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Design of Annular Linear Induction Pump for High Temperature Liquid Lead Transportation

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1. Introduction

EM(Electro Magnetic) Pump is used for the purpose of transporting liquid metal coolant with electrical conductivity in the LMR(Liquid Metal Reactor). The pump is divided into two parts, which consisted of the primary one with electromagnetic core and exciting coils, and secondary one with liquid lead flow. The main geometrical variables of the pump included core length, inner diameter and flow gap while the electromagnetic ones covered pole pitch, turns of coil, number of pole pairs, input current and input frequency. The characteristics of design variables are analyzed by electrical equivalent circuit method taking into account hydraulic head loss in the narrow annular channel of the ALIP. The design program, which was composed by using MATLAB language, was developed to draw pump design variables according to input requirements of the flow rate, developing pressure and operation temperature from the analyses.

2. Structure of ALIP

2.1 Electromagnetic Core

Structure of ALIP is shown in Fig. 1. In this illustration, electromagnetic core can be divided into two parts, inner core and outer core which induce magnetic field to axial direction and radial direction. So material for core must be ferromagnetic body which has high permeability. It also maintains magnetic characteristics and mechanical strength in high temperature and fast neutrons. For blocking loss of magnetic field and heat generation caused by eddy current in core inside, stacking isolated ferromagnetic plane is recommended. Especially, inner core have to be placed radial form in the duct for considering direction of magnetic field.

Outer core is manufactured by stacking chain of E type core. And use a material silicon steel plate coated by insulation organic matter. Outer core bunch is fixed by stainless steel square pipe and bolts with nuts. Inner core is manufactured by stacking I type core, be placed in the inner duct and sealed by cone for preventing contact with liquid lead [1, 2].

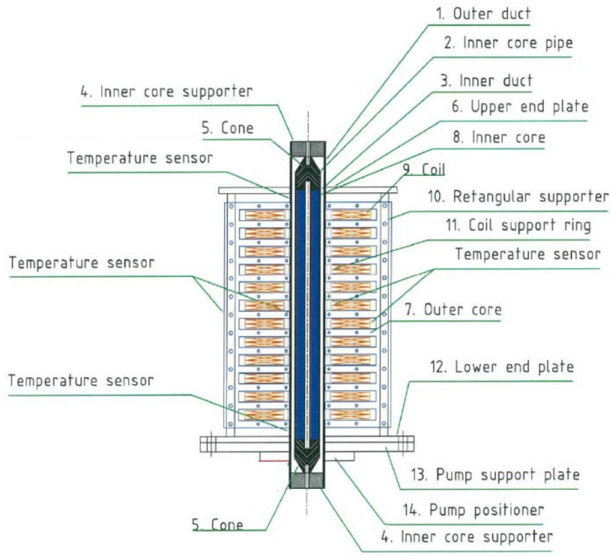

Fig. 1. Structure of ALIP

2.2 Electromagnetic Coil

Materials for electromagnetic coil must have heat-resisting and low electrical resisting properties in the environment of high temperature and neutron irradiation. In the case of ALIP, electromagnetic coils are twined circularly and flowing electric current directly. So insulation between coils is essential.

2.3 Insulating Material

Insulating materials must block electrical contact not only gap of coils but also between coil and outer core. Because of filling factor, thin insulating materials are better as electrical insulation is allowed. It must be twined circularly with electromagnetic coil, have flexibility and heat-resisting properties.

2.4 Structural members

Structural members mean components of pump except core, coil, and insulating material. These fix components (plates and supporters), protect from high temperature liquid lead (duct), helps flow of liquid lead (cone) and so on. Structural members must protect pump from high temperature lead in the aspects of heat and chemical reactivity. And don’t have to distort magnetic field. So austenite stainless steel is recommended because which is nonmagnetic material.

3. Analysis on the Design Parameters of ALIP

Basically ALIP which is driven by Lorentz electromagnetic force change driving power and efficiency by geometrical shape, size, and operating variables. The driving power and efficiency function can be derived by electrical equivalent circuit method. The pump was divided into two parts, which consisted of the primary one with electromagnetic core and exciting coils, and secondary one with liquid lead flow. The main geometrical variables of the pump included core length, inner diameter, flow gap, and so on while the electromagnetic ones covered turns of coil, number of pole pairs, input current, input frequency, and so on.

3.1 Electrical Equivalent Circuit Method

The ALIP can be illustrated like Fig. 2.as electrical equivalent circuit. In the Primary one, r_1 is wire wound resistance in the coil, X_1 is leakage reactance from the core, X_m is magnetization reactance from the core. r_2' is equivalent resistance of liquid metal. And relation function between developed pressure ΔP and average flow rate Q express like below [3, 4].

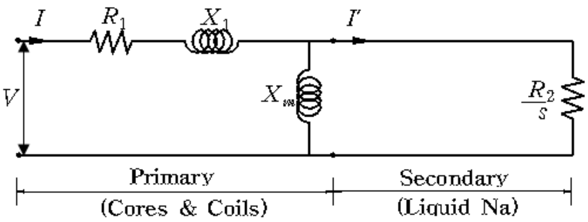

Fig. 2. Electrical Equivalent Circuit of ALIP

$$\Delta P = \frac{3I^2}{Q}\frac{R_2(1-s)}{s(R_2^2/X_m s^2+1)} \tag{1}$$

Equivalent resistance and equivalent reactance are given below. It used Laithwaite standard design formula calculated by magnetic circuit composed of geometrical and operational variables.

$$R_1 = \frac{\pi\rho_c q k_p^2 m^2 D_2 N^2}{k_f k_d p\tau^2} \tag{2}$$

$$X_1 = \frac{2\pi\mu_0\omega D_2\lambda_c N^2}{pq} \tag{3}$$

$$X_m = \frac{6\mu_0\omega}{\pi^2}(k_w N)^2\frac{\tau\pi D_0}{pg_e} \tag{4}$$

$$R_2 = \frac{6\pi D}{\tau p}p_r(k_w N)^2 \tag{5}$$

Substitution R_2 and X_m from (2),(3) to (1). Then, below formula is derived.

$$\Delta P = \frac{36\sigma s f\tau^2((\mu_0 k_w N I)^2}{pg_e^2\{\pi^2+(2\mu_0\sigma s f\tau^2)^2} \tag{6}$$

From the formula (6), can know that developed pressure is related with electrical variables like frequency, pole pairs and geometrical variables like flow gap, pole pitch, and so on. Like above, efficiency formula can be derived.

3.2 Characteristics of Design Parameters

From the developed pressure and efficiency formula by electrical equivalent circuit method, derive relations of design parameters. These are simplified in table. 1.

Table. 1. Characteristic of Structure Elements [2]

Structural Elements		Action Characteristics
Size of Outer Core	Increase	• Leakage reactance increase • Allowed Turns of coil increase
	Decrease	• By the decrease of leakage reactance, efficiency increase • Allowed turns of coil decrease
Duct Width	Increase	• For same output, need more current and efficiency decrease • Flow gap decrease
	Decrease	• output and efficiency increase • Flow gap increase
Pole Pitch	Increase	• Synchronous speed increase • Length of Inner core and weight, size of pump increase
	Decrease	• Size of pump decrease • Body force increase in same input
Number of Pole	Increase	• Dispersion of fluid thrust • Pump size increase • End effect decrease.
	Decrease	• Leakage reactance increase (in secondary part)
Size of Inner Core	Increase	• Pump weight increase • Area of duct increase (in same duct width)
	Decrease	• Pump weight decrease • Area of duct decrease (in same duct width)
Number of Coil	Increase	• Input current decrease in same output • Pump weight increase
	Decrease	• Input current increase in same output

4. Design Program Based on MATLAB

In the MATLAB code, sections for calculation are divided into 10. Each sections are 'Required specification', Electromagnetic variables', Geometrical variables', Electro-geometrical variables', 'Hydro dynamical variables', 'Equivalent impedance', 'Power factor and goodness factor', 'Developed pressure', 'Electrical input and efficiency', 'Design Specification'.

In the Required specification section, input 3 main outputs of pump. Pressure, temperature, and flow rate. And the code calculates other outputs like velocity for reaching to goal of 3 main outputs.

In the electromagnetic variables section, input current, turns of coils, frequency, pole pairs, electrical resistivity of materials based on temperature, and so on.

In the geometrical variables section, input basic size of pump like core length, flow gap, thickness of ducts, ratio of slot width to slot pitch and so on. Then the equipped formulas calculate the detailed sizes of pump components. So I don't have to do detail design for each components of pump.

In the other sections except last section, the code calculates outputs based on equipped formulas which are derived by equivalent circuit method. Also, hydrodynamics factors are considered.

In the last section, code show inputs and calculated outputs like Fig. 2.

	Design variables		values
Hydrodynamic	Flowrates	[L/min]	30
	Developed pressure	[bar]	1.02
	Temperature	[oC]	500
	Velocity	[m/sec]	0.489
	Slip	[%]	94.6
	Reynolds number		19023
	Head loss	[Pa]	14177.227
Geometrical	Core length	[mm]	300.0
	Outer core diameter	[mm]	403.2
	Inner core diameter	[mm]	39.4
	Intercore gap	[mm]	10.90
	flow gap	[mm]	6.60
	Inner duct thickness	[mm]	1.65
	Outer duct thickness	[mm]	1.65
	Slot width	[mm]	12.00
	Slot depth	[mm]	146.00
	Core depth	[mm]	171.00
	Core thickness	[mm]	25.00
	Stacked coil thick	[mm]	126.00
	Coil support ring	[mm]	10.00
	Space in slot depth	[mm]	10.00
	Tooth width	[mm]	12.00
	Slot pitch	[mm]	24.00
	Conductor width	[mm]	8.00
	Conductor thickness	[mm]	4.00
	Insulator thickness	[mm]	0.20
Electrical	Input current	[A]	47.0
	Input voltage	[V]	651
	Impedance	[Ohm]	13.8
	Input VA	[kVA]	53.0
	Input power	[kW]	12.7
	Power factor	[%]	23.9
	Goodnessfactor		0.1
	Pole pitch	[cm]	7.50
	Number of slot	[#]	12
	Turns/slot	[#]	60
	Number of pole pairs	[#]	2
	Slot/phase/pole	[#]	1
	Hydraulic efficiency	[%]	8.59

Fig. 2. Output of MATLAB Code

5. Conclusions

The analysis on the design of ALIP for high temperature liquid lead transportation was carried for the produce of ALIP designing program based on MATLAB. By the electrical equivalent circuit method, related formulas are derived, and produce frame of code based on the formulas. By the using of ALIP designing program, we don't have to bother about geometrical relationship between each component during detail designing process because code calculate automatically. And prediction of outputs about designing pump can be done easily before manufacturing. By running the code, we also observe and analysis change of outputs caused by changing of pump factors. It will be helpful for the research about optimization of pump outputs.

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