INTRODUCTION

When a supersonic flow is decelerated by the Lorentz force under conditions of strong magnetohydrodynamic (MHD) interaction, a gas-dynamic shock arises at which the supersonic flow transforms into a subsonic one. Situations in which the decelerated flow remains continuous refer to the case of weak MHD interaction.

Compression MHD shocks were first studied in [1]; in more detail, they were investigated in [2, 3] and, later, in [4, 5]. A comprehensive study of MHD flows with compression shocks was performed in [6] using an analogy between MHD and gas-dynamic flows. All of the above experiments were carried out with homogeneous plasma flows. Inhomogeneities of a nonequilibrium plasma flow may arise due to the onset of various instabilities [7], first of all, ionization instability, which develops faster than other instabilities. In this study, we assume that the reason why the plasma is nonequilibrium is that the electron temperature is higher than the temperature of the heavy component and the degree of ionization differs from its equilibrium value corresponding to the electron temperature. The formation of compression MHD shocks under conditions such that MHD interaction is accompanied by the generation of plasma inhomogeneities should possess specific features [8]. The aim of this study is to outline the conditions under which the formation of gas-dynamic shocks in the course of MHD interaction has already been comprehensively studied both experimentally and theoretically and to reveal special features of shock formation in flows in which plasma inhomogeneities may arise due to MHD interactions.

CLASSIFICATION OF MHD INTERACTIONS

MHD flows may be classified as follows: First, the gas-dynamic flow may be continuous or there may be an MHD shock induced by the Lorentz force. Second, the plasma in the flow may be homogeneous or there may be plasma inhomogeneities that arise from small initial variations in the plasma parameters due to the onset of plasma instabilities. The type of interaction is determined by the Stewart number $St$, which characterizes the ratio of the work produced by the Lorentz force to the gas kinetic energy, and the Hall parameter $\beta$, which is the ratio of the electron cyclotron frequency to the effective frequency of momentum transfer.

Let us consider a linearly widening MHD channel. A specific case of a linearly widening MHD channel is a channel in the form of a constant-height disk. Figure 1 shows a schematic of the MHD channel and the directions of the main vectors: the flow velocity $u$, the magnetic induction $B$, and the induced current density $j$. Here, $x_0$ and $x_e$ are the distances from the vertex of the channel to the beginning and the end of the MHD inter-

![Fig. 1. Scheme of a linearly widening channel.](image-url)
The classification of the types of MHD interaction. Here, $S_{t0} = \sigma B^2 x_0/\rho_0 u_0$ and $\beta = \omega c s/v$.

The regimes in which plasma flows are stable and unstable against the onset of ionization instability are separated by the critical value of the Hall parameter. The Hall parameter is defined as

$$\beta = eB/m_\nu v, \quad v = n_e c_e Q_{ea} + n_i c_i Q_{ei},$$

where $v$ is the frequency of momentum transfer in collisions of electrons with atoms and ions; $n_a$ and $n_i$ are the atom and ion densities, respectively; $c_e$ is the mean electron velocity; and $Q_{ea}$ and $Q_{ei}$ are the cross sections for momentum transfer in collisions of electrons with atoms and ions, respectively (both averaged over the Maxwellian electron distribution function).

The classification of the possible types of interaction is illustrated in Fig. 2. The $(S_t, \beta)$ plane is divided into the following domains corresponding to different types of MHD interaction: type I is weak interaction in a homogeneous plasma, type II is strong interaction in a homogeneous plasma, type III is weak interaction in a plasma that is unstable against the onset of ionization instability, type IV is strong interaction in a plasma that is unstable against the onset of ionization instability, and type V is superstrong interaction corresponding to the case where the shock comes out from the MHD channel towards the flow (this case is beyond the scope of the present study).

The critical value of the Stewart number that separates the regimes with weak and strong MHD interaction in homogeneous plasmas (domains I and II) can be estimated using the results of the previous theoretical and experimental studies [4, 5]. It was shown that the position $x_{sh}$ of a stationary compressional MHD shock in a linearly widening short-circuited channel can be described over a wide range of the Mach numbers (1 < $M < 5$) by the following simple formula

$$x_{sh}/x_0 = (\gamma S_{t0})^{0.5},$$

where $\gamma$ is the adiabatic index.

As the MHD interaction parameter increases, a continuous MHD flow transforms into a flow with a compressional shock. The shock first arises at the end of the channel: $x_{sh} = x_c$. The corresponding value of the Stewart number $S_{t01}$ at which the shock arises defines the upper boundary of domain I:

$$S_{t01} = (x_c/x_0)^{2-\gamma^{-1}}.$$

As the Stewart number increases, the shock shifts closer to the entrance of the channel and, at

$$S_{t02} = 1/\gamma,$$

it reaches the ultimate position $x_{sh} = x_0$, which corresponds to the upper boundary of domain II. At $S_{t0} > S_{t02}$, the shock comes out from the channel toward the flow.

In the parameter range corresponding to an ionizationally inhomogeneous plasma (domains III, IV), no distinct boundary can be drawn between the regimes with weak and strong interaction. This is because the critical value of the Hall parameter at which ionization instability develops and plasma inhomogeneities arise depends on the sort of gas and on the degree to which the flow is far from the ionizational equilibrium. In the case of the full ionizational equilibrium, the critical value of the Hall parameter $\beta_{cr}$ can easily be estimated [6, 7]: $\beta_{cr} = 1–2$. At $\beta > \beta_{cr}$, ionization instability inevitably develops in the MHD channel because its growth time is much shorter than the flight time of the flow through the channel. In the absence of ionization equilibrium, the growth time of instability is determined by the characteristic ionization time. For pure noble gases, this time may be comparable to the flight time [9]. In this case, the critical conditions depend on both the Hall parameter and the ratio between the growth time of instability and the flight time. Hence, for each specific MHD channel, there is its own critical value of the Hall parameter. This is why the boundary between the regimes in which the flow is stable and unstable against the onset of ionization instability is drawn arbitrarily.