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Magnetic field analysis of an electromagnetic pump for sodium thermohydraulic test in the Sodium Test Loop for Safety Simulation and Assessment — Phase 1

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ABSTRACT

This study analyzed the magnetic field on an electromagnetic pump with a flow rate of 1380 L/min and a developed pressure of 4 bar designed for the sodium thermohydraulic test in the Sodium Test Loop for Safety Simulation and Assessment — Phase 1 (STELLA-1). The electromagnetic pump was used for the circulation of the sodium coolant in the intermediate heat transport system (IHTS) of the Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) with an electric power of 150 MWe, which is being developed in Korea. The magnetic field distribution in the narrow channel and the inner core of the electromagnetic pump was calculated through a numerical analysis method using ANSYS Maxwell to predict its performance characteristics. The end effect by the magnetic field distortion at the pump entrance and exit caused by the finite core length of the electromagnetic pump, which could result in the decrease of the developed pressure, was analyzed. The end effect analysis of the magnetic field considered the modified winding of coils in the outer core of the electromagnetic pump for the end effect reduction. The results showed that the electromagnetic pump performance would be thus improved.

1. Introduction

The intermediate heat exchanger (IHX) of the Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) is a counter-current flow type heat exchanger that transports heat from the primary heat transport system (PHTS) sodium coolant to the intermediate heat transport system (IHTS) sodium coolant (Hahn et al., 2009). The IHX has a dominant impact on the performance of the heat transport system of the PGSFR. Therefore, the heat exchange on the components of the coolant system and the heat transfer in the IHX must be identified by an appropriate simulation in the sodium flow environment (Lee et al., 2016). A device that would enable easy control of the developed pressure and the flow rate with good maintenance and safety characteristics is needed in performing the simulation (Bessho et al., 1992; Cuevas et al., 2006; Smolentsev et al., 2010; Kosuke et al., 2011).

An electromagnetic (EM) pump is considered to generate sodium circulation satisfying those conditions because, structurally, it does not have an impeller, which directly contacts the working sodium with a strong chemical reaction property and can control the flow rate by varying the power supply (Verkamp and Rhudy, 1966; Maidana et al., 2011; Kim, 2014). Therefore, the EM pump with a flow rate of 1380 L/min and a developed pressure of 4 bar is designed and fabricated for the sodium thermohydraulic experiment at the Sodium Test Loop for Safety Simulation and Assessment—Phase 1 (STELLA-1), which is being developed at the Korea Atomic Energy Research Institute.

As one of the steps to estimate the EM pump characteristic, the magnetic field is analyzed because the magnetic field distortion causes the end effect at both ends of the pump to influence the developed pressure of the EM pump and the flow stability (Baker and Tessier, 1987; Fanning et al., 2003; Kirilov et al., 2004). The magnetic field distribution in the narrow channel and the inner core of the EM pump is calculated by numerically solving Maxwell's equations using ANSYS Maxwell, which is commercially used as a numerical analysis code (Koroteevaa et al., 2016). The magnetic field in the various coil winding conditions of the EM pump is analyzed for decreasing the magnetic field distortion at both ends of the EM pump to improve the pump performance (Araseki et al., 2000).

The EM pump is fabricated using the design variables generated

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Nomenclature

$\boldsymbol{B}$	Magnetic flux density
$\boldsymbol{E}$	Electric field
$\boldsymbol{H}$	Magnetic field strength
$\boldsymbol{J}$	Current density
μ	Magnetic permeability
ω	Input angular frequency

from numerical analysis by Transient Magnetic method in the ANSYS Maxwell. The magnetic field in the narrow annular flow gap affecting electromagnetic force is compared for numerically predicted and measured values.

2. Theoretical approach

The annular linear induction EM pump (ALIP) in Fig. 1 can be divided into two parts in terms of function. The first part is the narrow channel composed of the inner and outer duct pipes. The flow gap between both ducts is where the liquid sodium flows down (Kim, 2014). The material of non-magnetic SUS 316 is used for both ducts to avoid the radial magnetic field distortion and considering the chemical reactivity of sodium and physical properties such as tensile strength. The second part is the electromagnet made up of inner and outer cores and coils generating a time-varying sinusoidal transverse magnetic field, where a silicon coated steel plate is used for the electromagnetic core material to lead the magnetic path (Yang and Kraus, 1977; Tillack and Morley, 1998). The copper coil winding generates a sinusoidal transverse magnetic field to the axial direction along the inner core and to the radial direction along the E-shaped teeth of the outer core when a three-phase alternating current is applied to the coils (Shamsuddeen et al., 2008). The inner and outer cores with a high magnetic permeability forms a strong magnetic field. Table 1 presents the properties of the materials used for the 3D modeling of the ALIP in the ANSYS Maxwell. Joule's ohmic loss is decreased

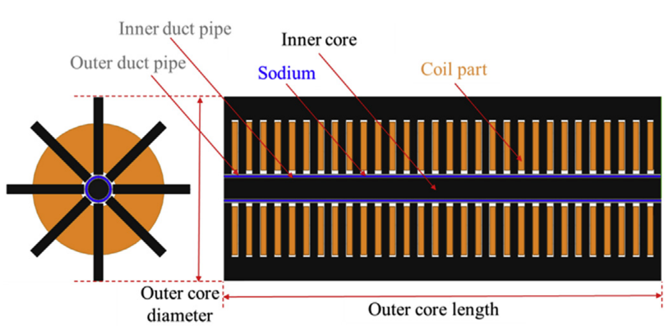

Fig. 1. Cross-section of the EM pump.

using an oxygen-free copper coil with a small electrical resistance and a laminated core insulation stacked with thin plates to reduce the generation of the eddy effect.

The current in the flow gap is induced by Faraday's law in the circumferential direction from the sinusoidal time-varying magnetic field of the axial direction in the inner core. Accordingly, the electromagnetic force is produced in the axial direction of the EM pump from the vector product of the induced current in the circumferential direction and the magnetic field in the radial direction perpendicular to it. The magnetic field leading to the electromagnetic force is obtained by solving Maxwell's equation, which is composed of Ampère's law, Faraday's law, and Gauss's law for magnetism as represented in Eqs. (1)–(3) (Nasar, 1976), by using ANSYS Maxwell for the pump with a finite length.

$$\text{Ampere's law}: \ \nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{1}$$

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

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

The electric field intensity ($\boldsymbol{E}$), magnetic induction ($\boldsymbol{B}$), and current density from the real coil arrangement ($\boldsymbol{J}$) have the function of a sinusoidal form temporally seen in Eq. (4) as follows:

$$\begin{aligned}
\boldsymbol{E}(\mathrm{r},\theta,\mathrm{z}) &= \mathrm{Re}\left[\left(E_r\hat{r} + E_\theta\hat{\theta} + E_z\hat{z}\right)e^{iwt}\right] \\
\boldsymbol{B}(\mathrm{r},\theta,\mathrm{z}) &= \mathrm{Re}\left[\left(B_r\hat{r} + B_\theta\hat{\theta} + B_z\hat{z}\right)e^{iwt}\right] \\
\boldsymbol{J}(\mathrm{r},\theta,\mathrm{z}) &= \mathrm{Re}\left[J_\theta e^{iwt}\right]\hat{\theta}
\end{aligned} \tag{4}$$

Ampere's law in Eq. (1) is extended to Eq. (5) using a curl in the cylindrical coordinates. The current density, $\boldsymbol{J}$ passing through the coils only has a circumferential component, as represented in Eq. (6). Therefore, Eqs. (5) and (6) are combined to obtain Eq. (7), where the radial and axial components are diminished.

$$\begin{aligned}
\nabla \times \boldsymbol{B} = Re\left[e^{iwt}\right]\Bigg[&\left(\frac{1}{r}\frac{\partial B_z}{\partial \theta} - \frac{\partial B_\theta}{\partial z}\right)\hat{r} + \left(\frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r}\right)\hat{\theta} \\
&+ \frac{1}{r}\left(\frac{\partial (rB_z)}{\partial r} - \frac{\partial B_r}{\partial \theta}\right)\hat{z}\Bigg]
\end{aligned} \tag{5}$$

$$\mu\boldsymbol{J} = \mu\mathrm{Re}\left[J_\theta e^{iwt}\right]\hat{\theta} \tag{6}$$

$$\mu J_\theta = \frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r} \tag{7}$$

In the same manner, the left side of Faraday's law in Eq. (2) is extended to Eq. (8), and the magnetic field is divided into the components of the radial, circumferential, and axial directions, as represented in Eq. (9). Eqs. (8) and (9) are combined to Eq. (10)

Table 1
Properties of materials in the EM pump 3D modeling.

Component	Material	Properties		
		Electrical conductivity [Siemens/m]	Density [kg/m^3]	Relative permeability
Core	35PN250	1.81 E+06	7872	–
Duct	SUS 316	1.35 E+06	8055	1
Flow gap	Sodium	5.18 E+06	878	1
Coil	Copper	2.56 E+07	8933	1
Near the ALIP	Air	0	1.161	1