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Design of small annular linear induction electromagnetic pumps for STELLA-2

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1. Introduction

The control system of STELLA-2 for sodium heat flow is required to maintain the electric output, temperature and flow rate in accordance with simulated transient behavior test conditions, and it is necessary to design a pump that can supply the required flow rate accordingly. Since annular linear induction electromagnetic pump has a more complicated structure than other electromagnetic pumps, it is necessary to develop a design optimization method to solve this problem.

In this study, the design methodology of the STELLA-2 annular linear induction electromagnetic pump was set up, and the electromagnetic pump design data with optimized performance using genetic algorithm was presented.

2. Methods and Results

2.1 Electromagnetic Pump Design Analysis

Electromagnetic pumps are divided into conduction pumps and induction pumps depending on the driving method. The induction type electromagnetic pump basically uses the time-varying magnetic field due to the characteristics of the driving method, and it can be classified according to the generation method of the magnetic field.

The induction type electromagnetic pump to be applied in this study induces the magnetic field by the current, and then induces the induction current induced in the induction magnetic field into the conductive liquid metal. Therefore, the induction magnetic field and the induced current are applied to the conductive liquid metal in the vertical direction, and the principle of transferring the conductive liquid metal by the Lorentz force in the direction of the vector product thereof. Unlike a conductive electromagnetic pump, there is no need to supply current directly to the conductive liquid metal, and there is no need to connect a heavy electrode to the duct.

Two methods are used for electromagnetic pump design analysis: electrical equivalent circuit analysis method and MHD (Magneto Hydro Dynamic) analysis method. An equivalent circuit analysis method is a method of analyzing characteristics by converting an electromagnetic pump into an electric circuit diagram such as an induction motor. The primary side is applied to the electromagnet part and the secondary side is applied to the liquid metal part. The geometric parameters and the operating parameters are converted into equivalent resistances and reactance on the equivalent circuit to derive a driving pressure relationship, which is used to analyze pump performance characteristics such as pump driving pressure or efficiency according to the variation of each variable.

A cross-sectional view of a linear induction electromagnetic pump for driving a conductive liquid metal is shown in Figure 1. The electromagnetic pump is divided into the primary by the core and the coil and the secondary by the conductive liquid metal.

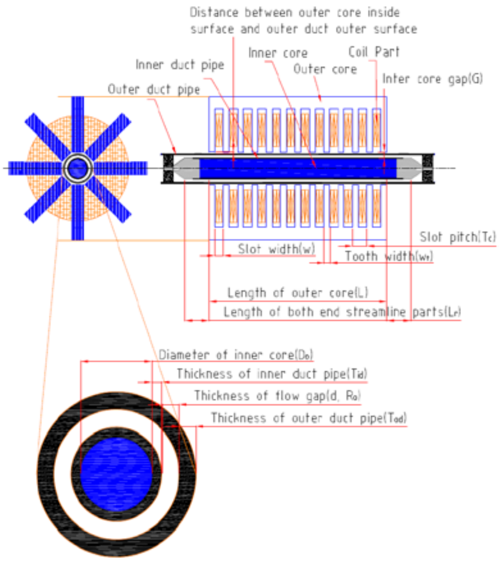


Fig.1. Cross-sectional view of a linear induction electromagnetic pump.

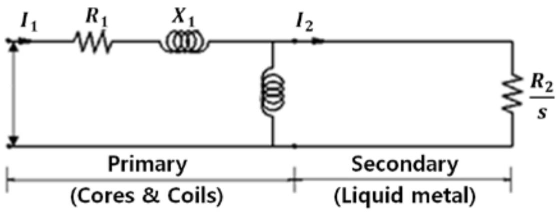


Fig. 2. Equivalent circuit.

In order to obtain the relationship between the conductive liquid metal driving pressure and the average flow rate of the ring-section linear induction electromagnetic pump through the electrical equivalent circuit analysis, the length of the pump core, the inner core diameter, the gap between the cores, the number of magnetic fields generated by the electromagnet, Pitch and other electrical operating parameters such as input current, voltage and frequency are converted into equivalent variables of the equivalent circuit given by Laithwaite's standard design formula.

A relational expression of the driving pressure, △P and the average flow rate, Q expressed by the variables on the equivalent circuit can be obtained from the balance equation of the power.

$$\triangle P = \frac{3I_1^2}{Q}\frac{R_2(1-s)}{s(R_2^2/(X_m^2 s^2)+1)} \quad (1)$$

Equivalent resistance and equivalent reactance are determined by Laithwaite's standard design formula, which is calculated from the magnetic circuit consisting of geometric pump design variables and operating parameters. Therefore, the following equations are given.

$$R_1 = \frac{\pi \rho_c q k_p^2 m^2 D_o N^2}{k_f\, k_d p \tau^2},$$

$$R_2 = \frac{6\pi D}{\tau p}\dot{\rho}_r (k_w N)^2 \quad (2)$$

The developed pressure can be obtained by rearranging the values of the equation 1 and inserting one by one into the values of the geometrical and electromagnetic variables.

$$\triangle P = \frac{36\sigma s f \tau^2 (\mu_0 k_w N I)^2}{p G_e^2 \{\pi^2 + (2\mu_0 \sigma s f \tau^2)^2\}} \quad (3)$$

In addition, the efficiency relation of the electromagnetic pump is expressed by using the driving pressure relation obtained previously. First, the efficiency is defined as the drive output for the input power. This is shown in following Equation for the equivalent circuit in Figure 2.

$$\epsilon = \frac{\triangle PQ}{3(I_1^2 R_1 + I_2^2 \frac{R_2}{s})} \quad (4)$$

This is expressed as the equation (5) when the electromagnetic pump is developed as a geometrical and electromagnetic variable relation.

$$\varepsilon = \frac{6k_w^2(1-s)}{\frac{\rho_c q k_p^2 m^2 \sigma G_e}{k_f k_d \tau}\{1+(\frac{\pi}{2\mu_0 f s \sigma \tau^2})^2\} + \frac{6k_w^2}{s}} \quad (5)$$

2.2 Genetic Algorithm

The annular linear induction electromagnetic pump has a complicated structure as compared with other electromagnetic pumps, so optimization design is difficult. To solve this problem, design optimization was performed using genetic algorithm. Genetic Algorithm is the engineering of genetic and evolutionary mechanisms of organisms in the natural world to deal with the adaptive capacity of living organisms [2]. As a kind of chromosome for solving the optimal design of electromagnetic pump using genetic algorithm, the thickness of the sodium channel, the inner core diameter, the core length, the winding width and the width relative to the slot pitch were selected. Other variables such as the frequency of the current, if necessary, may be added later. The fitness function to measure how good each chromosome is, that is, the fitness function, was chosen as the efficiency of the pump. In order to prevent the excessive current per unit area, the current per unit area of the copper conductor is 2.5 A/mm^2. To prevent corrosion and erosion due to the sodium flow, the flow rate of sodium is limited to 8 m/s.

2.3 STELLA-2 IHTS Electromagnetic Pump Design

IHTS electromagnetic pump design requirements are as follows. The electric frequency was fixed at 60 Hz assuming the general commercial use. The reference temperature of sodium is 400 ℃.

- Length constraint: 600 mm
- Head: 1 bar
- Flow rate: 1000 L / min

In the IHTS electromagnetic pump design, the above requirements are applied as input conditions, the optimum design of the electromagnetic pump using the genetic algorithm is obtained. The inner duct and the outer duct diameter values below the decimal point are appropriately cut and are replaced by that of the manufacturing industry. The solution for the IHTS electromagnetic pump optimal design is as follows. Table 1 shows the design specifications of the IHTS electromagnetic pump, and Figure 3 shows the flow rate versus developed pressure corresponding to the various current. Ⓡ means the operating condition.

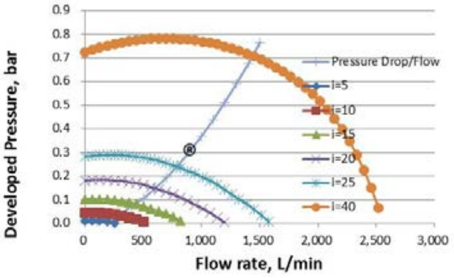
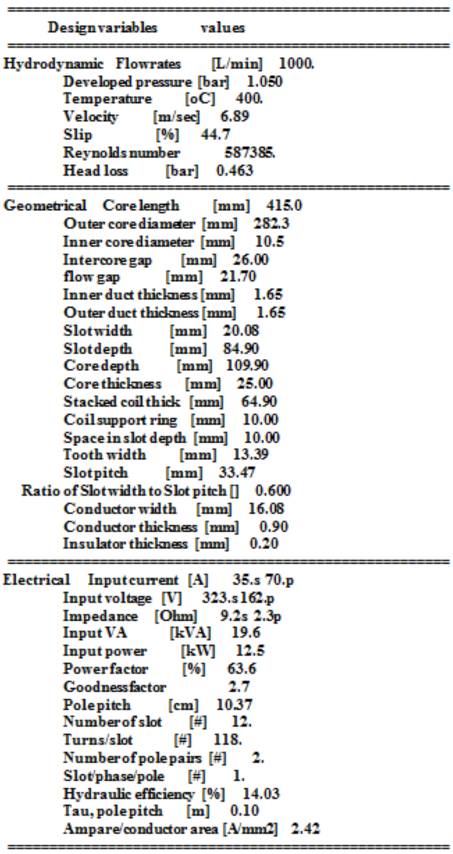


Fig.3. Flow rate versus developed pressure.

Table 1: design specifications of the IHTS electromagnetic pump



	Design variables		values
Hydrodynamic	Flowrates	[L/min]	1000.
	Developed pressure	[bar]	1.050
	Temperature	[oC]	400.
	Velocity	[m/sec]	6.89
	Slip	[%]	44.7
	Reynolds number		587385.
	Head loss	[bar]	0.463
Geometrical	Core length	[mm]	415.0
	Outer core diameter	[mm]	282.3
	Inner core diameter	[mm]	10.5
	Intercore gap	[mm]	26.00
	flow gap	[mm]	21.70
	Inner duct thickness	[mm]	1.65
	Outer duct thickness	[mm]	1.65
	Slot width	[mm]	20.08
	Slot depth	[mm]	84.90
	Core depth	[mm]	109.90
	Core thickness	[mm]	25.00
	Stacked coil thick	[mm]	64.90
	Coil support ring	[mm]	10.00
	Space in slot depth	[mm]	10.00
	Tooth width	[mm]	13.39
	Slot pitch	[mm]	33.47
	Ratio of Slot width to Slot pitch	[]	0.600
	Conductor width	[mm]	16.08
	Conductor thickness	[mm]	0.90
	Insulator thickness	[mm]	0.20
Electrical	Input current	[A]	35.s 70.p
	Input voltage	[V]	323.s 162.p
	Impedance	[Ohm]	9.2s 2.3p
	Input VA	[kVA]	19.6
	Input power	[kW]	12.5
	Power factor	[%]	63.6
	Goodness factor		2.7
	Pole pitch	[cm]	10.37
	Number of slot	[#]	12.
	Turns/slot	[#]	118.
	Number of pole pairs	[#]	2.
	Slot/phase/pole	[#]	1.
	Hydraulic efficiency	[%]	14.03
	Tau, pole pitch	[m]	0.10
	Ampare/conductor area	[A/mm2]	2.42

2.4 Influence of IHTS electromagnetic pump core length

When the length of the pump core is divided by the number of pole pair, it means the pole pitch, and the definition of the pole pitch means the distance between the N pole and the S pole formed in the flow path. The increase in pole pitch increases Laithwaite's Goodness Factor, which can magnetize the core with relatively low current values. In addition, the driving pressure relation is proportional to the secondary equivalent resistance, and when the pitch is too large, the secondary equivalent resistance is decreased and the driving force is lowered. As a result, when the graph of the driving pressure and the efficiency for the change of the pole pitch is derived, it can be seen that the maximum value appears at a specific value. Conversely, a reduction in the pitch of the pole leads to a decrease in the synchronous speed, that is, a decrease in the speed of movement of the pole and consequently a decrease in the speed of movement of the conductive liquid metal moving in the moving magnetic field[1]. Figure 4 shows the efficiency versus drive pressure versus core length.

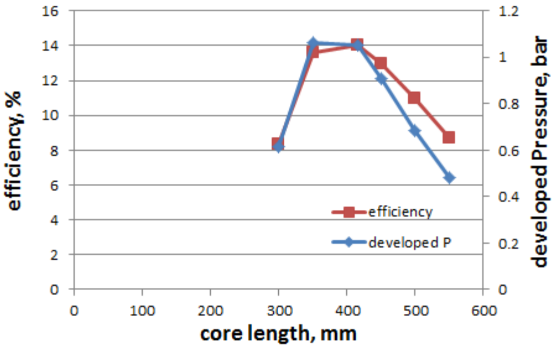


Fig.4. Efficiency and drive pressure versus core length.

2.5 Influence of gap between IHTS electromagnetic pump cores

The gap between the thickness of the inner and outer ducts of the pump and the flow width of the secondary side conductive liquid metal is called the gap between cores. This is closely related to the magnetic field value of the annular cross-sectional flow path width. The relationship of the input current to the change of this gap can be explained as follows. The increase in inter-core gap leads to a reduction in the magnetizing reactance to magnetize the electromagnet core of the electromagnetic pump, resulting in more input current for the same output. In other words, even if the same current flows through the coil, the narrower the gap is, the greater the reluctance value corresponding to the magnetic flux resistance is, and the smaller the magnetic flux crossing the fluid is. Therefore, as the gap between the cores becomes smaller, the magnetic field inside the fluid increases with the same input current, and the leakage flux decreases, resulting in a larger output. However, the gap between the cores having too narrow width causes problems in fabrication process and may lead to an increase in the frictional force with the duct wall due to the high flow velocity, which is accompanied by a geometrical consideration thereof [1].

Figure 5 shows the efficiency versus drive pressure versus liquid metal flow path width when the thickness of the inner and outer ducts is constant.

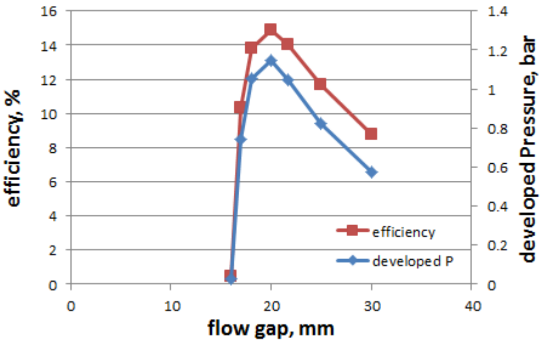


Fig.5. Efficiency and drive pressure versus flow gap.

3. Conclusions

Design methodology for electromagnetic pump design and optimization process of design parameters is described. Design optimization was made by using genetic algorithm

Electromagnetic pump design data for IHTS, DHRS, Cold Trap and Plugging Meter of STELLA-2 were produced.

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