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Invited Paper

Electromagnetic induction phenomena for a nonmagnetic non-electroconducting solid sphere moving in a magnetic fluid

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Abstract

The present paper is a continuation of the study of the electromagnetic induction phenomenon when non-electroconducting solids move in a magnetic fluid. New experimental data are given from which the electromotive force is determined as a function of size and velocity of spherical solids.

1. Introduction

The electromagnetic induction phenomenon arises when the electric conductor moves relative to the magnetic field source. The electromotive force E generating in an electric conductor is proportional to the rate of variation of the magnetic flux Φ linked with the conducting loop.

The magnetic fluid is unique in that it accomodate a continuous motion of solids through a magnetized medium [1,2].

A combination of fluidity and magnetic properties of magnetic fluids allows the electromagnetic induction phenomenon to be realized when the magnetic field source and electroconducting loop do not move relative to each other, e.g. when an air bubble [3,4] moves through the magnetic fluid. A solid moving in a magnetized magnetic fluid is the source of unsteady disturbances of the magnetic field and gives rise to a variable magnetic flux through an electroconducting loop that envelops the fluid.

2. Theoretical considerations

Let a spherical body of radius a move steadily through a magnetic medium ($\mu/\mu_0 \gg 1$) with velocity v along the direction of the symmetry axis of a circular electroconducting loop with radius R. The distance from sphere center to the loop varies according to $l = l_0 - vt$ where l_0 is the distance at the initial time moment $t = 0$. The entire system is acted on by the external uniform magnetic field H oriented along the loop symmetry axis. Also, the nonmagnetic sphere disturbs the magnetic field, and the resulting field outside the sphere is governed by the known solution to Maxwell's equations [5].

In weak magnetic fields, for the linear portion of the curve of magnetization of the magnetic fluid, its magnetization $M = \chi H$ and the magnitude of the electromotive force (emf) can be determined by the expression [4]

$$E = \frac{6\pi\mu_0 H v l R^2 a^3}{(l^2 + R^2)^{5/2}} \frac{(1+\chi)\chi}{2\chi + 3},$$

where χ is the magnetic susceptibility and μ is the permeability of the magnetic fluid, respectively; μ_0 is the magnetic permeability of vacuum. The maximum amplitude of the emf, E_a, is attained at $l = R/2$.

The parameter $E_* = \mu_0 H v a^3/R^2$ can be chosen as the characteristic electromotive force. Here, μ_0 is the magnetic permeability of vacuum and H is the intensity of the external magnetic field. Then the amplitude of the dimensionless electromotive force, $\bar{E}_a = E_a/E_*$, for a given value of the magnetic susceptibility χ is constant and is determined by the expression [4]

$$\bar{E}_a = 5.4 \frac{(1+\chi)\chi}{2\chi + 3}.$$

3. Experimental

In our experiment, Helmholtz' coils (Fig. 1) allowing vertical and horizontal fields to be generated served as the source of a uniform magnetic field. A nonmagnetic non-electroconducting sphere 2 suspended by a filament moved vertically upward in magnetic fluid 3 driven with electric motor 4. The sphere velocity was determined by the photoelectron pair 5. Coil 6 composed of 500 copper-wire turns (mean winding radius 24 mm) served as the electro-

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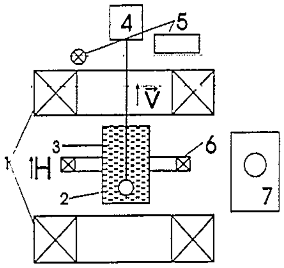

Fig. 1. Experimental set-up.

conducting loop. The electric signal induced in the coil was amplified and the amplitude of the emf was measured by an oscilloscope recorder 7. As a result, the electromagnetic induction phenomenon with the sphere moving both along and across the magnetic field could be studied using this device.

The magnetic transformer oil-base fluid (saturation magnetization 62.9 kA/m; density 1758 kg/m^3, dynamic viscosity 0.19 Pa/s) has the magnetization curve given in Fig. 2.

4. Results and discussion

The magnitude of the electromotive force is determined by the velocity and diameter of a moving sphere, by the value of the magnetic field, and by the conducting loop to sphere diameter ratio $L = R/a$.

When the sphere moves along the magnetic field, the dependence of the electromotive force on the sphere velocity is close to linear for different values of the field (Fig. 3) and the sphere radii (Fig. 4). A good coincidence of experimental and theoretical results is seen only in the region of weak magnetic fields where the relation $M(H)$ is linear. This is attributed to the fact that the theory has been constructed assuming constant magnetic susceptibility χ of the magnetic fluid while in the experiment χ decreases as the magnetic field increases. The experimen-

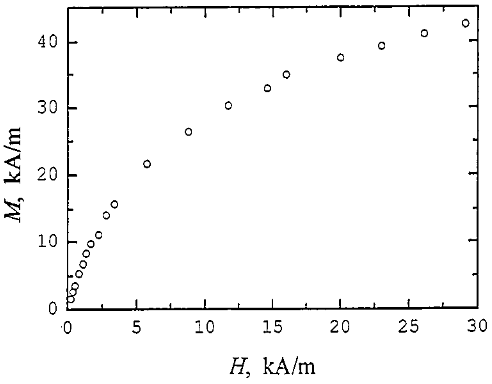

Fig. 2. Magnetization curve of the magnetic fluid.

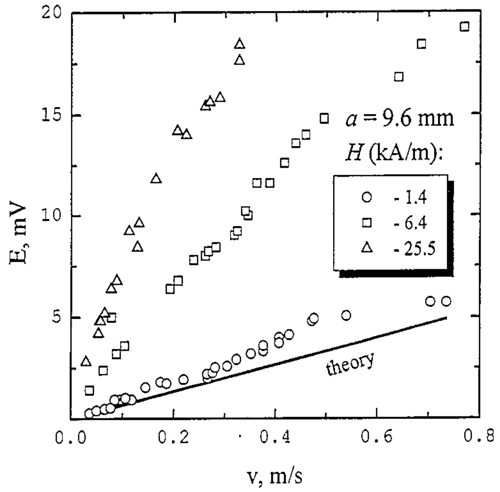

Fig. 3. Dependence of the electromotive force E on the sphere velocity v for different values of the vertical field H.

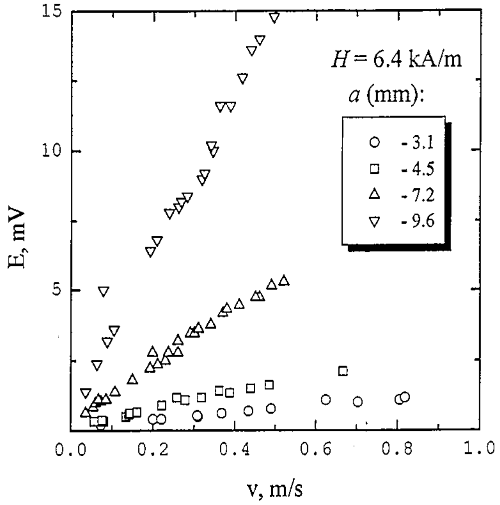

Fig. 4. Dependence of the electromotive force E on the sphere velocity v for different sphere radii a in vertical field H.

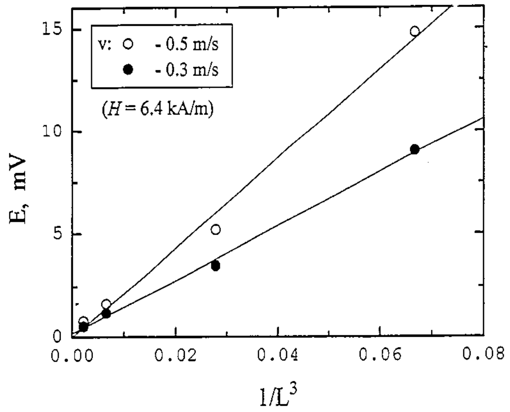

Fig. 5. Effect of the conducting loop to sphere diameter ratio $l = R/a$ on the electromotive force E (magnetic field is vertical).

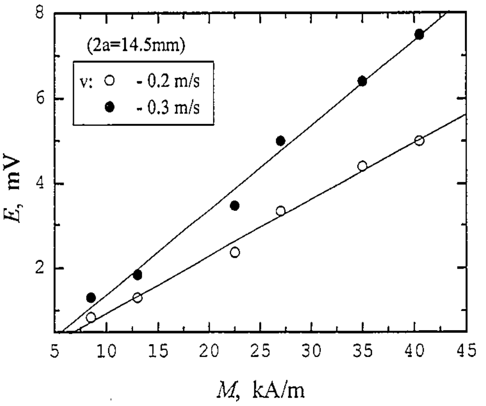

Fig. 6. The electromotive force E as a function of the magnetic fluid magnetization H.

tal potential $E(v)$ is much stronger for the fields of greater intensity.

Study reveals an inverse cubic dependence of emf on the ratio of sphere diameter to electroconducting loop, $1/L^3$ (Fig. 5).

The magnetic field intensity exerts a more dramatic effect on the emf in the region of weak fields. As the field increases, this dependence becomes weaker. It appears that the magnitude of the emf is practically linearly dependent on the magnetization of the magnetic fluid (Fig. 6), but it is independent of the intensity of the magnetic field, as follows from the theory.

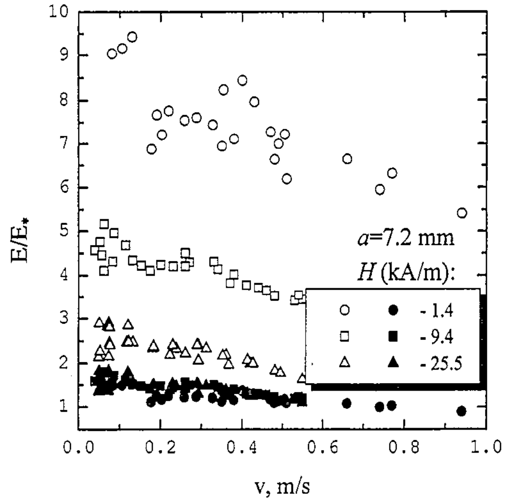

Fig. 7. Dependence of the dimensionless electromotive force E/E_* on the sphere velocity v.

When the characteristic emf is determined, not in term of the field intensity but in terms of the fluid saturation $E'_* = \mu_0 M v a^3/R^2$, all experimental points essentially approach each other (black points in Fig. 7) and are concentrated over the range of $\bar{E}' = E/E'_* \approx 1.5$.

In theory in a horizontal magnetic field, when a sphere moves along the symmetry axis of the electroconducting loop that passes through its center, emf must not be generated. In experiment, it has appeared that in horizontal magnetic field the value of the emf is an order of magnitude less than in vertical fields. Apparently, generation of the emf is bound up with a deflection of the sphere relative to the loop center.

5. Conclusion

The performed studies have demonstrated the generating of emf when a nonelectroconducting nonmagnetic body moves in the magnetic fluid in the presence of an external magnetic uniform field. A good coincidence between experiment and theory is seen in the region of weak magnetic fields when the experimental conditions more fit the statement of the linear problem.

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