Acta Scientific Applied Physics

Volume 2 Issue 3 August 2021

Review Article

Electromagnetic Pump

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Received: June 19, 2021

Published: July 09, 2021

Abstract

An electromagnetic pump is a pump that moves liquid in form of metal in particular, any electrically conductive liquid using electromagnetism phenomena. By law of physics of electromagnetic, a magnetic field can be defined as a set at right angles to the direction the liquid moves in, while a current is passing through it as well. This events, induce an electromagnetic force for the movements of the liquid. Applications of electromagnetic pump is including pumping liquid metal through any cooling system that are installed inside of liquid metal container in particular.

Keywords: Electromagnetic; Pump; Liquid; Heat Transfer; Neutronic; Electric Current; Pumping Liquid Metal

Introduction

Electromagnetic Pumps are passive pump system and have been integrated in use for pumping liquid sodium in auxiliary cooling circuits such as fill and drain from the container of such metallic liquid, and purification circuits of sodium cooled fast breeder nuclear reactors, such as Liquid Metal Fast Breeder Reactor (LMFBR).

However, it has been known that these pumps are not very efficient means of pumping any liquid, but despite their low efficiency these pumps are integrated and used in fast breeder nuclear reactors because of their high reliability and low maintenance due to absence of moving parts and that is why they are considered as a passive system. Besides, EM Pumps can be augmented for pumping impure sodium. For example, Indira Gandhi Centre for Atomic Research (IGCAR) institute has developed electromagnetic pumps of various capacities and successfully utilized them in experimental facilities.

Sodium is used as a coolant in fast breeder reactors because of its excellent neutronic and heat transfer characteristics. Sodium is a fairly good conductor of electricity also and this has led to development of many electromagnetic sensors and devices for use in liquid sodium. One such device is the electromagnetic pump which is used to pump liquid sodium in auxiliary circuits of a fast reactor and in various test facilities.

Though centrifugal pumps are used for pumping sodium in the primary and the secondary circuits of the reactor, electromagnetic pumps have been preferred in the auxiliary circuits. Low efficiency of these electromagnetic pumps prohibits their use in the main sodium circuits of a fast reactor. But their ability to operate even with impurities in sodium and their high reliability and almost maintenance free operation makes them an ideal choice. These electromagnetic pumps work on the principle that whenever a current carrying conductor is placed in a perpendicular magnetic field a force act upon it.

There are various types of electromagnetic pumps which can be mainly classified as conduction electromagnetic pumps and induction electromagnetic pumps [1]. In conduction electromagnetic pumps [1,2] the electric current in sodium flows via conduction from an external circuit which requires physical connection of the external circuit to the duct whereas in induction pumps, the current is induced in sodium without connecting an external circuit to the Stainless Steel (SS) duct. Since no physical contact is there with SS duct in case of induction pumps, they are considered to be more reliable compared to conduction pumps. Both the conduction and induction types of pumps have been developed and are in operation.

Indira Gandhi Centre for Atomic Research (IGCAR). Induction pumps are mainly of two types- the Flat Linear Induction Pump (FLIP) and the Annular Linear Induction Pump (ALIP). FLIP has a flat duct with stator normally on upper and lower part of the duct. It also has rectangular copper bars welded on its sides for providing a low resistance short circuit path and thereby increasing its efficiency. Besides, the flat duct is less suitable for high pressure applications therefore it was decided to use ALIP for Secondary Sodium Fill and Drain Circuit (SSFDC) of Prototype Fast Breeder Reactor (PFBR) presently under construction at Kalpakkam [3]. This pump is of flowrate $170 m^3/h$ and can deliver a head of $4 kg/cm^2$. This paper describes the design data of the pump and details of the testing of pump carried out at the Steam Generator Test Facility (SGTF) in IGCAR.

Electromagnetic pump working principle

Liquid metal loops are used for heat removal and for the study of certain magneto-fluidic phenomenon like MHD (Magneto-Hydro Dynamic) effects. These loops operate at high temperatures and carry fluids that are invariably toxic in nature. Ensuring the purity of fluid in a closed loop application needs non-intrusive pumps electromagnetic pumps. We have designed and analyzed a prototype electromagnetic pump to be used in mercury loop for carrying out various studies. This Electromagnetic pump is designed using permanent magnets which are mounted on periphery of rotor, which is rotated using DC motor. The liquid metal flows in a semicircular duct surrounding the rotor. See figure 1, where surface plot of magnetic field density superimposed with contours of magnetic potential of an electromagnetic pump simulated using Multiphysics software COMSOL®.

Figure 1: Schematic of heat removal liquid metal loops.

A magnetic field ($\vec{b}_{rc}$) always exists around the current ($\vec{I}$) carrying conductor. When this current carrying conductor is subjected to an external magnetic field ($\vec{B}_{rap}$), the conductor experiences a force perpendicular to the direction of $\vec{I}$ and $\vec{B}_{rap}$. This is because the magnetic field produced by the conductor and the applied magnetic field attempt to align with each other. A similar effect can be seen between two ordinary magnets.

This principle is used in an electromagnetic pump. The current is fed through a conducting liquid. Two permanent magnets are arranged to produce a magnetic field $\vec{B}_{rap}$ as shown in the figure 2. The supplied current has a current density ($\vec{J}$) and the magnetic field associated with this current can be called as 'Reaction magnetic Field ($\vec{b}_{rc}$)'. The two magnetic fields $\vec{B}_{rap}$ and $\vec{b}_{rc}$ attempt to align with each other, thus this causes mechanical motion of the fluid as illustrated in figure 2.

As we stated at the introduction of this appendix, a special type of liquid metal thermo-magnetic device is the Annular Linear Induction Pump (ALIP). It is known that electromagnetic pumps have a number of advantages over mechanical pumps: absence of moving parts, low noise and vibration level, simplicity of flow rate regulation, easy maintenance, and so on. However, while developing induction pumps, in particular ALIPs, we are faced with a significant problem of Magneto-Hydrodynamics (MHD) instability arising in the device. The manifestation of the instability does not allow linear induction pump development in a certain range of flow rate or the development of high efficiencies under certain flow rates and dropping pressure conditions.

Figure 2: Schematic of electromagnetic pump.

Linear induction pumps use a traveling magnetic field wave created by 3-phase currents, and the induced currents and their associated magnetic fields that generate a Lorentz force (See figure 3). The 3-phase winding arrangement for the solenoids usually follows the sequence AA ZZ BB XX CC YY where A, B, C denote the balanced 3-phase winding and X, Y, Z the opposite phase; for a direct balanced system, if $A = 0$, $\vec{B}=120^0$, and $C = 240^0$ then $X = 180^0$, $Y = 300^0$ and $Z = 60^0$. The correct winding sequence for the solenoids is obtained by arranging the sequence by the rising phase: AA ZZ BB XX CC YY. The complex flow behavior in this type of device includes a time-varying Lorentz force and pressure pulsation due to the time-varying electromagnetic fields and the induced convective currents that originate from the liquid metal flow, leading to instability problems along the device geometry. The determination of the geometry and of the electrical configuration of a thermo-magnetic device gives rise to an inverse magnetohydrodynamic field problem. When the requirements of the design are defined, this problem can be solved by an optimization technique.

Figure 3: Cross-section of an ALIP in a conceptual representation.

In figure B-3, ALIP, annular linear induction pump; Figure B-3(B) shows the cross section of the ALIP and it is an adaptation of a diagram originally drawn by Dong Won Lee, KAERI, Korea Atomic Energy Research Institute. This is adapted with permission [4].

The objective function which must be maximized in the optimization problem is derived from the main design requirement. Usually for an MHD device, this is the efficiency. Other design requirements can be taken into account as constraints. For a nonlinear system, such as for linear induction pumps, the main objective functions are low weight and high efficiency and so more than one maximum can exist. In this case a technique for global optimization must be used.

In a typical electromagnetic pump, the following basic principles do works as follows and can illustrated by figure 4 as:

- Liquid metal are conductors.
- Based on the Fleming's Left-Hand-Rule.
- Current flowing vertically through the liquid metal experiences a force ($\vec{F} = I\,\vec{L} \times \vec{B}$).

As it is illustrated in figure 5, more details and types of EM pump are revealed including different components involved with infrastructure of these types of pumps, that is used as part of cooling system in liquid metal breeder fissionable nuclear reactors [6].

Figure 4: Illustration of basic principles of electromagnetic pump.

Figure 5: Detailed components of electromagnetic pump.

Electromagnetic pump types

Types of Electromagnetic pumps includes:

- **Conduction pump:** In this case current is directly conducted into fluid through electrodes. Two variants, Alternative Current (AC) and Direct Current (DC).

- **Induction pump:** Current in the conducting fluid is induced by a traveling magnetic field.

- **Thermoelectric pump:** Current flowing through the liquid metal is derived directly from the thermal power contained in the hot liquid metal flow, such as the one that we can encounter in Liquid Metal Fast Breeder Reactor (LMFBR) of Generation III like French built Phoenix-II or Liquid Metal Breeder of Generation IV, such as Molten Salt Reactor (MSR) Sodium Cooled Fast Reactor (SFR). See Chapter 2 of the book by Zohuri [6].

As far as holistic observation of EM pump application is concerned, figure 6 presents such general application of device as two main driven scenario and they are:

- Cooling of nuclear reactor.
- Pouring and transportation of high temperature metals in foundry.

Figure 6: Simple applications of EM pump illustration.

If we take look at Electromagnetic pump form inside point of view as it is depicted via figure 7, we notice that the electrical current is induced by transformer action.

Figure 7: Schematic of electromagnetic pump from inside.

The transformer's primary coil T presented in figure 7 is connected to an AC single-phase power source. The transformer pole pieces are arranged in the shape of a picture frame and server as the carrier of magnetic flux. The transformer secondary winding S around the bottom leg of the picture frame as it is shown in figure 7 is molten metal and is formed by channels in ceramic parts. The turns ratio amplifies the electrical input current to produce very high amperage I in the molten metal.

Figure 8 is demonstration of a sectional view of electromagnet construction that is added, which consists of a C -Shaped pole piece and two excitation coils.

Figure 8: Further schematic of electromagnetic pump from inside.

The opening in the C straddles the necked-down section of the molten secondary turn, so the magnetic field H crossing the pole gap is perpendicular to the secondary current I, resulting in force Q to move metal through the pump.

In figure 9, we see the complete electromagnetic pump from inside perspective of infrastructure.

It is surrounded by or encapsulated in ceramic parts to protect it from molten metal contact to prevent any corrosions or any other side effects from liquid metal of internal nuclear core. Pump output Q is varied by controlling input power and can be regulated from almost drop-wise flow up to full bore delivery.

Figure 9: Complete schematic of electromagnetic pump from inside.

Figure 10: Working principle of annular linear induction pump [5].

Figure 11: Equivalent circuit of ALIP [5].

Working principle of annular linear induction pump (ALIP)

Like all other electromagnetic pumps Annular Linear Induction Pump (ALIP) works on the principle that whenever a current carrying conductor is placed in a perpendicular magnetic field a force acts on the conductor. The magnitude of this force is given by F=BIL, where "I" is the current through the conductor, L is the length of the conductor and B is the magnetic flux density in which the conductor is placed. In the case of ALIP, there is an annular region in which sodium flows, outside this annular region there are copper windings which are excited by 3-phase AC supply and produces a linearly moving magnetic field. This linearly moving magnetic field, according to Faraday's Law of induction, induces a current in the liquid metal (Figure-10). The interaction of this current and moving magnetic field produces a force on the sodium resulting in the pumping action as illustrated in figure 10, where it shows the working principle of Annular Linear Induction Pump [6].

Since the working principle of ALIP is similar to an induction motor, the equivalent circuit of ALIP (Figure 11) is also similar. At the same time there are some differences as compared to an inductor motor. Typical slip in induction motors is 0.05 or less whereas for ALIP typical slip is in the range 0.4-0.9 which leads to higher slip losses. The presence of ducts for containing sodium not only introduces additional resistive elements in the equivalent circuit but also leads to higher air-gap compared to that in an induction motor. These features lead to reduction in power factor and in efficiency when compared to that of an induction motor. Besides, end effects and hydraulic losses also lead to reduction in efficiency [5].

In figure 11, the following parameters do apply as:

R_1 -- Resistance of Stator Winding

X_1 -- Leakage Reactance of Stator Winding

X_m -- Magnetic Reactance

R_f -- Fluid Resistance

R_j -- Resistance of Inner Duct

R_w -- Resistance of Outer Duct

E -- Air-Gap Electromagnetic Force (EMF)

S -- Slip

Note that: The winding in the ALIP is circular pan-cake type and is different from conventional winding used in rotating induction motors.

Advantages and limitations of electromagnetic pumps

There exists some advantages to utilization of this pump in any application, where these EM pumps are installed, while along with such pros there exist some limitation for these pumps and they all listed below.

Advantages

- No moving parts, no vibrations or wear and tear.
- No seals, no splits
- Less maintenance and more reliable.
- Safe to be used.

Limitations of the Study

- Power losses due to back EMF, Ohmic heating.
- Limited uses since very few liquids are good conductors of electricity.

Conclusion

In conclusion, we can claim that EM pumps, are one of the best passive choice without integration of any external source of energy for moving parts to movie liquids from one side to another, specially, when are dealing with liquid metal environment, where we need heat transfer to take place. They rely on physics of electromagnetism phenomena for this purpose.

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