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Research articles

# Enhancement in heat transfer of a ferrofluid in a differentially heated square cavity through the use of permanent magnets

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The natural convection heat transfer of a magnetic nanofluid in a differentially heated cavity is investigated with and without an applied external magnetic field. The effects of volume fraction, magnetic field configuration, and magnetic field strength are investigated. Spherical $Fe_2O_3$ nanoparticles with a diameter of 15–20 nm are used in the nanofluids. Volume fractions ranging between 0.05% and 0.3% are tested for the case with no magnetic field, while only a volume fraction of 0.1% was tested in an externally applied magnetic field. The experiments were conducted for a range of Rayleigh numbers in $1.7 \times 10^8 < Ra < 4.2 \times 10^8$. The viscosity of the nanofluid was determined experimentally. An empirical correlation for the viscosity was determined, and the stability of various nanofluids was investigated.

Using heat transfer data obtained from the cavity, the average heat transfer coefficient and average Nusselt number for the nanofluids are determined. It was found that a volume fraction of 0.1% showed a maximum increase of 5.63% to the *Nu* at the maximum *Ra*. For the magnetic field study, it was found that the best-performing magnetic field enhanced the heat transfer behaviour by an additional 2.81% in Nu at $Ra = 3.8 \times 10^8$.



## 1. Introduction

When considering the key role that a fluid's thermophysical properties plays in the performance of a heat transfer system, it becomes clear as to why a nanofluid may want to be considered over conventional fluids. This is due to the enhancement of the thermal conductivity of conventional fluids brought about by the addition of nanosized particles mixed into the base fluid [1–5]. While the thermal conductivity may be enhanced by introducing nanoparticles into the fluid, this process has also been found to increase the viscosity of nanofluids as well [3–9]. Furthermore, if magnetic nanoparticles are used in the nanofluid, it has been shown that both the nanofluids viscosity and thermal conductivity can be altered by applying a magnetic field to the nanofluid [4,10–13].

Colla et al. [5] and Toghraie et al. [7] investigated the behaviour of the viscosity of $Fe_2O_3$–$H_2O$ and $Fe_3O_4$–$H_2O$ nanofluids, respectively. Both groups found that the addition of nanoparticles increased the viscosity of the nanofluid considerably. The maximum viscosity obtained was found to be more than twice that of the base fluid in both studies. Both groups also observed that the maximum viscosity obtained corresponded to the maximum tested volume concentration. In a study by Amani et al. [8], the effects of volume fraction and magnetic field strength on the viscosity of a $MnFe_2O_3$–$H_2O$nanofluid was investigated. Under no externally applied magnetic field, a maximum increase in viscosity of only 14% was found at a volume concentration of 3%. The same nanofluid showed an increase of 75% while under the influence of a constant magnetic field of 400 G. Ghasemi et al. [14] investigated the viscosity of an $Fe_3O_4$–Kerosene nanofluid. It was found that the nanofluid exhibited shear thinning behaviour. This study also found that applying a magnetic field to the nanofluid did indeed increase its viscosity. Furthermore, it was found that the nanofluid showed hysteretic behaviour having a greater viscosity after the magnetic field was removed than when compared to its initial state. Paul et al. [15] found similar results with a $Fe_3O_4$–$H_2O$ nanofluid exhibiting both hysteretic and shear thinning behaviour as well.

Nurdin et al. [3] showed that while $Fe_2O_3$–$H_2O$nanofluid had a larger thermal conductivity than its base fluid; this enhancement could be amplified in the presence of magnetic field with a maximum enhancement of 39.09% found for the 0.6% volume fraction case with a magnetic field of 300 G. This study also investigated the effects of the direction of the magnetic field. It was found that the magnetic field had an insignificant effect on the thermal

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**Nomenclature**

| | |
|---|---|
| $\dot{Q}$ | heat transfer, W |
| $\dot{m}$ | mass flow rate, kg/s |
| $C_p$ | specific heat, J/kg/K |
| $T$ | temperature, K |
| $A$ | area, $m^2$ |
| $h$ | heat transfer coefficient, $W/m^2 \cdot K$ |
| $k$ | thermal conductivity, $W/m \cdot K$ |
| $L$ | length, m |
| $g$ | gravitational acceleration, $m/s^2$ |
| $m$ | mass, kg |
| $V$ | volume, $m^3$ |
| $r$ | radius, m |
| $t$ | thickness, m |
| *Greek symbols* | |
| $\beta$ | thermal expansion coefficient, 1/K |
| $\rho$ | density, $kg/m^3$ |
| $\mu$ | viscosity, $Pa \cdot s$ |
| $\phi$ | volume fraction |
| *Subscripts* | |
| $o$ | outlet |
| $i$ | inlet |
| $h$ | hot |
| $c$ | cold |
| $s$ | surface |
| $nf$ | nanofluid |
| $f$ | base fluid |
| $min$ | minimum |
| $n$ | nanoparticle |
| $v$ | void |

conductivity in a perpendicular direction to the magnetic field. Philip et al. [13] found similar behaviour in $Fe_3O_4$–hexadecane nanofluids. This study showed a tremendous increase in thermal conductivity of 216% for a 4.5% volume concentration nanofluid in a 101 G magnetic field. The thermal conductivity also showed hysteretic behaviour similar to that of the viscosity.

The effect of stabilizer mass fraction to the thermophysical properties of metal oxide nanofluid was investigated by Khairul et al. [16] where they found that the amount of stabilizer (SDBS) used not only has an impact on the stability but the pH and zeta potential of the nanofluid as well. It was also found that the SDBS and pH had an influence on the viscosity and thermal conductivity of the nanofluid.

In the study by Ghodsinezhad et al. [17], the heat transfer of $Al_2O_3$–$H_2O$ nanofluids in a differentially heated cavity was investigated for $3.49 \times 10^8 \leqslant Ra \leqslant 1.05 \times 10^9$. For the 0.1% volume fraction case, an increase of 15% in the heat transfer coefficient was found. All other tested volume fraction either above or below 0.1% yielded poorer results. It was also noted that these results disagree with many of the numerical studies done for similar problems. Cadena-de la Peña et al. [18] experimentally analysed the heat transfer behaviour of AIN– and $TiO_2$–oil based nanofluid in natural convection inside a vertical annulus. The nanofluid was tested in the range $10^6 \leqslant Ra \leqslant 10^7$. Only the 0.01 wt% showed any improvement to *Nu* while the other cases showed a negative influence to the *Nu*. The study also found disagreement with numerical studies. Considering the work of Azizian et al. [19] where the influence of a magnetic field on the heat transfer behaviour of a $Fe_3O_4$–$H_2O$ nanofluid in forced convection is investigated, it was found that applying an external magnetic field to the nanofluid could yield an increase of up to 300% to the local heat transfer coefficient.

To summarise the literature presented, several groups have shown that magnetic nanofluids not only have increased thermophysical properties but also that these properties can be enhanced tremendously by the use of magnetic field leading to potential increases in heat transfer capabilities of the nanofluids. An example was presented, where due to the tunability of a magnetic nanofluid, it was possible to drastically increase the heat transfer performance of a magnetic nanofluid by excitation through an external magnetic field. For the case of interest to this study, namely natural convection, this can be more difficult to achieve due to the strong correlation between the flow behaviour and thermophysical properties as shown by Ghodsinezhad et al. [17] and Cadena-de la Peña et al. [18] where only one case in each study presented any enhancement. This, however, has not discouraged numerical investigations into magnetohydrodynamic (MHD) or MHD mixed convection phenomena [20–27], again showing promising results with regard to heat transfer performance. There is, however, a lack in experimental work to compare these numerical results too.

As such, the goals of this study is to experimentally investigate the heat transfer behaviour of a magnetic nanofluid in natural convection as a means to determine its feasibility as a heat transfer fluid for the case with and without an applied external magnetic field. The results obtained will also breach the gap between experimental and numerical work as it may be used to provide solutions that numerical work may be compared against.

## 2. Materials and methods

### 2.1. Nanofluid preparation

The nanofluid was prepared by dispersing $Fe_2O_3$ nanoparticles into deionised (DI) water. Spherical nanoparticles with a diameter of 15–20 nm, as specified by the manufacturer, were procured from US Nanomaterials Research, Inc. A mixing process was used to break down agglomerates present in the nanofluid and to ensure that the nanoparticles were dispersed homogeneously. A Hielscher UP200S ultrasonic mixer with pulse time set to 60% and amplitude set to 65% was used to carry out the mixing process. The mixing process was carried out for 40 min for 60 ml samples. After the initial mixing process, 95% pure sodium dodecyl sulphate (SDS) was introduced into the nanofluid. The nanofluid is sonicated again to ensure that the SDS is mixed in thoroughly. The same pulse time and amplitude setting were used. Sonication was only carried out for 2 min during this mixing process. The mass of SDS added to the nanofluid was chosen to be the same as the mass of nanoparticles as this ratio has been found to provide the maximum increase in stability of the nanofluid for various stabiliser [28,29]. The volume fraction of nanofluids prepared this way falls within the range of 0.05% and 0.4%. Table 1 shows the masses of the DI-water, dry nanoparticles and SDS used in the preparation of the 60 ml samples.

An SV-10 sine-wave vibro viscometer with a range between 0.3 mPa·s and 10000 mPa·s and accuracy of ±3% was used to determine the viscosity of the prepared nanofluids. The temperature of the nanofluid was varied from 15 °C to 60° C such that the viscos-