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HEAT AND MASS TRANSFER UNDER PHASE AND CHEMICAL TRANSFORMATIONS

RANGES OF RATES OF SUPERSONIC COMBUSTION IN A POROUS MEDIUM

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The results of investigations of the propagation of supersonic combustion in a tube completely or partially filled with a porous medium are presented. The relationship between the combustion-wave velocity, the medium parameters, and the properties of the combustible mixture has been established.

Introduction. The last few years have seen growing interest in the processes of combustion propagation and detonation in porous media (PM) and blocked-up spaces (BS) connected with the development of new technologies based on filtration combustion, as well as with the unsolved problems of explosion safety in different branches of industry.

It is known [1] that the velocity of the denotation wave propagating in a porous medium is, as a rule, lower than the Chapman–Jouget detonation velocity in a free tube, and this difference increases with decreasing initial pressure of the gaseous mixture. As follows from the previously published papers [2, 3], the mechanisms of ignition initiation and transfer in PM differ considerably from the case of combustion in a free space, since a PM is characterized by a much larger hydrodynamical drag coefficient and greater heat losses and, therefore, in the reaction wave propagating in a porous frame the pulse and energy losses from the wave front are much more significant and the gas flow is more strongly turbulized [3].

In general, the mechanism of propagation of fast combustion waves in a PM incorporates the elementary processes of convective energy transfer, diffusion, and heat exchange between the gas and the porous body. However, these processes are still not clearly understood [4]. Moreover, the mechanism of mixture ignition in the interpore space is not clearly understood either. It is believed that at lower velocities initiation occurs due to the penetration of the burning gas from the nearby pores, the flame-front acceleration under interaction with reflected shock waves, and the spontaneous ignition of the compressed mixture that follows. With increasing velocity, the gas ignites mainly as a result of the adiabatic compression after the reflected shock waves [3, 4].

At present, there is no detailed theoretical description of the processes of porous combustion that would permit a priori prediction of the flame velocity depending on the PM characteristics and the initial pressure. As a rule, to construct such a model and check its validity, one needs a set of experimental data varying over a wide range of change in the basic parameters. However, currently an extremely small amount of data on the rate of supersonic combustion depending on the mixture composition, the initial conditions, and the properties of the porous medium is available.

The aim of the present paper is to investigate the spectrum of supersonic combustion wave velocities in a tube completely or partially filled with a porous material, as well as to verify the empirical relationship established in [5] between the flame velocity, the PM characteristics, and the detonation properties of the combustible mixture.

Experimental Facility. In the experiments, we used two steel detonation tubes with an inner diameter of 25 and 50 mm and a length of 5 and 1.2 m, respectively. Both tubes were equipped with photo- and ionization sensors

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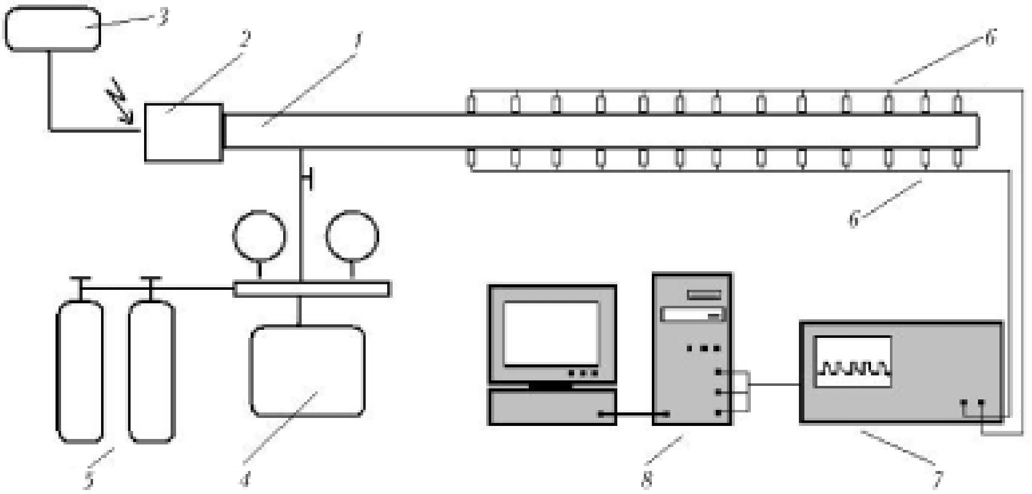

Fig. 1. Diagram of the experimental facility: 1) detonation tube; 2) ignition chamber; 3) ignition unit; 4) vacuum pump; 5) bottles with combustible mixtures; 6) photo- and ionization sensors; 7) oscilloscope; 8) computer.

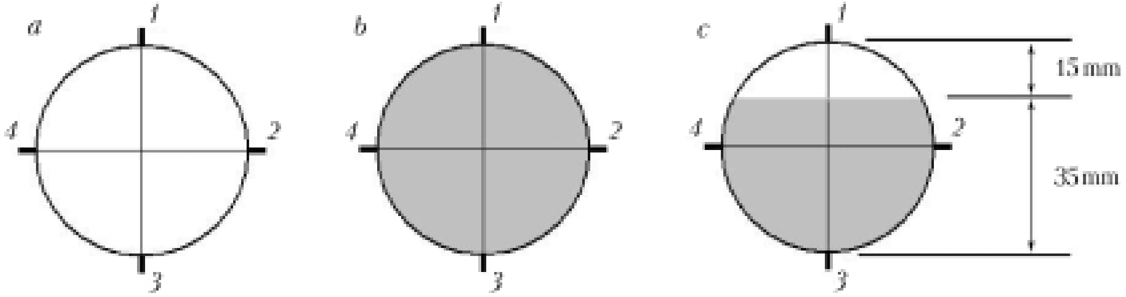

Fig. 2. Variants of detonation tube filling: a) hollow tube; b) tube with a porous filler; c) tube partially (70% by volume) filled with a porous material (1, 2, 3, 4 — lines on which ionization sensors are located).

to register the arrival time of the flame front and the velocity of its propagation along the tube axis, as well as with piezoelectric sensors to measure the pressure and the velocity of the leading shock wave front (Fig. 1). As pressure meters, we used PCB Piezotronics 113A22 and M102A sensors (147.1 mV/mPa). The ionization sensors were arranged in four lines along the tube axis, the spacing between the sensors in each line being 39 mm (Figs. 1 and 2). The measurement-section length was 1.2 m. Just before the experiment, the tube was evacuated to a residual pressure of 10^{-2} Torr and filled with the mixture at the required pressure. The mixture was prepared in a separate bottle by the partial-pressure method and held before use for no less than 24 h. Combustion was initiated by means of an ignition chamber with a high-voltage electric spark ignition. The signals from the sensors were registered by a digital measuring complex (the frequency of recorded signals was 0–200 MHz) and then processed by a computer.

The experiments were performed in a hollow tube, as well as in a tube partially or completely filled with a porous material (Fig. 2). As the porous medium, we used steel balls of diameter 5.5 mm; the porosity was 0.38, and the mean diameter of the pores was ≈1.833 mm.

We used a stoichiometric acetylene–oxygen mixture with a different degree of dilution with nitrogen $C_2H_2 + 2.5(O_2 + \beta N_2)$, where β is the ratio between the molar concentrations of nitrogen and oxygen (at $\beta = 0$ we obtain a $C_2H_2 + 2.5O_2$ mixture, at $\beta = 1.4$ — a $C_2H_2 + 2.5O_2 + 3.5N_2$ mixture, and at $\beta = 3.76$ — a $C_2H_2 +$ air mixture).

Principal Results. To exclude ambiguity in comparing the data and discussing the measurement data, we performed a set of experiments to elucidate the influence of the spatial (vertical or horizontal) orientation of the tube on the rate of combustion in a porous medium. In both cases, no marked differences in the propagation velocity within

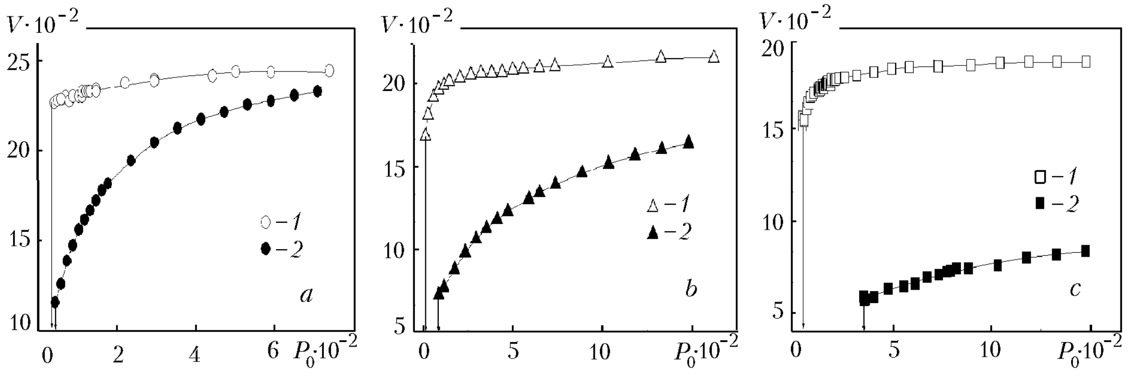

Fig. 3. Rates of supersonic combustion versus the initial pressure in a hollow tube (1) and in a tube with a porous filler (2): a) $C_2H_2 + 2.5O_2$ mixture; b) $C_2H_2 + 2.5O_2 + 3.5N_2$ mixture; c) $C_2H_2 +$ air mixture. V, m/sec; P_0, Torr.

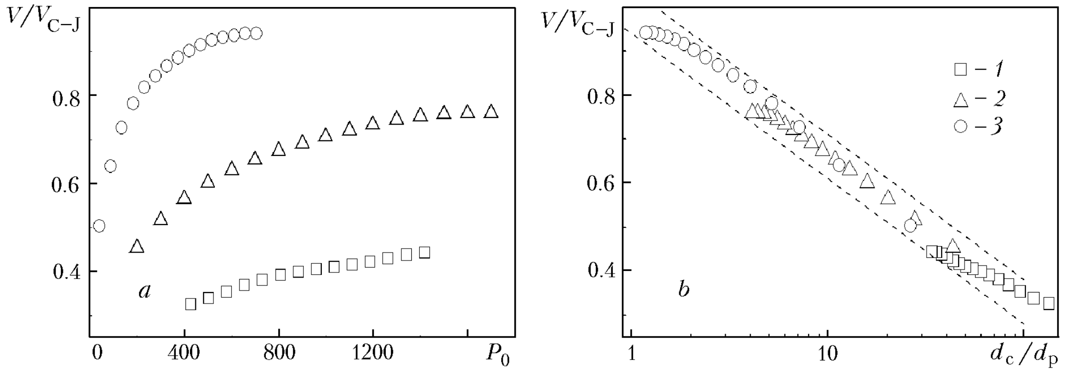

Fig. 4. Relative velocity of the supersonic combustion wave in a porous medium depending on the initial pressure (a) and the ratio of the tube critical diameter to the pore size (b): 1) stoichiometric mixture $C_2H_2 +$ air mixture; 2) $C_2H_2 + 2.5O_2 + 3.5N_2$ mixture; 3) $C_2H_2 + 2.5O_2$ mixture. P_0, Torr.

the measurement error were observed. The subsequent experiments were carried out only in a tube with a horizontal orientation.

Figure 3 presents the measurement data for the detonation velocity and the rate of supersonic combustion in a hollow tube and in a tube with a porous filler for various mixtures depending on the initial pressure. In both cases, the experiments were carried out until the propagation boundaries, i.e., the lower pressure boundaries, where the realization of the supersonic regime of combustion became impossible, were reached. It is seen that for the most sensitive acetylene–oxygen mixture the pressure boundaries differ not so significantly as for the least sensitive $C_2H_2 +$ air mixture, which points to a greater influence of the heat losses on the whole mechanism of combustion propagation in a PM, since the porosity was constant in all experiments and the losses due the hydrodynamic drag of the medium remained unchanged.

Figure 4a shows the relative flame-front velocities in the PM as a function of the initial pressure. It is seen that their values lie in the range from the Chapman–Jouget detonation velocity $V_{\text{C–J}}$ for the most sensitive stoichiometric mixture $C_2H_2 + 2.5O_2$ mixture to the minimum value measuring $\approx 0.3V_{\text{C–J}}$ in the acetylene–air mixture at a critical pressure. In the acetylene–oxygen mixture at atmospheric pressure, the wave in the PM propagates practically without attenuation, i.e., $V/V_{\text{C–J}} \approx 1$. This result is not surprising, since under such conditions the characteristic size of the attenuation cell for this mixture is ≈0.1 mm, i.e., it is much smaller than the average size of the pore. As the degree of dilution with nitrogen increases, the characteristic size of the detonation cell increases and, accordingly, the velocity deficit with respect to Chapman–Jouget detonation velocity begins to increase and reaches a value of $(0.3\text{–}0.4)V_{\text{C–J}}$ throughout the range of investigated pressures in the acetylene–air mixture. Moreover, unlike the case of combustion

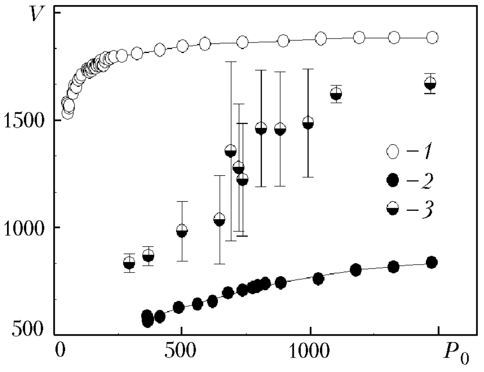

Fig. 5. Mean propagation velocities of the fast combustion wave along the tube channel: 1) hollow tube; 2) tube with a porous filler; 3) tube partially (70% by volume) filled with a porous medium (C_2H_2 + air mixture). V, m/sec; P_0, Torr.

in blocked-up spaces, a smooth character of the growth of the dependence of the relative velocity on the initial pressure is observed.

The measurement data have made it possible, based on the correlation equation proposed in [5], to refine the relation between the combustion-wave velocity in the porous medium, the detonation properties of the combustible medium, and the average size of the pore:

$$V/V_{\text{C–J}} = [1 - 0.33 \log (d_c/d_p)] \pm 0.05 , \tag{1}$$

where $d_c = 13\lambda$ is the critical diameter of the tube for the given conditions and $d_p \approx D/3$ is the characteristic size of the pores.

To calculate the critical diameter of the tube on the basis of the data of [6] and [7], we used the following approximation for the dependence of the detonation-cell cross section on the initial pressure:

$$\lambda = AP_0^{-1.1} , \tag{2}$$

where at $\beta = 0$ $A = 226$, at $\beta = 1.4$ $A = 2065.5$, and at $\beta = 3.76$ $A = 14{,}753.5$.

Figure 4b shows the resulting curve of the relative combustion-wave velocity $V/V_{\text{C–J}}$ depending on the value of d_c/d_p. It is seen that the supersonic combustion wave propagates in the porous medium in the range of values $0 < d_c/d_p \leq 100$. At a ratio of the critical diameter of the tube to the characteristic size of the pores of ≈ 1 the wave propagates almost at the detonation velocity, and at $d_c/d_p \geq 100$ it attenuates.

The above data completely confirm the results of [5], obtained in media with a different size of pores at a constant initial pressure, where it was established that

$$V/V_{\text{C–J}} = [1 - 0.35 \log (d_c/d_p)] \pm 0.1 . \tag{3}$$

To elucidate the influence of the degree of filling of the tube with a porous medium on the transformation of the fast regimes of combustion, we performed a run of experiments in a tube partially (70% by volume) filled with a PM.

Figure 5 shows the influence of the initial pressure on the mean propagation velocity of the combustion wave and the maximum deviation of the velocity from the mean value in the tube partially filled with a PM. It has been established that in the C_2H_2 + air mixture under certain conditions the combustion wave propagates along the tube axis with large velocity pulsations. In so doing, its lower boundary $V \approx 800$ m/sec is comparable to the rate of combustion in a porous medium and the upper boundary ≈1670 m/sec is close to the detonation velocity in a free channel. The experimental curve is smooth and a velocity jump in the region of the initial pressure of 600–650 Torr is observed. This is likely to be due to the fact that under the conditions of partial filling of the tube a part of the channel (about

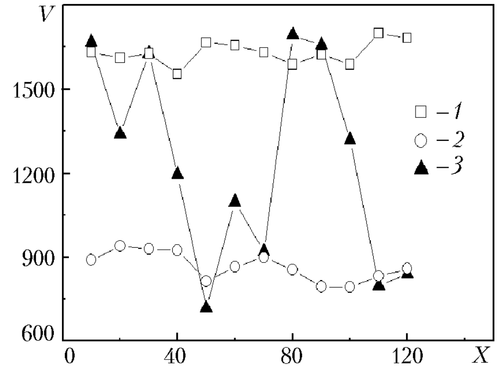

Fig. 6. Dynamics of change in the propagation velocity along the tube channel with partial (70% by volume) filling with a porous medium (C_2H_2 + air mixture): 1) P_0 = 0.5; 2) 1; 3) 1.5 atm. V, m/sec; X, cm.

15 mm) (see Fig. 2) remains free and at pressures of about 600 Torr the size of the detonation cell is comparable to the size of the free part of the tube. Thus, in the region of pressures above 650 Torr an almost stationary propagation of detonation in the free part of the channel is possible with some "unloading" of the pressure after the detonation front into the porous medium, which causes an insignificant decrease in the total velocity compared to the detonation velocity in the free channel.

The experiments have shown that in the transition region in the range of pressures from 600 to 1000 Torr the detonation wave propagates in the "galloping" regime (see Fig. 5). Figure 6 shows the dynamics of change in the wave velocity at different initial pressures in the stoichiometric mixture C_2H_2 + air. It is seen that for the "galloping" regime the velocity fluctuations along the tube axis constitute about 100% (from 800 to 1600 m/sec), whereas for both the regime of low velocities and the detonation the changes in the propagation velocity are insignificant. It has been found that under these conditions the period of longitudinal velocity pulsations is about 0.5 m, i.e., 10 calibers of the tube (Fig. 6).

Conclusions. As a result of the investigations performed, the supersonic combustion-wave velocities in a porous medium have been measured for a wide range of initial pressures in the stoichiometric acetylene–oxygen mixture with various degrees of dilution with nitrogen.

Different regimes of combustion in a tube partially filled with a porous medium have been revealed. It has been established that in such a system three characteristic regimes exist:

1 — the propagation velocity is close to the rate of supersonic combustion in a porous medium;

2 — the propagation velocity is comparable to the Chapman–Jouget detonation velocity for the given conditions;

3 — the velocity varies from the rate of combustion in a PM to the Chapman–Jouget ideal detonation velocity (intermediate "galloping" regime of propagation).

The validity of the correlation equation proposed in [5] has been confirmed.

It has been shown that in a porous medium there is a fairly wide spectrum of possible rates of supersonic combustion in a wide range of initial pressures. The wave velocity can take on values from $0.3V_{\text{C–J}}$ in the less sensitive acetylene–air mixture near the propagation boundary up to the detonation velocity in the acetylene–oxygen mixture at a high pressure. And the realization of a particular velocity regime is determined thereby by the ratio of the detonation tube critical diameter, which is a function of the initial pressure of the mixture, to the average size of the pore.

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NOTATION

A, coefficient; D, diameter of the steel balls forming a porous medium, mm; d_c, critical diameter of the tube for a given mixture, mm; d_p, characteristic size of the medium pores, mm; P, pressure of the mixture, Torr; V, propagation velocity of supersonic (detonation) combustion in a porous medium, m/sec; $V_{\text{C–J}}$, Chapman–Jouget detonation velocity, m/sec; *X*, distance along the tube axis, cm; λ, cross-section of the detonation cells, mm; β, ratio of molar concentrations of nitrogen and oxygen. Subscripts: p, pore; c, critical; 0, initial.

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