A Novel Electromagnetic Flowmeter for Liquid Metal of Nuclear Reactors

Xuejing Li*
Shanghai Institute of Measurement And Testing Technology, 201203, Shanghai,China
*Corresponding author’s e-mail: lixj@simt.com.cn

Abstract. Electromagnetic flowmeters (EMFM) play an important role in the cooling process of nuclear reactors, especially when the coolant is liquid metal. According to the working principle of the electromagnetic flowmeter, it is necessary to use a large-sized magnet to provide a uniform magnetic field, but this is very difficult for a core with limited space. This paper proposes a novel electromagnetic flowmeter with a single cylindrical permanent magnet. Compared with the conventional flowmeter, the volume of this electromagnetic flowmeter is greatly reduced. This paper perfects the theory of this single magnet flowmeter and compares it with the experimental results.

1. Introduction
Electromagnetic flowmeter (EMFM) measure of metal liquid is required in various technological processes ranging from the cooling of nuclear reactors to the dosing and casting of molten metals. The measurement principle of EMFM is to measure the flow rate by the potential difference caused by the flow of the conductive liquid through the measurement electrode in the magnetic field. [1-2]. The magnetic field of the flowmeter is composed of the magnetic field applied by the permanent magnet and the magnetic field generated by the conductive fluid. At present, the main problem of electromagnetic flowmeters during measurement is that in molten metals, especially at high temperatures, it is electrode corrosion and other interface effects, which can cause the parasitic potential differences will be caused by interface effect such as electrodes corrosion.

The excitation method of the electromagnetic flowmeter described in this paper is a non-contact technology, i.e. using a magnet installed on a fixed shaft, the magnet can rotate freely and magnetize vertically to provide a magnetic field for the measurement of the flowmeter [3-4]. The advantage of this design is that it enlarges the space limit of flowmeter. Many scholars have carried out research on this kind of new electromagnetic flowmeter. Smythe proposed an anti-shadow method to calculate the torque of a magnetic dipole rotating around an axis perpendicular to the thin plate [5]. Palmer found an analytical expression of the eddy current force on a circular current loop moving parallel to a thin conductive sheet of constant velocity [6]. Reitz and Davis used the Fourier transform method [7] to calculate the numerical solution of the force on the rectangular coil moving above the conductive plate. Kirpo et al. [8] analyzed the force of placing a magnetic dipole next to a slowly moving thin plate in any direction.

In this article, we analyzed the mathematical model of the rotary excitation module of the new electromagnetic flowmeter and measured a weakly induced magnetic field with a relative amplitude according to the Reynolds number $Rm = 10^{-4}$~$10^{1}$.
2. Theory analysis
This paper proposes an electromagnetic flowmeter (EMFM) with a single cylindrical permanent magnet, as shown in Fig. 1.

![Fig.1 Model of EMFM with free rotation magnetic](image)

The assumed conductivity of the medium $\sigma$ moves at a speed $v$ in the alternating current AC induced magnetic field $B$, alternating at an angular frequency $\omega$ harmonic.

From the Maxwell equation

$$E = -\nabla \Phi - \partial_t A$$  \hspace{1cm} (1)

$A$ is vector potential

$$B = \nabla \times A$$  \hspace{1cm} (2)

Where $\Phi$ is the scalar potential of the electric-field.

From Ohm’s law

$$j = \sigma(E + v \times B)$$  \hspace{1cm} (3)

From Eq. (1) (2) and (3)

$$j = \sigma(-\nabla \phi - \partial_t A + v \times \nabla \times A)$$  \hspace{1cm} (4)

Assuming the frequency of the alternating magnetic field to be sufficiently low to neglect the displacement current.

From the second Maxwell equation

$$j = \frac{1}{\mu_0} \nabla \times B$$  \hspace{1cm} (5)

From equation (5), the convection diffusion equation of the vector potential is obtained

$$\partial_t A + (v \cdot \nabla) A = \frac{1}{\mu_0 \sigma} \nabla^2 A$$  \hspace{1cm} (6)

Where $A$ is the gauge invariance, and $A$ has been used to specify the scalar potential as

$$\phi = v \cdot A - \frac{1}{\mu_0 \sigma} \nabla \cdot A$$  \hspace{1cm} (7)

The applied magnetic field changes with time

$$A_0(r,t) = A_0(r) \cos(\alpha t)$$  \hspace{1cm} (8)

Solution form
\[ A(r, t) = \mathcal{R}[A(r)e^{i\omega t}] \]  

Then Eq. (6) is the amplitude distribution of the vector potential which is form

\[ i\omega A + (\nu \nabla) A = \frac{1}{\mu_0 \sigma} \nabla^2 A \]  

(10)

The simple external magnetic field (2D) does not change along the direction of the unified vector \( j \). This vector can be specified by a single component of the vector potential

\[ \mathbf{B} = \nabla \times \varepsilon A = -\varepsilon \nabla \times A \]  

(11)

\[ A = \varepsilon A \]  

(12)

It means that \( \mathbf{B} \) has only two components in the plane perpendicular to \( \varepsilon \).

The \( \mathbf{B} \) interface between the conductive medium and the non-conductive medium is continuous at \( S \), so the boundary condition is

\[ |A|_S = |\partial_n A|_S = 0 \]  

(13)

Where \( |f|_S \) denotes the jump of a quantity \( f \) across the boundary \( S \); \( \partial_n \equiv (n \nabla) \) is the derivative normal to the boundary.

3. Experimental results and analyzing

3.1. The model of EMFM

As shown in Fig.2, the electrical conductivity of flow is 1.3e6S/m of NaK-78. The averaged velocity of the flow in the channel was adjustable in the range of 1.5m/s–3m/s. The magnet of flowmeter shown in Fig. 2 is consisted of a cylindrical SmCo-type permanent with diameter outer diameter \( R=12 \) mm, inner diameter is 25mm, wall thickness is 2.5mm and height \( L=35 \) mm. Magnetized perpendicularly to its axis with 0.5 T surface induction. The loop basically consists of circular tubes choose stainless steel.
3.2. Numerical results and analysing

(a)

Fig. 3 The relationship of average velocity and magnetic rotation frequency

(b)

Fig. 3 (a) two different distances between the magnet and the insulating pipe. It shows the flow sensor at the test section with a non-conducting pipe wall. Two different distances between the rotating magnet. Averaged flow velocities lower than 0.3m/s. This lower limit might be further decreased by a more elaborate fixing and bearing of the magnet axis.

We considered the velocity profile in the pipe modified by opening the valve of the test section partly. The higher flow velocities are created at the pipe side, where the magnet is placed. Fig. 3(b) shows different velocity profiles modified by various valve positions and 1mm distance to an insulating pipe wall. As seen, the sensor operation is almost insensitive of such a change of the velocity profile.

(c)
Fig. 3 (c) is a brass pipe with the valve completely open. The electric conductivity of the brass pipe is about 5 times higher than that of the melt. The influence of a relevant electric conductivity of the pipe wall on the sensor signal is shown. The rotation of the magnet is expected to induce electric currents mostly in the well-conducting pipe wall rather than in the melt. As a result, the driving torque due to the electric currents induced by the flow in the liquid metal is compensated by the braking torque due to the currents induced by the magnet rotation in the pipe wall at much lower rotation rates. Therefore, the obtained rotation rates are much lower compared to the case of an insulating pipe.

4. Conclusion
On the theoretical analysis and experimental data, the results of this paper can be summarized as follows:

1. The force and torque generated on the rotating magnet are related to the depth and range of the vortex.

2. Under the assumed conditions, considering the skin effect caused by the induced magnetic field, the mathematical model of the force and torque on the dipole is simplified.

3. At a certain speed, the driving torque generated by the layer translation and the braking torque generated by the rotation of the magnet are balanced. When ignoring mechanical friction or other external influences, the resulting rotational speed is independent of the strength of the magnet and the conductivity of the liquid metal compared to the driving torque. This is also the main advantage of this new electromagnetic flowmeter.

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