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Original Article

Numerical analysis of the electromagnetic force for design optimization of a rectangular DC electromagnetic pump

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A R T I C L E I N F O

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A B S T R A C T

The force of a DC electromagnetic pump used to transport liquid lithium was analyzed to optimize its geometrical and electrical parameters by numerical simulation. In a heavy-ion accelerator, which is being developed in Korea, a liquid lithium film is utilized for its high charge-stripping efficiency for heavy ions of uranium. A DC electromagnetic pump with a flow rate of 6 cm^3/s and a developed pressure of 1.5 MPa at a temperature of 200°C was required to circulate the liquid lithium to form liquid lithium films. The current and magnetic flux densities in the flow gap, where a Sm_2Co_{17} permanent magnet was used to generate a magnetic field, were analyzed for the electromagnetic force distribution generated in the pump. The pressure developed by the Lorentz force on the electromagnetic force was calculated by considering the electromotive force and hydraulic pressure drop in the narrow flow channel. The opposite force at the end part due to the magnetic flux density in the opposite direction depended on the pump geometrical parameters such as the pump duct length and width that defines the rectangular channels in the nonhomogeneous distributions of the current and magnetic fields.

1. Introduction

Electromagnetic pumps are employed to circulate liquid metals with high electrical conductivity using the Lorentz force whose value is calculated as the cross product of the current and the magnetic field perpendicular to it [1,2]. The heavy-ion accelerator, which is being developed in Korea, uses a liquid lithium film as a charge stripper [3] to increase the acceleration efficiency of uranium heavy ions. The uranium ions with a charge of 33+ become uranium ions with a charge of 78+, which pass through a liquid lithium film with a thickness of less than 25 μm. The DC electromagnetic pump causes the liquid lithium to circulate to generate thin liquid lithium films from a high-speed jet of 60 m/s at the injection nozzle of the charge-stripper system, which is subjected to a high hydraulic pressure loss at a low flow rate [4].

In the present study, the distributions of the current [5] and magnetic flux densities in the narrow channel of such pump with a finite-length permanent magnet were analyzed [6]. The developed pressure, which depends on the Lorentz force and hydraulic pressure drop, was analyzed by numerical simulation using the ANSYS code. Analyses were performed on the changes in the geometrical and electrical parameters by considering the distributions of the current and magnetic flux densities for the required pressure and flow rate [7]. The geometrical and electromagnetic parameters of the pump were optimized to satisfy the requirement of a developed pressure of 1.5 MPa and flow rate of 6 cm^3/s under an operating temperature of 200°C.

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2. Mathematical setup for analysis

The DC electromagnetic pump was divided into three parts, namely an electrode stub that transports current to the liquid metal, permanent magnets with a thickness of 50 mm to generate the magnetic flux for the liquid metal, and a 1-mm-thick pump duct [8], as shown in Fig. 1. The electrode stub and permanent magnets are arranged in the x and z directions, respectively, by applying the Cartesian coordinate system to the rectangular pump shown in Fig. 1 [9,10]. Liquid lithium flows along the y direction because of the developed pressure from the Lorentz force, which was generated by the vector product of the current through the electrode stub in the x direction and the magnetic field B from the permanent magnets in the z direction [11]. The governing equations, which consist of magnetohydrodynamic equations, to solve the force generated in the DC electromagnetic pump are expressed in Equations (1)–(5). This set of equations was solved using the ANSYS code to determine the magnetic field and current density.

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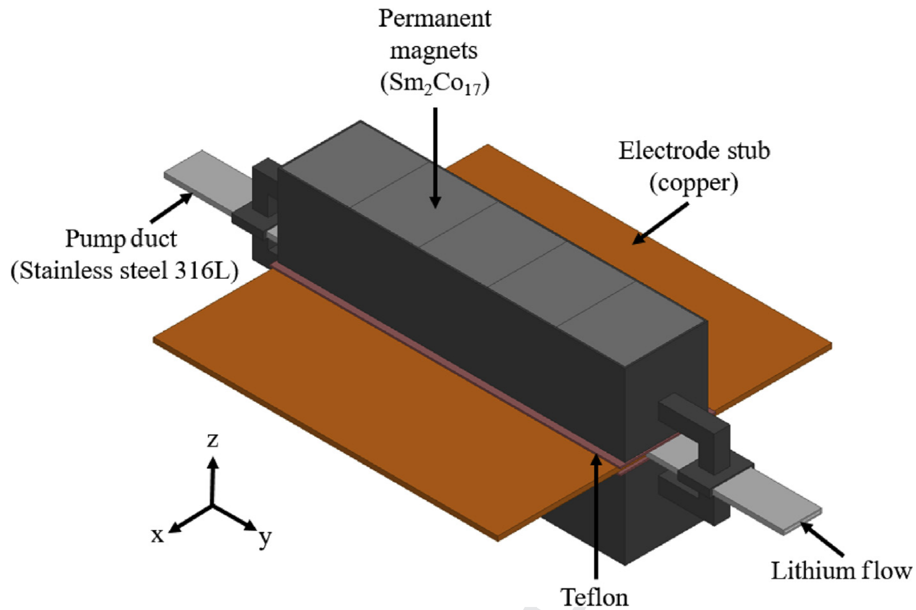

Fig. 1. Schematic of the DC electromagnetic pump.

The Maxwell equations were applied to solve the induced magnetic flux density, and Ohm's law was used to calculate the current density. The force and pressure drop of the DC electromagnetic pump were calculated using the Navier–Stokes equation, where the electromagnetic force $J \times B$ was added to the last term in Equation (5) as an external force [12].

$$\text{Ampere's law: } \nabla \times \vec{\mathrm{B}} = \mu_0\left(\vec{J} + \varepsilon_0\frac{\partial E}{\partial t}\right) \tag{1}$$

$$\text{Faraday's law: } \nabla \times \vec{\mathrm{E}} = -\frac{\partial \vec{\mathrm{B}}}{\partial \mathrm{t}} \tag{2}$$

$$\text{Gauss's law for magnetism: } \nabla \cdot \vec{\mathrm{B}} = 0 \tag{3}$$

$$\text{Ohm's law}: \vec{\mathrm{J}} = \sigma\left(\vec{\mathrm{E}} + \vec{\mathrm{V}} \times \vec{\mathrm{B}}\right) \tag{4}$$

$$\text{Navier} - \text{Stokes equation}: \frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} = -\frac{1}{\rho}\nabla\left(\vec{p} + \vec{p_h}\right) + \nu\nabla^2\vec{v} + \frac{1}{\rho}\vec{J_t} \times \vec{B} \tag{5}$$

The components of the electric field, current density, magnetic flux density, and velocity of fluid are expressed in Equations (6)–(11) according to the Cartesian coordinate system. The z-direction electric field of the DC electromagnetic pump was disregarded because of the nonconductive material (Teflon) between the permanent magnet and pump duct to avoid a z-direction current from flowing to the permanent magnet and narrow the gap of the flow channel, as expressed in Equation (6). The permanent magnet creates a magnetic field because of its rotating electrons. The microscopically small circulating current in the permanent magnet was negligible in the analysis of the induced current. Therefore, the magnetic flux density was divided into an external magnetic flux density from the permanent magnet and the induced magnetic flux density from the current density to avoid confusion in the magnitude of the induced magnetic flux density according to Equation (8). The fluid velocity was only taken along the y direction owing to the laminar flow at the low Reynolds number according to Equation (11).

$$\vec{E}_t(x,y,z) = E_x\hat{x} + E_y\hat{y} \tag{6}$$

$$\vec{J}_t(x,y,z) = J_x\hat{x} + J_y\hat{y} + J_z\hat{z} \tag{7}$$

$$\vec{B}_t(x,y,z) = \vec{B}_e(x,y,z) + \vec{B}_i(x,y,z) \tag{8}$$

$$\vec{B}_e(x,y,z) = B_{e,x}\hat{x} + B_{e,y}\hat{y} + B_{e,z}\hat{z} \tag{9}$$

$$\vec{B}_i(x,y,z) = B_{i,x}\hat{x} + B_{i,y}\hat{y} + B_{i,z}\hat{z} \tag{10}$$

$$\vec{v}(x,y,z) = v_y\hat{y} \tag{11}$$

Ampere's law in Equation (1) can be expressed as Equations (12)–(15) using the curl operator calculation in the Cartesian coordinate system where the time-varying electric field term was not considered because the DC electromagnetic pump used the DC source. Only the induced magnetic flux density was affected by the current density because the external magnetic flux density was affected by the small circulating current in the permanent magnet.

$$\nabla \times \vec{\mathrm{B}}_{\mathrm{i}} = \mu_0\vec{J}_t \tag{12}$$

$$\nabla \times \vec{\mathrm{B}}_{\mathrm{i}} = \left(\frac{\partial \mathrm{B}_{\mathrm{i,z}}}{\partial y} - \frac{\partial \mathrm{B}_{\mathrm{i,y}}}{\partial z}\right)\hat{\mathrm{x}} + \left(\frac{\partial \mathrm{B}_{\mathrm{i,x}}}{\partial z} - \frac{\partial \mathrm{B}_{\mathrm{i,z}}}{\partial x}\right)\hat{\mathrm{y}} + \left(\frac{\partial \mathrm{B}_{\mathrm{i,y}}}{\partial x} - \frac{\partial \mathrm{B}_{\mathrm{i,x}}}{\partial y}\right)\hat{\mathrm{z}} \tag{13}$$

$$\mu_0\vec{J}_t = \mu_0\left(J_x\hat{x} + J_y\hat{y} + J_z\hat{z}\right) \tag{14}$$

$$\frac{\partial \mathrm{B}_{\mathrm{i,z}}}{\partial y} - \frac{\partial \mathrm{B}_{\mathrm{i,y}}}{\partial z} = \mu_0 J_x,\quad \frac{\partial \mathrm{B}_{\mathrm{i,x}}}{\partial z} - \frac{\partial \mathrm{B}_{\mathrm{i,z}}}{\partial x} = \mu_0 J_y,\quad \frac{\partial \mathrm{B}_{\mathrm{i,y}}}{\partial x} - \frac{\partial \mathrm{B}_{\mathrm{i,x}}}{\partial y} = \mu_0 J_z \tag{15}$$