EXPERIMENTAL STUDY OF FLOATING OF MAGNETIC BODIES IN A
MAGNETIZABLE FLUID

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One of the phenomena observed in a magnetizable fluid is the floating in such a fluid
of bodies having a greater specific gravity than the fluid itself. The floating of magnetic
and nonmagnetic bodies in magnetizable fluids was first investigated by Rosensweig [1, 2].
The main features of this phenomenon have been established theoretically, experiments being
mainly qualitative in character. The results of an experimental study of the floating of
nonmagnetic bodies in a magnetizable fluid [3] located in an inhomogeneous magnetic field
are in good agreement with the relationships obtained by Rosensweig [2] for the volume force
acting on the body.

The use of floating bodies in magnetizable fluids ("fluidmagnetic buoyancy") in the con-
struction of a series of technical devices, some of which are listed in [2, 4], calls for a
more detailed study of this phenomenon. Mathematical modeling of the floating of magnetic
bodies is particularly difficult in view of the complexity of describing the magnetic field
of a permanent magnet near the boundary separating the magnetic fluid and the surrounding
medium.

In the present paper we report the results of an experimental study of the forces acting
on a magnetic body placed in a magnetizable fluid. The magnetic body was a permanent magnet
made from barium ferrite (density $\rho_M = 4.64$ g/cm$^3$) shaped as a parallelepiped of horizontal
dimensions $18.9 \times 19 \text{ mm}^2$ and height 12.6 mm. The magnet was magnetized perpendicular to the
horizontal surfaces, which were set up parallel to the bottom of the vessel. The magnetic
field intensity at the center of the horizontal surface of the magnet was $6.74 \times 10^4 \text{ A/m}$.

The permanent magnet was stuck to one end of a copper rod, the other end of which was
attached to the pan of a VLA-200 analytical balance. The vessel, filled with magnetizable
fluid, was placed on the flat platform of a micrometer which could be displaced in the verti-
cal direction. By means of a stop screw, the position of the vessel could be fixed at any
height to within 0.1 mm. The displacement of the micrometer was 150 mm.

In accordance with the Bernoulli equation for a stationary magnetizable fluid [5]

$$p + \rho gh - \int_0^H M dH = \text{const.} \quad (1)$$

the pressure $p$ in the fluid is greater at places where the magnetic field intensity $H$ is
greater. Here $M$ is the magnetic moment of the fluid per unit volume induced by field $H$. The
nonuniformity of the pressure leads to the appearance of volume magnetic forces.

If the source of the magnetic field is immersed in the magnetizable fluid, the magnetic
lines of force are refracted at the boundary separating the two media of different magnetic
permeabilities. If the magnetic permeability of the fluid is higher than that of the medium
surrounding it, then the magnetic lines of force in the magnetizable fluid must be bunched

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together near the separating interface [6]. Accordingly, as the magnetic body approaches the walls of the vessel, a force which repels the body from the walls will act. Evidently, as the magnet is raised toward the surface of the magnetizable fluid, i.e., toward the fluid–air boundary, a force will act on the body, tending to attract it into the fluid.

Thus, in the absence of external sources of the magnetic field, the force acting on a magnet immersed in a magnetizable fluid in a vessel can be written

\[ F = F_M + F_A \]  

(2)

where \( F_M \) is the magnetic force, directed upward near the bottom of the vessel and downward near the free surface of the fluid, and \( F_A \) is the difference between the Archimedes force and the weight of the magnet.

The magnet can be balanced at any height by applying an additional force \( F' \), equal in magnitude to \( F \) but opposite in direction. In the region near the bottom of the vessel, a suitable weight must be added to the pan of the balance to which the magnet is attached in order to balance the magnetic body. In the region near the surface of the fluid, a state of equilibrium is achieved by adding weights to the other pan of the balance.

The force \( F_A \) can be written

\[ F_A = gV(p - p_\infty) - P \]  

(3)

where \( g \) is the acceleration of gravity; \( V \) is the volume of the magnetic body; \( p \) is the density of the magnetizable fluid; \( p_M \) is the density of the material of the permanent magnet; \( P \) is the total weight of the copper rod to which the magnet is attached plus the weight of the mounting unit.

The experiment consisted of measuring the balancing force \( F' \) with the aid of small weights for a given position of the magnetic body along the height of the vessel. Then, having measured \( F \) experimentally and estimating \( F_A \) from (3), the volume magnetic force \( F_M \) is readily determined using (2). The positive direction is taken to be vertically upward.

Three chemically prepared magnetizable fluids were used in the experiments: FMF-1, FMF-2, and FMF-3, in which the carrier liquid was kerosene, the surface-active material oleinic acid, and the magnetic phase magnetite (Fe₃O₄). The fluids differed in the concentration of solid magnetic material, which mainly determined the density of each. The densities of the three fluids were \( \rho_1 = 1.471 \), \( \rho_2 = 1.085 \), and \( \rho_3 = 0.948 \) g/cm³. The saturation magnetizations equaled, respectively, \( M_1 = 4.8 \times 10^4 \), \( M_2 = 2.1 \times 10^4 \), \( M_3 = 1.2 \times 10^4 \) A/m.

The weight of the permanent magnet was 21.76 G and the weight of the unit connecting the magnet to the measuring system was 13 G. For the three magnetizable fluids used in the experiments, the Archimedes force equaled, respectively, 6.6, 4.87, and 4.26 G.

Figure 1 shows the measured dependence of \( F_M \) for FMF-1 on distance \( L \), measured from the bottom of the vessel to the lower horizontal surface of the magnet. In this figure the numbers 1, 2, and 3 correspond to values of \( h = 43, 60, \) and 80 mm. The curves correspond to the vessel being filled with magnetizable fluid to three different levels \( h \). It can be seen that the force \( F_M \) reaches its greatest value near the bottom of the vessel, and in the region \( L = 0-10 \text{ mm} \) it is independent of the level \( h \) to which the vessel is filled, which is also measured from the bottom of the vessel. We note that at \( L = 8 \text{ mm} \) the magnetic force completely balances the sum of the other forces acting on the magnet, as a result of which the magnetic body can freely float in the fluid. With further increase of \( L \), the magnetic force changes sign and begins to pull the magnet into the fluid; the force \( F' \) required to balance the magnetic body is accordingly applied in the opposite direction — vertically upward. Depending on the level to which the vessel is filled with magnetizable fluid, there is observed in the region \( L > 8 \text{ mm} \) either a quite rapid growth of magnetic force with increasing \( L \) (for \( h = 43 \text{ mm} \)) or an almost flat region \( (h = 60, 80 \text{ mm}) \), the length of which depends on the value of \( h \). In this manner, the larger the value of \( h \), the broader the range of values of \( L \) in which the magnetic force is close to zero.

The variation of the magnetic force \( F_M \) with distance for fluids of different magnetizations is shown in Fig. 2, where the numbers 1, 2, and 3 correspond, respectively, to FMF-1, FMF-2, and FMF-3. Reducing the magnetization of the fluid leads, naturally, to a considerable reduction of \( F_M \) at each point along the height, although the form of the curves is essentially the same. It is interesting that the region where \( F_M \approx 0 \) decreases with increasing magne-
tization of the fluid. Free floating of the magnetic body also occurs for the fluids with smaller magnetizations, but at distances closer to the bottom of the vessel.

As the magnetic body approaches the fluid–air boundary, the resultant pressure gradient and the corresponding force deform the free surface of the fluid. As a result, the dependence of the force on distance in the vicinity of the free surface differs considerably from the dependence $F_M = F_M(I)$ at the bottom of the vessel. It is interesting that curvature of the free surface was visually observed in the transition zone from the flat part of the dependence $F_M = F_M(I)$ to the more rapid growth of $F_M$. Thus, for the vessel filled to $h = 80$ mm, curvature of the surface was observed at $\zeta \approx 40$ mm, while for $h = 60$ mm, deformation of the free surface was observed for $\zeta \approx 25$ mm.

We note that, besides the bulging of the free surface, stable cone-shaped peaks were observed on it with increasing $\zeta$, the number of which varied from 2 to 8 and depended, for a given $\zeta$, on the magnetization of the fluid. The height of the peaks also depended on the magnetization of the fluid and reached $\sim 12$ mm.

An important characteristic as far as the technical exploitation of a magnetizable fluid is concerned is the stiffness of the fluid–solid body system. Figure 3 shows a typical plot for FMF-1 of the dependence on $\zeta$ of the gradient of the magnetic force, which characterizes the stiffness of the system [7]. The stiffness of the system increases considerably in the range $\zeta < 10$ mm. At the same time, the stiffness tends to zero in the vicinity of the fluid–air boundary. Experiments showed that for the fluids with smaller magnetizations, the quantity $\Delta F_M/\Delta \zeta$ is much less at all points along the height; i.e., the stiffness of the system is directly connected with the magnetization of the fluid.

**LITERATURE CITED**

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