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ELECTRON HEATING IN HALL FIELDS OF M. P. D. GENERATORS

by

H. NEU

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Joint Nuclear Research Centre
Ispra Establishment

Paper presented at the
Symposium on Magnetoplasmadynamic Electric Power Generation
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In the paper presented, the conditions are investigated under which the electron temperature in a high velocity gas stream could be raised several times higher than the gas temperature by passing a MPD Channel. Using calculations of the electron energy distribution and the mean energy of the electrons it is found that a strong electron heating is possible only in a monoatomic gas when the ratio of magnetic field strength to gas pressure is so large that the electrons are

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gyrating around the magnetic field lines. In this case, the electric Hall field generated inside the MPD channel in the direction of the gas flow is much larger that the Lorentz field perpendicular to the flow.

The electron temperature elevation in a monoatomic gas flow has been calculated for a MPD generator with segmented electrodes and the "Hall Generator" type. It is found that, for the practically interesting cases, the electron temperatures are approximately proportional to the gas temperature, to the square of the Mach number of the flow and to the square of the quantity $\omega\tau$ (= electron cyclotron frequency times the mean collision time of the electrons). For example, in a MPD generator with segmented electrodes, a generator efficiency of 80 % and a Mach number 3 an electron temperature 5 times the gas temperature should be reached when $\omega\tau$ is about 5. This $\omega\tau$ figure is technically reasonable and it makes no difficulties to realize that. For a subsonic flow (Mach number little less than one) the same efficiency and electron temperature could be achieved only when $\omega\tau$ is greater than 15. This may be realized better with a Hall generator type.

With the strong heating of the electrons to a temperature several times the gas temperature it should be possible to ionize sufficiently a noble gas flow seeded with alkali vapor at gas temperatures down to some hundred °C.

If this could be realized experimentally, a real chance exists that a high temperature gas cooled fission reactor of the Dragon type is usefull for direct electrical power generation using the MPD generator principle.

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Electron heating in Hall fields of m.p.d. generators

H. Neu

Introduction

Commercial electric power generation directly from nuclear-fission heat using m.p.d. principles seems to be possible if the problem of non-thermal ionization can be solved. Several proposals for non-thermal ionization methods have been made and discussed[1,2,3]. These proposals are interesting only if the power supply for the ionization is no greater than a few per cent. of the generated power output. This condition is automatically satisfied if the generated electric field itself can be used for sufficient ionization[4]. In this case the electric power for the ionization is a part of the Joule dissipation.

The paper discusses the conditions for heating the electrons by the generated field inside the channel to temperatures several times the gas temperature, the electron energy distribution function, and the practical application of the heating effect.

Approximate Formulae for the Electron Distribution Function and the Mean Energy

It is assumed that the electric field E and the magnetic field B are perpendicular and in a steady state, that only elastic collisions between electrons and neutral atoms are significant, and that the neutral atoms have a Maxwellian distribution and a temperature T. According to Chapman and Cowling[5] and Wu[6] the isotropic part of the electron-velocity-distribution function is

$$f^{(0)}(v)$$
$$=A\exp\left\{-\int\frac{mv}{\frac{1}{3}m_a(e\lambda/mv)^2E^2[1+(e\lambda/mv)^2B^2]^{-1}+kT}\,dv\right\} \tag{1}$$

where m and m_a are, respectively, the masses of electrons and atoms, λ is the mean free path of electrons, which may be a function of the electron velocity v, and A is the integration constant.

The collision-time approximation.—The integration of eqn. 1 is very easy if the collision time $\lambda/v=\tau$ is assumed to be constant, so that

$$f^{(0)}=A\exp\left(-\frac{\frac{1}{2}mv^2}{\chi+kT}\right) \tag{2}$$

where
$$\chi=\frac{m_a/3(e\tau E/m)^2}{1+(e\tau B/m)^2}$$

In the constant collision time approximation the distribution function is Maxwellian with an electron temperature $T_e=T+\chi/k$. We assume that the electric field gives only a small perturbation of the isotropic distribution function f^0. Using the expressions

$$\left.\begin{aligned} eB/m&=\omega\\ \omega\tau&=\beta\end{aligned}\right\} \tag{3}$$

the mean electron energy can be calculated from eqn. 2:

$$\frac{1}{2}m\langle v^2\rangle=\frac{3}{2}kT_e=\frac{m_a}{2}\left(\frac{E}{B}\right)^2\frac{\beta^2}{1+\beta^2}+\frac{3}{2}kT \tag{4}$$

From the second approximation the drift velocity u is calculated[6] to be

$$u=\frac{E}{B}\frac{\beta}{\sqrt{(1+\beta^2)}} \tag{5}$$

For $\beta\ll 1$ the drift velocity is nearly $e\lambda E/(mv)$. This is equal to the drift in the absence of magnetic field. For $\beta\gg 1$, u is nearly E/B (eqn. 5), the well-known collision-free drift velocity; $\beta=2\pi$ corresponds 1 collision per gyration. Comparing eqns. 4 and 5 it is found that the elevation of the electron temperature is proportional to the kinetic energy of the electron drift.

The dependence of mean free path on electron velocity.—It can be shown that in most practical cases eqn. 4 is approximately valid also for varying $\lambda(v)$. Now τ is the collision time at the mean velocity $\langle v\rangle$, so that

$$\tau=(\lambda/v) \tag{6}$$

where $v=\langle v\rangle$.

Generally the velocity distribution is somewhat affected by the shape of $\lambda(v)$. However, from eqn. 1, the velocity distribution is nearly independent of $\lambda(v)$ in the velocity range $v\ll e\lambda B/m$. Using the definitions of eqns. 3 and 6, this means that the distribution is nearly Maxwellian in the range $v\gtrsim 2\langle v\rangle$. This may be interesting for strong magnetic fields ($\beta\gg 1$), when the distribution is important for the calculation of the excitation and ionization. In weak magnetic fields ($\beta\ll 1$) the distribution function is not Maxwellian, but falls more steeply, e.g. in the mean-free-path approximation ($\lambda=$ Constant) the distribution is of a Druyvesteyn type [$\propto\exp(-v^4)$].

Electron Temperature Elevation in Three Different m.p.d. Configurations

Three well-known configurations are investigated: continuous electrodes with transverse power extraction, segmented electrodes with transverse power extraction, and the Hall generator[7] with axial power extraction. The flow is in the x-direction and the magnetic field in the y-direction.

In Table 1 the electric fields are given, as obtained from m.p.d. theory[8]. α is the load factor and v_p the flow velocity: the generator efficiency η is defined by $\eta=EJ/v_pJ_zB$, where J is the load current density and J_z the current density transverse to the flow. The relative electron temperature elevation $(T_e-T)/T$, is calculated by eqn. 4 using the relation $v_p=M(\gamma kT/m_a)^{1/2}$, where M and γ are the Mach number and the ratio of the specific heats, respectively.

It is seen from eqns. 7–9 that the elevation of the electron temperature is small for $\beta<1$, if high generator efficiencies η are desired. Therefore the generator with continuous electrodes is not very useful. Much more promising are the configurations in which a Hall field can develop. In Figs. 1 and 2, eqns. 8 and 9 are demonstrated for $\gamma=5/3$ (monatomic gases). For $\beta\leqslant 5$ the segmented-electrodes generator only is

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