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Magnetohydrodynamic Effects of Heterogeneous Spray Detonation

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Abstract—Electrical power on the board of an aircraft with a liquid-fuel pulse-detonation engine is proposed to be produced by a magnetohydrodynamic (MHD) generator placed at the outlet of the jet nozzle. MHD effects of the pulsed heterogeneous (spray) detonation of *n*-heptane–oxygen mixtures with addition of a potassium carbonate aqueous solution (ionizing additive) to the detonation products are studied. The MHD channel electrodes are demonstrated to steadily generate voltage pulses with an amplitude of up to 3 V. Three types of shape of individual pulses are observed: single pulses, double pulses, and double pulses with a short-term change in the sign of the voltage. Increasing the frequency of operation of the PDE from 20 to 40 Hz does not affect the amplitude and shape of the voltage pulse. Reducing the magnetic induction from 0.6 to 0.3 T decreases the amplitude of the voltage pulse across the MHD channel electrodes, but the shape of individual pulses remains virtually unchanged. Leaning the fuel mixture reduces the generated voltage. Addition of mechanoactivated Mg-MoO_3 energetic nanocomposite to the fuel mixture does not cause significant changes in the shape and amplitude of voltage pulses.

Keywords: MHD effect of heterogeneous detonation, liquid fuel, pulse-detonation engine

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INTRODUCTION

Today's aerospace propulsion technology widely uses jet engines operating on the Brayton thermodynamic cycle. For many decades, these engines have been refined, so a further improvement of their performance requires large capital investments. An alternative solution, making it possible to substantially enhance the thermodynamic efficiency of modern jet engines, is to use combustion chambers with an increased total pressure. The total pressure in the combustion chamber can be increased, for example, by changing the combustion mode. In its thermodynamic efficiency, the most attractive mode of combustion is detonation. The detonation wave enables to reach the highest possible concentration of chemical energy stored in the fuel (energy is released in a thin layer of shock-compressed mixture), so that during the expansion of the detonation products, the maximum useful work is done [1, 2].

There are two basic schemes of detonation combustion: in periodic detonation waves propagating along the combustion chamber (pulse-detonation engines (PDEs)) [3] and in detonation waves continuously circulating in the tangential direction across the combustion chamber (continuous-detonation engines [4]). Both schemes are considered promising for air-jet and rocket engines.

Since such engines have no moving elements, electric power on the board of the aircraft, required for the operation of the systems of ignition, control, navigation etc., was suggested to be produced by a magnetohydrodynamic (MHD) generator installed near the nozzle outlet. It is expected that, at a sufficiently high electric conductivity and velocity of the detonation products, this simple design can provide the required power supply at the expense of a relatively small increase in the weight and size of the aircraft.

The first experimental studies of the MHD effects produced by gas detonation were apparently performed in [5, 6], where a linear MHD generator (a 16-mm-diameter channel with segmented electrodes and a transverse magnetic field with an induction of 0.23 T) was attached to a pulse-detonation combustor operating on a methane–oxygen gas mixture with small additives of a readily ionized metal salt (an aqueous solution of potassium carbonate (K_2CO_3)). The maximum plasma conductivity achieved in these experiments was 3.3 S/m (for comparison, the conductivity of seawater is ~3 S/m). Unfortunately, the authors of [5, 6] did not describe the design of the MHD generator, characteristics of its operation, and primary experimental data.

The authors of [7] performed experimental studies on the MHD effect produced by the single-pulse detonation of an oxyacetylene gas mixture with small additives of methanol and cesium hydroxide solution. In [7], the experiments were carried out using a of

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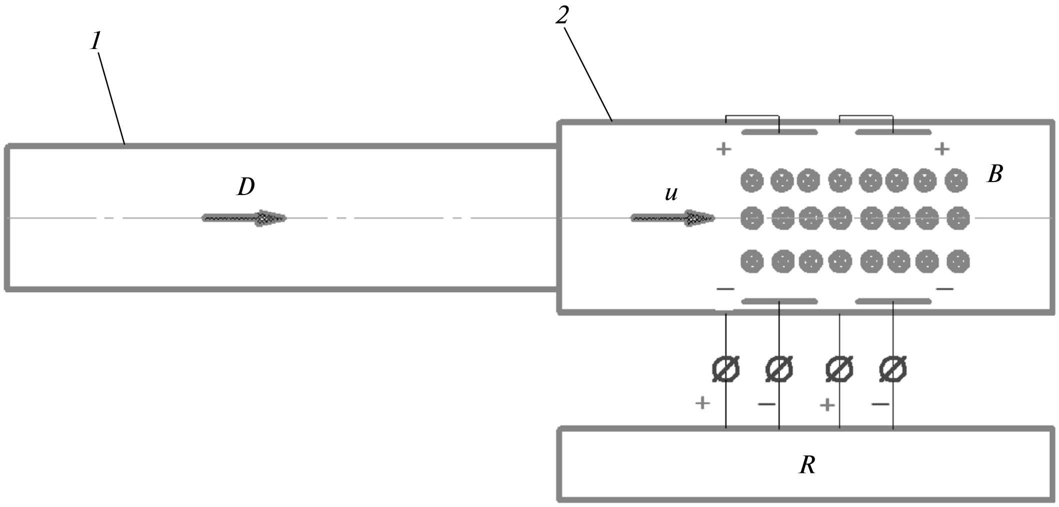

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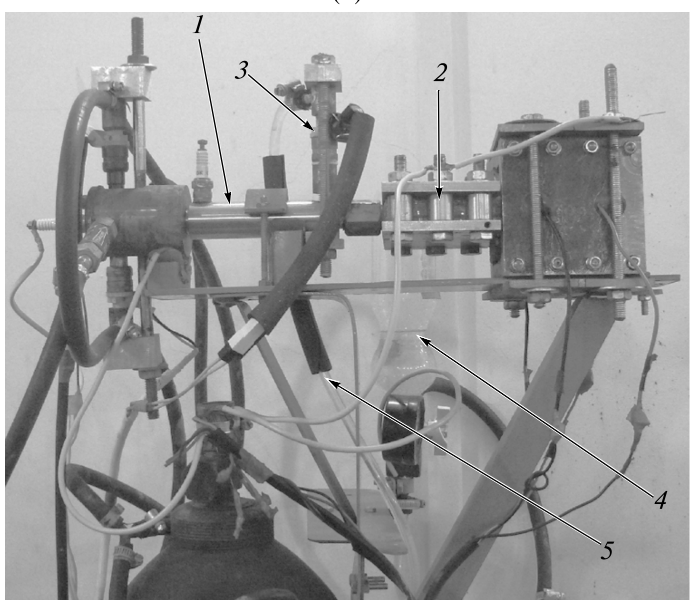

Fig. 1. (a) Schematic diagram and (b) photograph of the experimental MHD generator: (*1*) micro-PDE, (*2*) MHD channel, (*3*) injector, (*4*) reservoir, and (*5*) pipeline; *D* is the detonation velocity, *u* is the velocity of the detonation products; *B* is the magnetic field induction, and *R* is the resistive load.

25.4-mm-diameter 1-m-long detonation tube connected to a rectangular epoxy resin MHD channel, 25.4×20 mm in cross section and 0.3 m in length, with two continuous copper alloy electrodes spaced 25.4 mm apart. The additive was injected into the fresh mixture in portions through an auto fuel injector before the arrival of the detonation wave. A uniform transverse magnetic field with an induction of 0.6 T was created by two assembled permanent magnets of length 0.3 m. The maximum conductivity of the plasma achieved in the experiments [7], at an average detonation velocity of ~2380 m/s, was 6 S/m. The paper [7] gives examples of records of the interelectrode voltage and current in the absence and in the presence of an external load.

The works [8, 9] theoretically examine the MHD effects caused by pulsed gas detonation. Two-dimensional equations for an MHD flow of stoichiometric hydrogen–air mixture containing 1 vol % cesium in a planar rectilinear PDE channel, 20 mm in width and 100 mm in length, with an expansion nozzle were solved at magnetic inductions from 1 to 8 T. It was demonstrated that, in order to achieve high performance characteristics of the MHD generator, sufficient to realize cyclic direct detonation initiation, it is necessary to use a nozzle with an optimal degree of expansion, providing the best combination of the velocity and temperature of the detonation products and segmented electrodes with properly selected size and positioning and size. According to the calculations performed in [8], the plasma conductivity can be as high as 250 S/m. In [9], a similar problem was solved for an MHD flow of stoichiometric hydrogen–air mixture with 2 wt % cesium in a planar rectilinear PDE channel, 10 mm in width and 100 mm in length, without the nozzle or with a convergent-divergent nozzle, at a magnetic field induction of 4 T. It was shown that the use of a convergent-divergent nozzle enhances the characteristics of the MHD generator. The maximum plasma conductivity predicted by the calculations in [9] was ~10 S/m.

An analysis of the literature shows that all the known works on the subject are devoted to studying the MHD effects caused by gas detonation, whereas the most effective mode of combustion in perspective detonation engines is the heterogeneous detonation of sprayed regular liquid fuels. We were first [10] to experimentally study of the MHD effects of pulsed heterogeneous detonation of sprays. In this paper, the generator of detonation pulses was a micro-pulse-detonation liquid-fuel rocket engine intended to stabilize spacecraft systems [11, 12] (capable of producing calibrated thrust pulses at a frequency of up to 150–200 Hz) with an attached linear MHD generator consisting of a 10×10-mm-section, 100-mm-long epoxy-resin MHD channel with four pairs of sectioned steel electrodes. Permanent samarium–cobalt magnets created in the MHD channel a uniform transverse magnetic field with an induction of 0.42 T. In all the experiments, the micro-PDE operated on a fuel-lean mixture of liquid *n*-heptane with gaseous oxygen, (oxidizer-to-fuel equivalence ratio of ~2) at a frequency of 20 Hz. The pulse-average detonation velocity was ~2200 m/s. The experiments were carried out in the absence and in the presence of the ionizable agent (aqueous potassium carbonate solution). In all experiments, the segmented electrodes in the MHD channel steadily generated voltage with an amplitude of 2.5 V and a frequency set by the operation of the micro-PDE. Adding aqueous potassium carbonate to the fuel mixture resulted in an about twofold increase in the amplitude of the voltage pulse as compared to operation without it.

The purpose of the present work was to carry out a systematic experimental study of the MHD effects of spray detonation observed in [10].

EXPERIMENTAL SETUP

The generator of detonation pulses was a prototype of a micro-pulse-detonation liquid-fuel rocket engine, the design and operation of which were described in [11, 12]. The micro-PDE (position *1* in Fig. 1) was attached to a linear MHD generator (position *2* in Fig. 1), consisting of an MHD channel, 8×40 mm in section and 110 mm in length, with two

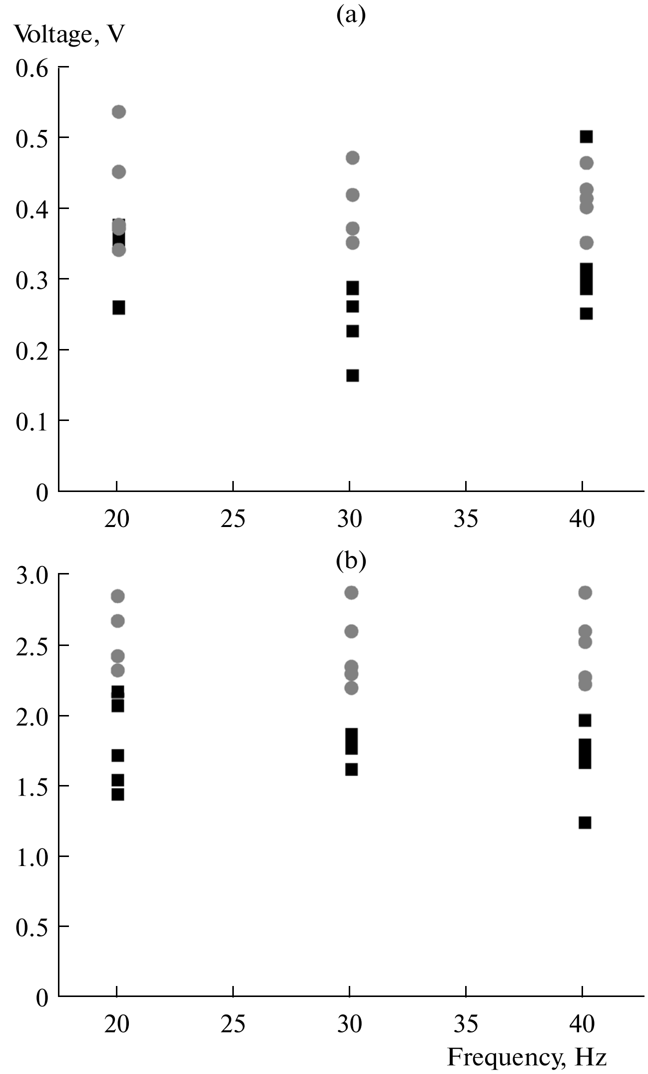

Fig. 2. Effect of the frequency of operation of the micro-PDE on the amplitude of the voltage pulse across the MHD channel electrodes ((●) electrode 1, (■) electrode 2) at a magnetic field induction of 0.6 T and resistive loads of (a) 1 and (b) 10 Ohm.

pairs of segmented steel electrodes (hereinafter, electrodes *1* and *2*) connected to a resistive load *R* (Fig. 1a). Permanent samarium–cobalt magnets created a uniform transverse magnetic field with an induction of 0.3 to 0.6 T, which was measured with a teslameter. The relative error of measurement of the magnetic induction did not exceed ±2.5%. In all the experiments, the micro-PDE operated on a mixture of liquid *n*-heptane with gaseous oxygen at a frequency of 20 to 40 Hz. The oxidizer-to-fuel equivalence ratio of the mixture was varied from 1.5 to 2.0 by varying the oxygen pressure in the micro-PDE. The ionizing additive was a 50% saturated aqueous solution of potassium carbonate. The additive was injected into the MHD channel with a ZMZ-6354 fuel injector (position *3* in Fig. 1) located near the outlet nozzle of the micro-PDE, connected

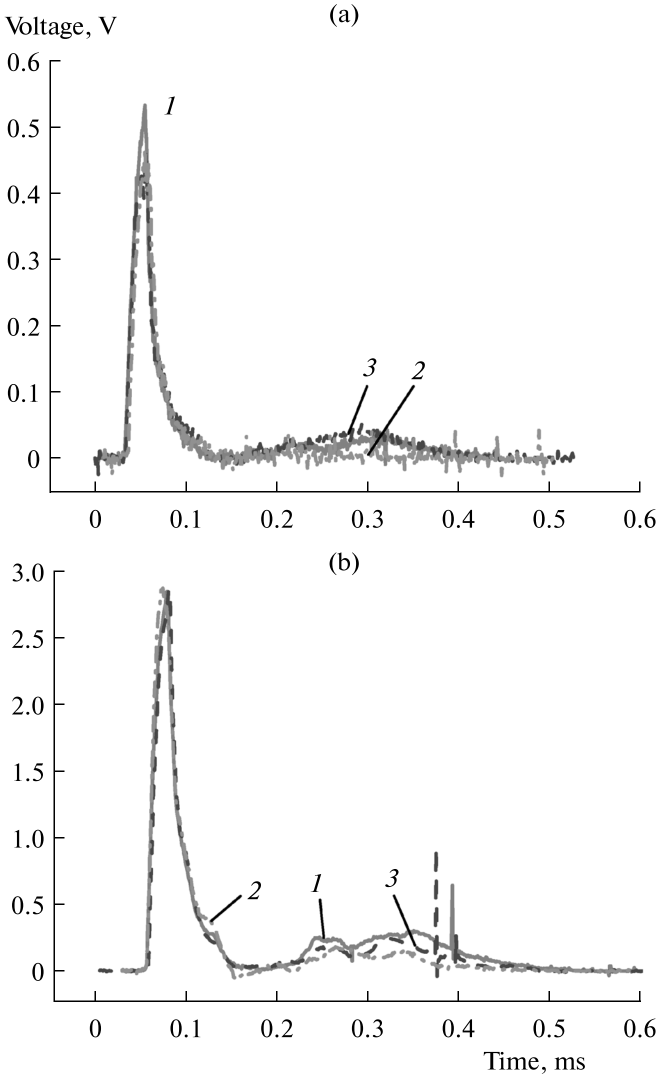

Fig. 3. Dependence of the shape of the voltage pulse across the MHD channel electrodes on the frequency of operation of the micro-PDE ((*1*) 20, (*2*) 30, and (*3*) 49 Hz) at a magnetic field induction of 0.6 T and resistive loads of (a) 1 and (b) 10 Ohm.

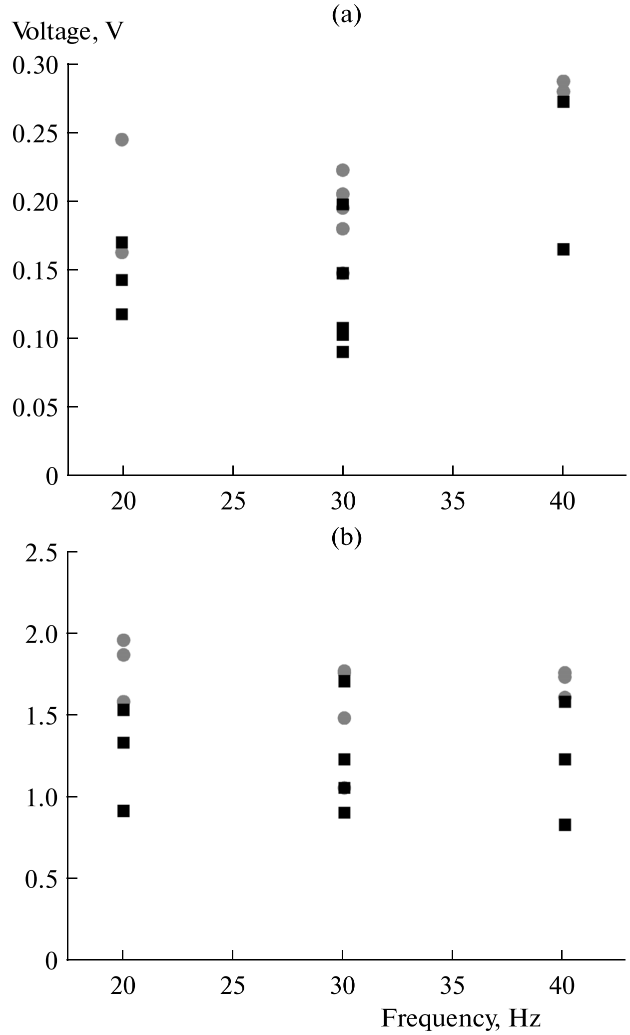

Fig. 4. Effect of the frequency of operation of the micro-PDE on the amplitude of the voltage pulse across the MHD channel electrodes ((●) electrode 1, (■) electrode 2) at a magnetic field induction of 0.3 T and resistive loads of (a) 1 and (b) 10 Ohm.

to reservoir *4* via conduit *5*. The productivity of the injector was (5 ± 0.2) g/s (at a pressure in reservoir *4* of at least 3.5–4.0 atm), so that the content of additive in the combustible mixture was 4–5 wt %. Furthermore, as an energetic additive, we used mechanoactivated Mg–MoO_3 nanocomposite in an amount of up to 2.5 wt %.

EXPERIMENTAL RESULTS

We investigated how the voltage generated across the electrodes of the MHD channel at different resistive loads depends on the frequency of operation of the micro-PDE, magnetic field strength of the MHD generator, composition of the combustible mixture, and presence of mechanoactivated metal-containing nanocomposite.

Figures 2 and 3 show the experimental results on the effect of the frequency of operation of the micro-PDE on the voltage generated across the electrodes of the MHD channel (Fig. 2) and on the shape of the voltage pulse (Fig. 3) at external resistive loads of 1 and 10 Ohm. It can be seen that increasing the frequency of the micro-PDE has virtually no effect on the voltage amplitude (up to 3 V) and the voltage pulse shape. This result is quite expected, since on the one hand, the voltage across the electrodes depends on the velocity of the plasma in the MHD channel (ceteris paribus), and on the other, increasing the frequency of operation of the micro-PDE within 20–40 Hz has no effect on the detonation velocity in a single pulse [11, 12].

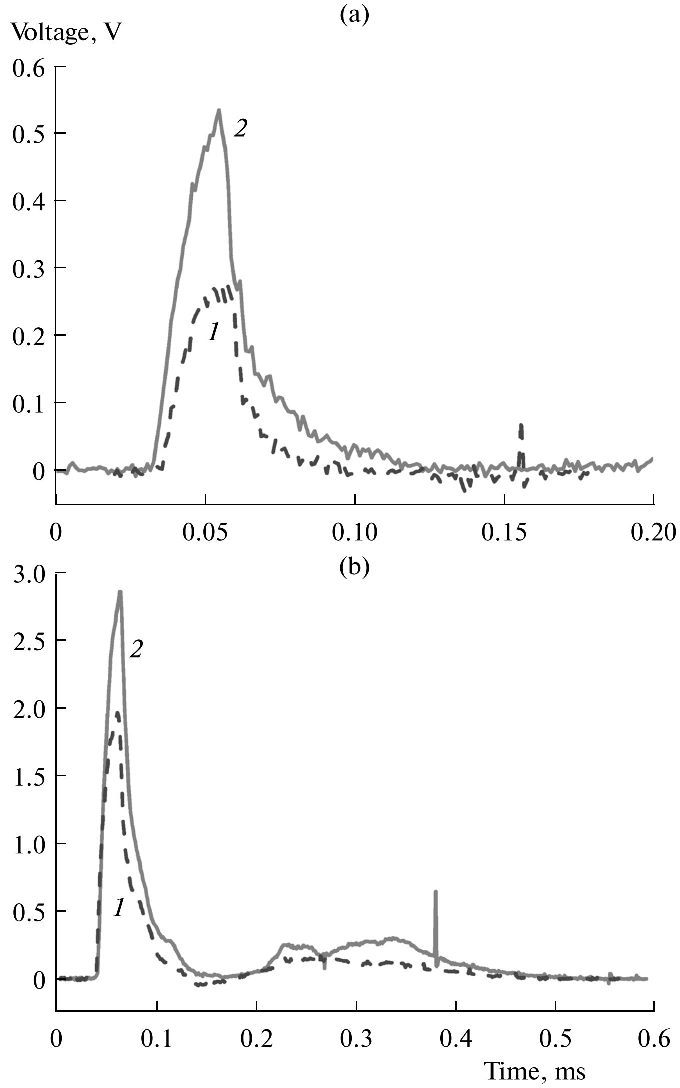

Fig. 5. Shape of the voltage pulse across the MHD channel electrodes at a micro-PDE operation frequency of 20 Hz, resistive loads of (a) 1 and (b) 10 Ohm, and magnetic inductions of (*1*) 0.3 and (*2*) 0.6 T.

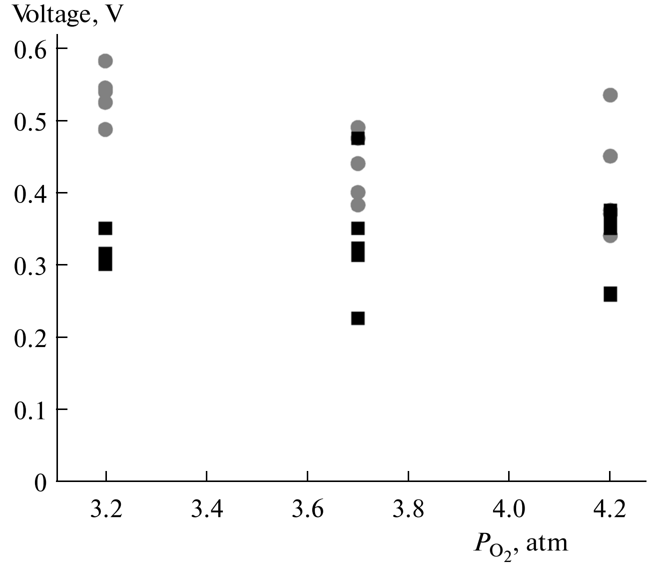

Fig. 6. Effect of the excess oxygen pressure at the inlet of the micro-PDE combustion chamber on the amplitude of the voltage pulse across the MHD channel electrodes at a magnetic field induction of 0.6 T, resistive load of 1 Ohm, operation frequency of 20 Hz: (●) electrode 1 and (■) electrode 2.

Figures 4 and 5 show the experimental results on the effect of the induction of the magnetic field in the MHD channel on the amplitude (Fig. 4) and shape (Fig. 5) of the voltage pulse generated across its electrodes at different frequencies of operation of the micro-PDE at two values of the external resistive load. It can be seen that reducing the magnetic induction decreases the amplitude of the voltage pulse across the MHD channel electrodes; however, the shape of a single voltage pulse remains practically unchanged.

Figure 6 shows the experimental results on the effect of the combustible mixture composition on the amplitude of voltage pulses generated across the MHD channel electrodes at a micro-PDE operation frequency of 20 Hz and an external resistive load of 1 Ohm. In the experiments, the composition of the combustible mixture was varied by changing the oxygen supply pressure from 3.2 to 4.2 atm at a constant rate of cyclic feed of liquid fuel. The oxidizer-to-fuel equivalence ratio was varied from 1.5 to 2.0. As can be seen, a leaning of the mixture reduces the voltage across the MHD channel electrodes, which is quite expected because of a lower velocity and temperature of the detonation products.

Figure 7 displays the experimental results on the influence of the mass concentration of Mg–MoO_3 nanocomposite in the fuel on the amplitude of voltage pulses generated across the MHD channel electrodes at a micro-PDE operation frequency of 20 Hz and various values of the external resistive load. The concentration of Mg–MoO_3 in the fuel was set during its pretreatment (addition and mixing) as described in [13]. In all experiments, the cyclic supply of mixed fuel and the oxygen supply pressure remained constant. Figure 7 shows that the effect of nanocomposite additives is mixed. At the resistive load of 1 Ohm, Mg–MoO_3 additives lead to a decrease in the voltage amplitude compared to the operation on clean fuel. However, at the resistive load of 10 Ohm, adding 1.25 wt % Mg–MoO_3 results in a voltage amplitude increase, from 2.8 to 3.1 V. With a further increase in the additive concentration, to 2.5 wt %, the voltage pulse amplitude reduced to a value comparable to that recorded during the operation of the device on clean fuel. This ambiguity is apparently associated with the influence of the additive on the characteristics of the detonation wave. To explain the observed effects, further studies are needed.

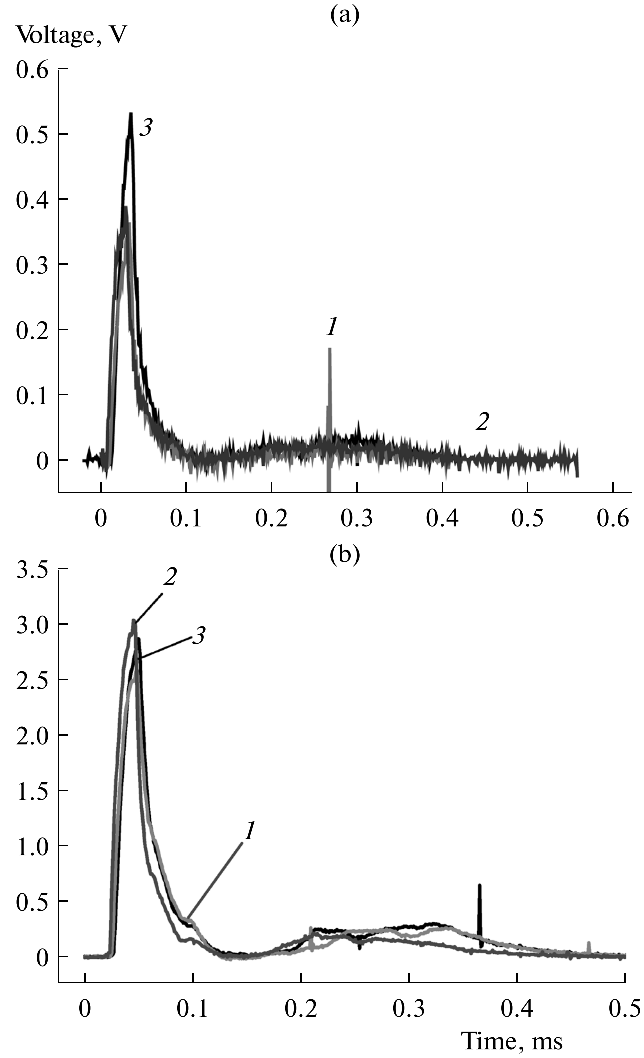

Fig. 7. Effect of Mg–MoO_3 additive to fuel ((*1*) 2.5, (*2*) 1.25, and (*3*) 0 wt %) on the amplitude of the voltage pulse across the MHD channel electrode at a magnetic field induction of 0.6 T, operation frequency of 20 Hz and resistive loads of (a) 1 and (b) 10 Ohm.

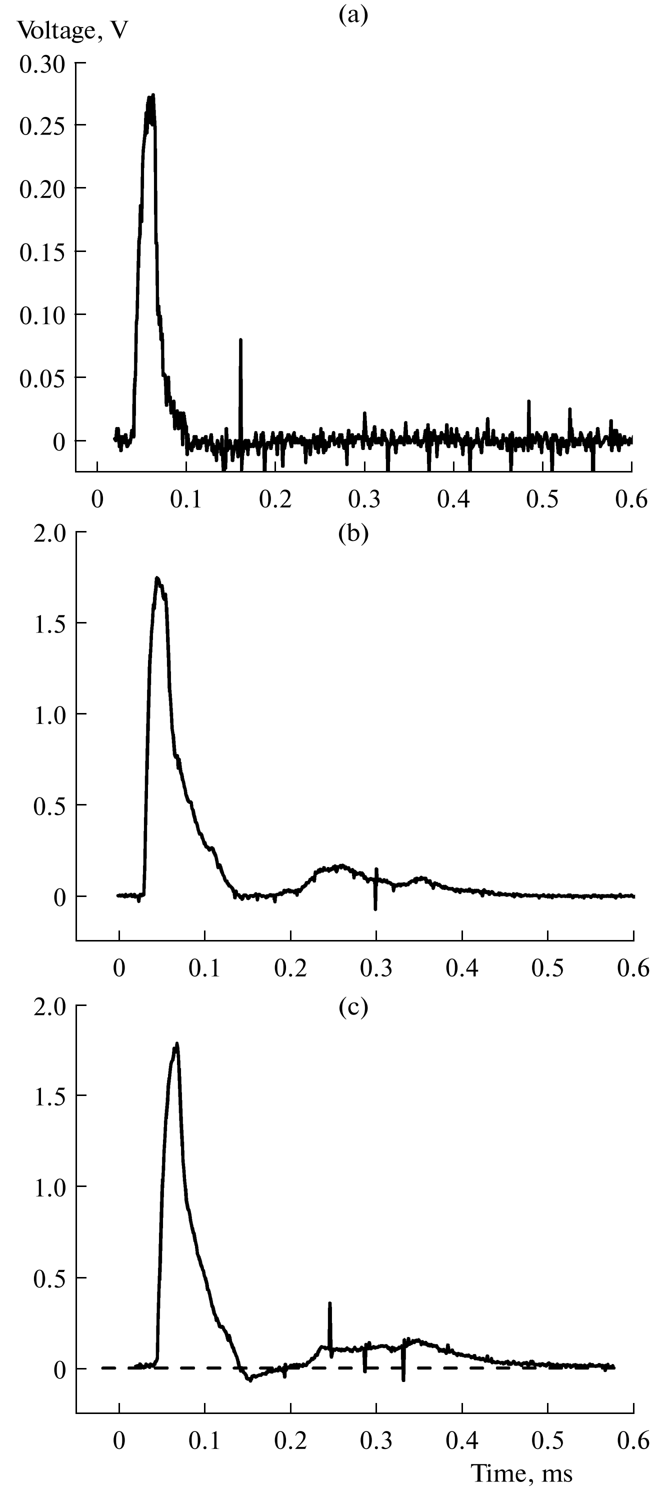

Fig. 8. Typical shapes of the pulse across the MHD channel electrodes: (a) single pulse, (b) double pulse, and (c) double pulse with a short-term change in the sign of the voltage.

The experiments demonstrated that voltage pulses generated across the MHD channel electrodes can have one of the three types of shape shown in Fig. 8. For all the three types of shape of the voltage pulse, the first peak (of duration ~100 μs) is related to the passage of the detonation front between the electrodes of the MHD channel. The sharp drop of the voltage in the first peak is caused by the deceleration and cooling of the detonation products in the rarefaction wave behind the detonation front. The observed rate of voltage drop is ~20 kV/s. The secondary peak in the voltage pulses in Figs. 8b and 8c (~200 μs long) is apparently related to the arrival of the rarefaction wave from the open end of the MHD channel, which causes a temporary acceleration of the outflow of residual detonation products and, as a consequence, an increase the voltage across the electrodes. The negative voltage segment between the two peaks can be associated with a short-term change in the direction of flow in the MHD channel [8].

CONCLUSIONS

Thus, experimental studies of the MHD effects of single-pulse heterogeneous (spray) detonation with detonation products seeded with a 50% saturated aqueous solution of potassium carbonate (ionizing additive) were performed. It was shown that the electrodes across the MHD channel sustainably generated voltage pulses with an amplitude of up to 3 V and a frequency set by the micro-PDE. Increasing the frequency of the PDE from 20 to 40 Hz produced essentially no effect on the amplitude and shape of the voltage pulse. Decreasing the magnetic induction from 0.6 to 0.3 T reduced the amplitude of the voltage pulse across the electrodes of the MHD channel, but the shape of individual pulses remained practically unchanged. Leaning the liquid fuel mixture decreased the MHD voltage. Adding mechanoactivated Mg–MoO_3 energetic nanocomposite to the fuel combustible mixture in an amount of up to 2.5 wt % did not lead to significant changes in the shape and amplitude of the voltage pulses. Three types of shape of the voltage pulse across the MHD channel electrodes were observed: single pulses, double pulses, and double pulses with a short-term change in the sign of the voltage.

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