Effects of magnetic field on heat transfer coefficient in ferrofluid-based computer cooling systems

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Abstract. The aim of this study is to investigate the liquid cooling system of computer processors on nanomagnetic liquids by numerical simulation and experimental research of heat transfer processes in the object under study. The research presents the results of numerical simulations and experimental studies of the heat transfer process in a heat exchanger of a liquid cooling system of computer processors based on ferrofluids under the influence of a magnetic field. The effect of the magnetic field on the thermal resistance of the system and the heat-transfer coefficient of the wall-liquid at various magnetic field intensities was estimated. The numerical model of the heat transfer process in the processor-heat exchanger system was studied as well.

1. Introduction

An increase in the degree of integration of microcircuits made it possible to repeatedly increase the density of the layout of elements and, as a result, the processing power of processors. The disadvantage of this approach is the increase in the density of heat fluxes of processors. Therefore, the main limiting factor for maximizing the processing power of the processor is the thermal solution that the processor cooling system can provide. A decrease in the quality of thermal management leads to an increase in the temperature of the processor and the activation of the thermal protection system of the processor. In this project, the task is to study the liquid cooling system of computer processors on nanomagnetic liquids by numerical simulation and experimental study of heat transfer processes in the studied object. A liquid cooling system based on ferrofluids or nanomagnetic liquids is a system that has a number of the following features. A liquid cooling system is a system in which the cooling of electronic components occurs during heat and mass transfer using a liquid coolant [1-3]. For this study, ferrofluids, or ferromagnetic fluids, which are a colloidal solution of magnetic particles in a liquid based on aqueous or oily chemicals, are proposed as a liquid coolant.

The essence of determining the influence of the thermophysical properties of ferrofluids in heat transfer systems is shown in [4-6].

2. Materials and methods

2.1. Preparation of nanoferrofluids for the experiment

Ferrofluids are colloidal mixtures consisting of nanoscale ferromagnetic or ferromagnetic particles suspended in a carrier fluid, usually an organic solvent or water [7]. Unlike commonly used kerosene-
based carrier liquids, this study used non-combustible liquids with low volatility based on Fe3O4 magnetites and aqueous solutions of ethylene glycol, and the stability of the colloidal liquid was evaluated. The liquid is composed of 48% of ethylene glycol, 48% of distilled water, 3% of magnetite powder with a dispersion of 5 μm, 1% of surfactant.

2.2. The study of the heat transfer process in a liquid cooling system of a computer based on ferrofluids

Ferrofluids, or ferromagnetic fluids, are a colloidal solution of magnetic particles in a liquid based on aqueous or oily liquids. Under the influence of a magnetic field, a nanomagnetic liquid will also change physicochemical properties, for example, viscosity and wetting. The combination of these factors requires studying the influence of the magnetic field on the heat transfer coefficient in the heat exchanger of the cooling system. The experimental heat exchanger of a liquid cooling system based on ferrofluids mounted on a processor is shown in figure 1. In the figure, the numbers indicate: a non-magnetic case with a chamber 1, a heat exchanger wall connected to the processor and an electromagnet made of soft magnetic stainless steel 2, a heat exchanger wall connected to an electromagnet made of soft magnetic stainless steel 3, fittings for output 4 and input 5 of liquid, magnetic circuit 6, fastening elements 7. Coolant enters the chamber of heat exchanger 1. On the surface of the processor packaging in contact with wall 2, the process of heat transfer to the cooling nanomagnetic liquid passes extending through the magnetic field in the gap between the magnetic circuit 6 and the wall 2.

![Figure 1](image)

**Figure 1.** Heat exchanger of a liquid cooling system based on ferrofluids.

The aim of the study is to investigate the dependence of the heat transfer process and the thermal resistance of the heat exchanger of the liquid cooling system based on ferrofluids on the parameters of the fluid flow and magnetic field in the heat exchanger. The study will be conducted by numerical simulation and thermophysical experiment.

The studies [8] proposed the method of three-dimensional calculation of heat flows in cooling systems of processors, including liquid ones. The studies [9] presented practical results of using this method. The process of heat transfer in the case of liquid cooling of the processor follows the path of the semiconductor chip of the processor - processor packaging - heat exchanger wall - cooling system fluid. The heat transfer process in the contact zones will be described through the boundary conditions of the second and third kind, respectively [10].

The stationary heat equation without internal heat sources is the Laplace equation in Cartesian coordinates:
\[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \]  

where: \( T \) - is temperature, \( x, y, z \) - are coordinates.

We set the boundary conditions:

- for \( S_1 \) (boundary conditions of the second kind):
  \[ q_i = \frac{P_1}{S_1} \]  
  where \( q_i \) - is the heat flux from the surface of the semiconductor chip of the processor, \( P_1 \) - is the power of the heat flux allocated from the area \( S_1 \) of the semiconductor chip of the processor;

- for \( S_2 \) (a boundary condition of the third kind based on the Newton law of cooling):
  \[ q_2 = \alpha(T - T_a) \]  
  \[ \alpha(T - T_a) = -\left(\lambda_x \frac{\partial T}{\partial x} + \lambda_y \frac{\partial T}{\partial y} + \lambda_z \frac{\partial T}{\partial z}\right) \]  
  \[ P_2 = \int_{S_2} q_2 dS \]  
  where \( q_2 \) - is the heat flux from the surface of the heat exchanger wall to the coolant of the liquid cooling system, \( \alpha \) - is the heat transfer coefficient, \( \lambda \) - is the heat conductivity coefficient, \( T_a \) - is the temperature of the coolant, \( P_2 \) - is the heat flux power allocated from the area \( S_2 \);

- energy conservation condition:
  \[ P_1 = P_2. \]

The system of differential equations was solved by the finite element method using SolidWorks Simulation [11].

For a numerical solution we set the boundary conditions:

- heat flux power \( P_1 = 25W \);
- contact surface area of the processor with the processor packaging \( S_2 = 2.25 \cdot 10^{-4} m^2 \) and the diameter of the heat exchanger chamber \( D_2 = 0.02m \);
- the temperature of the coolant is 24 °C.

The coefficient of thermal conductivity \( \lambda_2 \) of the processor packaging is constant and equal to the coefficient of thermal conductivity of copper. The coefficient of thermal conductivity \( \lambda_1 \) of the wall of the heat exchanger made of soft magnetic material is equal to the coefficient of thermal conductivity of stainless steel.

3. Results and discussion

The distribution of the temperature field over the cross section along the axis of symmetry in the processor package and the heat exchanger wall, depending on the value of the heat transfer coefficient, is shown in figure 2.
To create a magnetic field, the heat exchanger was placed in the gap of a U-shaped electromagnet with an inductance of 0.615H. A current I of 0A, 1.6A, 3.2A was passed through the winding of the electromagnet. The flux of magnetic induction B was respectively, 0Wb, 0.492Wb, 0.984Wb.

![Figure 2](image.png)

**Figure 2.** Distribution of the temperature field over the cross section along the axis of symmetry in the processor package and the heat exchanger wall depending on the value of the heat transfer coefficient $\alpha \left[ \frac{W}{(m^2 \cdot K)} \right]$: a) 750, b) 1000, c) 1250, d) 1500, e) 1750, f) 2000.

To create a fluid flow through the heat exchanger, an Alphacool DC-LT pump was used with a passport flow rate of 120 liters per hour at 3600 rpm. A heat source with a power of 25W, a coolant temperature of 24°C. The experiment series were repeated three times. The results of an experimental study of the dependence of the temperature difference between a heat source and a ferrofluid-based coolant at varying pump speeds and magnetic fluxes are shown in figure 3.

The results of the thermophysical experiment to study the temperature difference between a processor crystal and a cooling fluid based on ferrofluid with a 3% magnetite particle concentration showed that in the entire range of pump speeds from 240 to 3050 rpm, the increase in the flux of magnetic induction from 0 to 0.984 Wb leads to an increase in the thermal resistance of the system. Thermal resistance for the same value of the pump speed increases by 2.1% on average.

Comparing the experimental results and the results of numerical simulation of heat transfer processes in a heat exchanger, we can obtain the dependence of the average heat transfer coefficient on the surface of the wall-ferrofluid of the heat exchanger of the liquid cooling system and the dependence on various pump speeds and magnetic flux. These results are shown in figure 4.
Figure 3. The graph of the dependence of the temperature difference between the heat source and the cooling fluid based on ferrofluid at various pump speeds and magnetic flux B 1) 0Wb; 2) 0.492Wb; 3) 0.984Wb.

Figure 4. Graph of the dependence of the average heat transfer coefficient $\alpha$ on the wall-ferrofluid wall surface of a heat exchanger of a liquid cooling system at various pump speeds and magnetic flux B 1) 0Wb; 2) 0.984Wb; 3) 1.968Wb.

4. Conclusions

From the results of numerical modeling and a thermophysical experiment we can conclude that the magnetic field influences the heat transfer processes in the liquid cooling system of computer processors based on ferrofluids. It is necessary to carefully consider the relationship between the viscosity coefficient of ferrofluid and the heat transfer coefficient.

The heat transfer coefficient in this case characterizes the intensity of heat transfer between the surface of the body and the coolant and takes into account the specific conditions of this process. Unlike the coefficients of thermal conductivity and thermal diffusivity, the heat transfer coefficient is not a thermophysical characteristic of a substance; its determination is possible as a result of a thermophysical experiment. The most significant influence on the value is exerted by the thermal conductivity coefficient, specific heat, density, dynamic and kinematic viscosity of the liquid. Besides, an increase in viscosity leads to an increase in the thickness of the boundary layer. The thermal resistance of the boundary layer is decisive in the processes of convective heat transfer [10].

The results of the thermophysical experiment to study the dependence of the heat transfer coefficient between the wall of a heat exchanger and a cooling fluid based on ferrofluid with a 3% concentration of magnetite particles showed that over the entire range of pump speeds from 240 to 3050 rpm, an increase in magnetic flux from 0 to 0.984 Wb leads to the heat transfer coefficient. The heat transfer coefficient for the same value of the speed of the pump is reduced by of 3.1% on average.

When studying the liquid cooling systems of computer processors based on ferrofluids one must take into account an increase in the thickness of the boundary layer due to an increase in the viscosity of the coolant in a magnetic field. There are two factors worth mentioning here: the dependence of the viscosity of ferrofluids on the concentration of particles and the factor of an increase in the boundary layer during the flow of ferrofluids with a change in the magnetic field flux vector.

The reason for the increase in the thickness of the boundary layer is the processes of interaction of ferromagnetic particles and their influence on the properties of ferrofluids in a magnetic field.
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