Heat transfer in magnetic fluids in magnetic and electric fields

Zhanna Vegera
MIREA - Russian Technological University, 78 Vernadskogo ave., Moscow, 119454, Russia
E-mail: vegera@mirea.ru

Abstract. The article presents the results of an experimental study of the heat transfer process in magnetic fluid under the influence of electric and magnetic fields of various configurations. It is shown that a constant electric field leads to an increase in the heat transfer coefficient when a certain threshold value of tension in a thin layer of magnetic fluid is reached. The possibilities of controlling the heat transfer process using the additional effects of homogeneous and inhomogeneous magnetic fields are found.

1. Introduction
Magnetic fluids are ultrafine colloids of ferromagnets with a unique combination of fluidity and the ability to interact with an external magnetic field [1-3]. This property makes them promising for use as heat carriers in devices with controlled heat transfer. However, experimental work indicated the absence of the influence of the magnetic field on the thermal conductivity of the magnetic fluid [4], which indicates a weak dependence of the structure of magnetic colloids on the magnitude of its intensity. New prospects for the development of studies of this kind appeared after the discovery of the interaction features of magnetic fluids with an electric field. In particular, it opens up the possibility of using the mesoscale structures discovered in [5–7]. This paper presents the study results of heat transfer in a thin layer of magnetic fluid placed in an electric and magnetic field, with the aim of creating devices with controlled magnetic and electric fields of heat transfer.

2. Materials and methods
The work presents the study results of heat transfer to a magnetic fluid in a system of horizontal plane-parallel brass electrodes with a radius of 5 cm. In this case, the upper electrode was heat releasing; it was heated by pumping water of a given temperature using a liquid thermostat through a heat-releasing system tightly pressed to the upper surface of the electrode. It allowed studying the processes of heat transfer in the absence of natural convection due to inhomogeneous heating of a liquid in the gravitational field. The thickness of the layer of the investigated magnetic fluid was 1 mm; the temperature difference did not exceed 30 K. A magnetite type liquid in kerosene with oleic acid was chosen as the study object as a stabilizer. Its saturation magnetization was 15 kA/m, and the volume concentration of the dispersed phase was 8%. The random scatter of the results did not exceed 8%.

To study the dependence of the heat transfer coefficient of a magnetic fluid on a magnetic field, the setup was equipped with a magnetizing system - a cubic coil with a five-section winding, which allows one to create a uniform magnetic field in a volume that is much larger than the volume occupied by the studied sample.
3. Results and discussion

It was established that the action of a constant electric field leads, at a certain threshold value of the interelectrode voltage, to a significant increase in heat transfer in the studied sample of magnetic fluid (figure 1). Here, $\alpha_0$ and $\alpha_e$ are the heat transfer coefficients in the absence and presence of an electric field, respectively.

![Figure 1](image1.png)

**Figure 1.** The dependence of the relative heat transfer coefficient on the interelectrode voltage (● - in the absence of magnetic field, ○ – in vertical magnetic field, $H = 9$ kA/m).

To determine the cause of the detected increase in heat transfer, observations were made using an optical microscope of a thin layer of magnetic fluid enclosed between two glass plates with a conductive coating. The layer thickness was $\approx 100$ μm.

It turned out that when the electric field in the layer is close in magnitude to the intensity corresponding to the beginning of the increase in the heat transfer coefficient, laminar electroconvection flows develop in the sample (figure 2). It should be noted that the observed bulk electroconvection is not directly related to the presence of colloidal particles in the medium; they play the role of passive indicators of emerging stable flows [6]. With an increase in the cell voltage above the critical one, the flows pass into a turbulent mode, which leads to increased heat transfer and an increase in the heat transfer coefficient.

![Figure 2](image2.png)

**Figure 2.** Electro-convective flows in magnetic fluid.

The latter circumstance served as the basis for using the magnetic field to regulate the process of heat transfer through the effect on electroconvection. It was found that the additional effect of a magnetic
field with a strength of $H=9 \text{kA/m}$ directed vertically has practically no effect on the change in the heat transfer coefficient (figure 1).

On the contrary, the action of a magnetic field of the same intensity, but directed horizontally, has a significant effect on the dependence of the heat transfer coefficient on the intensity of a constant electric field (figure 3), which may be due to a change in the nature of the convective motion of the liquid under the influence of a magnetic field [8]. An external magnetic field creates ponderomotive forces in the volume of the colloid, which stimulate the development of electroconvection flows, leading to intensification of heat transfer.

![Figure 3](image)

**Figure 3.** The dependence of the relative heat transfer coefficient on the interelectrode voltage (● - in the absence of magnetic field, ○ – in horizontal magnetic field, $H = 9 \text{kA/m}$).

The influence of an inhomogeneous magnetic field on the process of heat transfer in a magnetic fluid in the presence of electroconvection is somewhat different. When a measuring cell with a test sample is placed in an inhomogeneous magnetic field, the gradient of which coincides with the direction of gravity [9], the threshold value of the electric field strength increases at which the heat transfer coefficient begins to grow (figure 4). Thus, an inhomogeneous magnetic field has a stabilizing effect, inhibiting electroconvection.

![Figure 4](image)

**Figure 4.** The dependence of the relative heat transfer coefficient on the interelectrode voltage (● - in the absence of a magnetic field, ○ – in inhomogeneous magnetic field).
In the hydromechanics of liquids in external electric and magnetic fields, the question of ponderomotive forces is one of the main ones. From the point of view of the thermodynamic approach, the total force acting on a unit volume of a liquid medium consists of two components (in SI system, all designations are generally accepted) [10]:

Electric
\[ \vec{f}_e = \rho \vec{E} - \frac{1}{2} \vec{E}^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[ \varepsilon \left( \frac{\partial \varepsilon}{\partial \gamma} \right) \right], \]

and magnetic
\[ \vec{f}_m = \vec{j} \times \vec{B} - \frac{1}{2} \vec{B}^2 \nabla \mu + \frac{1}{2} \nabla \left[ \mu \left( \frac{\partial \mu}{\partial \gamma} \right) \right], \]

where current density can be expressed as follows:
\[ \vec{j} = \sigma \vec{E} + \rho \vec{V} + D^- \nabla \rho^- - D^+ \nabla \rho^+ + \nabla \times (\vec{B} \times \vec{V}). \]

In the last expression, the first term is the ohmic current, the second one is the convective current, the next two terms are the diffusion currents of negative and positive ions. The last term is the eddy convective bias current. Magnetic fluid is a weak electrolyte, where the current carriers are both magnetite particles [11] and impurity ions falling into it as a result of preparation. Thus, in theoretical terms, a solution to a whole range of interesting and complex physical problems is to be considered for the successful practical application of hydro-electromagnetic phenomena.

4. Conclusion

Studies have shown that in the presence of electroconvection in a flat layer of a magnetic fluid, the heat transfer intensity depends on the orientation of a uniform magnetic field. The effect of an inhomogeneous magnetic field leads to an increase in the threshold electric field strength corresponding to the beginning of heat transfer intensification.

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