End Loop Shorting in Nonequilibrium MHD Generators

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Theme

THE characteristics of the plasma are examined in the exit region of a nonequilibrium MHD generator which is shorted axially by highly conducting gas layers along the electrode walls. The axial extent of the exit region is governed by conditions at the generator exit which are in turn affected by the exit region's ability to prevent shorting currents from flowing. For operating conditions of interest, this length is determined. The important parameters which govern it and the aerodynamic techniques which minimize it are delineated. Thus, if the ends of the generator play an important role in determining the characteristics of the shorting wall layers, the means identified here may be used to minimize the conductance of the exit region.

Contents

A theoretical model which describes the experimentally observed behavior of a nonequilibrium MHD generator satisfactorily,[1] hypothesized that highly conducting layers exist on the elctrode walls which short the generator through the end regions at open circuit. These layers exist because the transverse current flow is impeded at the electrode wall and the finite size electrodes locally short the Hall field, leading to a larger conductivity there than in the main flow.[2–4]

The exit end of an internally shorted nonequilibrium MHD generator near open circuit may be described as an active generator section where the magnetic field is nonzero, followed by an exit region where the field vanishes. On the electrode walls, layers of highly conducting gas are assumed to flow from the generator out through the exit. Figure 1 shows a plan view of the exit of a shorted generator. The main body of the flow in the generator (freestream) generates an electric field $E_y = kU_GB$ which is a small fraction of the open circuit electric field U_GB due to the internal shorting. The voltage E_yd, where d is the generator width in the y direction may be assumed to be applied to the main exit region flow, if the characteristic recombination length of the layers is larger than that of the exit region freestream.

The electron temperatures and therefore the scalar conductivities in the generator and the exit region are comparable in magnitude, if the gas dynamic conditions in the two regions are identical and if the joule heating parameter βk is of order 1. Here β is the Hall parameter and k the load factor. It follows then that the load factor which can be realized in the generator, for constant area flow with high-conductivity wall layers is

$$k = [(1 + \beta^2)\, l_E/l_G + 1]^{-1}$$

which is indeed small for $\beta \sim 5$ and an appreciable exit region length, l_E where the conductivity is comparable to that in the generator. Here l_G is the generator length as shown in Fig. 1.

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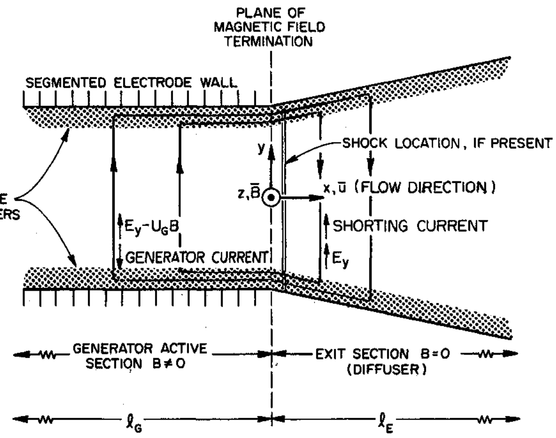

Fig. 1 Exit end of nonequilibrium MHD generator showing the active section, the diffuser, the wall layers, and the circulating current.

The behavior of the generator exit region is investigated by means of the steady, one-dimensional conservations equations applied to the electron and heavy gas components. Ohm's law, the energy equation and the kinetic condition describe the behavior of the electron gas. The heavy gas flow is assumed isentropic, except for the presence of shocks, because of the large interaction length consistent with internally shorted operation.

The plasma conditions are listed in Table 1. The governing equations may be integrated to obtain the variations of electron density, transverse current density and electron temperature for several elementary situations: isentropic flow with no area change, normal shock wave at the magnetic field termination plane followed by isentropic constant area flow, isentropic flow in a converging or diverging duct.

The initial conditions are the specified electron temperature, βk, flow stagnation temperature and pressure, and initial Mach number. At the generator exit plane, $x = 0$, equilibrium is assumed at the specified electron temperature.

Table 1 Flow parameters for Fig. 2

Fluid: helium + 0.003 cesium
Stagnation pressure: 5 atm
Stagnation temperature: 2000°K

M_G	T_{e_0}, °K	βk	L_K, cm	L_η, cm	n_{e_0}, mϕ^3
1.2	2000	0.5	0.155	0.00162	3.24×10^{19}
2.2	2000	0.5	0.363	0.00382	2.12×10^{19}
1.2 (curve A)	1600	0.15	0.173	0.234	1.64×10^{18}

The nondimensional electron energy and kinetic equations involve length scales $L_E = \varepsilon_i/(m_e v_{c_0} a_s)$ and $L_K = a_s/(k_{b_0} n_{e_0})$ respectively, where a_s = stagnation speed of sound, m_e = the electron mass, v_c = electron collision frequency, ε_i = seed ionization potential, k_b = ionization rate coefficient and n_e = electron density. The 0 subscript refers to conditions at the generator exit plane. These lengths are a measure of the relative importance of electron density changes demanded by the falling electron energy and those changes permitted by the kinetics of the electron-electron-ion encounters. The longer of these lengths is the scale for the recombining plasma. In particular if $L_E >> L_K$, then the electrons remain in Saha equilibrium.

For the conditions listed in Table 1, Fig. 2 shows the variation of the electron density, $n = n_e/n_{e_0}$ in the flow direction. The normalizing density n_{e_0} varies with flow Mach number for constant stagnation conditions as indicated in Table 1.

The joule heating parameter (βk) is chosen sufficiently small so that the recombination occurs. Experimentally, values of βk between 0.1 and 0.5 are observed.[1] For isentropic flow the electron density (and temperature) falls rapidly because of the low gas static temperature and density associated with supersonic flow. When a shock is located at the generator exit n does not fall much because of the higher static temperature. When there is no Joule heating ($\beta k = 0$), the electron density falls very rapidly, by two orders of magnitudes in four centimeters.

The effect of low initial electron temperature is shown in the curve labeled (A). A value of $\beta k = 0.15$ is chosen to achieve an asymptotic electron density which is approximately 10% of the density at $x = 0$. Lowering the initial electron temperature effectively lengthens the scale for the recombination by freezing the electron density and consequently increases the severity of the shorting through the end region. For a well working large-scale nonequilibrium generator, the high electron temperature in the generator should shorten the recombination length scale to the point where the shorting is not serious.

From Fig. 2, it is evident that shock waves near the exit region must be avoided for high exit region impedance. The asymptotic state reached behind the shock wave may easily be determined from the electron energy balance. The ratio of asymptotic to initial electron temperature and hence density through the Saha equation, may be shown to depend on the flow (shock) Mach number, the ratio of generator electron temperature to stagnation temperature and the joule heating parameter, βk. The asymptotic to initial electron density ratio variation with these parameters is shown in Fig. 3. The severity of the shock in the exit region is clearly evident.

Recombination at a rate faster than for constant area flow may be achieved by one or both of the following flow channel area variations: diverging the extensions of the electrode walls to reduce the electric field in the exit section, or converging the extensions of the insulator walls to reduce the velocity of the flow and increase the density.

Rapid recombination may also be achieved if zero current flows through the exit section. With the wall layers present, this may be implemented through the use of a weak shock wave behind the last set of electrode pairs. With the magnetic field continued beyond the electrodes, the velocity (and magnetic field strength) behind the shock may be tailored such that the induced electric field in the exit section is just equal to the electric field in the generator. Since the difference in these electric fields gives rise to the current flow in the exit region, it may be made suitably small, to thus maximize the end region resistance. This shock wave is not strong enough to seriously degrade the performance of the MHD generator.

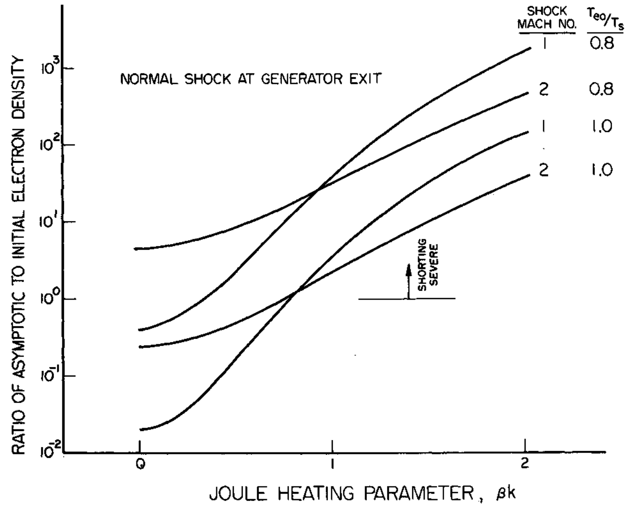

Fig. 3 Ratio of asymptotic to initial electron densities for flow with a shock at the generator exit.

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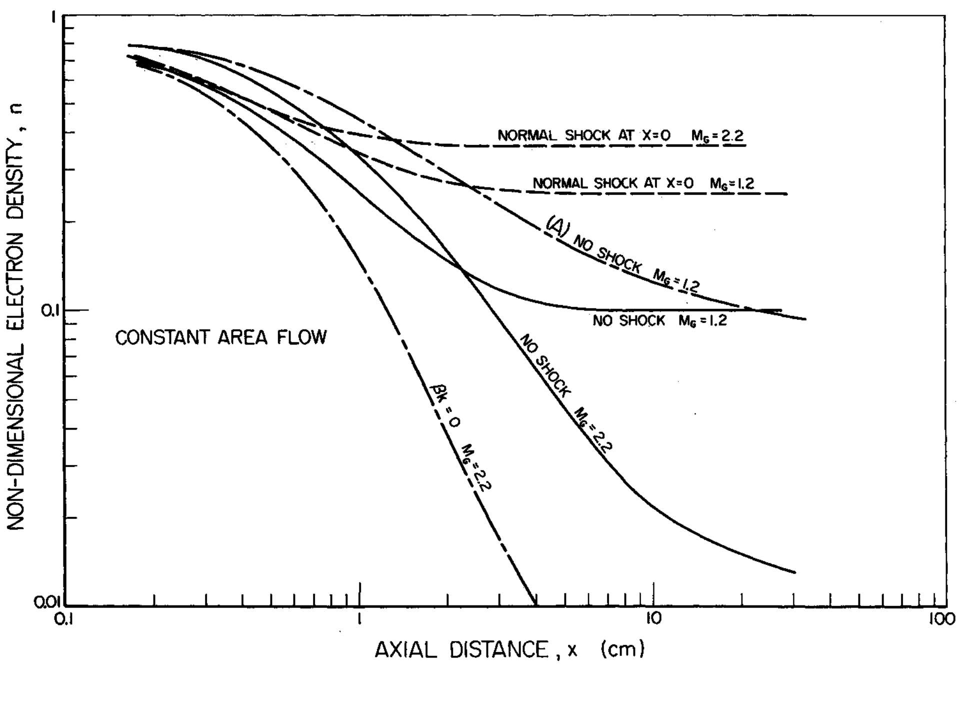

Fig. 2 Variation of the electron density in the exit region for isentropic and normal shock flow in a constant area exit section.