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Magnetic-field analysis of an MHD channel in a liquid-metal circulation system of a prototype GenIV sodium fast reactor

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ABSTRACT

A helical-type direct current (DC) electromagnetic pump with a developed pressure of 10 kPa and flow rate of 0.005 m^3/s was analyzed at a temperature of 226 °C for an active decay heat-removal system (ADHRS) of a prototype GenIV sodium fast reactor. The rectangular-type DC electromagnetic pump, which was selected for the ADHRS, required a very large current (>1000 A). A helical-type DC electromagnetic pump was considered to provide multiple current to a pump duct to reduce the input current requirement. The magnetic flux density of a permanent magnet is one of the important factors that determine the performance of the electromagnetic pump. The magnetic field for the flow channel of the helical-type DC electromagnetic pump was analyzed in which a Sm_2Co_{17} permanent magnet was used to generate the Lorentz force for the circulation of liquid metal. The Lorentz force, which directly affected the developed pressure of the electromagnetic pump, was increased proportional to the magnetic flux density, which led to the increase in the velocity of the liquid metal in the flow channel. The permanent magnet in the +z and −z directions and the ferromagnetic material added in the r direction increased the magnitude of the magnetic flux density, which led the magnetic flux line to the flow channel. The arrangement of the permanent magnet system showed the optimized geometry of the inner ferromagnetic material with a radius of 110 mm and outer ferromagnetic material with a thickness of 30 mm and height of 70 mm. The average value of the magnetic flux density in the liquid-metal flow channel was 0.848 T under maximum condition by considering the mechanical and spatial restrictions.

1. Introduction

Electromagnetic pumps, instead of mechanical pumps, are used to circulate liquid metal owing to their advantages such as the absence of moving and sealing parts while eliminating the possibility of liquid-metal leak (Kim, 2014). A direct current (DC) electromagnetic pump was considered for an active decay heat-removal system (ADHRS) to transport liquid sodium to a prototype GenIV sodium fast reactor (PGSFR). When normal heat removal from the reactor is not possible, passive decay heat-removal system (PDRC) and ADHRS are used to remove residual heat from the reactor. ADHRS is operated under force convection condition, whereas PDRC is operated under natural convection condition. The ADHRS considers the electromagnetic pump driven by an electromagnetic force generated from the Lorentz force for the forced sodium circulation in the sodium loop, which contains a blower with a finned-tube sodium-to-air heat exchanger (FDHX), as shown in Fig. 1 (Lee, 2013). The helical-type DC electromagnetic pump is adopted to circulate liquid sodium with high electrical conductivity (Ohse, 1985; Baker, 1987) via an electromagnetic force (or Lorentz force) generated from the vector product of the current density and magnetic field (Nashine, 2007; Gutierrez, 1965). This process is adopted because the electromagnetic pump structure has no sealing part and an impeller, which can cause failure during the transportation of high-reactivity liquid sodium. In particular, the helical-type DC electromagnetic pump requires a low current compared with a rectangular-type one because it can obtain multiple current from the geometry of the pump duct. Magnetic flux density is one of the main factors that contribute to the generation of the pumping force from the Lorentz force and the induced electromotive force in the circular channel of the helical-type DC electromagnetic pump, which affects the specification of the flow rate and the developed pressure of the electromagnetic pump (Nashine, 2006; Blake, 1957). The magnetic flux density generated from the combined arrangement of the permanent magnet and ferromagnetic material in the flow channel in the electromagnetic pump is analyzed, where the Lorentz force produced by the vector product of the externally driven current and magnetic field in the liquid-metal flow inside the channel drives the pump (Oka, 2012). The pumping

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Nomenclature

B	Magnetic flux density [T]
B_e	Magnetic flux density of the permanent magnet [T]
$B_{e,r}$	R-direction magnetic flux density of the permanent magnet [A/m^2]
$B_{e,z}$	Z-direction magnetic flux density of the permanent magnet [A/m^2]
B_i	Magnetic flux density of the electrode stub [T]
$B_{i,r}$	R-direction magnetic flux density of the electrode stub [A/m^2]
$B_{i,z}$	Z-direction magnetic flux density of the electrode stub [A/m^2]
$B_{i,\theta}$	θ -direction magnetic flux density of the electrode stub [A/m^2]
B_{n,S_i}	Normal component of magnetic flux density at inner ferromagnetic material region
B_{n,S_m}	Normal component of magnetic flux density at permanent magnet region
B_{n,S_o}	Normal component of magnetic flux density at outer ferromagnetic material region
B_{n,S_p}	Normal component of magnetic flux density at pump duct region
B_t	Total magnetic flux density [T]
E	Electric field [(kg·m)/(s^3·A)]
E_r	R-direction electric field [(kg·m)/(s^3·A)]
E_t	Total electric field [(kg·m)/(s^3·A)]
E_z	Z-direction electric field [(kg·m)/(s^3·A)]
f	Force density [kg/(s^2·m^2)]
H	Magnetic-field intensity [A/m]
H_m	Magnetic-field intensity of the permanent magnet [A/m]
H_t	Tangential component of magnetic-field intensity [A/m]
H_{t,S_i}	Tangential component of magnetic-field intensity at inner ferromagnetic material region
H_{t,S_m}	Tangential component of magnetic-field intensity at permanent magnet region
H_{t,S_o}	Tangential component of magnetic-field intensity at outer ferromagnetic material region
H_{t,S_p}	Tangential component of magnetic-field intensity at pump duct region
J	Current density [A/m^2]
J_r	R-direction current density [A/m^2]
J_t	Total current density [A/m^2]
J_z	Z-direction current density [A/m^2]
J_θ	θ -direction current density [A/m^2]
M	Magnetization [A/m]
p	Developed pressure of pump [A/m]
R_i	Inner ferromagnetic material radius [m]
R_o	Radius up to the outer ferromagnetic material [m]
R_p	Radius up to the pump duct [m]
R_m	Radius up to the permanent magnet [m]
S_i	Inner ferromagnetic material region
S_o	outer ferromagnetic material region
S_p	Pump duct region
S_m	Permanent magnet region
t	Time [s]
v	Velocity of fluid [m/s]
v_θ	θ -direction velocity of fluid [m/s]
ε_0	Permittivity in vacuum [F/m]
μ_0 χ_m	Permeability in vacuum [H/m]
μ_r	Relative permeability
ρ	Density of liquid metal [kg/m^3]
σ	Electrical conductivity of liquid metal [1/($\Omega\cdot$m)]
χ_m	Magnetic susceptibility

force appears as a function of the magnetic flux density and pump geometrical variables in which a higher magnetic flux density is needed to enhance the hydraulic efficiency of the helical-type DC electromagnetic pump (Kikuchi, 1977). In the present study, the magnetic field is analyzed and optimized in terms of the arrangement of the permanent magnet according to the direction of the magnetic field and the geometrical size of the ferromagnetic material.

2. Analysis of a helical-type DC electromagnetic pump

The helical-type DC electromagnetic pump (Marti, 2015; Lee, 2017) contains four types of components: ferromagnetic material, permanent magnet (Zhu, 1992), electrode stub, and pump duct (Ho, 1977), as shown by the schematic in Figs. 2 and 3. The Lorentz force is generated by the vector product of the current of the electrode stub and the magnetic flux density of the permanent magnet where the liquid metal flows in the θ direction along the helical-type pump flow channel that receives the electromagnetic force generated by the current in the z direction and the magnetic flux density in the r direction, as shown in Fig. 2 (Bennecib, 2009). The Navier-Stokes equation for magnetohydrodynamics (MHD) is used to drive the developed pressure of the electromagnetic pump, as expressed in Eq. (1), and the magnetic flux density used in Eq. (1) is determined by Maxwell's equation of Ampere's law, Faraday's law, and Gauss's law for magnetism and Ohm's law expressed in Eqs. (2)–(5) using the finite element method (FEM) (Moffatt, 1978; Arumugam, 1985; Hughes, 1995).

$$\text{Navier}-\text{Stokes equation}: \rho\left(\frac{\partial}{\partial t}+v\cdot\nabla\right)v=\vec{J}_t\times\vec{B}-\nabla p \quad (1)$$

$$\text{Ampere's law}: \nabla\times\vec{B}=\mu_0\left(\vec{J}+\varepsilon_0\frac{\partial E}{\partial t}\right) \quad (2)$$

$$\text{Faraday's law}: \nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t} \quad (3)$$

$$\text{Gauss's law for magnetism}: \nabla\cdot\ \vec{B}=0 \quad (4)$$

$$\text{Ohm's law}: \vec{J}=\sigma(\vec{E}\theta+\vec{v}\times\vec{B}) \quad (5)$$

The equations of the electric field, current density, magnetic flux density, and velocity of the fluid are expressed in Eqs. (6)–(11). The electric field in the θ direction is eliminated due to the symmetry of the pump duct. The magnetic flux density is divided into external magnetic flux density of the permanent magnet and induced magnetic flux density of the electrode stub. The external magnetic flux density in the θ direction is eliminated because of the symmetry of the permanent magnet and ferromagnetic material. The velocity of the fluid has only a θ-direction component because the pump duct is built in the direction. The z-direction component is negligible because the pump-duct circumference is much higher than the pump-duct radius. In other words, the angle of the pump duct is almost equal to zero.

$$\vec{E}_t(r,\theta,z)=E_r\hat{r}+E_z\hat{z} \quad (6)$$