub- and supersonic conditions is significantly different. In the first case, there is smooth pressure variation in the compression wave; in the second, there is a pressure discontinuity at the leading shock front of the wave.

Bubble detonation has only recently been discovered [1-7], and the corresponding theory is far from complete. Deficiencies of the theoretical modeling of this process include inadequate description of the dynamics of bubble-mixture motion. Thus, in [8, 9], the liquid was assumed to be incompressible and in [10-12] the system of nonlinear hydrodynamic equations was linearized to obtain model quasilinear equations (of Korteweg-de Vries-Burgers type with additional terms), which is only suitable for qualitative description of the evolution of the pressure-wave profile.

The unwieldiness and opacity of accurate kinetic calculations of gas-phase chemical reactions is such that existing theoretical studies of bubble detonation are based on simple approximate models which are generally not well-founded in physical terms and of low accuracy. In particular, the molecular mass of gas was assumed to be constant in [8-17], and the thermal effect to be constant or monotonic, although data in [18, 19] and elsewhere indicate that, on account of recombination and dissociation, it is not always monotonic, and may vary over wide limits. In addition, existing models of bubble detonation [8-17] describe the adiabatic compression of gas in a bubble by the adiabatic of a chemically inert gas with a constant coefficient. In reality, as is well known, adiabatic processes in a chemically reacting gas differ significantly from the analogous processes in inert gas, and can by no means always be described in the same way (in particular, with large variation in gas density, temperature, and pressure, as in a bubble-detonation wave).
These deficiencies are such that none of the existing models of bubble detonation permit quantitative calculation of
the wave parameters without fitting on the basis of experimental data. In addition, the models of [8-11] do not describe the
qualitative dependence of the wave velocity on the volume fraction of gas in the mixture.

With the aim of eliminating these deficiencies, a one-dimensional single-velocity model of detonation in a system
consisting of bubbles of chemically reacting gas in a chemically inert liquid is proposed below.*

The dynamics of bubble-mixture motion is described on the basis of the widely adopted realistic model of [21]. The
viscosity and compressibility of the liquid are taken into account. The heat liberation and molecular mass of the gas and the
adiabatic process in the gas in chemical equilibrium in the bubble are calculated on the basis of a highly accurate approximate
kinetic model [18, 19, 22-24].

Note that existing experimental and theoretical studies of the process correspond to sufficiently low initial pressures
of the mixture (p₀ ≈ 1 atm). The detonation was (DW), which is supersonic with respect to the equilibrium sound velocity
c₀ in the mixture, is subsonic with respect to the frozen sound velocity c₀ in the two-phase medium.† That a bubble-detonation
wave may travel at a velocity supersonic with respect to c₀ was not previously known. At the same time, the energy saturation
of a bubble medium increases with increase in p₀ since the amount of chemically reacting gas mixture per unit mass of liquid
increases. Correspondingly, the detonation rate will also increase. Since c₀ depends weakly on p₀, it must be expected that
the bubble-detonation wave may become supersonic with respect to c₀ with increase in p₀. In fact, calculations by the above
model have shown the propagation of the bubble-detonation wave at a velocity supersonic relative to c₀ for the first time.

The following notation will be used: p, ρ, u are the pressure, density, and velocity of the medium; ρ, δ, η are the
density, surface tension, and dynamic viscosity of the liquid; r is the bubble radius; N is the bubble concentration per unit
volume; β is the volume fraction of gas in the mixture; T, μ are the temperature and molecular mass of gas; μ, μₐ, μₘᵢₙ, μₘₐₓ
are the molecular masses of gas in the atomic, most dissociated, and most recombined states; R is the universal gas constant;
E_D is the mean dissociation energy of the reaction products; A, K₊ are the rate constants of dissociation and recombination
of the generalized reaction products; γ is the adiabatic index of the gas; Θ is the effective excitation temperature of the
vibrational degrees of freedom of the molecules; B, n are the Theta adiabatic constants; subscript 0 corresponds to parameters
in the initial state, 00 to the initial state with p = 1 atm and T = 293.15 K, and g to the gas.

MODEL OF BUBBLE DETONATION

The model of detonation in the given bubble medium is based on the following fundamental assumptions.

- The gas is ideal:

\[ p_D/\rho_D = RT/\mu. \]  

(1)

- Chemical reaction occurs in the gas. Up the end of the induction period, the gas is chemically nonreacting:

\[ \mu = \mu_0. \]  

(2)

After the end of the induction period, the gas is instantaneously in a state of chemical equilibrium, which is shifted as the
mixture moves downstream. To calculate the specific internal energy of the gas, the chemical-equilibrium state will be
described on the basis of the approximate model [18, 19, 22, 23]:

\[ U = \left[ \frac{3}{4} \left( \frac{\mu}{\mu_m} + 1 \right) + \frac{3}{2} \left( \frac{\mu}{\mu_m} - 1 \right) \Theta/T - 1 \right] \frac{RT}{\mu} + E_D \left( \frac{1}{\mu} - \frac{1}{\mu_{min}} \right), \]  

(3)

\[ \frac{p_g}{\mu} \left( 1 - \frac{\mu}{\mu_{max}} \right)^{3/2} \Theta/DRT = AT^2F \left( 1 - e^{-2/\Theta} \right)^{3/2} / 4K_+, \]  

(4)

which eliminates the need for the traditional artificial assumptions regarding the heat liberation and molecular mass of the gas
[8-17].

*Some of the results given here were first reported in [20].
†Note that the detonation wave in the gas, gas-bubble, and gas-film mixtures is supersonic with respect to both c₀ and c₀.  
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