Evaluation of diamagnetic nanofluid ability to heat transfer in the strong magnetic field

A Roszko and E Fornalik-Wajs
AGH University of Science and Technology, Department of Fundamental Research in Energy Engineering, al. Mickiewicza 30, 30-059 Krakow, Poland

E-mail: roszko@agh.edu.pl

Abstract. The main goal of this paper was to analyze the strong magnetic field influence on the diamagnetic fluids. The experimental analysis of thermo-magnetic convection of silver nanofluid and distilled water were presented. The effect of various magnetic induction values and various temperature differences on the transport processes were checked. Estimation of the heat transfer was able due to the thermoelement signal analysis. The results revealed changes in the convection due to the nanoparticles addition in some ranges stronger, in other weaker, under applied conditions. It was proven, that heat transfer of diamagnetic fluid (single and two-phase) could be influenced by the strong magnetic field application.

1. Introduction
Since 1990s, when the strong magnetic field became available, ideas of its utilization are continuously growing and one of the research directions is toward weakly-magnetic substances and their behaviour in such environment. At the moment, these investigations have mainly fundamental meaning, however the possible applications can be found in medicine or engineering dealing with nanofluids.

Most common materials are classified as diamagnetics, which have a constant and negative magnetic susceptibility, so they are repelled from magnetic field. Water is one of those diamagnetic substances. Moreover, its physical properties can be affected with magnetic field application [1,2]. Therefore, many numerical and experimental studies concerning magnetic field influence on water in different enclosures were reported [3-5]. On the other hand, the nanofluids are very specific ones and rather difficult to find in the nature. They were created to change the properties of commonly available fluids. The attention was paid, for example to their thermal conductivity (engineering applications) [6] or magnetic (medicine – contrast for magnetic imaging) [7]. The investigations regarding influence of magnetic field on weakly-magnetic nanofluids are mostly numerical [8,9]. First attempts of authors to experimental analysis were reported in [10-12]. In these papers two aspects of research were undertaken: flow structure and heat transfer. The flow structure analysis was problematic, because optical method of flow visualization (e.g. PIV, PIT) could not be applied due to the nanofluid opaqueness. Therefore, the signal analysis using the Fast Fourier Transform was the only way to get an information about the flow structure.

In the present paper the strong magnetic field effect on the diamagnetic single-phase fluid (distilled water) and two-phase nanofluid were investigated. The main purpose of this studies was to examined possibility of heat transfer control by the strong magnetic field and its evaluation. Special
consideration was focused on the effect of nanoparticle addition and the results comparison with pure water ones.

2. Experimental methodology

2.1. Working fluids
The studied fluids were distilled water and nanofluid containing distilled water and 0.1 vol.% of 50-60 nm size silver nanoparticles. The nanofluid was prepared by two-step method with ultrasonic mixing (using pulse mode: 2 seconds ON, 2 seconds OFF) for 40 minutes. Such method of mixing was applied in accordance to suggestions reported in [13]. This stage of experiment has great significance due to the difficulties in proper preparation of nanofluid [14]. It needs to be emphasized that both of nanofluid components are diamagnetics, therefore the magnetic buoyancy forces acting on them by external magnetic field have the same direction.

The thermo-physical properties of nanofluids were calculated on the basis of formulas presented in [10] and their values are shown in table 1. It should be mentioned that for each measurement series the thermo-physical properties were calculated taking into account average temperature value inside the enclosure.

Table 1. Thermo-physical properties of Ag0.1 nanofluid

| Property                        | Symbol | Unit              | Values for measurement at ΔT = 5 K | Values for measurement at ΔT = 8 K | Values for measurement at ΔT = 15 K |
|--------------------------------|--------|-------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Thermal conductivity           | $k_{nf}$ | [W·(mK)$^{-1}$]  | 0.6018                              | 0.6044                              | 0.6105                              |
| Density                        | $\rho_{nf}$ | [kg·m$^{-3}$]  | 1009.70                             | 1009.39                             | 1008.55                             |
| Specific heat                  | $c_{p,nf}$ | [J·(kg·K)$^{-1}$] | 4176.35                            | 4175.38                            | 4173.67                            |
| Thermal expansion coefficient  | $\beta_{nf}$ | [K$^{-1}$]     | 21.2·10$^{-5}$                      | 22.75·10$^{-5}$                    | 26.25·10$^{-5}$                    |
| Dynamic viscosity              | $\mu_{nf}$ | [kg·(m·s)$^{-1}$] | 9.84·10$^{-4}$                     | 9.48·10$^{-4}$                     | 8.70·10$^{-4}$                     |
| Mass magnetic susceptibility   | $\chi_m$ | [m$^3$·kg$^{-1}$] | -14.3·10$^{-9}$                   | -14.3·10$^{-9}$                   | -14.3·10$^{-9}$                   |
| Volume magnetic susceptibility | $\chi$   | [-]              | -14.4·10$^{-6}$*                   | -14.4·10$^{-6}$*                   | -14.4·10$^{-6}$*                   |

* - measured value at 20°C

2.2. Experimental apparatus
Schematic view of experimental system is presented in figure 1. Superconducting magnet is able to generate up to 10 Tesla of magnetic induction and in such case the square magnetic induction gradient is equal to 900 T$^2$/m. Place, where maximal gradient occurs, corresponds with the area where the strength of the magnetic buoyancy force has the maximal value and thus the greatest impact. Accordingly, an experimental cubical enclosure was situated in that selected location during the experiments (see figure 1(a), position of the vessel indicates the maximal magnetic induction gradient). The cube side walls were made of Plexiglas and in one of them six thermocouples were placed (arranged as in figure 1(b)). The top wall was made of copper and above it was cooling chamber with flowing water maintained at constant temperature by a thermostatic bath. The bottom wall was also made of copper and underneath it was a rubber-coated nichrome wire used as a heater, it was connected with a DC supply unit. The temperature of magnet test section (in the form of opening
going through the whole device, shown schematically in figure 1(a)) was 18°C, that is why thermostating bath was preparing the cooling water of this temperature. The temperature of heated wall could be adjusted (through the changes of supplied power) to obtain the required temperature difference. In both, cooled and heated walls were placed three thermocouples. The recorded signals from all of temperature sensors were stored on PC computer using data acquisition system. Stored data enabled the heat transfer and flow structure analyzes.

![Figure 1](image)

**Figure 1.** Experimental (a) apparatus and (b) enclosure [10].

3. Signal analysis methodology

The signals recorded during the measurements were used for further calculations and analysis. The analyses were performed in two directions – the heat transfer and the flow structure. The first direction is within the scope of this paper, whereas the second one was outside of it.

3.1. Heat losses

A first significant step was to investigate the heat losses dependence on the temperature difference in the system. It was assumed in accordance with [15] that the heat losses depended only on the kind of fluid and the present temperature difference, but did not depend on phenomena occurring inside the enclosure. The cube was inverted to obtained the conductivity state inside it. The heated wall was at the top, while the cooled one – at the bottom. In order to better system insulation the vessel was covered with cotton wool. Furthermore, after stabilization and stratification of fluid in the system the measurements were performed for 5 minutes. Subsequently, the magnet was activated and restabilization lasted from half to one and half hour. The measurements were conducted for magnetic induction values: 2, 4, 6, 8, 9 and 10 Tesla. All steps were repeated for four temperature differences: 3, 5, 8 and 15 K. Therefore, based on the obtained results the formula for silver nanofluid was as follows:

\[ Q_{\text{loss,Ag0.1}} = 0.07445 \cdot \Delta T \]  \hspace{1cm} (1)

where \( \Delta T \) is the temperature difference.

Equation (1) represents the function of one variable (temperature difference) even the influence of magnetic field and properties change were also investigated. However, these parameters had minor influence on the total losses, that is why they were omitted in the final function.

Determination of heat losses for distilled water was done in similar way. Procedure was slightly different because there were six studied temperature differences: 2, 3, 5, 10, 17 and 22 K and magnetic field influence was not considered. The dependence of heat losses for water could be expressed as:

\[ Q_{\text{loss,water}} = 0.06917 \cdot \Delta T \]  \hspace{1cm} (2)
The presented equations were applied for Nusselt number calculations described in the next subsection.

3.2. Thermo-magnetic convection measurements
In the next step the measurements of convection state were performed without and with magnetic field utilization. Taking into account convective and conducted heat rates, the Nusselt number could be written as:

$$\text{Nu} = \frac{Q_{\text{net, conv}}}{Q_{\text{net, cond}}}$$

(3)

where $Q_{\text{net, conv}}$ represents the convective heat rate and $Q_{\text{net, cond}}$ – the conducted one. The convection and conduction heat rates were calculated in accordance with the method first described in [15] and adopted in following way:

$$Q_{\text{net, conv}} = Q_{\text{conv}} - Q_{\text{loss}}$$

(4)

$$Q_{\text{theor, cond}} = \frac{k \Delta T d^3}{d} = k \Delta T d$$

(5)

where $Q_{\text{conv}}$ is the heat rate supplied to the system, $Q_{\text{loss}}$ is the lost heat rate, $k$ is the thermal conductivity coefficient of water and nanofluid in respective cases, $d$ is the cubical enclosure size.

In accordance to the assumption, that the heat loss did not depend on the phenomenon occurring inside the cubical enclosure and substituting (4) and (5) to (3) the Nusselt number could be defined:

$$\text{Nu} = \frac{(Q_{\text{conv}} - Q_{\text{loss}})(k \Delta T)}{d}.$$  

(6)

Knowing all of necessary components the Nusselt number was determined. The results of heat transfer are represented as Nusselt number dependence on thermo-magnetic Rayleigh number.

Estimation of thermo-magnetic Rayleigh number was done with the following formula:

$$\text{Ra}_{\text{Tm}} = \text{Ra}_t [1 - \gamma B_z (B_{\text{max}})^3 (\partial B_z/\partial z)(B_{\text{max}})^3]$$

(7)

where $\text{Ra}_t$ is the thermal Rayleigh number written as:

$$\text{Ra}_t = g \beta \rho c_p \left( \frac{\mu k}{d} \right)^{-1} d^3 \Delta T$$

(8)

while $\gamma$ is the magnetization number described as:

$$\gamma = \chi_m B_{\text{max}}^2 \left( \frac{\mu_m \gamma d}{\mu} \right)^{-1}$$

(9)

and $g$ is the gravitational acceleration; $\beta$ is the thermal expansion coefficient of water or nanofluid; $\rho$ is the density of water or nanofluid; $c_p$ is the specific heat of water or nanofluid; $\mu$ is the dynamic viscosity of water or nanofluid; $k$ is the thermal conductivity of water or nanofluid; $d$ is the characteristic dimension; $\Delta T$ is the temperature difference; $\chi_m$ is the mass magnetic susceptibility of water or nanofluid; $B_{\text{max}}$ is the magnetic induction in the centre part of coil; $B_z$ is the magnetic induction in the position of enclosure centre; $\mu_m$ is the vacuum magnetic permeability. The value of $B_z$ and $\partial B_z/\partial z$ were calculated numerically [10] based on the superconducting magnet coil technical data [16] and led to the relations:

$$B_z = 0.6265 \cdot B_{\text{max}},$$

(10)

$$\partial B_z/\partial z = -5.8742 \cdot B_{\text{max}}.$$  

(11)

4. Force system
In the experimental enclosure heated from the bottom and cooled from the top the nanofluid convection was present. In such system, placed in the magnetic field the additional force appeared – the magnetic buoyancy force. Its direction and strength depended on magnetic field strength and orientation, kind of fluid and its properties. The position of enclosure corresponded to the highest force magnitude and it was discussed in the previous section. The fluid was diamagnetic, and if its temperature exceeded the reference temperature the magnetic buoyancy force was attracting it. When its temperature was lower than the reference temperature it was repelled from the area of strong magnetic field. At the same time, the gravitational buoyancy force was present and acting on the hot fluid upward and on the cooled fluid downward. Actually, in the chosen position the gravitational and
magnetic buoyancy forces were in opposite directions. A small attenuation of convection was expected from this force system, because the gravitational force dominated (it was about two times stronger than the magnetic one).

Values of the forces could be calculated by following equations:
the gravitational buoyancy force:
\[ F_g = -g \rho \beta (T - T_0) \]
(12)
the magnetic buoyancy force:
\[ F_m = \chi_n \rho \beta (T - T_0) \left( \frac{2 \mu_n}{\mu_{\text{air}}} \right)^{-1} \nabla B^2 \]
(13)
where \( T_0 \) is reference temperature equal to the arithmetical average of cooled and heated walls’ temperature.

5. Results and discussion

5.1. Heat transfer results for water and Ag0.1 nanofluid at 5 K of temperature difference
In figure 2 the influence of particle addition on the heat transfer performance was verified. The comparison between water and Ag0.1 nanofluid at 5 K of temperature difference are shown. The heat transfer results are represented by ratio between actual Nusselt number and the Nusselt number value for natural convection at 0 T of magnetic induction. Such way of data presentation was done for clear distinction of magnetic field influence on analyzed fluids.

![Figure 2. Nusselt number ratio dependence on the thermo-magnetic Rayleigh number](image)

For weak values of magnetic induction (up to 4 T) and lowest values of thermo-magnetic Rayleigh number there were almost no changes of the Nusselt number values. Observed influence of magnetic field could be found at 8 T, which corresponded to about -1.8 \times 10^7 and -1.9 \times 10^7 of thermo-magnetic Rayleigh number for water and nanofluid, respectively.

The Nusselt number ratio values \( \frac{\text{Nu}}{\text{Nu}_0} \) where \( \text{Nu}_0 \) indicates the Nusselt number without magnetic field) for water decreased with increasing strength of magnetic field. The maximal value of water Nusselt number was obtained for natural convection (without magnetic field application). It suggested that the magnetic buoyancy force reduced the convection of diamagnetic fluid under applied conditions. On the other hand, the ratio values increased with increasing magnetic induction for Ag0.1 nanofluid. To understand and to explain these results the magnetic buoyancy force will be recalled.

Water and silver are both diamagnetics, however silver has about 100 times higher magnetic susceptibility than water. Therefore, the magnetic field influenced the nanoparticles much stronger. At 8 Tesla of magnetic induction \( (\text{Ra}_{\text{TM}} \approx -1.8 \times 10^7) \) the small enhancement effect was observed. It looked like the magnetic buoyancy force was “mixing” the fluid, trying to trap it close to the heated and cooled plates but was not able to keep it there. Since the magnetic susceptibility of silver is higher than the water one, authors supposed that the nanoparticles were playing role of mixing agents. The
difference of magnetic susceptibility could caused the heat transfer enhancement effect. The gravitational buoyancy force was responsible for the fluid movement as in the natural convection case.

Furthermore, the heat rates analysis was performed to study this phenomena in details. The heat rates are represented by ratio between the convective and conduction heat rate to corresponding heat rates without magnetic field. The results of convective and conduction heat rate ratios are shown in figure 3(a) and (b).

The values of convective heat rate were close to each other up to 6 T and they are decreasing for water while increasing for Ag0.1 of higher than 6 T of magnetic induction. On the right hand-side diagram the conduction heat rate ratio values did not change much, however it could be said that for water the values were higher than for Ag0.1 nanofluid.

![Convective and conduction heat rate ratios versus magnetic induction](image)

**Figure 3.** (a) Convective and (b) conduction heat rate ratios versus magnetic induction

5.2. Heat transfer results for Ag0.1 nanofluid at 5 K, 8 K and 15 K of temperature difference

The graphical relation between the Nusselt and thermo-magnetic Rayleigh numbers for Ag0.1 nanofluid of various temperature differences and various magnetic induction are presented in figure 4.

![Nusselt number versus thermo-magnetic Rayleigh number](image)

**Figure 4.** Nusselt number versus thermo-magnetic Rayleigh number

The Nusselt number at first increased then decreased for all studied temperature differences. The reasons of such trend are related to the force system and their mutual interaction. The maximal value of Nusselt number occurred at 9, 8 and 8 T for 5, 8 and 15 K of temperature difference, respectively.

The convective and conduction heat rates ratios were determined and they are presented in figure 5. The convective heat rate ratio values were similar up to 6 T, for all temperature differences. However, the values were increasing for higher than 6 T of magnetic induction at smallest temperature
difference. For other temperature differences the convective heat rate ratios were decreasing at the strongest magnetic field. Whereas, the results of conduction heat rate ratio did not present clear tendency, the values were almost constant.

![Graph showing convective and conduction heat rate ratios versus magnetic induction.](image)

**Figure 5.** (a) Convective and (b) conduction heat rate ratios versus magnetic induction

6. **Summary**

In this paper the experimental analysis of thermo-magnetic convection of distilled water and silver nanofluid were presented. The detailed steps of the analyzed signal procedure were described. The influence of various magnetic induction values and various temperature difference on the transport processes were checked. Mutual interaction between the gravitational and magnetic buoyancy forces had influence on the nanofluid behaviour during the experiments. The magnetic buoyancy force values was about 49% of the gravitational buoyancy ones for each case.

The obtained results revealed nanoparticles addition effect on the convection enhancement in some ranges under applied conditions. It was proven that the heat transfer of diamagnetic fluid (single or two-phase) could be changed by strong magnetic field application. The results demonstrated some ability to control the diamagnetic fluid flow with magnetic field utilization, however to understand the full potential of this method further investigations are needed. It is also necessary to compare this results with numerical calculations, which will be done in the next step of undertaken subject.

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