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PHYSICAL CHEMISTRY

Reactor for Waste Gasification with Highly Superheated Steam

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Abstract—Using highly superheated steam (HSS) with a temperature of above 2000 K for oxygen-free gasification/detoxification of industrial, municipal, and toxic waste, the organic component of waste can be completely converted to syngas or power gas. It was proposed for the first time to produce such HSS by cyclic detonation of stoichiometric ternary mixtures fuel–oxygen–steam at a near-atmospheric initial pressure and to feed it into a cooled flow-type spherical reactor as supersonic countercurrent two-phase jets together with finely divided waste particles. Three-dimensional gas-dynamic calculations showed that the cyclic feed of supersonic jets into the reactor gives rise to intense vortex zones of high-temperature HSS. Waste particles repeatedly enter into these vortex zones and are gasified or heat-treated, and the shock waves accompanying the feed of the supersonic jets prevent particle agglomeration. In the quasi-stationary operation process, a small overpressure is maintained in the reactor (to prevent the suction of atmospheric air), and the median mean residence time of the particles is sufficient for their complete gasification.

Keywords: highly superheated steam, industrial and municipal wastes, pulse-detonation steam superheater, spherical reactor, high-temperature vortex zones

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Previously [1, 2], a new (detonation) method to produce highly superheated steam (HSS) at atmospheric pressure was proposed. Such steam forms in a pulse detonation superheater (PDS) by the cyclic detonation of the ternary gas mixture fuel–oxidant–steam, with HSS being additionally produced as a product of the detonation of the fuel. The fuel can be hydrogen, power gas ($CO + H_2$), natural gas, propane, and others, and the oxidant can be oxygen, air, or oxygen-enriched air. It was shown [3, 4] that by the cyclic detonation of the ternary mixture propane–oxidant–steam can give HSS with a temperature above 2250 K at atmospheric pressure, and the products of the detonation of the stoichiometric ternary mixture can consist mainly of HSS (80%) and CO_2 (20%). Treatment of industrial, municipal, and toxic waste with such a gas can completely convert the organic component of waste to a gas mixture of CO and H_2 [5], which can further be used both as a power gas for a PDS and cogeneration of heat and electric power, and as a feedstock for producing synthetic motor fuels (e.g., from coal refuse). The high attractiveness of the idea under consideration raises the question of its practical implementation.

This work presents the results of three-dimensional gas-dynamic calculations of the two-phase flow in a model flow-type reactor intended for gasification/detoxification of waste (e.g., coal refuse, lignin, sawdust, fly ash, etc.) with HSS obtained by the detonation method. The purpose of the calculations was to get an insight into the flow pattern in the reactor and estimate the main characteristics of the operation process. For definiteness, the following simplifying assumptions were made: (1) the reactor is spherical, (2) the reactor walls are cooled and have constant temperature T_w, (3) the detonation products consist only of HSS, (4) the waste is constituted by spherical particles of equal diameters d_p, and (5) the self-heating of particles and their mass loss are ignored.

Figure 1 presents the schematic, computational mesh, and boundary conditions for a spherical reactor of volume V_R. Two PDSs shaped as coaxial detonation tubes of diameter d_{in} and length L are connected to the reactor at diametrically opposite points. Near the outlet sections of the detonation tubes, particle feeder are installed, each ensuring particle mass flow rate $m_{p,in}$. In the upper part of the reactor, an exhaust outlet tube of diameter d_{out} for the removal of gases and particles is mounted in the diametral plane perpendicular to the axis of the detonation tubes.

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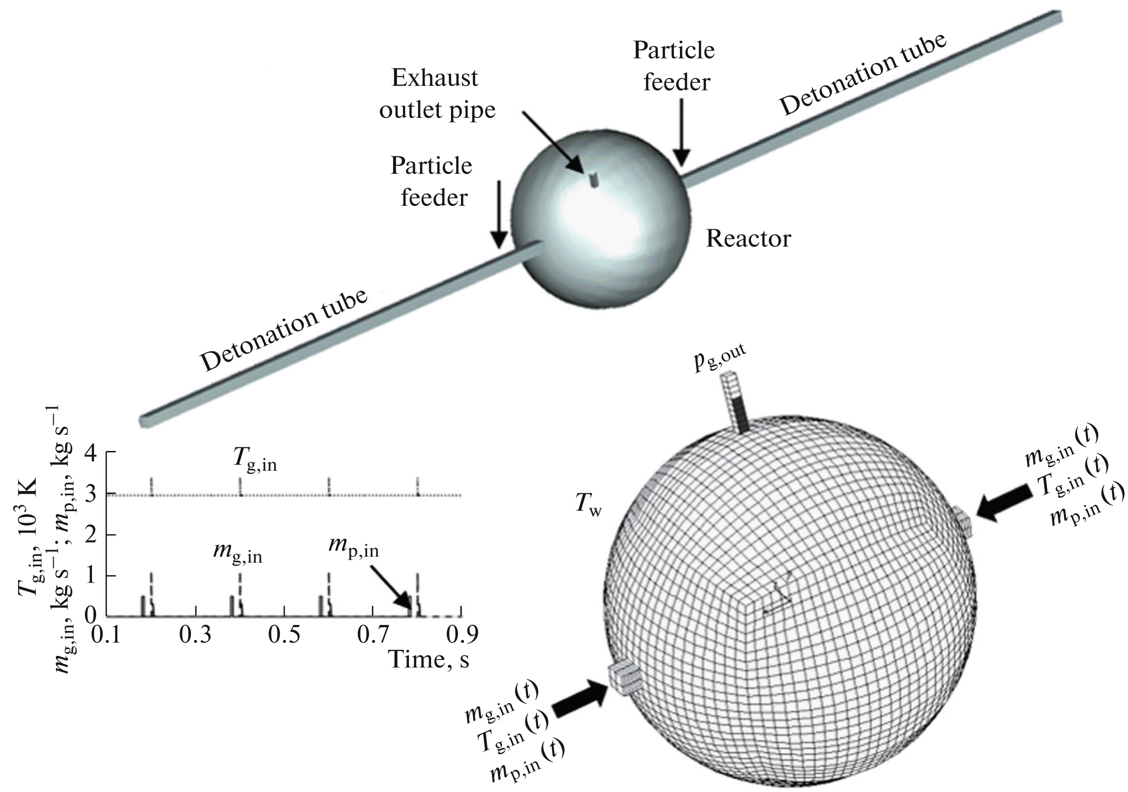

Fig. 1. Schematic, computational mesh, and boundary conditions for a spherical reactor.

The two-phase flow in the reactor is calculated using a tested computational procedure [6, 7]. The turbulent gas flow is calculated on a structured mesh; and the motion of particles, by the Lagrangian method. The numerical method is based on the finite-volume discretization of the flow equations with the first order of approximation in time and the second order of approximation in space using wall functions on rigid walls. The equations of motion of particles are solved by an explicit scheme. The computational mesh comprises 1×10^5 cells. With decreasing the average cell size, the flow pattern remains virtually unchanged.

The following scheme of the operation of the reactor was considered. Initially, the detonation tubes are filled with a stoichiometric ternary gas mixture fuel–oxidant–steam with temperature T_m up to the inlet sections of the reactor. Then, detonation waves travel in the tubes at constant supersonic velocity D and enter the reactor as strong counterpropagating shock waves with the accompanying supersonic jets of the hot detonation products. Along with the jets, portions of waste particles fed by the particle feeders are injected to the reactor. After the decrease in the pressure in the detonation tubes to the initial value, they are filled with the ternary mixture again, and the process is repeated. The frequency of detonation shots is f. The waste particles entering the reactor are involved in the vortex motion caused by the countercurrent supersonic HSS jets. Circulating in the reactor, the waste particles periodically enter high-temperature zones in the central part of the reactor, where they are generally thermally decomposed or gasified. The periodic strong shock waves accompanying the feed of the supersonic HSS jets prevent the agglomeration of the particles circulating in the reactor, and also their sedimentation and stratification under gravity. After a certain initial transition period, a quasi-stationary operation process in the reactor is established, in which all the average parameters (pressure, HSS temperature, etc.) remain constant: on the one hand, with each detonation shot, new portions of HSS and particles enter the reactor; and on the other, the gas and particles continuously leave the reactor through the exhaust outlet tube. The problem is to choose such values of the governing parameters V_R, d_{in}, d_{out}, L, m_p, d_p, f, and T_w that ensure the long-term residence of particles in vortex zones with temperatures above 2000 K.

Below, a specific example of the calculation is given, which demonstrates the flow pattern in the reactor and all the main characteristics of the operation process after reaching the quasi-stationary mode. In this example, the following governing parameters are specified: $V_R = 0.11$ m^3, $d_{in} = 0.05$ m, $d_{out} = 0.012$ m, $L = 2$ m, $m_p = 0.005$ kg/s, $d_p = 100$ µm, $f = 5$ Hz, $T_w =$

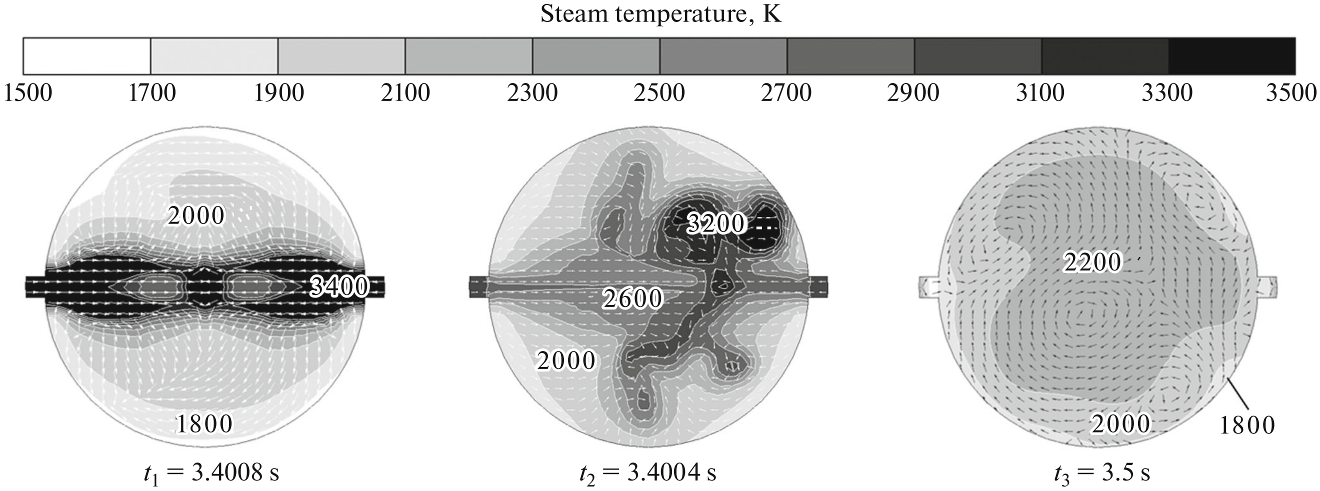

Fig. 2. Calculated HSS flow pattern in the reactor at three times of one detonation shot.

650 K, and T_m = 395 K. At the inlet of the reactor, the variables depending on time t are given: the mass flow rate $m_{g,in}(t)$ and temperature $T_{g,in}(t)$ of the gaseous products of the detonation of the stoichiometric ternary mixture 60% H_2 + 30% O_2 + 10% H_2O, and also the mass flow rate $m_{p,in}(t)$ of particles. The inset in Fig. 1 illustrates the dependences $m_{g,in}(t)$ and $T_{g,in}(t)$ obtained by a preliminary three-dimensional calculation for a detonation tube of length L = 2 m, connected to the reactor. The calculated detonation velocity of such a mixture is $D \approx 2800$ m/s.

Figure 2 shows the flow pattern as three instantaneous fields of temperature and the velocity vector in the diametral plane of the reactor that passes through the axis of the detonation tubes at times t_1, t_2, and t_3. The time period spanned by the fields is about 100 μs, which corresponds to the half of the time interval between detonation shots. The flow pattern similar to that in Fig. 2 is repeated 5 times per second (f = 5 Hz). In the bulk of the reactor, where the temperature exceeds 2000 K, vortex structures are clearly seen.

Figure 3 presents the calculated time dependences of the instantaneous values of the (*1*) maximum, (*2*) mass-average, and (*3*) minimum HSS temperatures in the reactor, and also (*4*) the instantaneous values of the temperature of HSS flowing past each of the particles (about 20000 values). The regular HSS temperature peaks correspond to the states in the detonation waves. The regular portions of the temperature decrease are due to the expansion of the detonation products and their cooling because of the interaction with the reactor walls. The minimum HSS temperatures occur near the reactor walls. The vertical dashed straight lines indicate the times t_1, t_2, and t_3 in Fig. 2. The positions of the points corresponding to the instantaneous temperature of HSS flowing past particles show that the particles mainly move far from the reactor walls: the temperature of HSS flowing past particles is always higher than the instantaneous minimum gas temperature. Indeed, the histograms in Fig. 3 demonstrate that, once the detonation wave enters the reactor, most of particles (97%) are surrounded by HSS with a temperature 1700–2100 K. In 0.6 ms after the detonation shot, about 93% of the particles are in contact with the HSS flow with a temperature of 1900–3500 K, and in ~100 ms after the shot, virtually all the particles are in the HSS flow with a temperature 1900–2300 K. Immediately before the next detonation shot, only 3% of the particles are contacted by the HSS flow with a temperature of 1400–1500 K.

Figure 4 presents the calculated residence time distribution function of particles in the reactor. In the considered example, the residence time of particles in the reactor is up to 10–15 s, and their median mean residence time is about 2 s. Estimates show that, under these conditions, more than 80% of the particles are contacted by HSS with a temperature above 2000 K for at least 1 s. Under these conditions, the particles are guaranteed to be completely gasified. For example, the times of the vaporization of droplets of rapeseed and sunflower oil methyl ester ($C_{18}H_{34}O_2$) produced by the transesterification of oil and methanol with catalysts (sodium or potassium hydroxide) with diameters of d_p = 0.1 and 1 mm even at a temperature of 1000 K are less than 10 ms and 1 s, respectively [8]. Using the published data [9], it is easy to show that, at temperatures above 2000 K, the rate of the gas-phase oxidation of organic substances and soot by steam and carbon dioxide is extremely high; therefore, the rate of the overall gasification reaction is limited by the rate of the thermal destruction or vaporization of particles.

Thus, it was demonstrated for the first time that highly superheated steam with a temperature above 2000 K can be produced by a detonation method and can further be used for gasification/detoxification of

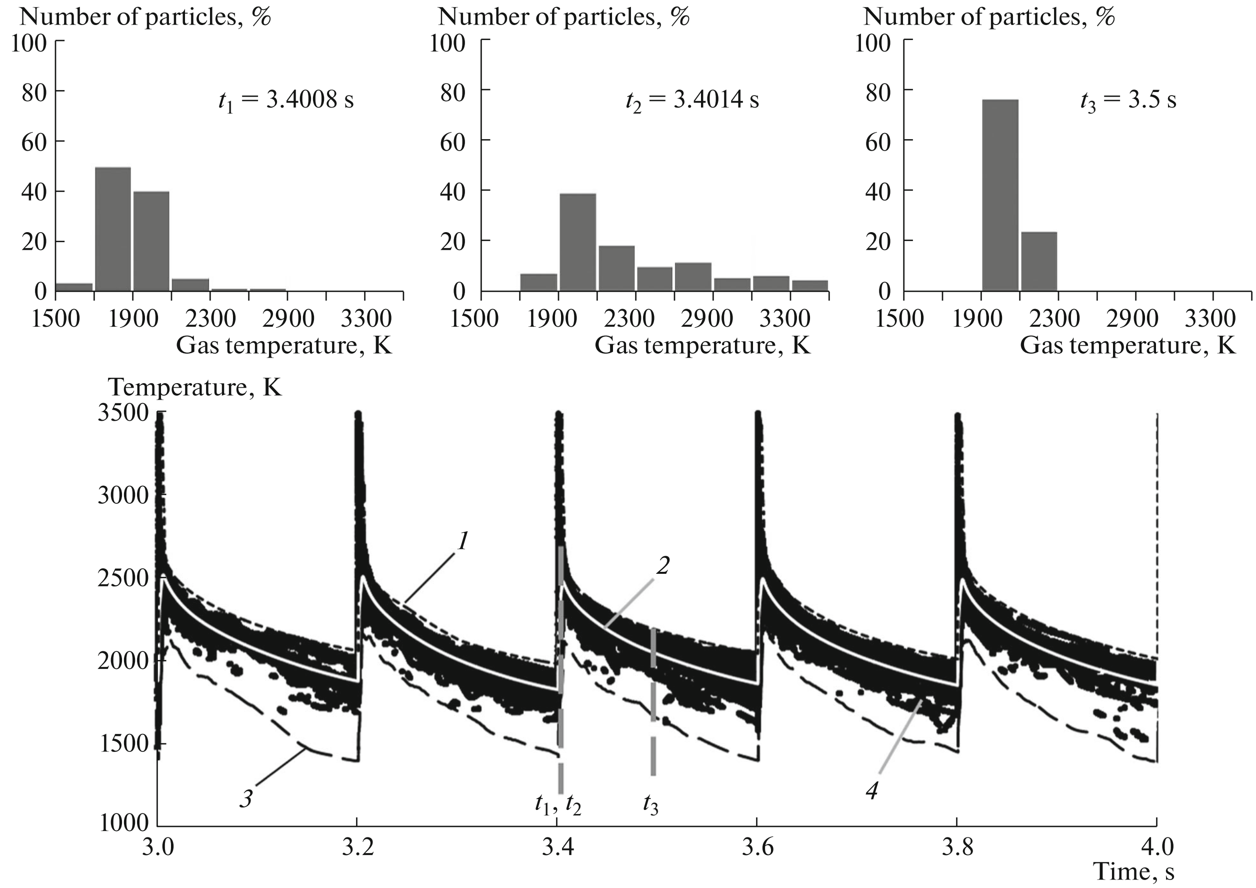

Fig. 3. Instantaneous temperature distribution functions of HSS flowing past particles (top) and the calculated time dependences of the instantaneous HSS temperatures: (*1*) maximum, (*2*) mass-average, and (*3*) minimum temperatures and (*4*) temperature of HSS flowing past particles.

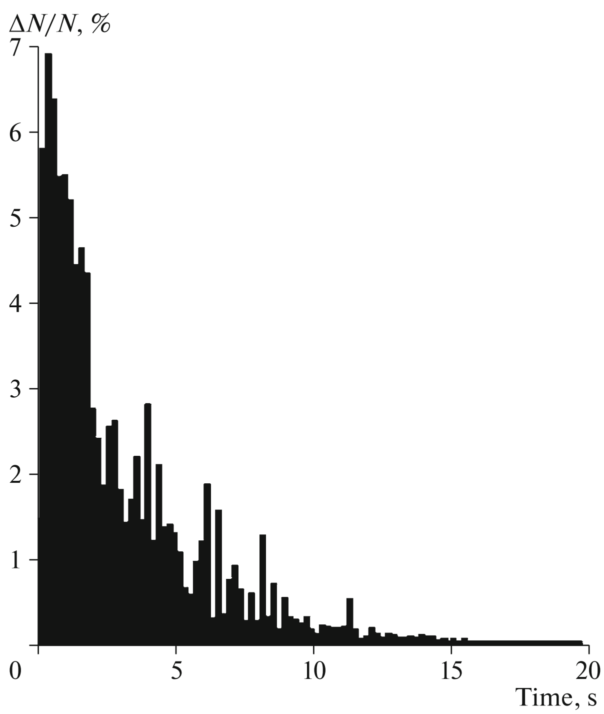

Fig. 4. Calculated residence time distribution function of particles in the reactor.

industrial, municipal, and toxic waste (coal refuse, lignin, sawdust, fly ash, etc.) in a spherical flow-type reactor with pulse detonation superheaters. By the three-dimensional gas-dynamic calculations of the two-phase flow in the reactor, the flow pattern with high-temperature vortex zones was studied, and the main characteristics of the operation process were determined. Further investigations on this subject will be aimed at experimentally implementing the proposed technology.

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