

Comparative study of convective heat transfer in water and water based magnetizable nanofluid for thermal applications

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An experimental research carried out to investigate the convective heat transfer in a water based magnetizable nanofluid by natural convection is reported. The hot wall was a flat disk, heated from below. The open air played the role of the cold wall, as the upper surface of the fluid was free, at atmospheric pressure and temperature. Comparative tests were conducted using distilled water and water based magnetizable nanofluid. Several heating regimes were tested. The addition of nanoparticles in a usual heat transfer fluid as water led to a decrease in the heat transfer performance by natural convection.

(Received February 25, 2008; accepted April 2, 2008)

Keywords: Magnetizable nanofluid, Natural convection heat transfer, Nanoparticles

1. Introduction

The use of magnetic nanofluids (widely known as ferrofluids or magnetic fluids) – a special class of nanomaterials, as heat transfer fluids, had become a topic of intensive research starting about a decade ago [1-9]. The possible applications envisaged the use of phase-change heat transfer (boiling/condensation) or forced convection heat transfer modes. Both terrestrial and microgravity applications were taken into consideration due to the possibility to replace the gravitational field by the magnetic field in micro-g environments. Examples of such possible applications are: cooling systems for electric transformers, magnetocaloric heat pipes, pulsating heat transfer tubes and heat sinks. It should be noted also that, opposite to usual magnetic liquids prepared for their traditional applications (sensors, sealings etc), the magnetizable nanofluids for heat transfer should have a low concentration of magnetic nanoparticles in order to make them competitive with the non-magnetic nanofluids. On the other hand, an advantage of using magnetizable nanofluids, beside the possibility of control by an applied magnetic field, is the vast experience in preparation of such complex fluids gained over more than three decades [e.g. 11-14].

Recent results presented in the open literature state that among the possible mechanisms that may affect the convective heat transfer in nanofluids (similar to the case of magnetizable nanofluid in zero magnetic field) are the transport mechanisms associated to the relative (slip) velocity developed by the nanoparticles with respect to the carrier fluid, such as: inertia, Brownian diffusion, thermophoresis, Magnus effect, fluid drainage and gravity. A model proposed by Buongiorno [15] for convection

transport in nanofluids states that, when the turbulent transport of nanoparticles dominates, the particles are carried by turbulent eddies, while if the opposite case occurs, Brownian diffusion and thermophoresis may become important slip mechanisms. Also, several other mechanisms are related to the larger increase in the effective thermal conductivity for a very low volume fraction ($\Phi \leq 1\%$) of solid nanoparticles of less than 10 nm in size, like ballistic transport of energy carriers within nanoparticles, formation of nanoparticle structures through agglomeration (in fractal-like shape), clustering and networking [16].

Natural convection in usual heat transfer fluids was widely studied both experimentally and numerically, for various types of configurations. However, for various reasons (like low heat transfer coefficient, uniqueness of the problem in closed cavities configuration), in the case of nanofluids this heat transfer mode was less approached [16]. Our work has as final target a new type of heat exchanger for automotive thermal management applications using a magnetizable nanofluid as working fluid and an applied magnetic field to control the heat transfer process. The study reported here envisaged the evaluation of the natural convection heat transfer characteristics for a magnetizable nanofluid of low concentration in comparison with the carrier fluid, for a certain configuration of cavity that may be suitable to accomplish our target.

2. Experiment

The water-based magnetizable nanofluid tested in this work is part of a series of magnetizable nanofluids (water-based and hydrocarbon-based) specially prepared

and characterized within the framework of our research project [14,16]. The sample properties at 20 °C are as follows: density $\rho_{\text{MNF}} = 1082 \text{ kg/m}^3$, viscosity $\eta_{\text{MNF}} = 2.4 \cdot 10^{-4} \text{ Pa}\cdot\text{s}$, specific heat capacity $c_{p,\text{MNF}} = 3863.044 \text{ J/kgK}$, saturation magnetization $M_s = 50 \text{ Gs}$, volume fraction of magnetite (Fe_3O_4) nanoparticles $\Phi = 1.02 \%$. In Fig. 1 is shown the experimental setup used to analyze the natural convection heat transfer in a tube, heated from below.

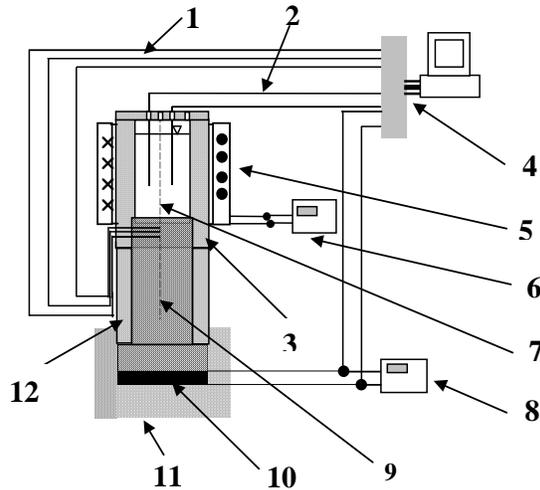


Fig. 1. The setup for the natural convection experiment.

The experimental cell (3) is a cylinder made of acrylic resin ($d_{\text{int}} = 16 \text{ mm}$, $H = 50 \text{ mm}$). The heating surface (9), made of aluminum ($d_{\text{surf}} = 18 \text{ mm}$) is placed at the bottom side of the cell. A nickel heater (10) of resistance $R = 0.14 \Omega$ powered by a power supply (8), is used to heat the surface. The temperature inside the magnetizable nanofluid (7) and in the heating surface was monitored by K-type thermocouples (1,2). The cell and aluminum bar were insulated by acrylic resin (12), while the resistance heater was placed in a ceramic insulating frame (11). The effect of an applied DC magnetic field generated by a coil (5) can be also studied using the same setup. The coil is powered by a power supply (8). The experimental data were collected using a data acquisition system NI 6042E (4), embedded in a PC using a dedicated LabView program. A SCXI 1000 amplifier was used to achieve high accuracy temperature measurements.

The experiments were carried out at constant heat flux. To determine the heat flux and the heated surface temperature, a set of three thermocouples were placed in the axis of the aluminum bar at known distances (3, 5 and 5 mm), close to the heated surface. The heat flux was estimated from the Fourier law, based on the temperature gradient between two thermocouples (T_{p1} mounted at 13 mm and T_{p3} at 3 mm, from surface):

$$\dot{Q} = \frac{\lambda_{Al}}{x} (T_{p1} - T_{p3}) \quad [W] \quad (1)$$

where $\lambda_{Al} = 235 \text{ W/m}\cdot\text{K}$ is the aluminum thermal

conductivity and $x = 10 \text{ mm}$ is the distance between the position of thermocouples in the axis of the bar.

The heated surface temperature was determined using the indication of the thermocouple placed nearest to the surface (at 3 mm) and the heat flux given by Eq. (1):

$$T_p = T_{p3} - \dot{q} \frac{\delta}{\lambda_{Al}} \quad [K] \quad (2)$$

where $\delta = 3 \text{ mm}$.

The average liquid temperature at stationary conditions, far from the surface (T_i), was determined from the readings of the set (2) of thermocouples in Fig. 1 (T_{i1} and T_{i2}):

$$T_i = (T_{i1} + T_{i2})/2 \quad (3)$$

The heat transfer coefficient, h , was determined based on the Newton's law:

$$h = \frac{\dot{q}}{(T_p - T_i)} \quad [W/m^2K] \quad (4)$$

where $\dot{q} = \dot{Q}/A$ and $A = \pi d_{\text{int}}^2/4$.

The experiments were run at first with distilled water, for several regimes of heat flux (heating of the surface) to test the experimental cell and compare the results with known empirical correlations. Then, there were repeated using the sample of water-based magnetizable nanofluid for the same heat flux conditions.

3. Results

The results obtained for the natural convection heat transfer using distilled water were compared with a known correlation from literature. In this type of heat transfer mode the deciding factor is the Rayleigh number:

$$Ra = Gr \cdot Pr = \frac{g\beta\Delta T l^3}{\nu^2} \cdot \frac{\nu}{\alpha} \quad (5)$$

where g is the gravitational constant, β is the volume expansion coefficient, l is the characteristic length ($l = 0.9d_{\text{int}}$), ν is the kinematic viscosity, α is the thermal diffusivity. There are a considerable number of empirical correlations in literature for natural convection heat transfer, for different types of geometries and fluids. Most of these have the form:

$$Nu = CRa^n \quad (6)$$

where Nu is the Nusselt number ($Nu = hl/\lambda$), C and n being constants, depending on the value of Ra .

In Fig. 2 is shown a comparison between the experimental results and a well known correlation for natural convection from a plate heated from below [17]:

$$Nu = 0.54Ra^{1/4} \quad (7)$$

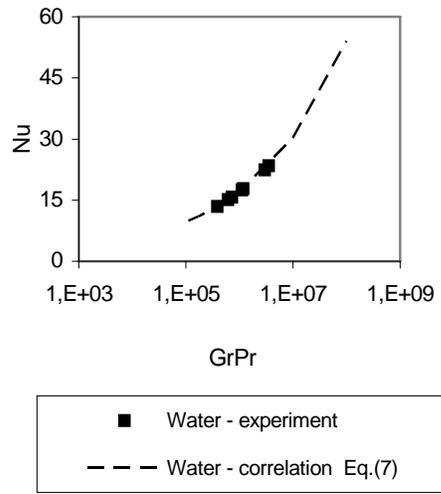


Fig. 2. Comparison of experimental results for distilled water with correlation (7).

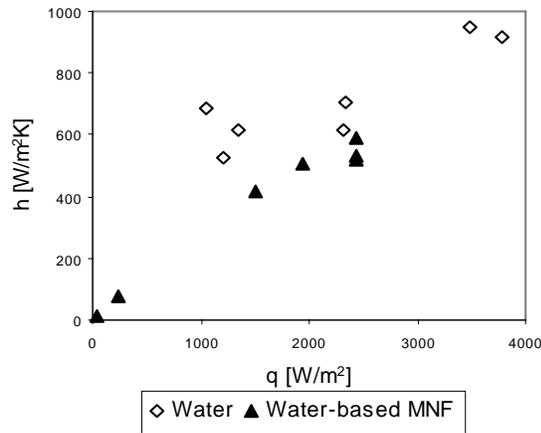


Fig. 3. Comparison of experimental results of water and magnetizable nanofluid at steady state conditions.

One can observe that the present experimental results are well described by Eq. (7).

In Fig. 3 are shown the experimental results for water and the magnetizable nanofluid sample at steady state. It was found that, for the same input of heat flux, the heat transfer coefficient of the magnetizable nanofluid is lower in comparison with that of water. Thus, the effect of addition of solid metallic nanoparticles in water is negative for natural convection heat transfer, similar to other experimental results using non-magnetic water-based nanofluids (Ti-O2 nanofluids, CuO nanofluids) [18,19].

4. Discussion

The analysis of our experimental results, using measured or estimated values of the thermophysical

properties of the magnetizable nanofluid and literature data for water to calculate the Grashof and Prandtl numbers show an interesting behavior, for the same average temperature:

$$T_{med} = (T_l + T_p) / 2 \tag{8}$$

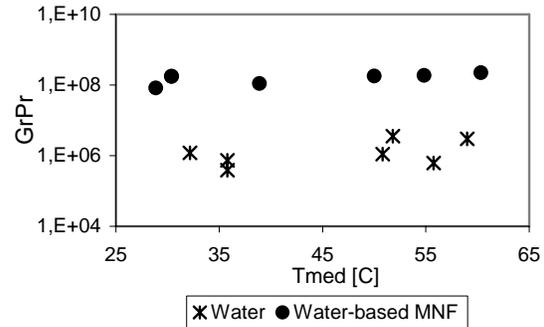


Fig. 4. The influence of the thermophysical properties of the magnetizable nanofluid and water on Gr·Pr.

As shown in Fig. 4, the value of Gr·Pr is in average 10³ times higher for the magnetizable nanofluid but, also due to a higher thermal conductivity of the magnetizable nanofluid, the value of Nusselt number is lower than that for water. It means that in order to obtain a value of the natural convection heat transfer coefficient for the magnetizable nanofluid similar to that of water, in the same working conditions, the turbulence should be further increased. That is, what actually “makes the difference” (influence the convective heat transport) in nanofluids are their thermophysical properties.

The application of a time-varying (e.g. rotating) magnetic field in the case of a nanofluid with particles having rigid dipole moment might give a solution to the problem.

5. Conclusions

The goal of the present research is the development of a new type of heat exchanger for automotive thermal management system using a magnetizable nanofluid as heat transfer fluid of low concentration, specially prepared for this application. This paper presents the results of the evaluation in the case of natural convection heat transfer.

We have tested the heat transfer performance of a magnetizable nanofluid ($\Phi = 1.019\%$) for a certain range of heat flux density and surface average temperature that are of interest for our case and using a configuration suitable for this purpose.

In the explored range of heat flux density, we obtained lower values of the heat transfer coefficient for the magnetizable nanofluid than those for the carrier fluid (water), the relative difference between the corresponding coefficients ranging from 4 to 16%. These results agree with other experimental data for non-magnetic water-based nanofluids, in the case of natural convection heat transfer

mode [18,19].

The influence of the addition of nanoparticles in the carrier fluid on the thermophysical properties reflected in the values of the characteristic numbers Grashof and Prandtl, for the same average temperature of the nanofluid and carrier fluid, is determined.

Acknowledgments

This work is funded by the National Council of University Research of Romania (CNCSIS), Research Grant type A, No. 665/2005.

References

- [1] M. Takahashi, K. Shinbo, R. Ohkawa, M. Matsuzaki, A. Inoue, *J. Magn. Magn. Mater.* **122**, 301 (1993).
- [2] V. Gogosov, A. Ya. Simonovskii, *Magnitnaya Hidrodinamika* **29**, 62 (1993).
- [3] S. Kamiyama, K. Ueno, Y. Yokota, *J. Magn. Magn. Mater.* **201**, 271 (1999).
- [4] K. Nakatsuka, B. Jeyadevan, S. Neveu, H. Koganezawa, *J. Magn. Magn. Mater.* **252**, 360 (2002).
- [5] L. Vékás, M.-I. Piso, I. Potencz, D. Bica, *Proc. 1-st Int. Symp. Microgravity Res. & Appl. Phys. Sci. Biotechnology, Sorrento, Italy, 2000*, p.183.
- [6] F. D. Stoian, Gh. Pop, D. Bica, V. Stoica, O. Marinică, L. Vékás, *Proc. 3-rd Int. Symp. Two-Phase Flow Modelling and Experimentation, Pisa, Italy, Eds: G. P. Celata, P. Di Marco, A. Mariani, R. K. Shah, 2004*, p. 971.
- [8] A. Postelnicu, *Int. J. Heat Mass Trans.* **47**, 1467 (2004).
- [9] S. Kenjereš, K. Hanjalič, *Int. J. Heat Fluid Flow* **25**, 549 (2004).
- [11] R. E. Rosensweig, *Ferrohydrodynamics*, Cambridge Univ. Press (1985).
- [12] B. M. Berkovsky, V. Bashtovoi (Editors), *Magnetic Fluids and Applications. Handbook*, Begell House Inc., New York (1996).
- [13] D. Bica, *RO Patent 90078*, 1985.
- [14] L. Vékás, D. Bica, O. Marinică, M. Raşa, V. Socoliuc, F. D. Stoian, *J. Magn. Magn. Mater.* **289**, 50 (2005).
- [15] J. Buongiorno, *Transactions of ASME, J. Heat Transfer*, **128**, 240 (2006).
- [16] X.-Q. Wang, A. S. Mujumdar, *Int. J. Therm. Sci.* **46**, 1 (2007).
- [17] D. Ștefănescu, A. Leca, L. Luca, A. Badea, M. Marinescu, *Heat and Mass Transfer. Theory and Applications (in Romanian)*, Teaching and Pedagogical Publ. House, Bucharest (1983).
- [18] D. Wen, Y. Ding, *6-th World Conf. Exp. Heat Trans., Fluid Mech., Thermodyn., Matsushima, Miyagi, Japan, 2005*, Paper 2-b-9.
- [19] C. H. Li, G. P. Peterson, *Proc. 9th AIAA/ASME Joint Thermophysics and Heat Transfer Conf., San Francisco, California, 2006*, Paper AIAA 2006-3120.

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