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STUDIES OF THE CURRENT CLOT EVOLUTION IN AN EXPERIMENTAL MHD GENERATOR

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ABSTRACT

The present paper is intended to analyse a current clot evolution in the experimental MHD generator. The analysis is based on the time-dependent and one-dimensional numerical model of the physical processes taking place in MHD Shock Tunnel Facility. The luminous precursor appearance downstream from the current clot and the skirt-like form of the current signal are explained in the framework of the two-layer electrodynamical model.

INTRODUCTION

The plasma flow in MHD generator with the current carrying nonuniformities consists of the alternating hot and cold gas portions. The hot portion of the gas seeded with an alkali compound takes care of the electrical conduction. Consequently, the Lorentz force is counteracted by the local pressure gradient mainly generated by the pushing action of the cold gas portion. In this way the expansion work is delivered by the cold gas portion. The decreasing of the cold portion temperature till 1600K increases the enthalpy extraction coefficient up to 35-40%[1].

The experimental investigations of MHD generator with current carrying clot are carried out with Eindhoven Shock Tunnel Facility[2,3]. A stable generation of hot clot in the supersonic flow has been achieved in the first experiments[2]. Rather great decay of the current clot has been observed during its propagation in MHD channel. For the first time the self-sustained current carrying plasma clot moving through MHD channel without destroying has been created in the supersonic flow[3] by increasing of the initial heating length of the clot.

The present paper is intended to analyse a current clot evolution in the experimental MHD generator. The analysis is based on the time-dependent and one-dimensional numerical model[2,4] of the physical processes taking place in MHD STF. The two-layer electrodynamical model has been developed to take into account a sharp decreasing of an electrical conductivity in the boundary layer on the electrode walls. The luminous precursor appearance downstream from the current clot and the skirt-like form of the current signal are explained in the framework of this model.

EXPERIMENTAL ARRANGEMENT

The experiments have been carried out in the Eindhoven Shock Tunnel MHD Facility[3]. MHD STF consists of a shock tube, MHD channel and a dump tank. The shock tube is separated from MHD channel by the frail diaphragm which is destroyed by the incident shock wave. Before the run the driver section and diaphragm section are filled with He up to a pressure p = 11 bar and p = 5.5 bar correspondently, the test section is filled with a mixture of CO, O_2, and N_2 up to p=0.111bar, MHD channel and a tank are filled with an air up to p = 500 Pa. The electrical conductivity of the gas in the test section is provided by 5 cm^3 injection of saturated solution of CH_3COOCs in C_3H_7OH. The magnetic field is constant over the channel length and has a maximum value of 3.3 T. The standard load is 5 Om for each electrode pair.

A hot flow portion is formed by means of a discharge pulse obtained from a capacitor of 1 mF charged to 6000 V prior to the experiment. With a spark gap switch the voltage is applied to the first five connected electrode pairs during 10 ms resulting in a pulsed arc in the channel. The responses of several downstream electrode pairs to the passage of the hot flow portion has been measure.

NUMERICAL SIMULATION

The experimental studies are accompanied by a numerical simulation of the main physical processes taking place in MHD STF. The further developed model[2,4] is used. The main physical processes accounted in the model are the unsteady flow of the gas mixture, the ignition and detonation combustion of CO in O_2, the formation of the hot clot by means of a discharge pulse and generation of electrical current in MHD channel.

Gasdynamical model

The numerical model is based on a one-dimensional and time dependent gasdynamical description. The unsteady flow in MHD STF is described by the one-dimensional unsteady gasdynamical equations for the reactive mixture of molecular gases[4]:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}=\mathbf{H}, \qquad (1)$$

where

$$\mathbf{U}=A\cdot\begin{bmatrix}\rho\\ \rho u\\ E\\ \rho\alpha_i\end{bmatrix},\ \mathbf{F}=A\cdot\begin{bmatrix}\rho u\\ \rho u^2+p\\ (E+p)u\\ \rho u\alpha_i\end{bmatrix},\ \mathbf{H}=\begin{bmatrix}\rho\\ p\cdot\frac{d\ln A}{dx}+f\\ q+uf\\ r_i\end{bmatrix},$$

$i=\{CO, CO_2, He, H_2O, O, O_2\}$- gas mixture component;
α_i — a mass fraction of gas component i;
f,q — a density of body forces and energy sources correspondently.
r_i — a density of i-component production;
The rest designations are convenient.

The set of Eq.(1) is closed by the thermal and caloric equations of the gas state:

$$p=\sum_i\frac{\alpha_i}{\mu_i}\rho RT,\ e_i=\int_0^T c_{vi}\,dT,\ i=1,...,6.$$

The dependence of the heat capacity from the temperature is taken into account[5].

The ignition and combustion of CO and O_2 mixture is described by one brutto-equation of chemical kinetics

$$CO+\frac{1}{2}O_2\leftrightarrow CO_2,$$

and combustion rate is defined by the empirical formula[6], which is take into account a chain mechanism of CO combustion at presence of water vapors:

$$K_{CO}=5.678\cdot10^{12}\cdot T^{-3/2}[CO][O_2]^{0.5}[H_2O]^{0.5}\exp(-16000/T)$$

The oxygen dissociation at high temperature is taken into account directly:

$$O_2+M\leftrightarrow 2O+M$$

with the oxygen atoms recombination rate[7]

The reversed reaction rates are derived using the chemical equilibrium constants[5].

$$K_0 = 10^5 / T \cdot [O]^2 \cdot [M].$$

Electrodynamical model

Electrodynamical model describes the formation of the hot clot by means of a discharge pulse and the electrical current generation during the hot clot propagation in MHD channel. The considered experiments[2,3] differ in that the current clot propagates in the channel with rather cold walls. The first attempt to take into account a lower conductivity and a large voltage drop in the boundary layer[2] led to qualitative agreement of the calculation results with the experimental data.

Here a more complicated two-layer arc-diffusive electrodynamical model is suggested. The cross-section of the channel is divided into three regions: the core of the flow, the turbulent part of the boundary layer and a viscous sublayer. Ohm's law for the one electrode section of MHD channel with regard to the resistance of each region is written as

$$uBy = I \cdot (R_{\text{core}} + R_{\text{layer}} + R_{\text{a}} + R_{\text{load}}),$$

where R_{core}, R_{layer}, R_{a} , R_{load} — resistance of the core, the turbulent layer, sublayer and load correspondently.

The diffusive mode of the discharge is assumed for the core and the turbulent layer:

$$V = I \cdot (R_{\text{core}}(T) + R_{\text{layer}}(T_{\text{L}})),$$

and an arc-diffusive mode is assumed for the sublayer:

$$V = I \cdot R_{\text{a}}, \quad R_{\text{a}} = \begin{cases} R_0, I < I_{\text{cr}} \\ 0, I > I_{\text{cr}} \end{cases}.$$

The temperature T of the flow core is found from the solution of gasdynamical Eq.(1). The energy equation for the turbulent layer is introduced to determined the turbulent layer temperature T_{L}:

$$\frac{\partial}{\partial t} E_{\text{L}} + \frac{\partial}{\partial x}(E+p) \cdot u_{\text{L}} = (q+uf)_{\text{L}}$$

which is transformed to the equation for the temperature disturbance δT_{L} due to Joule dissipation:

$$\frac{\partial \delta T_{\text{L}}}{\partial t} + u_{\text{L}} \cdot \frac{\partial \delta T_{\text{L}}}{\partial x} = \frac{j^2}{\rho \cdot c_v \cdot \sigma(T_{\text{L}})}$$

The turbulent layer velocity is assumed to be equal $u_{\text{L}} = 0.75u$.

The sublayer resistance is very large and it is determined by the diffusive regime of current flow in the initial state. The core of the flow and the turbulent layer are heated and sublayer is pierced during the discharge pulse. The break down of the sublayer is determined from the condition:

$$I + \delta I > I_{\text{cr}}, \qquad (2)$$

where

$$\delta I = I \cdot \left(\frac{\delta \varepsilon}{\varepsilon} - \frac{\delta R_{\text{core}}}{R_{\text{core}}} - \frac{\delta R_{\text{layer}}}{R_{\text{layer}}} \right)$$

is disturbance of the electrical current due to gas flow disturbances in the flow core and the turbulent layer.

The value of critical current I_{cr} is chosen from the preliminary experimental data treatment and is made up 5 A.

RESULTS AND DISCUSSIONS

The physical experiments are simulated by computer experiments. The calculation results are compared with the measured date of gasdynamical and electrodynamical values and are used to base the suggested conception of the current clot propagation in the experimental MHD channel.

Pressure measurements

The current clot propagation takes place at the complicated gas flow due to the detonation combustion of CO in O_2. The considered experiment differs from experiment[2] in that the frail diaphragm has been mounted between the shock tube and MHD channel. The calculated pressure is compared with the experimental pressure records in Fig.1,2. In experiments the pressure has been recorded by seven transducers. Three transducers have been mounted in the tube at the distance of -0.1m,-0.41m,-6.935m, from the end plate and four transducers have been placed in the channel at the distance of 0.52m, 0.625m, 1.025m and 1.425m from the tube. The calculated pressure agrees qualitatively and quantitatively with the experimental records for the all transducers. The pit in the pressure dependence from the time between 5 and 10 ms is a consequence of the detonation CO combustion[2]. Two results have been received due to the mounting of the additional diaphragm divided MHD channel from the tube and due to the gas pumping out to more lower pressure of 500 Pa. First, the gas capacity of the dump tank increased and the secondary shock wave[2] from the tank did not appear in this experiments. Second, the frail diaphragm between the tube and MHD channel put out the gas kinetic energy behind the incident shock wave and intensity of the incident shock wave in the channel decreases in 2-4 times (Fig.2).

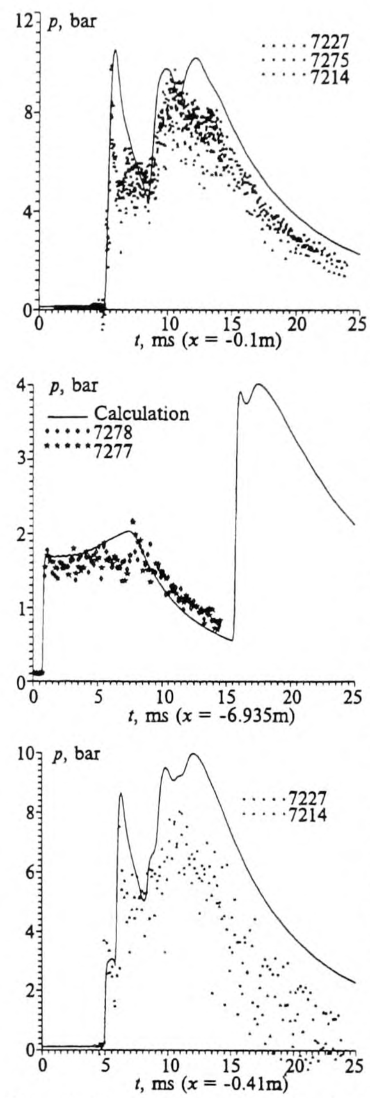

Fig. 1. Pressure records in the tube.

Current clot propagation

The current clot propagation in MHD channel has been registered by the electrical current measurements at several electrode pairs and also by the measurement of the plasma luminescence at 40-th electrode pair.

The Joule heat is released in the turbulent layer and flow core during the discharge pulse on the first five electrode pairs. The Joule dissipation in the core and turbulent layer is inversely proportional to the layers conductions. The turbulent layer is largely overheated during the discharge pulse. The flow core is overheated to a smaller degree.

The disturbances associated with discharge pulse are carried downstream by sonic wave and gas flow. The luminous signal data at 40-th electrode pair for the runs № 7277 and 7278 at B =0 and for the run № 7275 at B=3.3T are plotted in Fig.3. The flow disturbance calculated with formula (2) in reduction units is plotted by dash line and calculated electrical current is plotted by solid line in Fig.3 also. The recorded luminous signal has two well-defined maximums with the greater intensity of the second maximum. The first maximum coincides in time with the arrival of the gasdynamical disturbance calculated

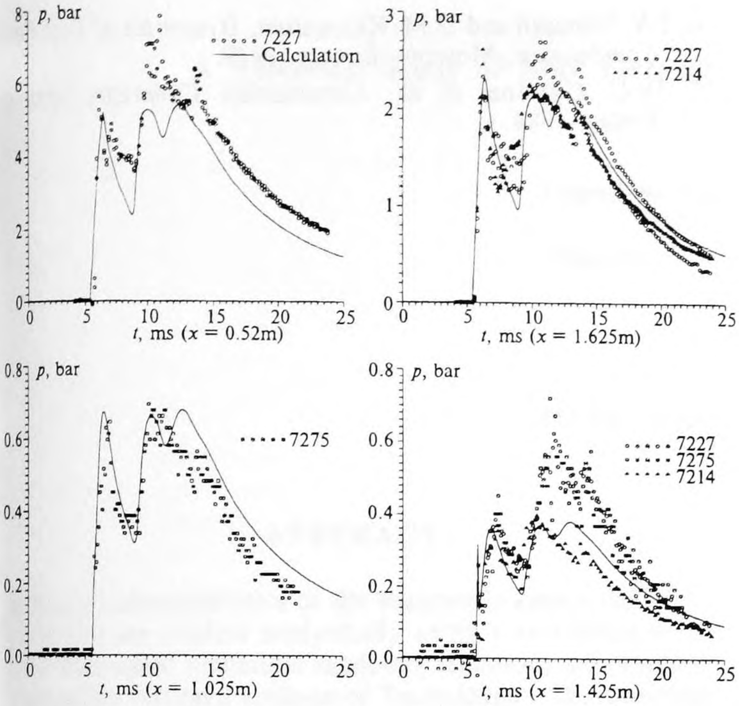

Fig. 2. Pressure records in the channel.

with formula (2) at the observation point. This disturbance (precursor) propagates downstream with the velocity u+c =3140m/s. The second maximum of the luminous signal coincides with the maximum amplitude of the gasdynamical disturbance. This disturbance — the plasma clot overheated during pulse discharge reaches the observation point with core flow velocity. The radiation registration from the channel using the slit photo-scanning of the channel central part (fig.4) confirms qualitatively the flow structure in the vicinity of the overheated clot. The main peculiarities — the precursor, the main clot and warmed up part of the boundary layer, are pronounced in Fig.4. The relative splitting of the marked out elements of the flow structure coincides quantitatively with the calculation results.

The experimental records of the electrical current at the six electrode pairs are plotted in Fig.5. The calculated electrical current is plotted by solid line and the reduction gasdynamic disturbance (2) is also presented by dash line in Fig.5. The experimental records have revealed maximum at 9th, 19th and 29th electrode pair and two maximums at 50th, 69th and 78th electrode pair. The first maximum in this figure correlates in time with the maximum amplitude of the gasdynamical disturbance. It means that the overheated core portion approaching the corresponding electrode pair increases the core conductivity causing the growth of the electrical current. Later the overheated portion of the boundary layer approaches the considered electrode pair. In this case the increase of the average conductivity is more significantly and generated electrical current is greater. The numerical model resolves the appearance of the electrical current due to the motion of the overheated core towards the electrode pair as well as the maximum of the electrical current due to the motion of the overheated turbulent layer. The similar behavior of the electrical current signal is observed also in the run № 7227 plotted in Fig.6.

The numerical model does not describe the decreasing of the electrical current in the interval between the passage of the overheated core and turbulent layer portions over the corresponding electrode pair. It is probably because of the model does not take into consideration the background current on the level of 5A through the electrode pair. The background current will be taken into account in the numerical model in future.

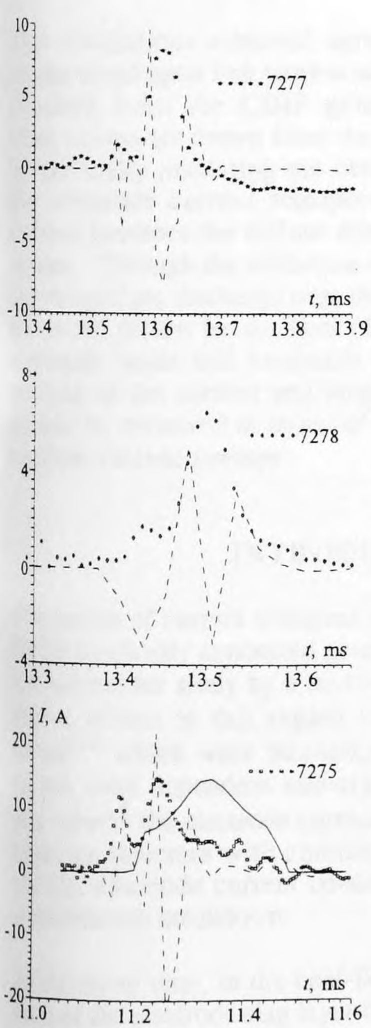

Fig. 3. Luminous signal records and electrode current

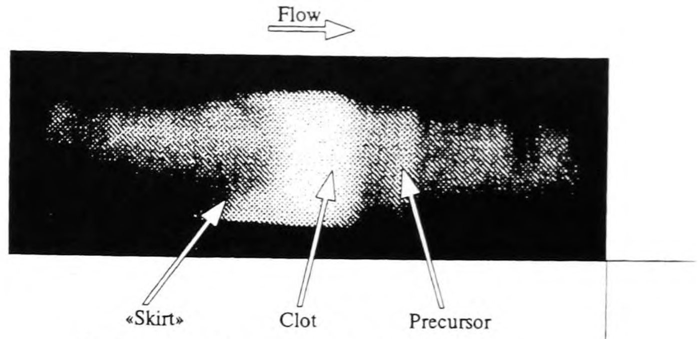

Fig. 4. Streak picture of the run 7276.

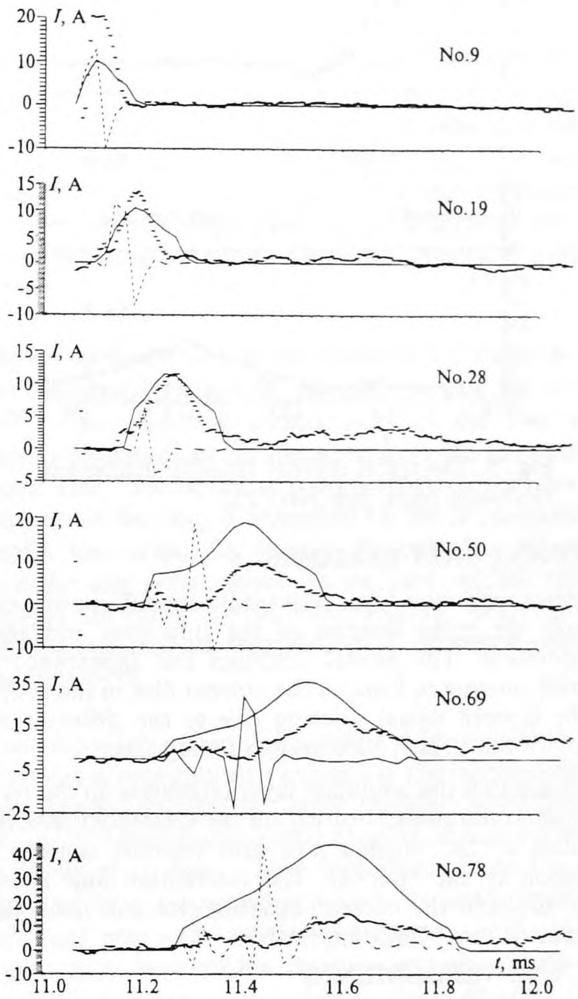

Fig. 5. Electrical current records at different electrode pairs, run No.7275.

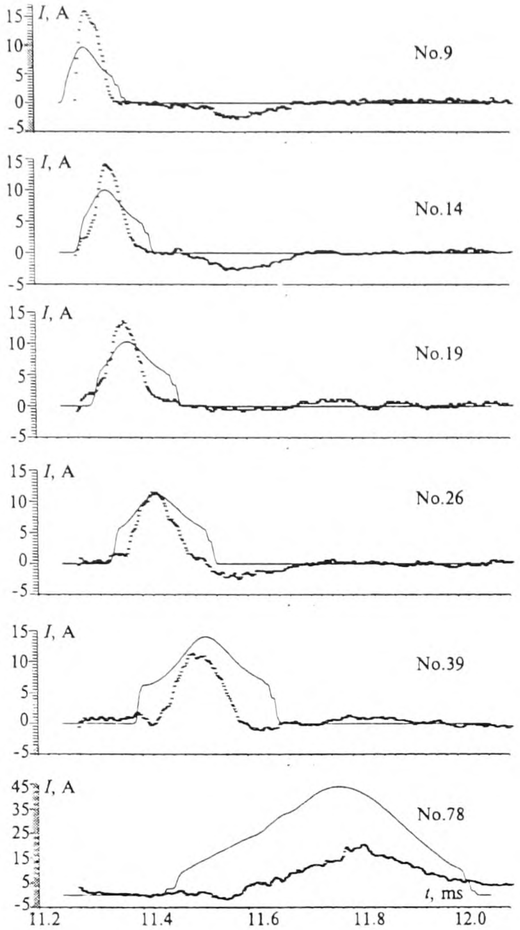

Fig. 5. Electrical current records at different electrode pairs, run No.7227.

CONCLUSION REMARKS

The developed two-layer electrodynamical model explains correctly the main features of the luminous and electrical measurements. The model describes the appearance of the precursor moving in front of the current clot in the sonic wave and the current signal splitting due to the different moving velocity of the stream core and boundary layer.

It turns out that the boundary layer resistance on the electrode walls has an important bearing on the electrodynamical characteristics of the current clot and restricts sharply MHD interaction in the channel. The interaction and energy exchange between the current carrying clot and main flow are weak due to low MHD interaction.

ACKNOWLEDGMENTS

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