The basic approach to the performance test of the ALIP for GENIV sodium fast reactor

H R Kim and Y B Lee

1 Ulsan National Institute of Science and Technology, 50 UNIST-gil, Uljoo-gun, Ulsan, Republic of Korea
2 Korea Atomic Energy Research Institute, 150 Dugjin-dong, Yuseong-gu, Daejeon, Republic of Korea

E-mail: kimhr@unist.ac.kr

Abstract. The annular linear induction electromagnetic pump (ALIP) with the flowrate of 900 L/min and the developed pressure of 4 bar has been designed by electric equivalent circuit analysis. It was fabricated by the consideration of materials compatible to the sodium environment of high temperature. Basic characteristic test of the ALIP was carried out in advance for its installation to the integral effect Test Loop for safety simulation and Assessment (STELLA) loop to confirm the sodium-thermo-hydraulic components. The test showed that the magnetic field had been linearly increased when the input current was increased, where input current and voltage had represented linear relation each other. The generated electromagnetic force was proportionate to the square of the applied current. The velocity of the aluminium pipe was proportionally increased when the input current was increased. It was verified that the basic characteristic of the ALIP showed a good accordance with the theoretical calculation.

1. Introduction

An annular linear induction electromagnetic pump (ALIP) has been used for transportation of electrically conducting liquid metal [1, 2]. Advantages of no rotating parts which diminish the corrosion due to contact with liquid metal and of no maintenance for a long time, have made the EM pump possible to be alternative for the circulation of sodium coolant in the prototype GENIV sodium fast reactor (PGSFR). The concept for the design of linear induction motors is used for designation of the EM pump. An electrical equivalent circuit with primary and secondary resistances and reactances given by pump geometrical and electromagnetic variables is used for the design analysis of the EM pump. The EM pump with the flowrate of 900 L/min and developed pressure of 4 bar is designed and fabricated considering material for the environment of high temperature sodium [3]. In the present study, the basic operation tests for the pump are carried out on the change of input current before installing it in the sodium loop for verifying the elements of the sodium-thermo-hydraulic experimental system.

2. Design of ALIP

2.1. Basic Concept
Figure 1 shows the cross sectional view of the annular linear induction EM pump. It has two parts of primary and secondary ones. The electromagnet composed of the stacked silicon-iron cores and driving copper coils forms primary part. The ducts of a narrow annular gap for the sodium flow makes secondary part. First of all, the pump has geometrical variables including inner core diameter, inter-core gap and the outer core length and electromagnetic ones of frequency, input voltage and current. The optimized design variables are drawn by analysis on the developed pressure and the efficiency using the equivalent circuit.

![Figure 1. Cross-sectional view of the EM pump.](image)

2.2. Circuit Analysis

The EM pump connected by 3-phase AC power has the resistance by copper winding and liquid sodium, magnetization and leakage reactance. The pump is analyzed on one phase because it has the balanced three-phase inputs. In Figure 2 is represented the electric equivalent circuit for one phase with primary part composed of the coils and cores, and the secondary one of the sodium flowing along the channel of the pump [3].

From balance between input and output power using the electric equivalent circuit variables from the pump geometrical and electromagnetic ones in Figure 2, the developed pressure is derived as a function of flowrate and other variables as seen in Equation (1), where slip, \( s \) is defined as the ratio of difference between synchronized flowrate and fluid flowrate to the synchronized flowrate [3], where the resistances and reactances of the circuit are represented in Equation (2) ~ (5) given by Laithwaite’s standard design formula [3].

![Figure 2. Electric equivalent circuit of the EM pump](image)

\[
\Delta P = \frac{3I^2}{Q} \frac{R_s(1-s)}{s(R_s^2/X_m^2s^2 + 1)} \\
R_s = \frac{\pi\rho qk_m^2 m^2 D_0 N^2}{k_f k_p p \tau^2} \\
X_s = \frac{2\pi\mu_0 \omega D_0 \lambda N^2}{pq}
\]
\[ X_m = \frac{6\mu_e \sigma \tau \pi D_e (k_w N)^2}{\pi^2 p g_e} \]  \hspace{1cm} (4)

\[ R_2 = \frac{6\pi D_e \rho_c (k_w N)^2}{\varphi} \]  \hspace{1cm} (5)

Substituting Equation (2) ~ (5) into Equation (1), the developed pressure of the pump and its efficiency are derived as functions of electromagnetic and geometric variables in Equation (6) and (7).

\[ \Delta P = \frac{36 \sigma^2 f \tau^2 (\mu_e k_w N)^2}{pg_e^2 \left( \pi^2 + \left(2\mu_e \sigma f \tau^2 \right)^2 \right)} \]  \hspace{1cm} (6)

\[ \varepsilon = \frac{\Delta P \cdot Q}{\sqrt{3VI \cos \phi}} = \frac{6k_w^2 (1 - s)}{\pi^2 + \left(2\mu_e \sigma f \tau^2 \right)^2 + 6k_w^2 \cos \phi} \]  \hspace{1cm} (7)

The developed pressure and efficiency are calculated for the different geometrical and electromagnetic variables to be optimized.

3. Fabrication and test of the EM pump

3.1. Fabrication of ALIP

The designed ALIP was fabricated for Sodium integral effect Test Loop for safety simulation and Assessment (STELLA-1) for testing components such as sodium-air heat exchanger (AHX) and sodium to sodium decay heat exchanger (DHX) in the STELLA-1 loop. In Figure 3, the completed 3-phase ALIP with a flowrate of 900 L/min and a developing pressure of 4 bar was shown [3], where the ALIP would be installed in a vertical direction to meet full filling of liquid sodium in the pump as seen in Figure 3.

![Figure 3. The completed ALIP for sodium circulation in STELLA loop](image)

Flowrate: 900 L/min
Developing Pressure: 4 bar
Temperature: 550 °C

Figure 4 represented the system for the basic operation test of the ALIP where input voltage was controlled by using 3-phase AC slidacs with range of 0~380 V. Solid aluminum pipe with outer and inner diameter of 130 mm and 122 mm each was inserted into the narrow annular gap of the pump.
The force generated by pump and velocity of the aluminum pipe, which were equivalent to the developed pressure and flow velocity of sodium flow, respectively, were measured when the voltage and current were changed in the room temperature. The electrical conductivity of the aluminum was order of $10^7 \text{/(ohm m)}$, similar to that of sodium while the density and viscosity are different each other, and the phases of the aluminum and liquid sodium are solid and liquid. However, the operation of the pump can be verified due to the same principle of electromagnetic force generation on the aluminum and sodium with high electrical conductivity.

![Figure 4. The basic operation test device of the EM pump](image)

3.2. The basic function test of the EM pump

The input current of the pump was linearly increased as input voltage of each phase (R, S and T) of three phase power is increased as represented in figure 5.

![Figure 5. The input current and voltage applied to the EM pump](image)

The magnetic flux density in the gap of the pump, where the liquid sodium flows, was linearly increased when the input current was increased as understood by Ampere’s law [4] in figure 6 (a). It was twice higher in case of 2-parallel connection than in case of 6-parallel connection where the pump had six pole pairs. Figure 6 (b) represented that the stand-still force was increased in proportion to the square of input current as it was increased. It was thought because the developed pressure
corresponding to the electromagnetic force generated in the pump was given by the function of square of the current in Eqn. (8), where the ratio of secondary resistance to magnetizing reactance multiplied by slip, \( R_s/(X_m s) \), of the pump was negligible.

\[
\Delta P = \frac{3I^2}{Q} \frac{R_s (1-s)}{s(R_s^2/X_m s^2 + 1)} = \frac{36\pi^2 f r^2 (\mu_n k_r NI)^2}{\rho g_s \left( \pi^2 + (2\mu_n \sigma m r^2)^2 \right)}
\]

(8)

\[
\Delta P = \frac{3I^2}{Q} \frac{R_s (1-s)}{s(R_s^2/X_m s^2 + 1)} = \frac{36\pi^2 f r^2 (\mu_n k_r NI)^2}{\rho g_s \left( \pi^2 + (2\mu_n \sigma m r^2)^2 \right)}
\]

The magnitude of the generated force was much larger when the pump was connected in the 2 parallel method than in the 6-parallel method. As a result, the pump was understood to generate larger pumping power when it was connected 2–parallelly.

![Figure 6. (a) The magnetic induction and (b) standstill force of the ALIP](image)

Figure 6. (a) The magnetic induction and (b) standstill force of the ALIP

The magnitude of the generated force was much larger when the pump was connected in the 2–parallel method than in the 6-parallel method. As a result, the pump was understood to generate larger pumping power when it was connected 2–parallelly.

![Figure 7. The measurement of velocity of the aluminium pipe in the annular channel of the EM pump](image)

Figure 7. The measurement of velocity of the aluminium pipe in the annular channel of the EM pump

In figure 7, the higher the current was, the larger the velocity of the aluminium pipe was. The measurement showed that its velocity and current were linear. Actually, the factor, \((2\mu_n \sigma m r^2)^2\), in Equation (8) is numerically much small by calculation for the designed ALIP and slip is proportionate to velocity. Therefore, the relation between the velocity and current is found to be linear when the developed pressure is fixed in Equation (8).

4. Conclusion

The ALIP for sodium circulation in the STELLA loop was designed and completed using equivalent circuit analysis for the requirement of the flowrate of 900 L/min and developed pressure of 4 bar. It was understood the basic characteristic experiment including force and velocity showed a good accordance with the theoretical prediction.

Nomenclature
cos $\phi$  power factor
$D$  outer duct diameter [m]
$D_0$  inner core diameter [m]
$f$  input frequency [Hz]
$g$  gap between outer and inner cores [m]
$g_e$  effective gap [m]
$I$  applied current [A]
$K$  hydraulic pressure loss coefficient
$k_d$  slot depth (t) / slot width (w)
$k_f$  slot filling factor (0.5-0.6)
$k_p$  slot pitch (t_c) / slot width (w)
$k_v$  winding factor
$l$  tooth pitch [m]
$L$  pump core length
$m$  number of phase
$N$  coil turns
$p$  number of pole pairs
$q$  number of slot per phase per pole pair
$R_1$  primary equivalent resistance [ ]
$R_2$  secondary equivalent resistance [ ]
$Q$  flowrate of the sodium [m$^3$/s]
$Q_s$  synchronized flowrate [m$^3$/s]
$s$  slip (=1-$Q/Q_s$)
$t$  slot depth [m]
$T$  pump outer core diameter [m]
$t_c$  slot pitch [m]
$w$  slot width [m]
$X_m$  magnetizing reactance [ ]
$\Delta P$  developed pressure of the pump [N/m$^2$]
$\Delta P_L$  head loss in the loop [N/m$^2$]
$\epsilon$  pump efficiency
$\mu_0$  magnetic permeability of vacuum [H/m]
$\phi$  phase angle between voltage and current
$\tau$  pole pitch [m]
$\rho$  sodium density [kg/m$^3$]
$\sigma$  electrical conductivity of the fluid [1/ ]
$\omega$  angular frequency (=2$\pi$)

References
[1] Blake L R 1959 Electro-magnetic pumps for liquid metals Journal of Nuclear Energy Part B Reactor Technology 1 (2) 65-76
[2] Carroll D G and Boardman C E 2002 The super-PRISM reactor system Nuclear Engineer 43 (6) 165–168
[3] Kim H R 2010 The design of the annular linear induction em pump with a sodium flowrate of 35 kg/sec Korean Nuclear Society Spring Meeting Pyeongchang Korea
[4] John D K 1983 Electromagnetics (New York : McGraw-Hill Book Company)
[5] Merle C P and David C W 1991 Mechanics of Fluids (Tokyo: Prentice-Hall International Inc.)