Capillary Hydrodynamic Phenomena in Gas-Free Combustion

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The capillary effects of gradient filtration and melt microflows in combustion waves of heterogeneous systems are analyzed on the basis of experimental data obtained by video recording, local dynamic pyrometry, and investigation of hardening structures. Relations between the parameters of convective phenomena and combustion dynamics and the mechanism of activation of the heterogeneous combustion interaction by melts are established for Ti–B–Cu, FeO–Al–Al2O3, Ni–Al, and Ti–Ni powder mixtures and model bimetallic compositions.

Key words: heterogeneous systems, melts, capillary convection, filtration, combustion.

INTRODUCTION

The combustion characteristics of gas-free (low-gas) systems are largely determined by convective processes in melts. Generally, convection can be caused by surface tension, gravity, and gas pressure. For the reaction conditions in high-porosity powder systems based on metals, oxides, and other components, the action of the indicated factors can be estimated from the corresponding energy value:

\[ E_s \approx \frac{\sigma}{d} \approx 10^3 \text{–} 10^7 \text{ J/m}^3, \]
\[ E_g \approx \rho gh \lesssim 5 \cdot 10^4 \text{ J/m}^3, \]
\[ E_p \approx \Delta p \lesssim 10^4 \text{ J/m}^3. \]

Here \( E_s \), \( E_g \), and \( E_p \) are the potential energy densities of surface tension, gravity, and gas pressure, respectively, \( d \approx 10^{-3} \text{–} 10^{-7} \text{ m} \) [1] is the particle size of the mixture, \( \sigma \approx 1.0 \text{–} 3.0 \text{ J/m}^2 \) [1] is the surface tension of the melt, \( \rho \approx (1 \text{–} 5) \cdot 10^3 \text{ kg/m}^3 \) is the density of the mixture, \( g \) is the acceleration due to gravity, \( \Delta p \) is the gas pressure gradient in the sample, which is limited by the rupture strength of the mixture, and \( h \approx 0.01 \text{–} 0.1 \text{ m} \) is the size of the sample.

From the estimates, it can be seen that, for \( d < 10^{-4} \text{ m} \), the motion of melts in the reaction wave is dominated by capillary forces.

By the present time, among the combustion processes of heterogeneous systems, the effect of capillary flow of melting particles of one component between the solid particles of another component on the scale of the reaction cell of powder mixtures has been studied in greatest detail.

This effect was first found for the Ti–C system in [2], where it was shown that the capillary flow of titanium could significantly activate combustion due to an increase in the reaction surface of the components. For a large size of melting particles in the Ti–C and Ti–B systems, according to [3, 4], a capillary combustion mode occurs, in which the reaction rate is determined by the capillary flow kinetics.

In addition to the indicated effect, there is a wide range of other, less understood, capillary phenomena of heterogeneous combustion, including melt filtration on the scale of the combustion wave and Marangoni convection, which are the subject of the present paper.
EXPERIMENTAL TECHNIQUES

The initial components were powders of PTM, PTÉM, PTÉS, and PTÉK titanium, PMS-1 copper powder, black amorphous boron of 98.8% (by mass) purity, PNK-2L7 and PNÉ-1 nickel, ASD-4, PA-4, PA-2, and PA-1 aluminum, and FeO and Al₂O₃ graded chemically pure. Variation in the particle size of the components was achieved by sieve screening of the initial powders into narrow fractions or by granulation of the powders with the subsequent sintering of the granules in a vacuum furnace and sieve fractionation. The titanium and boron powders were subjected to preliminary thermal vacuum treatment at temperatures of 1173 and 1573 K, respectively, to remove volatile impurities.

The components were mixed in the required proportions and cylindrical samples of diameter \((20-30) \times 10^{-3}\) m, height \((50-70) \cdot 10^{-3}\) m, and relative density \(\rho_r = 0.4-0.9\) were prepared. Low-density samples were placed in a quartz shell. Combustion of the mixtures was initiated using a heated electrical wire and an igniting composition in a sealed reaction chamber with argon at a pressure of \(10^5\) Pa or in air with a protective argon flow.

In some experiments, the reaction systems were bimetallic compositions made of Ni–Al and Ti–Ni twisted-pair wires. The mass content of the corresponding metals in the wires was not less than 99%.

Combustion was recorded by a Panasonic NV-DAIEG video camera equipped with an 50-fold magnification optical system. The burning velocity was determined by processing video records, which fixed current averaged displacements of the combustion front in unit time.

The temperature of the process was determined by a color pyrometry technique using a special system [5], which consisted of a video camera and a computer and was adjusted by the reference radiation of a SI-10-300U photometric lamp. This system allowed local dynamic temperature fields in the visible thermal radiation range to be determined with an error not more than 50 K. The temperature was also monitored by a 5% W/Re–20% W/Re thermocouple \(10^{-4}\) m thick placed in the sample.

The sample surface was illuminated by CuBr vapor laser radiation to determine the dynamics of structural transformations. Use of optical filters adjusted to the laser wavelength provided clear video images of the system topography throughout the transformation. This was achieved due to the high brightness of the light flux reflected from the sample surface, which surpassed the thermal radiation intensity of the reaction wave in the wavelength range used.

RESULTS AND DISCUSSION

Gradient Capillary Filtration

This type of mass transfer, noted earlier in [6, 7], should be treated as the final stage of capillary redistribution of the melt in the combustion wave of partially melting powder systems. The initial stage involves relatively isotropic capillary flow of the melting particles between the solid particles on the scale of the reaction cell, and the final stage involves directed (along the combustion propagation) filtration of the melt between the solid particles in the wave layer in which the temperature varies from the melting point of the lowest-melting component to the melting point of the highest-melting component (or the maximum combustion temperature) under the capillary pressure gradient. The necessary conditions of gradient filtration as an isolated phenomenon are the following: the completion of the capillary flow process on the scale of the reaction cell before the diffusive mixing of the system; the greater thickness of the combustion wave than that of the reaction cell size. These conditions are usually met at \(d \leq 10^{-5}\) m.

The capillary pressure gradient in the filtration layer is generally caused by distributions of the temperature, melt composition, capillary channel size, and the wettability parameters of the solid particles along the combustion wave. As a first approximation, the linear filtration velocity can be obtained using the Poiseuille formula for the capillaries formed by the gaps between the solid particles under the assumptions of a one-dimensional temperature field in the liquid, constant