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VOLTAGE-CURRENT CHARACTERISTICS OF HARTMANN BOUNDARY LAYERS IN PLASMAS*

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Abstract

In some steady-flow plasma devices it has been found empirically that the applied voltage increases proportionate to the increase of magnetic field, the constant of proportionality being a characteristic dimension of the device times the "ionization velocity," i.e., the velocity at which a gas atom possesses a kinetic energy equal to its ionization potential. The significance of this observation, first made by Fahleson[1] in a homopolar experiment, was discussed by Alfven[2] who interpreted the observation in terms of the relative motion of a neutral gas through a plasma. Subsequent experiments on magnetoplasmadynamic (MPD) arcs[3] have shown a similar relationship between voltage and magnetic field intensity, and it is sometimes supposed that there are similar physical processes in these various experiments which cause the same effect. Indeed, the theory of Lin[4], which treats the homopolar flow as a quasi-steady rarefied gas flow with slip between the plasma and neutral components, explains quantitatively the voltage-magnetic field relationship of Fahleson's experiments, at least for low currents. No equivalent theory exists for the MPD arc.

We have developed an alternative explanation of the voltage-current characteristics measured by Fahleson, based on the properties of a Hartmann boundary layer in a continuum-type plasma. We assume that the bulk of the gas rotates freely, the current flowing only in thin Hartmann layers near the end walls where it balances the viscous drag. Assuming a negligible voltage drop at the electrodes, we calculate the voltage difference between the electrodes as a function of magnetic field, initial pressure, applied current and atomic weight, and find agreement with the measurements[1,5] within a factor of two under all conditions. (We believe our calculations are more appropriate to the experiments than are Lin's, since all mean free paths are much less than the size of Fahleson's apparatus.) According to this point of view, the homopolar voltage-current characteristics are determined entirely by the relationship between the current per unit length and electric field in a Hartmann layer on the end surfaces of the device.

The physical model of the Hartmann layer we propose is as follows: Because of the very high Hall parameter of the electrons, the current is carried mainly by the ions. The consequent Joule heating of the ions is conducted in part to the cold wall and partly toward the core of the rotating plasma, in which this latter portion of the electrical energy input is given up to the electrons by elastic collisions. The electrons, which are thermally insulated from the wall by a sheath, lose an equal amount of energy by ionizing collisions with atoms to produce electron-ion pairs which subsequently diffuse to the wall.

Assuming constant (average) transport properties, it is possible to integrate the equations of motion and energy for the heavy particles as well as the ambipolar diffusion equation for the charged particles. By assuming that the heavy particle and electron temperatures are nearly equal in the core of the gas, these integral equations relate the total current to the electric field, the electron temperature and degree of ionization appearing as parameters. The resulting relationship has approximately the form:

$$E = (c_1 + c_2 I)B$$

in which E is the electric field, B is the magnetic field, I is the current per unit width of Hartmann layer, c_1 is a constant about equal to one half of the ionization velocity and c_2 is a constant independent of density. Thus for very small currents ($\ll c_1/c_2$), the voltage is independent of current, as found by Fahleson[1]. For large enough current so that $c_2 I \approx c_1$, that is, sufficiently large to about double the low current voltage, the calculated temperature about equals the ionization energy divided by Boltzmann's constant.

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