Preionization in a Magnetoplasmadynamic Generator

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Theme

PREIONIZATION of a seeded noble gas plasma may be necessary to efficiently operate in the nonequilibrium ionization mode. This is particularly true for closed-cycle magnetoplasmadynamic systems where the maximum temperatures are limited by material considerations. A two-dimensional analytical model with nonuniform properties in the presence of combined magnetically induced and applied electric fields has been developed to evaluate the influence of the plasma temperature, pressure, Mach number, magnetic field, seed ratio, electrode separation distance, and current on the terminal voltage of a single pair of preionization electrodes located in a constant area channel. Finite ionization and recombination rates, ion slip, electron pressure gradients, plasma velocity profiles, and electrode sheath voltage drops are included. The nonlinear coupled governing equations are solved numerically using an interative relaxation technique. Ion slip was found to be an important consideration in predicting regions of unstable operation. Plasma instabilities with Hall parameters greater than about 3 were found to have a very significant effect on the terminal voltage, however, the influence of these instabilities decrease for Hall parameters greater than about 14.

Contents

A critical problem encountered in closed-cycle magnetoplasmadynamic (MPD) power generation is achieving a high electrical conductivity while operating at gas temperatures that are compatible with existing materials. If the required internal electric field exceeds the magnetically induced field, it is necessary to raise the conductivity by preionization. The internal electric field is dependent on the physical properties of the plasma such as the temperature, pressure, Mach number, magnetic field, electrode separation distance, current, and seed ratio

Early two-dimensional theoretical studies with magnetically induced electric fields were based on uniform electrical conductivities. Experimental measurements, however, reveal the presence of large nonuniformities in plasma properties near the electrodes. These nonuniformities are primarily a result of induced Hall voltages which distort the current distribution causing nonuniform Joule heating of the electrons. Oliver and Mitchner[1] used a similar numerical technique to solve the coupled electromagnetic and energy equations. They considered nonuniform electrical conductivities; however, their study was limited to low Hall parameters. In this study, a two-dimensional analytical model has been developed to parametrically analyze the plasma and channel characteristics that affect preionization for a single pair of Faraday-type electrodes located in a constant area channel.

The plasma is assumed to flow between two parallel thermal and electrically insulated walls (see Fig. 1). The bulk plasma is separated from the solid boundaries by a thin collisionless sheath region. The bulk plasma properties are governed by the following set of equations:

Electron Continuity Equation: The electron continuity equation is

$$\partial n_e/\partial t + \operatorname{div}(n_e \mathbf{v}_e) = \dot{n}_e \tag{1}$$

where n_e is the electron number density, t is time, $\mathbf{v}_e$ is the electron velocity, and $\dot{n}_e$ is the rate of production of electrons which is given by Kerrebrock[2] as a function of the volume recombination coefficient.

Electromagnetic Field Equations: The electrostatic field $\mathbf{E}$ is given by the steady-state Maxwell-Faraday equation

$$\operatorname{curl} \mathbf{E} = 0 \tag{2}$$

The conservation of electric charge for a quasineutral plasma is

$$\operatorname{div} \mathbf{J} = 0 \tag{3}$$

where $\mathbf{J}$ is the total current density.

Electron Energy Equation: The energy equation is written in a form similar to that given by Kerrebrock,[2] but includes separate terms for the elastic and inelastic collision losses.

$$(D/Dt)[n_e(\tfrac{3}{2}kT_e + eE_i)] + n_e(\tfrac{3}{2}kT_e + eE_i)\operatorname{div}\mathbf{v} + \operatorname{div}\mathbf{q}_e + P_e \operatorname{div}\mathbf{v} = \mathbf{j}_e \cdot \mathbf{E}' - w_{el} - w_{inel} \tag{4}$$

where k is Boltzmann's constant, T_e is the electron temperature, e is the electron charge, E_i is the ionization potential, $\mathbf{v}$ is the bulk plasma velocity, $\mathbf{q}_e$ is the electron heat flux, P_e is the electron pressure, $\mathbf{j}_e$ is the electron current density, $\mathbf{E}'$ is the electric field in coordinates moving with the plasma, w_{el} is the elastic collision loss, and w_{inel} is the inelastic collision loss. The elastic loss term considers the carrier gas, seed, and positive ions. The inelastic loss term includes radiation, diffusion, and recombinations of the excited state atoms and positive ions. Generalized Ohm's Law is given by

$$E'_x = \frac{1+\beta_e\beta_p}{\sigma_e} J_x + \frac{\beta_e}{\sigma_e} J_y - \frac{\mu_e}{\sigma_e}\frac{\partial}{\partial x}(kn_e T_e) \tag{5}$$

and

$$E'_y = \frac{1+\beta_e\beta_p}{\sigma_e} J_y - \frac{\beta_e}{\sigma_e} J_x - \frac{\mu_e}{\sigma_e}\frac{\partial}{\partial y}(kn_e T_e) \tag{6}$$

where $\beta_e = \mu_e B$ is the Hall parameter of the electrons, $\beta_p = \mu_p B$ is the Hall parameter of the ions, and σ_e is the electrical conductivity.

Equations (1–6) were solved simultaneously for the electron number density, electron temperature, and the current density

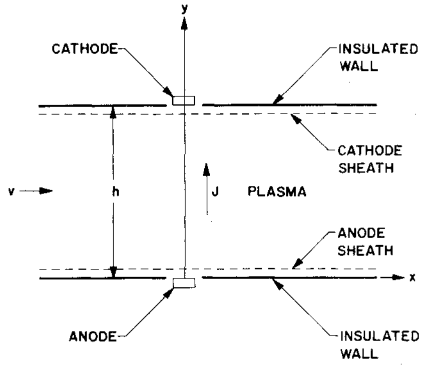

Fig. 1 Coordinate system and channel geometry.

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using a finite difference iterative relaxation technique. Even though the total current density is approximately equal to the electron conduction current density and the divergence of the total current density is zero, the divergence of the electron conduction current density is not zero but is equal to the divergence of the ion conduction current density ($\text{div}\,\mathbf{j}_e = \text{div}\,\mathbf{j}_p$). The velocity of the plasma is assumed constant in the flow direction, however, a profile across the channel has been considered.

The current distribution is skewed as a result of the Hall effect and is concentrated at the downstream edge of the anode and at the upstream edge of the cathode where the electron temperature and therefore the electrical conductivity is a maximum. Similar distributions have been experimentally measured by Fischer[3] and by Brederlow and Dodel.[4]

The voltage across the bulk plasma (excluding the sheath and electrode effects) is

$$V_y = \int_0^h E_y\,dy \tag{7}$$

where $E_y = E'_y - uB$. The sheath and electrode surface equations were adapted to this study directly from the work of Talaat[5] on thermionic converters. The terminal voltage is

$$V = \phi_C - \phi_A + V_y - V_{SC} + V_{SA} \tag{8}$$

where ϕ_C and ϕ_A are the virtual cathode and anode work functions and V_{SC} and V_{SA} are the cathode and anode sheath voltage drops. The results presented are based on tungsten electrodes partially covered with cesium at the stagnation plasma temperature. Externally heating the cathode decreases the fraction of cesium coverage which increases the virtual work function and decreases the sheath voltage drop.

The performance of an MPD generator is very strongly affected by the applied magnetic field. The magnetically induced electric field must be greater than the required electric field if the generator is to operate in the power mode. The presence of a magnetic field created Hall voltages which distorts the current pattern causing an increase in the internal resistance of the plasma which in turn increases the required electric field. Experimental evidence has shown the existence of instabilities which are related to the magnetic field through the electron Hall parameter. These instabilities have lead to a reduction in generator performance above a Hall parameter of about 3. Brederlow and Zinko,[6] using argon seeded with potassium, experienced instabilities above a Hall parameter of 3, but the influence of these instabilities noticeably decreased above a Hall parameter of about 14.

Figure 2 shows the predicted terminal voltage, the average magnetically induced voltage, the average voltage required across the bulk plasma, and the average Hall parameter of the electrons as a function of the magnetic field. As the magnetic field is increased from 0 to about 1.5 webers/m^2 (corresponding to a Hall parameter between 0 and 3), the terminal voltage increases. The Hall voltage also increases which causes an increase in the diagonal displacement of the current raising the internal resistance of the plasma and the required voltage. For a Hall parameter between 3 and 14, the terminal voltage experiences a negative slope (similar to the unstable region observed in some static discharge tests), and the required plasma voltage increases at a more rapid rate. Examination of the current distribution curves in this region reveal the existence of eddy currents, particularly near the electrodes. The nonuniformities in plasma properties due to the pronounced skewing of the current patterns provide low resistance paths for the formation of local eddy currents which contribute to the rapid increase in the required voltage. Above a Hall parameter of 14, the voltage slope again becomes positive, the required voltage decreases, and the eddy currents appear to decrease in intensity and are confined to fewer regions. The theoretical results of this study are in good agreement with the experimental measurements of Boschi, Merzagora, and Tamburrano[7] and with Biblarz and Eustis.[8]

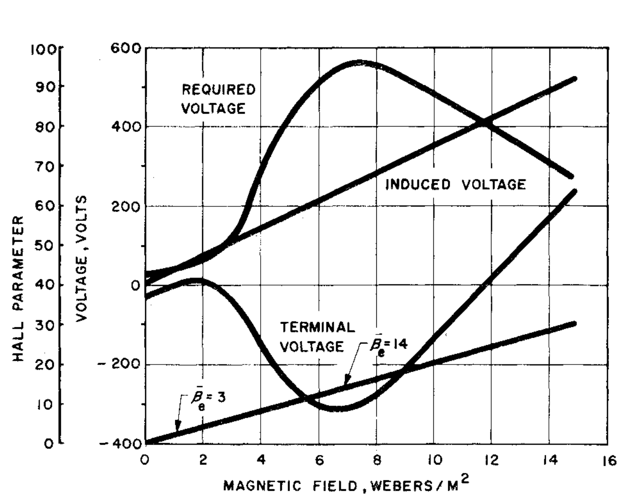

Fig. 2 Voltage and average electron Hall parameter variation with magnetic field. $T_o = 1500$ K, $P = \frac{1}{2}$ atm, $M = 0.6$, $h = 3$ cm, $I = 1$ amp, helium plus 1% cesium seed.

Because of the parametric nature of this study, the governing equations include many terms which have been neglected in previous studies which concentrated on specific operating regions. The electron continuity equation considers the gradient of the electron current density which has usually been neglected. Ion slip and electron pressure gradients have been included in the electromagnetic field equations. The electron energy equation considers the contributions from thermal convection, electron heat flux, electron pressure gradient, Joule heating, elastic, and inelastic collision losses. Net diffusion and radiation exchange between both the excited state atoms (the first resonance doublet was considered) and ions with the walls of the channel are included in the inelastic loss equation.

The electron and ion mobilities are not assumed constant. The electron mobility includes the average collision cross section of the carrier gas, the neutral seed atoms (as a function of electron temperature), and of the positive ions (as a function of electron temperature and number density). The mobility of the ions is a function of plasma pressure and temperature and of the electron temperature and density.

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