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DETERMINATION OF THE NUCLEAR-INDUCED ELECTRICAL CONDUCTIVITY IN A NUCLEAR-DRIVEN MHD DEVICE

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Abstract

The continual need for more efficient energy conversion techniques for space, sea, and terrestrial systems has renewed interest in nuclear-driven magnetohydrodynamic (MHD) energy conversion. The concept of nuclear-driven MHD energy conversion utilizes a flow seeded with a neutron absorbing species. The energy released in neutron absorption or fission processes is used to ionize the flow and enhance electrical conductivity. Research into the use of $^3He/^4He$ mixtures in the 1960's and 1970's suggested the enhancement is insufficient for MHD purposes. However, new calculations suggest a region of conditions not previously considered may provide significant conductivity enhancement. Specifically, at densities less than standard atmospheric density and neutron flux greater than $1x10^{12}$ /cm^{2}s, conductivity greater than 10 mho/m may be achievable. These calculations also suggest conductivity's of several hundred mho/m may be possible for an achievable range of conditions. Additionally, the nuclear-induced conductivity is strongly density dependent and weakly temperature dependent. Therefore, higher flow velocities, and hence higher power densities than those used in traditional MHD channels utilizing thermal ionization are possible. In order to confirm these promising calculations, a series of experiments has been proposed.

Introduction

The power density of a typical magnetohydrodynamic (MHD) generator is linearly proportional to the electrical conductivity and quadratically proportional to the flow velocity. Therefore, increasing the conductivity and velocity results in a more compact, and hence less costly system.

MHD energy conversion concepts have traditionally utilized thermal ionization processes to enhance the electrical conductivity of the flow. Since the expansion process used to accelerate the flow as it enters the MHD channel results in a decrease in static temperature, an optimum Mach number exists which balances the reduction in conductivity and increase in flow velocity associated with lowering the static temperature. As a result, the generator power density is limited by the temperature dependence of the ionization process.

In order to reduce the effect of the static temperature on the power density, nonthermal ionization processes have been considered. The process of interest here is nuclear-induced ionization, also referred to as neutron-induced ionization. This process utilizes the interaction between the neutron flux of a nuclear reactor and a neutron absorbing species in the MHD flow to enhance the electrical conductivity. The neutron absorption process results in the production of high energy ionized nuclear fragments. The kinetic energy of these fragments is transferred to the flow through collisions with the bulk constituent atoms which results in excitation and ionization processes. Since the ionization process is not based on thermal collision processes, the static temperature of the flow is not as significant.

One such flow consists of a mixture of ^3He and ^4He. The ^3He interacts with the neutron flux through the $^3He(n,p)T$ interaction. The proton and triton produced in the interaction have approximately 760 keV kinetic energy. Transfer of this energy to the bulk fluid produces on the order of 10^4 ionization's per (n,p) reaction. As a result, a population of free electrons forms which enhances the electrical conductivity.

The concept of nuclear-driven MHD energy conversion using a $^3He/^4He$ flow was

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first experimentally studied by a group lead by J. Braun[1] at AB Atomenergi (ABA) in Sweden from the mid-1960's to the 1970's. This research considered ^3He with a temperature ranging from 300 K to 1600 K and density ranging from 1/4 to 1 times standard atmospheric density[2,3]. The maximum neutron flux considered was 10^{11} /cm^{2}s. Based on the measurement of the electrical conductivity for this limited range of conditions, the investigators concluded the nuclear-induced conductivity enhancement in pure ^3He was insufficient to be valuable for MHD energy conversion. The AB Atomenergi research remains to date the most extensive experimental study of conductivity enhancement in ^3He by neutron interaction.

Shortly after the work at AB Atomenergi began, a group at the University of Florida lead by W. Ellis began similar work which has continued sporadically to date with similar results[4]. A second group[5] at the University of Florida associated with the Innovative Nuclear Space Power and Propulsion Institute (INSPI) began related studies in the 1980's.

The conclusion of the AB Atomenergi work and the similar results of the other related projects would seem to discourage further study of the concept, however, new calculations show there exists a region of thermodynamic and neutron flux conditions which may result in significant conductivity enhancement. This paper reports on the results of these calculations and describes a set of experiments being proposed to confirm the results. First, the kinetic and conductivity models used for the calculations are described. Next, the results of these calculations are discussed including implications for MHD generator and nuclear cycle design. Finally, a proposed set of experiments aimed at confirming these results is described.

The Kinetic and Conductivity Models

In order to determine the expected degree of nuclear-induced conductivity enhancement in $^3He/^4He$ mixtures, a model of the processes involved is necessary. The model developed here is based on work in related areas of research including afterglow kinetics, nuclear-pumped laser kinetics, and other nuclear-induced ionization studies. Two investigations are of particular importance, the helium afterglow kinetic model developed by Deloche, et al.[6], and the two temperature model of nuclear-induced ionization in helium developed by Watanabe, et al.[5]

The model described here consists of two primary components, the kinetic model which describes the behavior of the species densities, and the conductivity model which uses the results of the kinetic model to calculate the electrical conductivity. The model makes several assumptions. First, the free electron temperature is assumed greater than or equal to the bulk temperature and the ion temperatures are assumed equal to the temperature of the bulk gas. Second, charge neutrality is assumed. Third, diffusion processes are assumed to be ambipolar. Fourth, the bulk density of the ^3He and ^4He is assumed constant. Fifth, the degree of ionization is assumed approximately less than 10^{-3}. Sixth, only atomic and diatomic helium species are considered. These assumptions are consistent with previous analyses[5,6] and should be valid for the range of conditions considered here.

The Kinetic Model

The kinetic model consists of a set of six nonlinear differential equations which describe the time rate of change of the particle density of He^+, He_2^+, He^*, He_2^*, and e, and the time rate of change of the electron temperature. The superscript asterisk denotes a neutral species in an excited state. Though many excited states are possible, this model includes all states in one density expression for a given species. The six model equations are very similar to those derived by Deloche, et al.[6], and Watanabe, et al.[5]

The processes included in the model are: primary collisions with nuclear fragments,

$$He + nf \rightarrow He^+ + e + nf \qquad (1)$$

$$He + nf \rightarrow He^* + nf \qquad (2)$$

atomic ion radiative, electron-assisted three body, and neutral-assisted three body recombination to the ground state,

$$He^+ + e \rightarrow He + h\nu \qquad (3)$$

$$He^+ + e + e \rightarrow He + e \qquad (4)$$

$$He^+ + e + He \rightarrow He + He \qquad (5)$$

and to an excited state,

$$He^+ + e \rightarrow He^* + h\nu \qquad (6)$$

$$He^+ + e + e \rightarrow He^* + e \qquad (7)$$

$$He^{+} + e + He \rightarrow He^{*} + He \quad (8)$$

molecular ion radiative, dissociative, electron-assisted three body, and neutral-assisted three body recombination,

$$He_2^{+} + e \rightarrow He_2^{*} + h\nu \quad (9)$$

$$He_2^{+} + e \Leftrightarrow He^{*} + He \quad (10)$$

$$He_2^{+} + e + e \rightarrow He_2^{*} + e \quad (11)$$

$$He_2^{+} + e + He \rightarrow He_2^{*} + He \quad (12)$$

atomic conversion,

$$He^{+} + He + He \rightarrow He_2^{+} + He \quad (13)$$

$$He^{*} + He + He \rightarrow He_2^{*} + He \quad (14)$$

metastable collisions,

$$He^{*} + He^{*} \rightarrow He^{+} + He + e \quad (15)$$

$$He^{*} + He^{*} \rightarrow He_2^{+} + e \quad (16)$$

$$He_2^{*} + He_2^{*} \rightarrow He^{+} + 3He + e \quad (17)$$

$$He_2^{*} + He_2^{*} \rightarrow He_2^{+} + 2He + e \quad (18)$$

$$He^{*} + He_2^{*} \rightarrow He^{+} + 2He + e \quad (19)$$

$$He^{*} + He_2^{*} \rightarrow He_2^{+} + He + e \quad (20)$$

and superelastic collisions,

$$He^{*} + e \rightarrow He + e \quad (21)$$

$$He_2^{*} + e \rightarrow 2He + e \quad (22)$$

Each interaction has an associated term in the model equations which includes a rate coefficient. The values used for the rate coefficients and associated data are those found in previous analyses, especially the analysis of Deloche, et al.[6] These values have been used extensively for a wide range of parameters with fairly good results.

In addition to interactions between species in the gas, the effects of external influences are also included in the model equations. The most significant effect is the ionization source term resulting from the ^{3}He(n,p)T interaction. The source term is included in the model equations, specifically the rate equations for He^+ and He^*, through the terms for the primary collision processes, (1) and (2).

A second external influence consistent with MHD energy conversion is the effect on electron temperature due to Joule heating. The energy input to the free electron population from Joule heating has been shown to be beneficial to the enhancement of the electrical conductivity[7]. Therefore, the electron temperature equation includes an appropriate term. However, all calculations discussed in this report are for a static volume of gas with no external fields, therefore, these calculations do not reflect any effects associated with Joule heating.

The Conductivity Model

Once the species densities have been calculated, the electrical conductivity can be calculated. The model of electrical conductivity used here is based on the model proposed by Lin, et al.[8] The conductivity is assumed to consist of two components. The first component is associated with collisions between electrons and neutral species. The second component is associated with collisions between electrons and ions. Each of these components represents a resistance to the flow of electron current similar to a circuit composed of resistors in series. As with the circuit analysis, the total resistance is the sum of the individual resistance's. In terms of the components of the conductivity, the total conductivity can be written

$$\frac{1}{\sigma_e} = \sum \frac{1}{\sigma_{e0}} + \sum \frac{1}{\sigma_{ei}} \quad (23)$$

where σ_{e0} is the conductivity associated with electron-neutral collisions and σ_{ei} is the conductivity associated with the electron-ion collisions. The summations are included because each neutral and ion species effects the conductivity separately.

The electron-neutral conductivity can be calculated using a rigid sphere approximation. Based on the model of conductivity for a weakly ionized plasma discussed by Chapman and Cowling[9], the electron-neutral conductivity term is

$$\sigma_{e0} = \frac{3}{8}\sqrt{\frac{\pi}{2}}\frac{n_e}{n_X}\frac{e^2}{(mkT_e)^{1/2}(4\pi\varepsilon_0)Q_{ex}} \quad (24)$$

where n_e and n_X are the electron and neutral particle density, respectively, e is the electron charge, m is the electron mass, k is Boltzmann's constant, T_e is the electron temperature, ε_0 is the permittivity of free space, and Q_{ex} is the electron-neutral collision cross section.

The electron-ion conductivity term can be calculate from the expression for a fully ionized gas developed by Spitzer, et al.[10]

$$\sigma_{ei} = 2\gamma\left(\frac{2}{\pi}\right)^{1/2}\frac{(4\pi\varepsilon_0)^2(kT_e)^{3/2}}{m^{1/2}e^2\ln\Lambda} \quad (25)$$

where

$$\Lambda = \frac{12\pi(\varepsilon_0 kT_e)^{3/2}}{n_e^{1/2}e^3} \quad (26)$$

and γ is a coefficient which describes the deviation of the real gas from a Lorentz gas.

This expression is applicable to a plasma consisting of singly charged ions which is consistent with the present analysis.

Computer Code

The six kinetic model equations are solved for the steady state condition by a computer code, CSOLVE. This code is based on the code PCD developed by Watanabe, et al.[5] The code divides the problem of solving the kinetic model equations into two steps. First the five particle density equations are solved simultaneously by the Newton-Raphson method. Second, the electron temperature equation is solved by the bisection method using the calculated particle densities. The new electron temperature is used to recalculate the five particle densities. This iterative procedure is repeated until the calculated densities and temperature converge within a specified accuracy. The densities and electron temperature calculated from the kinetic model are used to calculate the electrical conductivity using (23), (24), (25), and (26). The output of CSOLVE includes a table of values for the five particle densities, electron temperature, and electrical conductivity as a function of neutron flux.

The accuracy of the code was checked by comparing calculated values with the results of the experiments of Braun, et al.[2,3], and Ellis, et al.[4] Comparison between the calculated values and the experimental data was reasonable. The accuracy of the code will be further evaluated by comparison with the results of the experiments described below.

Model Predictions

Once the accuracy of the code was established, a series of calculations were performed to predict the behavior of the conductivity of pure ^{3}He over a broader range of conditions than previously considered. Specifically, the gas temperature was varied from 300 K to 2500 K, the gas pressure was varied from 1×10^{-4} atm to 416 atm, and the neutron flux was varied from 1×10^{10} /cm^{2}s to 1×10^{16} /cm^{2}s.

Figure 1 shows the calculated conductivity as a function of gas density. The gas density is represented by a relative density, n^*, which is defined by

$$n^* = 300\frac{p(atm)}{T_g(K)} \qquad (27)$$

or

$$n(1/cm^3) = 2.45\times10^{19}n^* \qquad (28)$$

so n^* equal to unity is standard atmospheric density. The solid lines connecting data points correspond to a gas temperature of 1500 K at a given neutron flux. The individual points show the range of values of the conductivity for the range of gas temperatures considered at the given neutron flux.

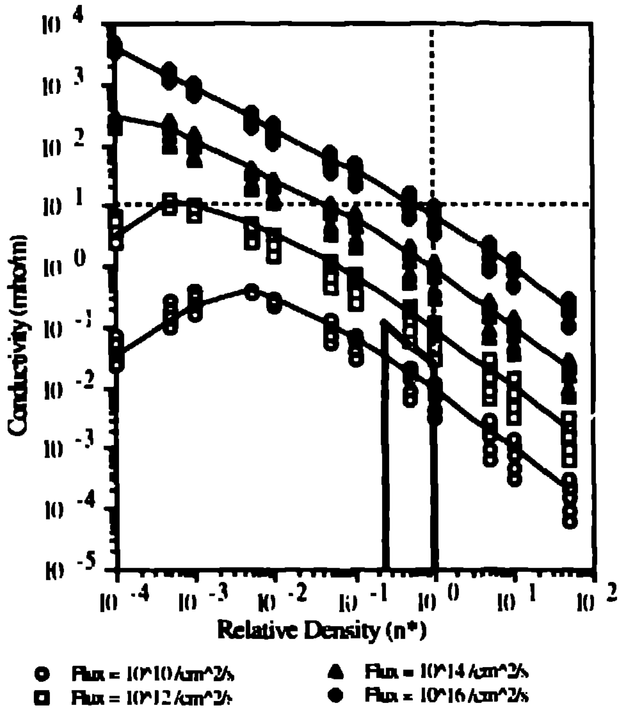

Figure 1. Electrical conductivity versus relative density for pure ^{3}He. Solid lines correspond to a gas temperature of 1500 K. Heavy lines show the limits of AHA experiments.

Figure 2 shows the predicted variation in conductivity as a function of gas temperature for a neutron flux of 1×10^{10} /cm^{2}s. Again, the calculated conductivity is plotted versus relative density. The solid lines show the behavior of the conductivity for a given gas temperature. Similar behavior is found for all values of neutron flux considered.

Notice the strong density dependence of the nuclear-induced conductivity. The conductivity has a region of maximum value corresponding to a small range of density for a given neutron flux. This maximum is the result of a balance between the rate of ionization and the rate of recombination. At densities below the maximum, the rate of ionization is insufficient to maintain the conductivity. At densities greater than the maximum, the rate of recombination overwhelms the rate of ionization

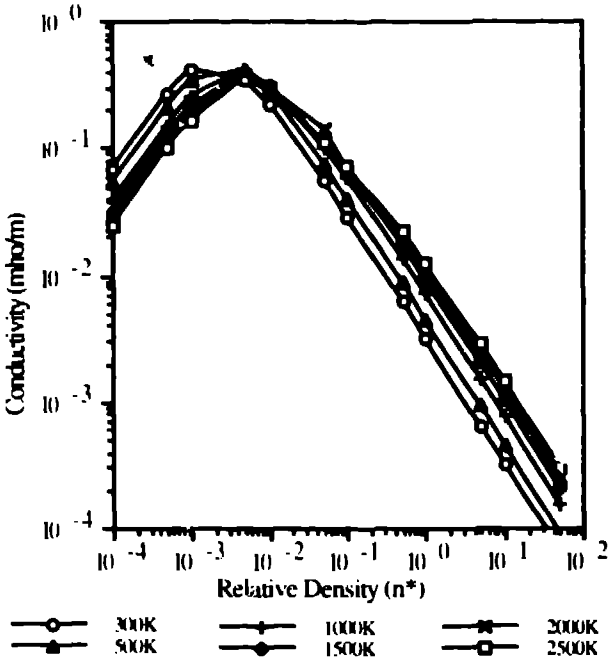

Figure 2. Electrical conductivity versus relative density for pure ^{3}He as a function of gas temperature with an applied neutron flux of 1×10^{10} /cm^{2}s.

As expected, the temperature dependence of the conductivity is weak. As the density approaches the corresponding maximum in conductivity, the temperature dependence becomes weaker. Notice the maximum conductivity for a given neutron flux is approximately independent of gas temperature as shown in Figure 2.

A particularly interesting behavior of the conductivity is the pivot in the temperature dependence around the maximum in conductivity. At densities below the maximum, the lower temperatures are predicted to result in higher conductivity. At higher densities, the higher temperatures result in higher conductivity.

A typical minimum level of conductivity useful for MHD energy conversion is 10 mho/m as represented by the horizontal line overlaid on Figure 1. The minimum neutron flux necessary to achieve this level of conductivity is 1×10^{12} /cm^{2}s. Since the upper limit in the thermal neutron flux for conceivable reactor designs is approximately 1×10^{17} /cm^{2}s, the vertical line at a relative density of 1 represents the maximum density likely to be useful for MHD energy conversion.

The region of parameters considered in the ABA experiments are shown by heavy lines in Figure 1. Comparing this region with the region of conditions considered useful for MHD energy conversion, the conclusions of the earlier work are understandable. For the conditions in the upper left quadrant in Figure 1, very high levels of conductivity seem possible, even compared to those achievable using typical thermal ionization processes.

For a given neutron flux and density, a similar enhancement in conductivity can be realized within an order of magnitude, over the entire range of temperatures considered in these calculations. This behavior is very different from the temperature-dominated behavior of thermally-induced conductivity. As a result, lower static temperatures, and hence higher flow velocities, are acceptable corresponding to a higher power density. Though there still exists an optimum expansion for a given neutron flux, the corresponding flow velocity is greater than those typical in systems using thermal ionization. Due to the minimization of the temperature dependence of the conductivity enhancement, significant improvement in the limitations in power density are possible compared to traditional MHD generators using thermal ionization.

Proposed Experiments

In order to confirm the results predicted by the model calculations, a set of experiments is being designed to measure the electrical conductivity of ^{3}He over a wide range of conditions. Specifically, the gas temperature will range from 300 K to 1500 K, the gas density will range from 1×10^{-4} to 1 standard atmospheric density, and the neutron flux will range from 0 to 1×10^{16} /cm^{2}s. In addition to confirming the predicted results, these experiments will also provide a qualitative measure of the accuracy of the model discussed above.

The behavior of the conductivity will be measured both directly and indirectly. A conductivity probe similar to that used in the AB Atomenergi research will be used to measure the conductivity directly using the principals of Ohm's law[4]. The electron density and temperature will also be measured using a combination of Langmuir probe and laser interferometry techniques.

The electron population and temperature measurements will provide an indirect means of determining the conductivity. The electron measurements will be used for comparison with the conductivity measurements and the model calculations.

The experimental apparatus and associated instrumentation is planned to be built and tested at Los Alamos National Laboratory. The experiments are planned to be carried out at the Penn State Breazeale Reactor facility.

Conclusions

The described calculation of the conductivity of pure ^{3}He over a broad range of conditions has motivated further study of the use of nuclear-induced conductivity in MHD energy conversion schemes. Due to the weak temperature dependence of the nuclear-induced conductivity, higher power densities seem achievable which would result in more compact, less expensive MHD generators. Also, the achievable level of conductivity is predicted to be comparable to or better than that possible with traditional thermal ionization processes. Combined with the advantage of an inert MHD flow, nuclear-driven MHD cycles using ^{3}He flows may have significant advantages over traditional MHD cycles using thermal ionization. These advantages include more compact generators for a given output power, simpler flow handling systems, longer lifetime, and lower cost.

As a result of these motivating factors, a series of experiments have been proposed to measure the actual nuclear-induced conductivity enhancement in pure ^{3}He. The results of these experiments will provide a baseline of information which will give direction to further analysis.

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