EFFECT OF PHASE VELOCITY NONEQUILIBRIUM ON FLAME PROPAGATION AND EXTINCTION

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The problem of flame propagation in the presence of inert particles is considered. The mathematical model used is based on the equations of the mechanics of multiphase media in a two-temperature, two-velocity approximation. Numerical calculations of combustion in the presence of a dispersed phase in zero gravity show that the flame does not quench. For flame propagation in the gravity field directed toward falling particles, a new phenomenon, namely, flame quenching, is revealed. It is shown that the quenching is due to the occurrence of feedback between the flame velocity and the magnitude of heat losses. Critical parameters for various values of the external mass force and particle size are determined.

A distinguishing feature of combustion in the presence of an inert dispersed phase is that a portion of the heat released in chemical reaction is expended on particle heating. The heat transport from the burning gas to the particles is proportional to the difference between the gas and particle temperatures and decreases as the particles are heated. This leads to some characteristic features of the behavior of the system. Joulin [1] performed an asymptotic analysis of the problem of combustion-wave propagation in the presence of inert particles. Fine particles were shown to act as an inert gas, i.e., the flame velocity decreases monotonically with increasing particle concentration. If the particle size exceeded a certain critical size, three different combustion-velocity modes were possible, and the intermediate mode was unstable. A stability analysis showed that the addition of inert particles facilitates destabilization of the plane flame front. A similar problem was solved by Ivleva et al. [2] for the combustion of gasless systems.

Mitani [3] examined, in addition to the effect of inert particles, the inhibition effect of evaporating drops. The dependence of the flame-propagation velocity on the mass concentration and size of dispersed inclusions was determined by the method of matched asymptotic expansions. As in [1, 2], a nonuniqueness region of steady-state combustion regimes was found for both drops and particles.

Granovskii et al. [4] calculated, using the Zel'dovich approach, flammable limits in a fluidized layer of a granular material. Unlike conditions of flame extinction in narrow ducts (critical Pekle number Pe ~ const), conditions of extinction in a fluidized layer are greatly dependent on the particle concentration. As the particle concentration increases, the critical flame velocity varies from \( U_a/\sqrt{e} \) to \( U_a/e \), where \( U_a \) is the adiabatic combustion velocity.

Dik et al. [5] studied analytically the inhibition effect of powders on flame-propagation velocity as a function of particle concentration and particle size. Using the method of a model source, the authors obtained an approximate solution that agrees qualitatively with experimental data. Later, this work was supplemented by a numerical investigation of the unsteady interaction of a combustion wave with a dust cloud in a diffusion thermal formulation [6]. Processing of the numerical calculation results yielded critical parameters of the dispersed material that ensure suppression of the combustion zone.
A review of theoretical results for flames propagating in gas mixtures with inert particles is given in [7]. Particular emphasis is placed on the effect of radiation heat transfer; the effects of gas particles and phase temperature nonequilibrium are also taken into account. For steady-state plane flames, the author has shown several flame-propagation regimes. Based on evolutionary equations, an analysis of transitions between steady-state regimes was carried out and the mechanism leading to relaxation combustion-velocity oscillations was found. The model [7] of a weakly curved, unsteady flame shows that radiation transfer leads to a nonlocal effect of the curvature on the combustion velocity, and, hence, on the flame shape. Also, a nonlinear evolutionary equation for weakly curved, unsteady flames was obtained.

Unfortunately, little experimental work has been devoted to the effect of inert particles on flame propagation. We mention here only the interesting and important result of [8-10]. The addition of a small amount of powder is shown to increase considerably the flame-propagation velocity in a duct. This effect was observed in both zero gravity and the gravity field. In [10] this behavior is explained by the fact that particles create turbulence in the mixture, thus increasing the combustion velocity.

Mention should also be made of papers on filtration combustion, e.g., [11], in which the front structure and steady-state and quasi-steady-state combustion mechanisms are analyzed in detail for different methods of implementing ignition processes, and combustion limits and unsteady effects in the reaction front propagation are studied. Although the system in this case is characterized by a much higher volume concentration of the solid phase, the approaches and results are in many respects similar to those for the case of gas combustion in the presence of a dispersed phase, in particular, when large particles are considered.

In all above-mentioned papers, the difference between the gas and particle velocities was ignored in theoretical consideration. Velocity nonequilibrium, however, should manifest itself markedly for sufficiently large particles, particularly, in the gravity field, in which the upward flame moves toward falling particles. As will be shown below, the phenomenon of phase velocity nonequilibrium has a significant influence on flame propagation and extinction.

This modeling of gas-flame propagation in the presence of inert inclusions uses the equations of the mechanics of multiphase media [12], which take into account the velocity and temperature nonequilibrium of phases. Numerical integration is used to determine the combustion-wave propagation characteristics and conditions of flame extinction. The phase velocity nonequilibrium is shown to have a significant influence on the character of heat removal from the combustion zone.

**FORMULATION OF THE PROBLEM**

We consider flame propagation in a plane closed duct in the presence of solid inert particles. Systems with a small volume concentration of the dispersed phase are studied. Crushing and evaporation of the particles, and their collisions with one another are not taken into account.

Combustion is initiated by hot combustion products in a small region adjacent to the center of the end wall of the duct. It is assumed that an exothermic, one-stage, irreversible chemical reaction of the first order with respect to the deficit component proceeds. The reaction rate obeys the Arrhenius temperature dependence. The thermophysical properties of the combustion products and the starting mixture are considered identical.

The system of equations describing the motion of the reacting gas with allowance for interphase interaction is written in dimensionless variables as

\[
\frac{\partial \rho_1}{\partial t} + \text{div} \rho_1 \cdot \vec{U}_1 = 0, \quad p = \rho_1 \Theta_1,
\]

\[
\frac{\partial \vec{U}_1}{\partial t} + (\vec{U}_1 \cdot \nabla) \vec{U}_1 = -\frac{1}{\gamma M^2 \rho_1} \cdot \nabla p + \frac{1}{\text{Re} \cdot \rho_1} \left( \Delta \vec{U}_1 + \frac{1}{3} \nabla (\nabla \cdot \vec{U}_1) \right) + \text{Fr}^{-1} \cdot \vec{j} - \vec{f},
\]

\[
\frac{\partial \Theta_1}{\partial t} + (\vec{U}_1 \cdot \nabla) \Theta_1 = \frac{\gamma}{\text{Pr} \cdot \text{Re}} \Delta \Theta_1 - (\gamma - 1) \Theta_1 \text{div} \vec{U}_1 + QD_\text{a} \cdot a \Phi(\Theta_1) - q,
\]

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