Annals of Nuclear Energy 114 (2018) 325–328

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Magnetic variation and power density of gravity driven liquid metal magnetohydrodynamic generators

Drew Ryan [a,*], Corey Loescher [a], Ian Hamilton [b], Robert Bean [a], Adam Dix [a]

[a] Purdue University, West Lafayette, IN 47907, United States
[b] Atlas Energy Systems, LLC, United States

ARTICLE INFO

Article history:
Received 7 August 2017
Received in revised form 10 December 2017
Accepted 15 December 2017
Available online 26 December 2017

Keywords:
Magnetohydrodynamics (MHD)
Liquid metal fast reactors
Electric power generation
Power optimization

ABSTRACT

Magnetohydrodynamics (MHD) is the study of electrically conducting fluids flowing through applied magnetic fields. MHD can be applied in power generation to produce electricity with no moving mechanical parts. By not using mechanical parts, MHD generators may potentially produce electricity with low capital costs. This form of electrical generation can be paired with advanced nuclear reactors to make the reactors more economically competitive. This paper studies a vertical gravity driven MHD generator system, specifically maximizing the electrical power density output. For an MHD system, there will be a specific magnetic field that, when applied, will produce a maximum power density for the system.

1. Introduction

Magnetohydrodynamics (or MHD) is the study of the effects of magnetic fields on electrically conductive fluids. There are numerous fields within MHD, including applications in geophysics, and propulsion (Angrist and Angrist, 1982); however the interest of this paper lies in MHD energy conversion. MHD energy conversion is most notable because it requires no moving parts aside from the flow of an electrically conductive fluid, such as the liquid metal coolant for a nuclear reactor.

MHD energy conversion has been studied and applied to numerous power systems. The first major studies of MHD generators utilized them as topping cycles for coal and gas plants (Decher, 1994). By ionizing the flue gas into plasma, the flow of the flue gas turned plasma could be utilized in an MHD generator to create power. These designs had several problems. Most notably that utilizing plasmas required large magnetic fields, which were, and still are, expensive and energy intensive to produce (Messerle, 1995). Later incarnations of MHD generators were applied to liquid metals for the blankets of fusion reactors, with a major concern being how to reconcile the large pressure drop within the MHD generator and gravity, which are often in perpendicular directions, with the desired flow in the blanket (Wang et al., 2002). Despite the breadth of literature in the field, there is little recent work on coupling MHD technology with modern nuclear reactor designs.

Liquid metal cooled nuclear reactors can utilize MHD energy conversion as a primary loop power generator. Utilizing an MHD generator could have several marked advantages for Gen IV reactors. MHD generators require no moving mechanical parts (Decher, 1997), and as a result can operate at a wide temperature range. When coupled with a natural convection reactor, a nuclear reactor can theoretically operate with no moving parts.

This paper analyzes the power density of a gravity driven single phase MHD generator system for a liquid metal cooled fast reactor. An optimization of the power density as a function of the applied magnetic field was performed under idealized conditions for a gravity driven flow. Conclusions were drawn on the maximization of any driven MHD systems and applications for nuclear power generation. No prior research was found that focused on optimizing MHD generators with respect to the applied magnetic field.

2. System description

The system under consideration for this analysis is a simple MHD generator system attached to a liquid metal fast reactor utilizing natural convection. The working fluid for this study is liquid lead, and was chosen because of its wide range of operating temperatures and availability of its thermodynamic and electromagnetic properties (Sobolev, 2011).

The liquid lead flows downward at atmospheric pressure through a vertical, rectangular duct with two opposing sides made of insulating material, and the other two opposing sides being continuous electrodes. The magnetic field is applied perpendicular to

* Corresponding author.
E-mail address: ryan103@purdue.edu (D. Ryan).

https://doi.org/10.1016/j.anucene.2017.12.047
0306-4549/

the flow through the insulating walls of the duct, as can be seen in Fig. 1. The liquid lead leaves the MHD generator at a temperature of 500 °C to re-enter the core, but this paper focuses solely on the MHD generator system and its power generation.

3. Theory and calculation

The two major underlying principles of any MHD system are electromagnetism and fluid dynamics. In analyzing any reactor, a common metric of comparison is the power density of the system. To do so, one must analyze both the electromagnetic and fluid components of the system, including a force balance on the fluid. There are three primary forces acting on the lead coolant: the induced Lorentz Force, gravity, and the friction force. The induced Lorentz Force is based in the underlying electromagnetism of an MHD generator, and this force can be easily determined.

The governing principle of the electromagnetics of MHD systems is the Hall Effect. If a moving charge, such as an electron in a conductive fluid, is present in a magnetic field, a force perpendicular to both the motion and the magnetic field will act on the moving charge. This force acts on the moving charges in the fluid and is responsible for generating an electric field in the fluid. The electric field of the fluid can be expressed as a function of the fluid velocity and the applied magnetic field.

$$\boldsymbol{E_{ind}} = \boldsymbol{v} \times \boldsymbol{B_{app}} \tag{1}$$

where $\boldsymbol{E_{ind}}$ is the electric field (V/m), $\boldsymbol{v}$ is the velocity of the fluid (m/s), and $\boldsymbol{B_{app}}$ is the applied magnetic field (T). The electric field is generated by the motion of the electric charges within the fluid. The motion of these charges is the induced current within the fluid, and the induced current density in the fluid is proportional to the induced electric field.

$$\boldsymbol{J_{ind}} = \sigma \boldsymbol{E_{ind}} \tag{2}$$

where $\boldsymbol{J}$ is the current density (A/m^2) and σ is the electrical conductivity of the fluid (S/m). The induced current in the fluid is also affected by the applied magnetic field, which creates the Lorentz Force. This Lorentz Force is a volumetric force acting in the direction antiparallel to the flow. The Lorentz Force can be expressed as a function of the induced current density and the magnetic field; or more fundamentally as a function of the conductivity the fluid velocity, and the magnetic field.

$$\boldsymbol{F_L} = \boldsymbol{J_{ind}} \times \boldsymbol{B_{app}} \tag{3}$$

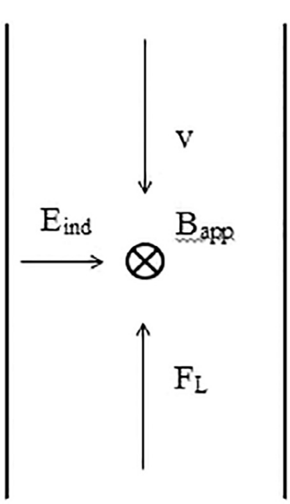

Fig. 1. A simple representation of the MHD duct. The direction of the conducting fluid flow, applied magnetic field, induced electric field, and induced Lorentz force are shown.

$$\boldsymbol{F_L} = \sigma((\boldsymbol{v} \times \boldsymbol{B_{app}}) \times \boldsymbol{B_{app}}) \tag{4}$$

where F_L is the induced Lorentz Force (N/m^3). With this basic information, it is important to keep in mind that the primary goal of this analysis is to maximize the power density of these systems. One can use the information on the current density and the induced electric fields to determine the power density relationship. The power density of the system is the product of the induced current density and the induced electric field.

$$P = \boldsymbol{J} \cdot \boldsymbol{E_{ind}} \tag{5}$$

where P is the power density (W/m^3). Combining equations (1) and (2) yields the following.

$$P = \sigma \boldsymbol{v}^2 \boldsymbol{B}_{app}^2 \tag{6}$$

With the relationship for the power density given in Eq. (6), it is clear that the power density on the generator is a function of the velocity of the fluid in the system. To determine that, it is important to study the fluid dynamics operating in the MHD generator.

The principles of fluid dynamics for an MHD system are markedly complex, with all the standard difficulties of fluid dynamics, but with the additional complexities of electromagnetism added. In this analysis, a volumetric force balance of the fluid will be used.

The force of gravity is the simplest force acting on the fluid. However, since this MHD generator is being applied to a reactor utilizing natural convection, the buoyancy force must be accounted for. For a downward gravity-driven system, a common method to account for the buoyancy force is with the Boussinesq Approximation (Blums et al., 1987). In the force balance, the volumetric force of gravity acting on the fluid will also account for the changes in density in the system.

$$F_g = \rho g(1 - \alpha T) \tag{7}$$

where F_g is the volumetric force of gravity (N/m^3), ρ is the density of the fluid (kg/m^3), g is the acceleration due to gravity (m/s^2), α is the coefficient of thermal expansion for the fluid (K^{-1}), and ΔT is the change in temperature (K). There are two forces countering the motion of the fluid: the induced Lorentz Force which was already derived and the frictional force of the lead along the walls of the chamber. For this analysis, the frictional force is approximated using the Darcy–Weisbach equation (Pritchard and Mitchell, 2015).

$$F_f = f_D \frac{\rho v^2}{2D} \tag{8}$$

F_f is the friction force (N/m^3), f_D is the Darcy friction factor, and D is the hydraulic diameter of the duct (m). The Darcy friction factor is determined from the Moody Charts (Pritchard and Mitchell, 2015). Although the velocity of the fluid is not currently known at this step in the analysis, the Reynolds number for this flow is controlled primarily by the density and viscosity of the lead. Since the velocity will not change by orders of magnitude based on the friction factor, a reasonable approximation for the friction factor was determined after several iterations.

The three volumetric forces acting on the fluid are the Lorentz Force, the gravity force, and the friction force. These can be arranged in a force balance to create a differential equation for the average velocity of the fluid.

$$\rho \frac{d\boldsymbol{v}}{dt} = -\rho \boldsymbol{g}(1 - \alpha\Delta T) + \sigma \boldsymbol{v} \boldsymbol{B}^2 + f_D \frac{\rho \boldsymbol{v}^2}{2D} \tag{9}$$

This force balance is based on the fluid system described in Section 2, with an upward positive and the fluid flows in the negative direction. This differential equation can be solved to determine the behavior of the velocity of the fluid in the MHD generator.