MAGNETOHYDRODYNAMIC EFFECTS OF HETEROGENEOUS DETONATIONS

V. S. Aksenov[1], K. A. Avdeev[2], F. S. Frolov[2], S. M. Frolov[2], V. S. Ivanov[2], S. N. Medvedev[2], and I. O. Shamshin[2]

[1]National Research Nuclear University
"Moscow Engineering Physics Institute" (NRNU MEPhI)
Moscow, Russia

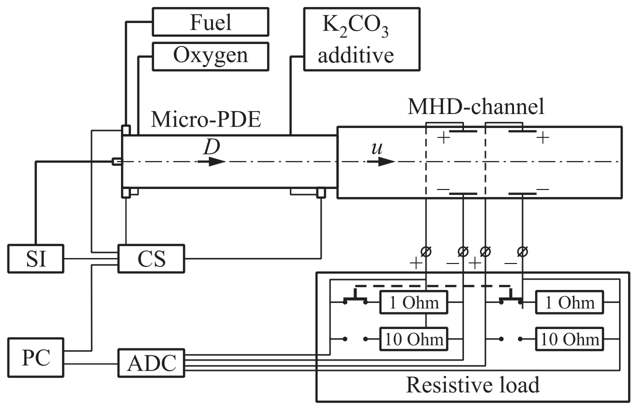
[2]N. N. Semenov Institute of Chemical Physics
Russian Academy of Sciences
Moscow, Russia
e-mail: smfrol@chph.ras.ru

For generating electrical energy on board an aircraft with a pulse detonation engine (PDE), a magnetohydrodynamic (MHD) generator mounted at engine nozzle exit can be used. All previous publications in the literature on this subject were related to investigations of MHD effects of gaseous detonations (e. g., experiments in [1] and calculations in [2]). However, it is expected that the most likely mode of combustion in practical PDEs will be heterogeneous detonation. The objective of this work is the experimental study of MHD effects of pulse heterogeneous (spray) detonations, which have been detected by the authors in [3] for the first time.

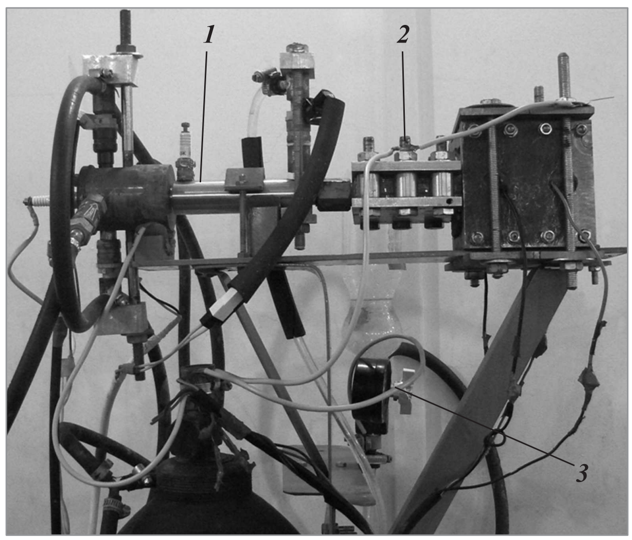
Experimental Setup and Technique

The laboratory setup (Fig. 1*a*) includes a micro-PDE with the supply systems of liquid fuel and gaseous oxygen and with the ignition system, a linear MHD-channel with the supply system of the ionizing additive, a resistive load, a control system, and a data acquisition system based on a personal computer (PC) and an analog-to-digital converter (ADC).

The micro-PDE (Fig. 1*b*) used in experiments is the device developed and tested in [3, 4]. It consists of a pulse ignition unit and a 150-millimeter long 8-millimeter inner diameter detonation tube at-



(a)



(b)

Figure 1 (a) Schematic of experimental setup: CS — control system, SI — ignition system and (b) overall view of the PDE with MHD-channel attached to nozzle exit: *1* — micro-PDE, *2* — MHD-channel, and *3* — injection system for ionizing additive tached to it via a threaded connection. The housing of the ignition unit is made of brass whereas the detonation tube is made of stainless steel. Gaseous oxygen is supplied into a cooling jacket with internal ribs. The channels of heat exchanger are arranged in such a way as to make the high-speed oxygen flow cross the jet of liquid fuel supplied by an automotive fuel injector and direct fuel into the nozzle hole that connects the feed system with the combustion chamber of the ignition unit. The combustion chamber has a complex shape, with divergent and convergent areas. The combustion chamber has holes in the walls for standard automotive spark plugs or screw caps. The micro-PDE operates on liquid n-heptane with the fuel-to-oxygen equivalence ratio of 1.4–1.5. The maximum detonation frequency is 200 Hz (when firing in vacuum). The mean detonation velocity in a single pulse is 2000 ± 50 m/s.

The MHD-channel (see Fig. 1b) is the 100-millimeter long and 8×40 mm cross section rectangular tube with two pairs of electrodes (hereinafter, electrodes 1 and 2). The channel is made of glass-fiber plastic, whereas the electrodes are made of the stainless steel. The samarium–cobalt permanent magnets with the closed magnetic core are used to create a uniform transverse magnetic field with the induction of ~ 0.6 T. The magnetic circuit is made of the conventional steel.

As the resistive load, the block of resistances is used. The voltage at MHD-channel electrodes is measured using *R-Technology QMbox QMS 90* ADC and *Power Graph 3.3 Professional* software.

To control the operation of MHD-generator, the digital controller is used which provides preset timing of oxidizer, fuel and ionizing additive supply, and electrical spark generation.

As the ionizing additive, the saturated aqueous solution of potassium carbonate is used. The main element of the injection system for introducing the solution into the MHD-channel is the standard automotive injector with the flow rate of 200 cm^3/min at 3.5–4-atm pressure in the system. The time interval of solution injection is selected so that the potassium concentration in the fuel–oxygen–additive mixture was 4–5 %(wt.).

In the experiments, the influence of detonation frequency, magnetic field intensity, and electric circuit resistance on the voltage at the MHD-channel electrodes has been studied. It is worth noting that in each experiment, the MHD-channel was subjected only to five consecutive detonation pulses regardless the pulse frequency. This is due to erosion

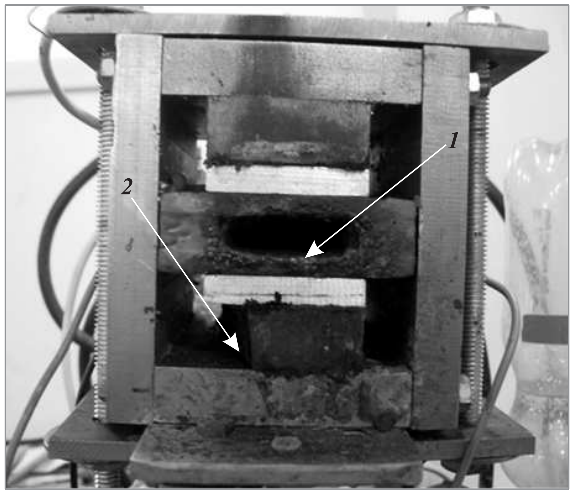


Figure 2 Photo of the MHD-channel exit section at the end of experimental campaign (*1* — mechanical damage of the inner wall; and *2* — mechanical damage of the magnet)

of MHD-channel walls. Figure 2 shows the photograph of the MHD-channel at the end of experimental campaign.

Figures 3 and 4 demonstrate the effect of the detonation pulse frequency on the voltage (see Fig. 3) and the shape of voltage signal (see Fig. 4) at MHD-channel electrodes connected to the electric circuit with two resistances (1 and 10 Ohm). Three values of the detonation pulse frequency were used, namely, 20, 30, and 40 Hz. The fuel injection time (15 ms) and additive injection time (18 ms) were kept constant; the injection pressures of fuel, additive, and oxygen were also kept constant.

It follows from Figs. 3 and 4 that the increase in the operation frequency affects neither the voltage magnitude nor the voltage signal shape and does not affect the voltage magnitude at different resistive loads. These results should have been expected, since on the one hand, the voltage on electrodes is proportional to the velocity of plasma in the MHD-channel, and on the other hand, increase in the micro-PDE operation frequency does not affect the detonation propagation velocity in a single pulse in the frequency range used [3].

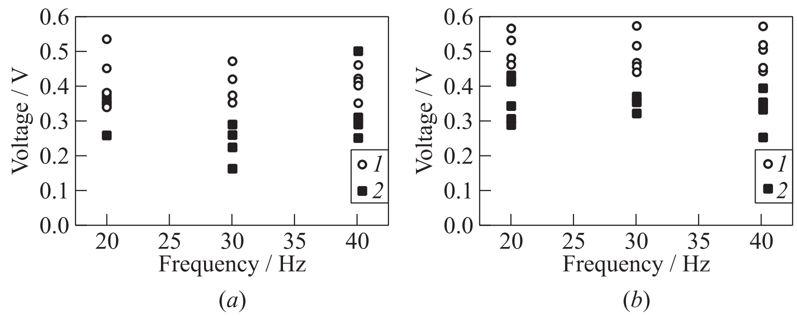


Figure 3 Effect of operation frequency on the measured voltage magnitude at MHD-channel electrodes (*1* — electrode 1 and *2* — electrode 2); magnetic induction 0.6 T; load 1 Ohm (*a*) and 10 Ohm (*b*)

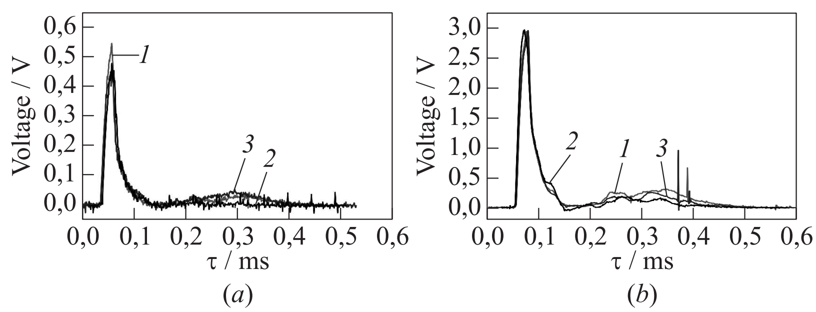


Figure 4 Typical records of voltage pulse at electrodes 1 as a function of operation frequency (*1* — 20 Hz; *2* — 30; and *3* — 40 Hz); magnetic induction 0.6 T; load 1 Ohm (*a*) and 10 Ohm (*b*)

Variation of the magnetic field intensity was achieved by installing aluminum inserts between the permanent magnets and the magnetic circuit (Fig. 5). The aluminum inserts made it possible to decrease the magnetic induction in the MHD-channel from 0.6 to 0.3 T. The magnetic field intensity was measured by the calibrated teslameter.

Figures 6 and 7 demonstrate the effect of the magnetic field intensity on the voltage (see Fig. 6) and the shape of voltage signal (see Fig. 7) at MHD-channel electrodes connected to the electric circuit with two

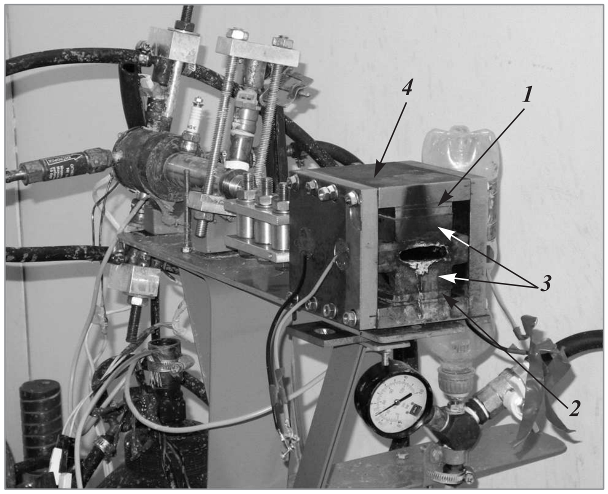


Figure 5 Photo of the MHD-channel with aluminum inserts: *1* — upper insert; *2* — lower insert; *3* — permanent magnets; and *4* — magnetic circuit

resistances (1 and 10 Ohm). Two values of the magnetic induction (0.3 and 0.6 T) and three values of the micro-PDE operation frequency (20, 30, and 40 Hz) were used. It is seen from Figs. 6 and 7 that the decrease in the magnetic field intensity leads to the reduction of the voltage magnitude at the MHD-channel electrodes. However, the shape of the voltage signals does not virtually change.

In general, three different types of voltage records shown in Fig. 8 were detected in the course of experimental studies. The first is the shape with a single peak (Fig. 8*a*, see also Fig. 7*a*), the second is the double-peak shape (Fig. 8*b*, see also Figs. 4 and 7*b*), and the third is the double-peak shape with the voltage sign reversal (Fig. 8*c*). In all cases, the primary peak in the voltage record is caused by the arrival of the detonation front at the MHD-channel electrodes. The duration of the primary peak is about 100 μs, which correlates well with the flow duration behind the propagating detonation in the experimental setup. The decrease in voltage in the primary peak is caused by the deceleration and cooling of the detonation products in the Zel'dovich–Taylor rarefaction wave following the detonation front.

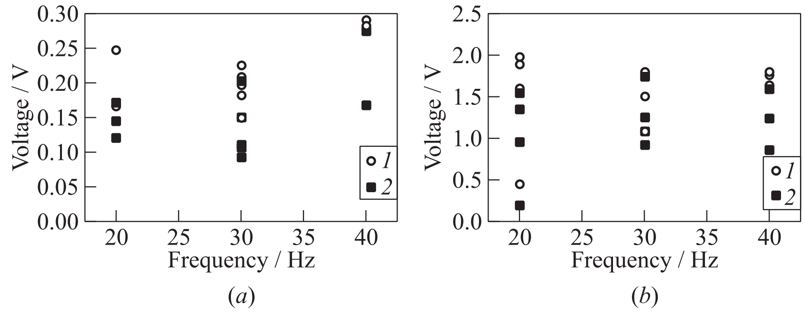


Figure 6 Effect of operation frequency on the voltage magnitude at MHD-channel electrodes (*1* — electrode 1 and *2* — electrode 2); magnetic induction 0.3 T; load 1 Ohm (*a*) and 10 Ohm (*b*)

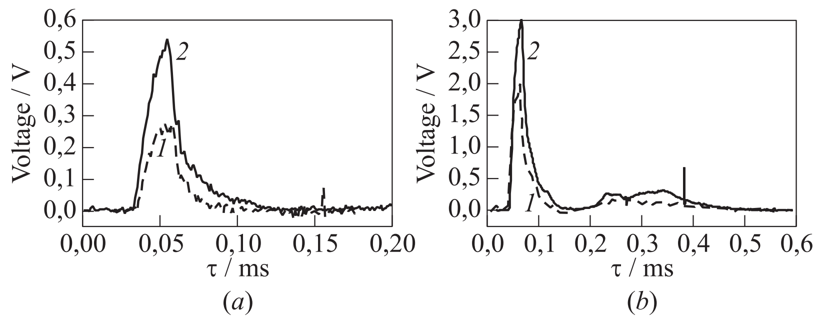


Figure 7 Typical records of voltage pulse at electrodes 1 as a function of magnetic induction (*1* — 0.3 T and *2* — 0.6 T) at operation frequency 20 Hz; load 1 Ohm (*a*) and 10 Ohm (*b*)

The secondary peak in Figs. 8*b* and 8*c* originates in about 200 μs after the detonation front arrival. Most probably, this peak is caused by the arrival of the rarefaction wave from the MHD-channel open end. This wave temporarily accelerates the outflow of the residual detonation products from the channel causing the increase in the MHD voltage. However, due to overexpansion of the detonation products, the flow velocity decreases leading to the decrease in the MHD voltage.

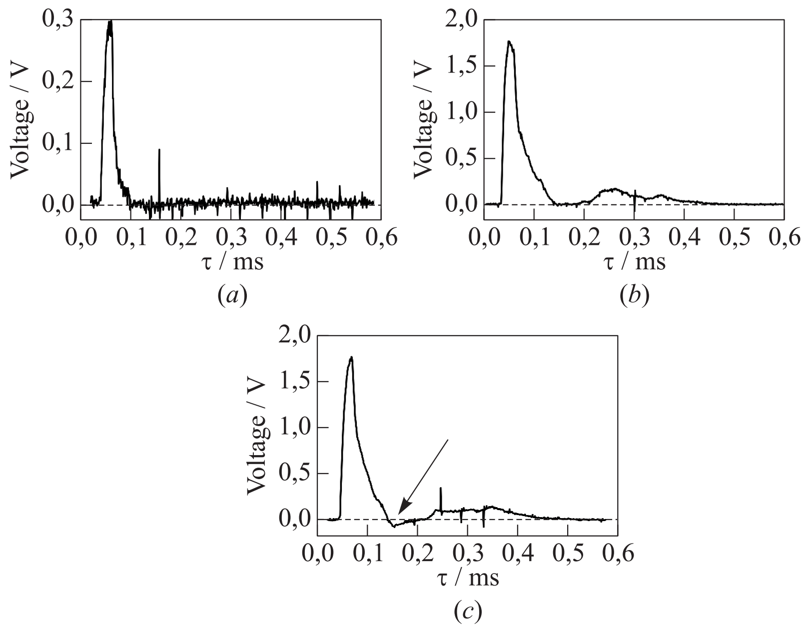


Figure 8 Three types of MHD voltage signals: (*a*) single-peak; (*b*) double-peak; and (*c*) double-peak with sign reversal

In some cases, the reversal of flow direction inside the MHD channel was detected as it follows from the voltage curve in Fig. 8*c*. In this case, the sign of the voltage changes to the opposite value just behind the first peak (shown by arrow in Fig. 8*c*). The flow reversal phenomenon was discussed in [5] and needs further studies.

Concluding Remarks

Thus, the experimental study of MHD effects of pulsed heterogeneous (spray) detonations was conducted. The experiments have shown that heterogeneous detonations are capable of generating regular voltage pulses in a reliable and reproducible manner with the pulse frequency predetermined by the operation frequency of the micro-PDE. This conclusion is not trivial because the two-phase reactive flow in the MHD-channel is accompanied with various side processes like wetting of electrodes by liquid fuel, etc., which can unpredictably deteriorate MHD effects. Since the heterogeneous detonation is expected to be the most appropriate combustion mode in practical PDEs, this outcome demonstrates the feasibility of MHD for the corresponding applications. The parametric studies of MHD effects indicate that the magnitude of voltage pulses increases with the magnetic field intensity and with the resistive load in the electric circuit, whereas the pulse frequency does not affect the voltage pulse magnitude. The voltage pulses were shown to exhibit three different shapes: single-peak, double-peak, and double-peak with sign reversal.

Acknowledgments

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