On generation of high speed plasma flow by injecting reactive heterogeneous jets in explosive gas mixture

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Background

Electric properties of explosions of various energetic materials attract attention of researchers in view of the need for powerful, pulse magnetohydrodynamic (MHD) generators. Nowadays powerful, pulse MHD generators apply either condensed high explosives (HE) or solid propellants and are used in geophysical investigations. However there are some shortcomings complicating the design, manufacturing, and operation of the conventional pulse MHD generators. First, the use of HE imposes severe constraints on the strength of explosion chambers. Second, the plasma needed to generate the pulse of current is produced in an inert gas. Therefore the ionised zone forms in the vicinity of the highly instable contact surface and the pulse duration is very short. Moreover, pulse duration is short due to fast decay of shock waves produced by HE. Pulse MHD generators based on solid propellants have other disadvantages, in particular, relatively low plasma density. Typical parameters of plasma produced in these generators are: (*i*) electron densities of 10^{14} - 10^{21} cm^{-3}; (*ii*) plasma flow velocities up to 10 km/s; (*iii*) specific conductivity up to 10^5 Sm/m; (*iv*) pulse duration ranging from 10^{-4} to several seconds; (*v*) electric current up to a few mega-amperes.

Along with high plasma conductivity pulse-current generators require high-velocity flows as the current is proportional to both the charge density and particle velocity. Alternative systems should have these two parameters competing with the known devices.

The objective of the present work is to explore a possibility of the use of heterogeneous metal - solid oxidizer suspensions in a gas phase as sources of high-density and high-velocity plasma. Thermodynamic analysis shows that the most efficient systems producing the highest concentration of charged particles are those based on potassium perchlorate and potassium nitrate as oxidizers and aluminum as a fuel. Replacement of air by a hydrogen-oxygen mixture significantly increases the ionization degree in the detonation products of low-energy mixtures such as carbon-containing compositions. Replacement of air in the MHD-channel by a hydrogen-oxygen mixture is also important for another reason. As mentioned above, the plasma flow velocity is a factor controlling performance of pulse MHD generators. Clearly, injection of the burning powdered mixture in a detonable gas should increase the plasma velocity because the plasma will move in the hot detonation products flowing in the same direction. In this case the generator design will be very simple, i.e. comprising the duct filled with the hydrogen-oxygen mixture and the injector filled with solid components. Initiation of the gaseous mixture in the injector will require a weak initiator, e.g. a conventional spark plug.

Experimental setup

The designed setup consists of three sections: injector, acceleration tube, and receiver (see Fig. 1). The injector is a high-pressure chamber 35 mm in diameter and 250 mm long, loaded with solid components (~50 g). The maximum propellant amount that can be loaded in the injector is 50 g, which would produce a solid-phase concentration in the test section of about 10 kg/m3. The propellant is ignited by burning a hydrogen-oxygen mixture at 5 atm. The injector is tightly sealed with a diaphragm. The burning powdered mixture is injected in the acceleration tube 1.2 m long and 70 mm in diameter filled with a hydrogen-oxygen mixture at atmospheric pressure.

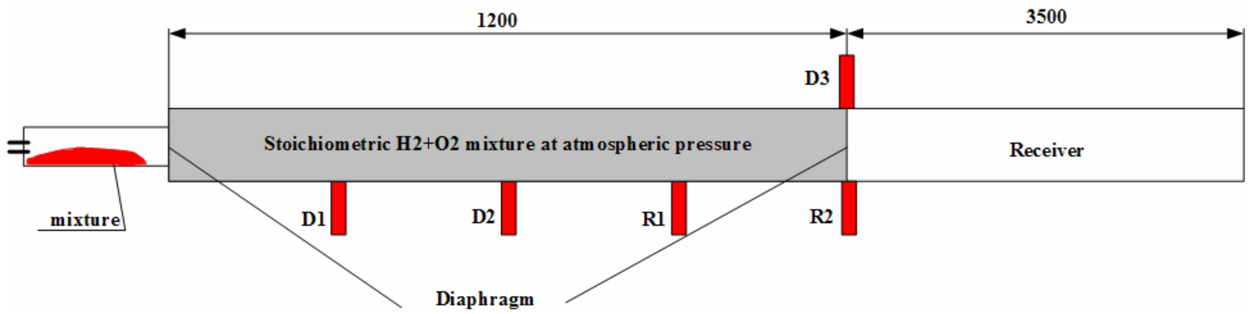

Figure 1. Experimental setup.

It is expected, that after injection, the products of partial combustion of the propellant suspension is heated and accelerated by the detonation products of the gaseous mixture in the acceleration tube. The wave and plasma velocity along the tube are measured with pressure (D_1, D_2 and D_3) and conductivity gauges (R_1 and R_2). Plasma conductivity is monitored with two double-electrode probes (the electrode length is 65 mm, diameter is 1.2 mm, the distance between the electrodes is 4 mm). The gaseous mixture in the injector is initiated with an exploding tungsten wire 40 μm in diameter.

Results

In experiments with ammonium perchlorate, the highest wave velocities V (up to 4000 m/s), are recorded at the end of the tube. In runs where ammonium perchlorate is replaced with potassium perchlorate the wave velocity and pressure slightly dropped but the conductivity of the products increases up to 10^3 Sm/m. This latter fact suggests, in compliance with thermodynamic calculations, that metal aluminium contributes significantly to the conductivity. The duration of the conductivity pulses is of order of 10 ms, (Table 1).

Table 1. Result of experiments.

Mixture composition	Duration of conductivity zone, ms	Max/typical conductivity, Sm/m	V, m/s		
			$D_1 - D_2$	$D_2 - D_3$	$R_1 - R_2$
NH_4ClO_4 (25 g) +Al (25 g)	4	160/70	**4273**	2711	**3520**
KNO_3 (25 g) +Al (25 g)	**11**	**950/300**	2848	1818	2413
KNO_3 (27 g) +Al (8 g)	5	100/60	3037	3815	2784
KNO_3 (25 g) +Al (12.5 g)	8	700/100	3028	3812	2765
KNO_3 (19 g) +Al (16 g)	9.5	800/150	2170	3960	2010

Numerical computations

The following problem was solved to model injection of a heterogeneous jet in a reactive environment. A tube with an orifice in one of the end plates is filled with a stoichiometric hydrogen-oxygen mixture (p_0 = 1 atm, T_0 = 300 K). At zero time, a jet of aluminum and ammonium or sodium nitrate particles at a specified temperature suspended in the products of detonation of the hydrogen-oxygen mixture (p_{inj} = 18.8 atm, T_{inj} = 4075, $[O_2]$ = 0.24, $[H_2O]$ = 0.73, $[H_2]$ = 0.03) is injected in the tube through the orifice. Two versions of the state of the reacting mixture were used in calculations: (*i*) a few chemical components concentrations of which are governed by a global kinetic mechanism are assumed to be present, (*ii*) instantaneous mixture composition in the gas phase is estimated from thermodynamic tables assuming equilibrium at each instant of condensed-phase conversion. Two sets of computations are performed. In the first set, the particle size is varied (from 2 to 50 μm for Al and from 1 to 160 μm for AN) at fixed injection velocity and duration. The density of the injected particles is 130 kg/m3, the jet velocity and duration are 1000 m/s and 0.1 ms in compliance with experiment. In the second set, the jet density, particle velocity, and injection duration are varied from 25 to 1200 kg/m3, from 500 to 1000 m/s, and 0.1 to 1 ms, respectively. The particle size is kept invariable.

Three zones are distinguished in the flow: (*i*) near the injector, where particles do not virtually burn and the pressure and velocity are nearly constant, (*ii*) reaction zone, where the pressure peaks and the particle velocity decreases, and (*iii*) rarefaction wave zone, where the flow is accelerated. The representative maximum particle velocities attained in the flow are listed in Tab. 2.

Table 2. Maximum pressures and particle velocities at various sizes of Al and AN particles (σ_S =130 kg/m^3; $u_{S,ing}$=1000 m/s; τ=0.1 ms; =130000 kg/(sec·m^2); m=13 kg/m^2).

Al, μm	AN, μm	$\mathbf{P}_{max}$, MPa	$u_{g,max}$, m/s			$\mathbf{P}_{max}$, MPa		
			0.48 m	1.0 m	1.44 m	0.48 m	1.0 m	1.44 m
3	1	95.7	2981	2957	2918	7.66	5.92	5.79
3	3	75.3	2956	3050	3068	10.4	6.70	6.36
3	6	30.5	2385	2782	2841	14.3	6.26	5.95

Calculations show that it is AN decomposition rate and particle size that control the maximum particle velocity in the tube. The highest particle velocities at AN and Al particle size of about 3 μ are observed at 1-1.5 m from the injector. To study the effect of the environment on the flow velocity we modeled injection of the same material in air. The gas velocity decreased by 450-500 m/s (about 15%) and the pressure gradient flattened. Computations performed at the particle size of 3 μ providing the highest gas velocity in the tube show that the gas velocity depends on the initial jet velocity only little, while the jet density increases the maximum particle velocity (see Tab. 3 and 4). The data listed in the Tables suggest that the pressure level in the major tube part can be reduced without losing the maximum gas velocity.

Table 3. Maximum velocities and pressures attained at various densities of the condensed phase in the jet (d_{AL}=$d_{NH_4NO_3}$ =3 μm, τ=0,1 ms)

$u_{S,ing}$, m/s	σ_S, kg/m^3	$\dot{m}$, kg/(sec·m^2)	$u_{g,max}$, m/s			P_{max}, MPa	P_{max}, MPa
			0.48 m	1.0 m	1.44 m	0.48 m	0-2 m
1000	100	100 000	2831	2918	2926	8.28	57.01
	600	600 000	3713	3893	3918	45.14	449.3
	1200	1 200 000	4135	4357	4395	87.76	1462.9
500	100	50 000	2336	2332	2335	4.25	32.23
	600	300 000	3276	3382	3390	17.22	271.6
	1200	600 000	3710	3865	3875	31.54	1113.7

The effect of the injection duration on the flow parameters in the tube is seen from Table 3. The time during which the high-speed flow persists is nearly doubled as the injection duration increases from 0.1 to 1 ms.

Table 4.. Maximum velocities and pressures at various injection durations (d_{AL}=d_{NH4NO3}=3 μm, $u_{S,ing}$=1000 m/s)

τ, ms	σ_S, kg/m^3	$\dot{m}$, kg/(sec·m^2)	$u_{g,max}$, m/s			P_{max}, MPa	P_{max}, MPa
			0.48 m	1.0 m	1.44 m	0.48 m	0-2 m
0.1	50	50 000	2502	2532	2548	5,00	27.67
1	50	50 000	2501	2532	2547	14,74	61.88
0.1	500	500 000	3611	3790	3829	37,89	352.2
1	500	500 000	3611	3790	3830	160,7	760.1

Apart from the gasdynamic parameters, calculations provided data on the ionization of the reaction products. Ion concentrations ranged between 0.01 and 0.1% in mixtures containing Al, where Al^+ is the major ionic component. Thermodynamic computations and experiment show that replacement of AN by potassium nitrate increase the ionization degree by an order of magnitude.

Concluding remarks

The feasibility of generation of high-speed plasma flows by injecting a mixture of reacting fuel and oxidizer particles in a reactive gaseous mixture is demonstrated. Plasma cloud velocities of 3 or 4 km/s can be attained at pressure levels in the tube of 0.2-1 GPa. The major factor governing the plasma acceleration is the pressure gradient (and hence the rate of particle burning) generated by energy release in the flow. It is shown that the pressure gradient is heavily dependent on the decomposition rate of the solid oxidizer and that there is an optimal ratio between the sizes of fuel and oxidizer particles. At injection durations exceeding 1 ms the duration of the high-speed plasma cloud flow remains nearly constant at 0.4-0.5 ms. The conductivity of the plasma cloud is fairly high, which makes the approach considered very promising in generation of high-intensity pulse currents in MHD generators.

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