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EXPERIMENTAL STUDY OF HEAT FLOWS IN THE WALLS OF A HIGH-ENTHALPY MHD CHANNEL

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There is currently considerable interest in the study of high-enthalpy MHD channels such as in MHD accelerators and MHD generators with a high unit energy removal. One of the most important factors determining the possibility of operating such equipment successfully is the limiting value of the heat flux in their walls. Theoretical analysis of heat-transfer processes under these conditions is very difficult due to their complexity. The most reliable data can be obtained mainly in experiments. Test data on heat transfer is also useful to explain features of gas flow in MHD units.

The present article reports results of experimental studies of local heat flows in the walls of an MHD channel during different regimes of its operation. Special attention was given to aspects of the reliability of measurement of heat flow to B-walls.

1. Experimental Method. Tests were conducted on a unit consisting of a Faraday MHD channel with sectional electrodes operating in the accelerator regime.

Figure 1 shows a basic diagram of the unit. Air heated in an electric-arc heater 1 and saturated with an easily-ionized addition agent 2 in a mixing chamber 3 is discharged through

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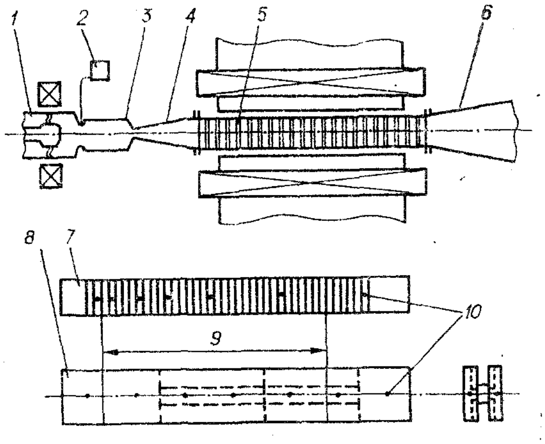

Fig. 1

a primary supersonic nozzle 4 into the channel of the MHD accelerator 5 formed by opposing electrode walls 7 and insulating walls 8 perpendicular to the electrode walls. Undergoing expansion in the secondary nozzle 9, the gas leaves the accelerator channel and enters the working part of the unit. It is then discharged through a flue 6. A detailed description of the unit was given in [1, 2].

Heat loss distribution was determined in MHD channels 470 mm in length and having a cross section F_{in} = 10 × 15 mm and F_{out} = 10 × 21 mm. The section supplied with electric power (position 9 in Fig. 1) was located in the region of a uniform magnetic field 370 mm long. In the tests we used several types of channels, the difference being in the design of the electrode and insulating walls and the sectioning parameter s/h = 0.4-1.

The thermal load on the wall of the MHD channel was determined by solving the inverse problem of heat conduction for a body of complex form with a gradual change in the thermal load over the measured nonsteady temperature field [3, 4]. The nonsteady temperature field in the walls of the channel was measured with Chromel—Alumel thermocouples with thermoelectrode leads 0.3 mm in diameter. Figure 1 shows the location of the thermocouples in the electrode and insulating walls of the channel (position 10).

Two types of insulating walls were used in the tests. The first (the solid line in Fig. 1) was a plate of ceramic BHA* 6 mm thick and 49 mm high. The thermocouples were installed in grooves and were secured by means of a mixture of powdered BHA and sodium silicate. The second type of insulating wall (dashed line) was made in the form of a two-layer system consisting of a copper base and a spray-coated, electrically insulating layer of ZrO_2 facing the flow. Additional insulating plates of BHA 2.5 mm thick were installed in grooves next to the electrode walls. Here, the height of the spray-coated surface facing the flow was either 10 mm or 6 mm. In the last type of side walls, as in the electrode walls, the thermocouples were installed in grooves and secured by means of copper cocks.

Besides the temperature of the walls of the MHD channel, we measured the distribution of static pressure, the voltages and currents in the electrodes along the accelerator channel, the total pressure after the electrodes, rates of flow of the gas and addition agent, and the pressure, current, and voltage in the heater. These parameters were recorded on N-010 and N-105 oscillographs synchronously with the recording of the nonsteady temperature field in the walls of the MHD channel.

Tests were conducted with the primary nozzle (M = 2). The gas-flow stagnation parameters were as follows (the gas was air + 1% KNa eutectic): temperature T_0 = 3700°K, pressure $p_0 = (1.55;\ 2.2)\cdot 10^5$ Pa.

Power was supplied along zones 160 and 280 mm long. During the tests we changed the total gas flow rate $G = (7;\ 10)\cdot 10^{-3}$ kg/sec, the magnetic induction B = 1-2.5 T, and the current through the electrodes I_e = 5-40 A. Here, the total current in the accelerator ranged with I_Σ = 100-1400 A.

*Ceramic BHA is boron alumonitride (50% BN + 50% AlN).

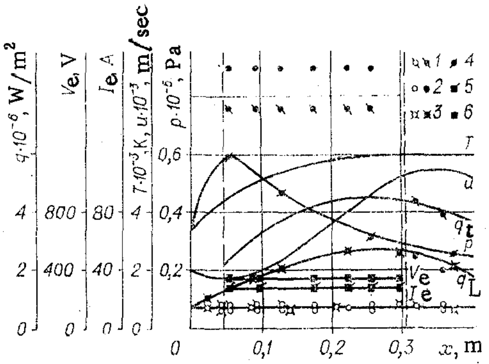

Fig. 2

Figure 2 shows experimental results on the distribution of the parameters along the MHD channel for typical operating regimes of the unit (G = 10 g/sec, B = 2.5 T, s/h = 0.5-0.42, I_Σ = 980 A, j = 35 A/cm^2 in the flow core); position 1 corresponds to the heat flux in the cathode wall; 2, in the anode wall; 3, in the side walls; 4, static pressure; 5 and 6, current and voltage on the accelerator electrodes. The clear points pertain to the regime without MHD acceleration.

2. Test Results. We first determined the heat fluxes in the walls of the channel during operating regimes without the supplying of power to the electrodes (clear points in Fig. 2). It was found that the heat flows in similar sections of all of the channel designs used were nearly the same for all regimes of heater operation. No differences in heat flux were seen between the cathode and anode walls and side walls. The introduction of the addition agent and the application of the magnetic field either individually or in combination did not appreciably change heat-transfer rate. A similar finding was made for insulating walls in [5, 6]. It should be noted that the magnetic induction reached appreciable values in our tests (B ~ 2.5 T).

The flow of current significantly changes the conditions of heat transfer in the MHD channel (dark points in Fig. 2). There is an increase in the thermal load along nearly the entire channel. However, the increase is different in different sections of the channel, and it is different for the cathode, anode, and side walls. It should be noted that the character of the heat-flux distribution in the walls along the channel is nearly independent of both the type of design of the MHD channel and the channel operating regime.

Three regions can be distinguished on the basis of the character of distribution of heat flow to the electrode walls along the channel: pre- and post-discharge zones and discharge zone. Each zone has its own law of change in heat flux along the channel.

In the predischarge zone, the increase in heat flux in the electrode walls connected with the flow of current in the discharge zone is fairly slight. It is seen in all of the investigated regimes and is evidently due to an increase in the heat content of the gas due to the occurrence of boundary effects. The greatest increase in heat-transfer rate is seen in the discharge zone. Here, there is a stable difference in heat flows to the cathode and anode walls. The flow of current in the MHD channel also led to a substantial increase in heat flow in the post-discharge zone, heat flow to the cathode wall being considerably greater than heat flow to the anode wall. This difference remains in effect over the entire post-discharge zone. It should be noted that the magnitude and character of the change in heat flux in the electrode walls are consistent with the findings in [7].

The measured distributions of heat flux in the side walls do not have such a pronounced division into different zones as in the case of the electrode walls. The supplying of power to the electrodes was accompanied by an increase in heat flux over the entire wall, with a monotonic increase in heat flux along the channel. The increase in heat flux in the predischarge zone is negligible and coincides with the case of the electrode walls.

We must point out the following. In the tests with the second type of wall in the form of a two-layer system of a copper base and an insulating coating of ZrO_2 with additional protection from the electrodes by plates of BHA, the recorded heat flux was almost one order of magnitude greater than the heat flux for the first type of wall in some cases. An analysis showed that this was due to so-called intermodular breakdown [8], the voltage of which was about 40 V in the gap. Thus, the main experiments were performed with side walls made of BHA.

The data obtained were analyzed using the electrogasdynamic flow pattern established for each regime from numerical solution of a system of quasiunidimensional magnetogasdynamic equations. As the boundary and closing conditions for the system we introduced experimental data on the distribution of pressure, current, and voltage in the MHD channel. The necessary corrections were introduced in the unidimensional equations to allow for the effect of the boundary layer and heat transfer, two-dimensional effects connected with the character of current flow in the channel, and the possibility of heating of the gas in the acceleration zone due to Joulian dissipation in the near-electrode layers and in the predischarge zone by currents caused by longitudinal edge effects. The method used and results of its verification for the conditions examined here were detailed in [2, 9, 10].

In performing the calculations we assumed that only convective heat transfer occurred on the insulating walls and in the nondischarge zones of the electrode walls. Heat flux due to electrode processes was added to the convective component in the discharge zone on the electrode walls. The convective component of heat transfer was calculated from the well-known relation for the high-temperature supersonic flow of a gas:

$$q = \mathrm{St}(h_f + h_w)\rho u,$$

where ρ and u are the density of the gas and the velocity of the flow; St is the Stanton number; h_w is the enthalpy of the gas at the temperature of the wall; $h_f = h_{wa} + \mathrm{Pr}^{1/3}u^2/2$ is the enthalpy of the gas at the adiabatic temperature of the wall; Pr is the Prandtl number. The friction coefficient for determining St was calculated by different methods: by the method in [11], which considers the effect of the magnetic field; from the drag of the channel, which was determined from the experimentally obtained distribution of static pressure along the channel [2]; by the method of determining enthalpy for laminar flow [12]; by the Spalding–Chi method for turbulent flow [13].

Figure 2 shows results of measurement (points) and analysis (lines) of gasdynamic and electrodynamic characteristics of flow in the MHD channel (p, T, and u are the pressure, temperature, and velocity in the flow core; q_t and q_m are the heat flows to the walls of the channel for turbulent and laminar flows).

The empirical values of heat flux for the entire length of the electrode walls in the regime without power supply to the electrodes, in the predischarge zone in the acceleration regime, and in the side walls in all regimes agree well with the values calculated by the method of determining enthalpy for laminar flow (see Fig. 2, q_m). In the post-discharge zone, the experimental values of heat flux to the anode wall agree with the values calculated by the method of determining enthalpy for laminar flow, while the experimental values of heat flux to the cathode wall agree with the values calculated by the Spalding–Chi method for a turbulent boundary layer (see Fig. 2, q_t).

Thus, around the anode wall, heat transfer corresponds to the conditions of a laminar boundary layer. Around the cathode wall, heat transfer corresponds to conditions of a turbulent boundary layer. This is evidently due to features of the discharge in the electrode regions of the discharge gap. According to [14], in the anode region, current flows along the entire electrode, and the concentration maximum is on the rear (downflow) part. The distribution of current and its flow are nearly steady in character. Current flow in the cathode region is distinctly nonsteady in character. Microarc channels by which the discharge to the cathode occurs are continually displaced in the direction of the flow, with the intensive formation of new channels and disappearance of old channels.

It should be noted that at relatively low current densities ($j \leq 10$ A/cm^2), the heat fluxes in the post-discharge zone calculated by the Spalding–Chi method are somewhat higher than the experimental values. This is evidently connected with the few number of microarcs existing at one time on the electrode and, thus, a lower degree of "agitation" of the flow.

The heat flow to the electrode walls in the discharge zone is determined mainly by the current flow and, most of all, by near-electrode processes. Comparison of the general level of the experimental heat flows with the calculated values of the convective component confirms this and also makes it possible to evaluate volt equivalents of heat loss for the anode ΔV_a and cathode ΔV_c on the assumption that the experimental values of heat flow are the sum of the flows due to near-electrode processes and convective flow. Under the conditions examined here, we obtained ΔV_c = 7-12 V, ΔV_a = 15-27 V.

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