EXPERIMENTAL STUDY ON CAVITY FLOW NATURAL CONVECTION IN A POROUS MEDIUM, SATURATED WITH AN Al_2O_3 60%EG-40%WATER NANOFLUID

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ABSTRACT

Natural convection is convection where the fluid motion is driven by buoyancy forces. Porous media and nanofluids have an impact on the heat transfer capabilities of thermal systems. The present experimental study is part of ongoing research and lies at the intersection of buoyancy driven flow in a cavity, porous mediums and nanofluids. The nanofluid consists of Al_2O_3 nanoparticles in the base fluid of 60% ethylene glycol (EG) and 40% water. A Rayleigh number range of $6 \times 10^3 < Ra^* < 1.6 \times 10^4$, for a volume fraction of 0.2% nanoparticles. The porous medium used is glass spheres of 16mm. In this research the effective viscosity of the nanofluid was determined experimentally while the effective thermal conductivity was available in the literature. The results showed that heat transfer is affected by both the porous medium and the nanofluid. The results show that the heat transfer in the case of porous media with nanofluid is more than the case of pure base fluid. However, more experimentation for a wider range of Rayleigh numbers will be a part of future works of this ongoing research.

NOMENCLATURE

Da	[-]	Darcy Number
g	$[m/s^2]$	Gravity Constant
H	[m]	Cavity Height
h	$[W/(m^2 \cdot K)]$	Convective Heat Transfer Coefficient
k	$[W/(kg \cdot K)]$	Conduction Heat Transfer Coefficient
K	$[m^2]$	Permeability
L	[m]	Cavity Length
Nu	[-]	Nusselt Number
Pr	[-]	Prandtl Number
Ra	[-]	Rayleigh Number
T	[K or ˙C]	Temperature
Special Characters		
β	[1/K]	Volumetric Expansion Coefficient
μ	$[Pa \cdot s]$	Dynamic Viscosity
ν	$[m^2/s]$	Kinematic Viscosity
ρ	$[kg.m^2]$	Density
ϕ	[-]	Nanofluid volume fraction or Porosity depending on the subscript
Subscripts		
bf		Base Fluid
f		Fluid
H		Height
L		Length
nf		Nanofluid
p		Nanoparticle
pm		Porous Medium
s		Solid Matrix

INTRODUCTION

Convective heat transfer in fluid-saturated porous medium has received much attention in the last few decades and is relevant to a wide range of applications such as underground heat pump systems, solar engineering, packed sphere beds, chemical catalytic converters, heat exchangers and geothermal applications. Extensive reviews of the subject are given in various textbooks for instance, Nield and Bejan [1], Vafai [2], Pop and Ingham [3], Ingham [4] and Bejan et al. [5].

Natural convection inside a porous filled cavity has attracted the attention of many researchers and is very applicable to solar receiver technology. Although more numerical works have been published, a few examples of experimental papers could be found. Prasad et al. [6, 7] presented experimental results for natural convective heat transfer in an annulus. Bories and Combarnous [8] presented numerical and experimental results in a sloping porous layer. The porous medium used was spherical glass beads. Seki et al. [9] presented an experimental study with a rectangular cavity. The fluids included water, transformer oil and ethyl alcohol.

A recent and emerging field, first coined by Choi [10], is the field of nanofluids. The field is based on the premise that suspending solid nanometer sized particles, with higher thermal conductivity, in a conventional heat transfer fluid, would augment the heat transfer capabilities of that fluid. Because nanoparticles could potentially be added to any liquid heat exchangers to augment heat transfer, the potential applications are endless. However, the addition of the nanoparticles to a fluid effects more than its thermal conductivity and different models to predict fluid properties and behaviors have been proposed. Buongiorno [11], Tiwari and Das [12] and Aybar et al. [13].

Free convection of nanofluids in clear cavities with differentially heated walls has been studied both numerically and experimentally. Hwang et al. [14] performed a numerical investigation on a rectangular cavity, following the experimental results presented by Putra et al. [15]. A previous 2D numerical work on Al_2O_3 is also presented by Khanafer et al. [16] Putra et al. [15] performed an experimental investigation of free convection of nanofluids in a horizontal cylinder that is heated from the one side and cooled from the other side. They reported paradoxical results; when the volume fraction was increased, the heat transfer rate was decreased. The work of Putra was extended by an experimental study performed by Nnanna et al. [17] of Al_2O_3 nanoparticles in water. Their focus was to estimate the range of volume fractions for which heat transfer is enhanced. They also wanted to determine the impact of volume fraction on the Nusselt number. They found that for small volume fractions $0.2\% < \phi_{nf} < 2\%$ heat transfer is augmented, but for higher volume fractions, the heat transfer coefficient is reduced due to the reduction of the Rayleigh number. Hu [18] presented experimental and numerical results for natural convection in a square cavity containing TiO_2-water nanofluid. Ho [19] presented an experimental study of Al_2O_3 in water in a vertical square enclosure. Their results are consistent with those found by Nnanna [17].

A further extension to the above mentioned fields is natural convection in porous medium filled cavity, saturated by a nanofluid. This problem has been studied numerically by numerous authors.

Sheremet et al. published a series of papers numerically studying free convection in a porous medium filled cavity saturated by a nanofluid, using Boungiorno's nanofluid model [20–23] or Tiwari and Das' nanofluid model [24, 25].

Grosan et al. 2015 [26] numerically studied this problem, while accounting for internal heat generation as well.

Dastmalchi et al. 2015 [27] presented a study of free convection of Al_2O_3 water nanofluid in a square cavity containing an aluminum porous medium.

Nguyen et al. 2015 [28] numerically studied natural convection of Cu-water nanofluid in a differentially heated non-Darcy porous cavity. The Rayleigh number range studied was $10 < Ra^* < 10^4$ while the solid volume fraction for the medium was $0.4 < \phi_{pm} < 0.9$ and $0\% < \phi_{nf} < 5\%$ for the nanofluid. They found the addition of nanoparticles in the porous medium generally resulted in the higher average Nusselt number in most flow regimes, however the average Nusselt number appeared to decrease with increased solid volume fraction.

The present study is an experimental study, examining buoyancy driven flow of a nanofluid in a square cavity, filled with a porous medium. Literature pertaining to an experimental study of the problem could not be found. The shape of the cavity is square, with two heated vertical walls. The nanoparticles used are Al_2O_3, which is chemically stable in water. While the base fluid is a 60% ethylene glycol (EG) and 40% water mixture, more widely known as antifreeze - a coolant used in many heat exchangers. A Rayleigh number range of $6 \times 10^3 < Ra^* < 1.6 \times 10^4$ and volume fraction of 0.2% particles is studied. The porous medium used is glass spheres of 16mm.

To the best of our knowledge, experimental investigation into natural convective heat transfer of nanofluids in a rectangular cavity filled with a porous medium has not been reported.

THEORY

Analytical Prediction for Heat Transfer

Different heat transfer regimes have been defined for natural convection in a 2D porous rectangular cavity which is heated from the sides. Figure 1 shows under which circumstances each of these heat transfer regimes are applicable. In this study, because the cavity is approximately square, the applicable expected regime is the high Ra regime III. However the cavity in the present experiments has a finite length and 3D effects plays a role.

Nield and Bejan [1] give an analytical prediction for the Nusselt number in the boundary layer Regime based on the Rayleigh number and cavity dimensions. However, this equation is only valid for 2D cavities, and consistently over predicts the Nusselt number.

$$Nu = 0.577 \frac{L}{H} Ra_H^{*1/2} \quad (1)$$

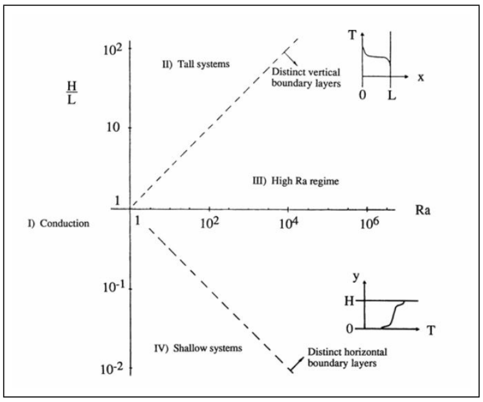

Figure 1: The four heat transfer regimes for natural convection in a two-dimensional porous layer heated from the side [1]

where the Rayleigh number must be based on the height of the cavity. It should also be noted that the equation of the Rayleigh number for a clear cavity (Eq. 2) differs from the one for porous medium (Eq 3) which takes the permeability into account.

$$Ra_L = \frac{g\beta(T_{Hot} - T_{Cold})L^3}{\nu\alpha} \quad (2)$$

$$Ra_L^* = \frac{g\beta(T_{Hot} - T_{Cold})KL}{\nu\alpha_m} \quad (3)$$

In fluid dynamics through porous media, the Darcy number (Da), represents the relative effect of the permeability of the medium versus its cross-sectional area. This can be represented mathematically

$$Da = \frac{K}{d^2} \quad (4)$$

where K[m^2] is the permeability of the medium and d[m] is the particle diameter.

EXPERIMENT AND PROPERTIES

Experimental Setup

Figure 2 shows a schematic of the setup. Opposing vertical walls are heated differentially using nearly constant temperature heat exchangers. Thermocouples are placed along the cavity to measure the temperature distribution inside the cavity. Cavity dimensions are 120.04×96.3×102.3mm (W×H×L). The cavity is placed inside an insulating box with an insulating lid, to prevent heat loss. The thermocouples link to a computer where data is logged.

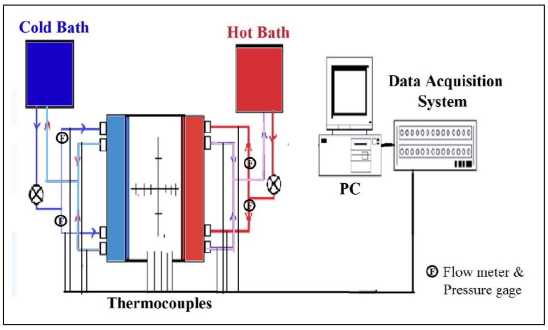

Figure 2: Schematic of Experimental Setup

Experimental Procedure

Nanoparticle dispersion of Al_2O_3 alpha from US Research Nanomaterials is used. The particle size is 30nm and the dispersion is 20wt% (mass fraction) in water. The density of the nanoparticles is given by the US Research Product Fact Sheet [29] at 20°C as 3.5-3.9 g/cm^3.

Before any experimentation could begin, it was first necessary to determine if the nanofluid would remain stable for the duration of the testing. A suspension was prepared and was observed. It was determined to remain stable for at least 24 hours. A new batch of nanofluid was prepared for the experiments, and testing did not exceed 7 hours for four runs.

The dispersion is first diluted in two small batches. The two batches are ultrasonicated, for two hours each. One final mixture is measured, containing the two small batches, diluted in more of the base fluid. This mixture is then ultrasonicated for 3 hours. Ultrasonication breaks up agglomeration of particles in the fluid. The final mixture is a mixture of 60% EG, 40% water as the base fluid with 0.2% volume fraction of nanoparticles suspended.

The cavity was filled with the glass spheres and shaken to ensure good packing. The nanofluid was poured carefully into the cavity, while measuring the amount of fluid used. This is in order to find the porosity of the cavity. The hot and cold baths, as well as the data acquisition system were already switched on. Four runs were recorded as follows:

- The bath temperatures are set for different temperatures as listed in Table 1.
- Steady state is reached at approximately 50 minutes after the start of the run. The last 15 minutes of the data acquisition period (25-40 minutes after steady state is reached) is aggregated as the steady state results.

Table 1: Wall Temperatures

Experiment Number	Hot Wall [°C]	Cold Wall [°C]
1	5	55
2	10	50
3	15	45
4	20	40

Nanofluid Properties

The nanofluid in this study is 0.2% volume fraction of Al_2O_3 in a base fluid of 60%EG-40%water. The particle diameter of the Al_2O_3 is 30nm. The properties of the nanofluid depend amongst others on the type of particles used, the size of particles, the base fluid and the temperature. In all cases temperature was taken into account when material properties were calculated.

Sundar [30] reported conductivity for nanofluid of Al_2O_3 in 60%EG-40%Water, which is used in this study.

According to mixing theory from Ho et al. [19] the density of the nanofluid is given by Equation 5. The density of the Alumina particles is $3900kg/m^3$.The density of the base fluid at different temperatures is taken from Ashrae Handbook [31].

$$\rho_{nf} = \phi_{nf}\rho_p + (1-\phi_{nf})\rho_{bf} \tag{5}$$

Viscosity of the nanofluid could not be found in the open literature and it was measured as a part of this work and the measurement results can be found in the results section. The viscosity equipment used is a sine-wave vibro-viscometer SV-10 from A&D Company Ltd., Japan, with viscosity measurement limits of 0.3-10,000 mPa.s. More detail on the viscosity measurement is available in our previous publication [32].

The heat capacity is given by Equation 6. [19]

$$\rho_{nf}c_{p,nf} = \phi_{nf}\rho_p c_{p,p} + (1-\phi_{nf})\rho_{bf}c_{p,bf} \tag{6}$$

Ho et al. [19] gives 2 expressions for the coefficient of expansion (β) for a nanofluid. They report that Equation 8 provides a better correlation to experimental results.

$$\beta_{nf} = \phi_{nf}\beta_p + (1-\phi_{nf})\beta_{bf} \tag{7}$$

$$\rho_{nf}\beta_{nf} = \phi_{nf}\rho_p\beta_p + (1-\phi_{nf})\rho_{bf}\beta_{bf} \tag{8}$$

For the base fluid the expansion coefficient was found by numerically finding the derivative of the density to temperature [31], using a central differencing scheme. Ho et al. [19] report the thermal expansion coefficient for alumina nanoparticles is 8.46 $\times 10^{-6}$.

Porous Medium Properties

The medium used is 16mm glass balls. Table 2 presents the material properties of the glass spheres [33].

Table 2: Glass Spheres Material Properties at 20°C

Property Name	Value
Sphere Diameter	16 [mm]
Thermal Conductivity	0.7 [W/(m·K)]
Density	2800 [kg/m^3]
Specific Heat	13.9633 [J/(kg·K)]

Porosity of a medium is measured by volume replacement method and found it equal to 0.429.

Carman-Kozeny relationship is chosen for the Permeability of the medium as

$$K = \frac{D_{p2}^2\phi_{pm}^3}{180(1-\phi)^2} \tag{9}$$

where D_{p2} is dependent on the distribution of sphere diameters. However, in this case all spheres have the same diameters, and as a result $D_{p2} = D_{pm}$. Therefore the Permeability was K = 3.43 $\times$ 10^{-7}m^2.

Different methods are available to determine the effective conductivity of the medium. In this case overall thermal conductivity is used as equation 10 [1]. Unlike porosity and permeability, conductivity is a function of temperature and of the fluid properties. A summary of the medium properties are given in Table 3.

$$k_m = (1-\phi)k_s + \phi k_f \tag{10}$$

Table 3: Porous Medium Properties

Property Name	Value
Porosity	0.429
Permeability	$3.43 \times 10^{-7} m^2$
Conductivity at 0°C	0.490 W/(m·K)
Conductivity at 25°C	0.499 W/(m·K)
Conductivity at 50°C	0.505 W/(m·K)

RESULTS AND DISCUSSION

Nanofluid Viscosity

Figure 3 shows the measured nanofluid viscosity compared to the base fluid. As expected, viscosity of nanofluid is more than the base fluid. However, the difference is more for lower temperatures.

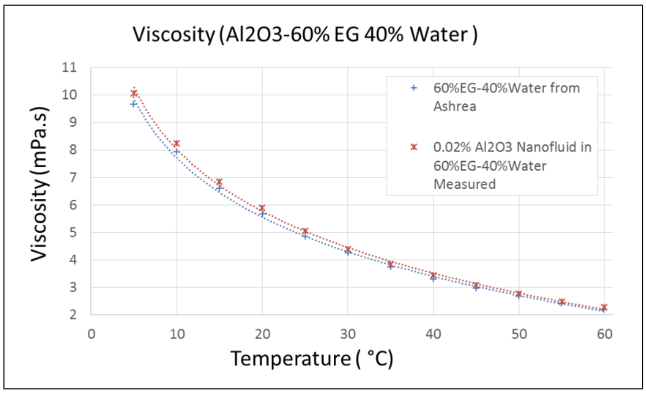

Figure 3: Viscosity of nanofluid vs base fluid

Cavity Experiment

Figure 4 shows the temperature distribution inside the cavity. Thermocouples were approximately equally spaced. From the high gradients close to the hot and cold walls, it is clear that natural convection took place.

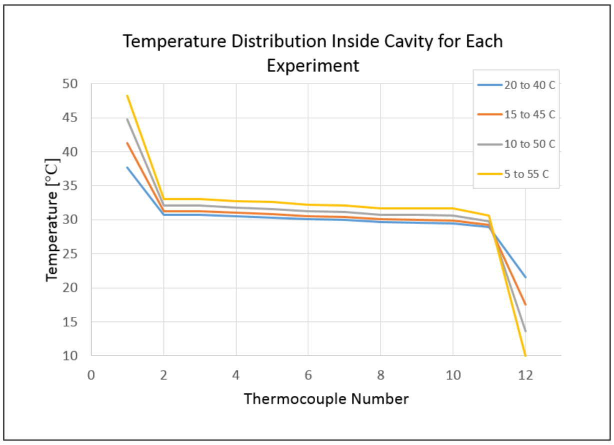

Figure 4: Temperature Distribution inside Cavity

Figure 5 shows the heat transfer for each configuration. Heat transfer was on average 3.5% higher for that of the nanofluid when compared to the base fluid in the porous medium. However, the highest amount of heat transfer was still encountered in the clear cavity (without porous media) and with the base fluid. The heat transfer in the clear cavity, was 6.9% higher than that of the nanofluid in the porous medium.

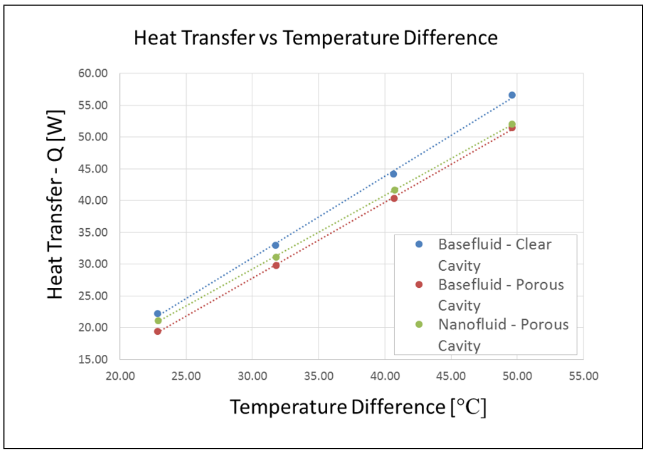

Figure 5: Heat Transfer vs Temperature Difference

Figure 6 & 7 show the clear cavity and porous cavity results for Rayleigh number vs Nusselt number. Logarithmic correlations were extracted from this data. Equations 11, 12 and 13 are respectively the correlations for the base fluid in clear cavity, base fluid in porous filled cavity and nanofluid in porous cavity. However, further works are required to justify the correlations.

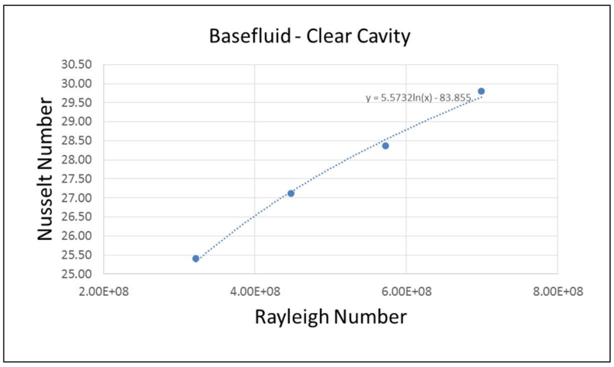

Figure 6: Nusselt vs Rayleigh for Clear Cavity

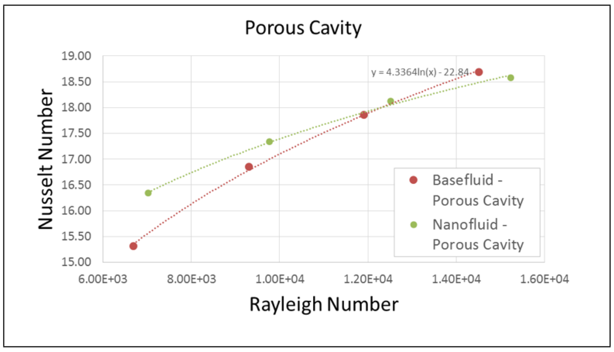

Figure 7: Nusselt vs Rayleigh for Porous Cavity

$$Nu = 5.5732 \ln(Ra_L) - 83.855 \quad (11)$$
$$Nu = 4.3364 \ln(Ra_L^*) - 22.84 \quad (12)$$
$$Nu = 2.9301 \ln(Ra_L^*) - 9.5926 \quad (13)$$

CONCLUSION

Experiments were run to investigate the impact for porous medium and a nanofluid on the heat transfer capabilities a buoyancy driven flow in a differentially heated square cavity. The results showed that heat transfer is affected by both the porous medium and the nanofluid. The clear cavity transferred the most heat and the least heat was transferred by the porous medium saturated with base fluid. Correlations for this range of Rayleigh numbers are developed. Future work will include more experiments in order to extend the range of Rayleigh numbers, Nusselt numbers, and nanofluids used.

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REFERENCES

[1] D. Nield and A. Bejan, *Convection in Porous Media*. Springer, 2006.

[2] K. Vafai, *Handbook of Porous Media*. New York: Taylor & Francis, 2005.

[3] I. Pop and D. Ingham, *Convective Heat Transfer: Mathematical and Computational Modeling of Viscous Fluids and Porous Media*. Oxford: Pergamon, 2001.

[4] D. Ingham, *Transport Phenomena in Porous Media III,*. Oxford: Elsevier, 2005.

[5] A. Bejan, I. Dincer, S. Lorente, A. Miguel, and A. Reis, *Porous and Complex Flow Structures in Modern Technologies*. New York: Springer, 2004.

[6] V. Prasad, F. Kulacki, and M. Keyhani, "Natural convection in porous media," *Journal of Fluid Mechanics*, vol. 150, pp. 89–119, 1985.

[7] V. Prasad, F. A. Kulacki, and A. V. Kulkarni, "Free convection in a vertical, porous annulus with constant heat flux on the inner wall - experimental results," *International Journal for Heat And Mass Transfer*, vol. 29, no. 5, pp. 713–723, 1986.

[8] S. A. Bories and M. A. Combarnous, "Natural convection in a sloping porous layer," *Journal of Fluid Mechanics*, vol. 57, no. 1, pp. 63–79, 1973.

[9] N. Seki, S. Fukusako, and I. Inaba, "Heat trannsfer in a confined rectangular cavity packed with porous media," *International Journal for Heat And Mass Transfer*, vol. 21, pp. 985–989, 1978.

[10] S. U. S. Choi, "Enhancing thermal conductivity of fluids with nanoparticles," *Proceedings of the 1995 ASME International Mechanical Engineering Congress and Exposition*, vol. 231, pp. 99–105, 1995.

[11] J. Buongiorno, "Convective transport in nanofluids," *ASME*, vol. 128, 2006.

[12] T. K. Tiwari and M. K. Das, "Heat transfer augmentation in a two-sided lid-driven differentially heated square cavity utilizing nanofluids," *International Journal of Heat and Mass Transfer*, vol. 50, pp. 2002–2018, 2007.

[13] H. Ş. Aybar, M. Sharifpur, M. R. Azizian, M. Mehrabi, and J. P. Meyer, "A review of thermal conductivity models of nanofluids," *Heat Transfer Engineering*, vol. 36, pp. 1085–1110, 2014.

[14] K. Hwang, J. Lee, and S. Jang, "Buoyancy-driven heat transfer of water-based Al2O3 nanofluids in a rectangular cavity," *International Journal of Heat and Mass Transfer*, vol. 50, pp. 4003–4010, 2007.

[15] N. Putra, W. Roetzel, and S. K. Das, "Natural convection of nano-fluids," *Heat and Mass Transfer*, vol. 39, pp. 775–784, 2003.

[16] K. Khanafer, K. Vafai, and K. M. Vafai, "Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids," *International Journal of Heat and Mass Transfer*, vol. 46, pp. 3639–3653, 2003.

[17] A. Nnanna, "Experimental model of temperature-driven nanofluid," *Journal of Heat Transfer*, vol. 129, pp. 697–704, 2007.

[18] Y. Hu, Y. He, S. Wang, Q. Wang, and H. I. Schlaberg, "Experimental and numerical investigation on natural convection heat transfer of TiO_2-water nanofluids in a square enclosure," *Journal of Heat Transfer*, vol. 136, 2014.

[19] C. J. Ho, W. K. Liu, Y. S. Chang, and L. C. C., "Natural convection heat transfer of alumina - water nanofluid in vertical square enclosures: An experimental study," *InternationalJournalofThermalSciences*, vol. 49, pp. 1345–1353, 2010.

[20] M. A. Sheremet and I. Pop, "Natural convection in a square porous cavity with sinusoidal temperature distributions on both side walls filled with a nanofluid: Buongiorno's mathematical model," *Transport Porous Media*, 2014.

[21] M. A. Sheremet and I. Pop, "Natural convection in a wavy porous cavity with sinusoidal temperature distributions on both side walls filled with a nanofluid: Buongiorno's mathematical model," *Journal of Heat Transfer*, vol. 137, 2015.

[22] M. A. Sheremet and I. Pop, "Conjugate natural convection in a square porous cavity filled by a nanofluid using Buongiorno's mathematical model," *International Journal of Heat and Mass Transfer*, vol. 79, pp. 137–145, 2014.

[23] M. A. Sheremet, I. Pop, and M. M. Rahman, "Three-dimensional natural convection in a porous enclosure filled with a nanofluid using Buongiorno's mathematical model," *International Journal of Heat and Mass Transfer*, vol. 82, pp. 396–405, 2015.

[24] M. A. Sheremet, T. Grosan, and I. Pop, "Free convection in a square cavity filled with a porous medium saturated by nanofluid using Tiwari and Das' nanofluid model," *Transport Porous Media*, vol. 106, pp. 595–610, 2015.

[25] M. A. Sheremet, S. Dinarvand, and I. Pop, "Effect of thermal stratification on free convection in a square porous cavity filled with a nanofluid using Tiwari and Das' nanofluid model," *Physica E*, vol. 69, pp. 332–341, 2015.

[26] T. Grosan, C. Revnic, I. Pop, and D. B. Ingham, "Free convection heat transfer in a square cavity filled with a porous medium saturated by a nanofluid," *International Journal of Heat and Mass Transfer*, vol. 87, pp. 36–41, 2015.

[27] M. Dastmalchi, G. A. Sheikhzadeh, and A. A. A. Arani, "Double-diffusive natural convective in a porous square enclosure filled with nanofluid," *International Journal of Thermal Sciences*, vol. 95, pp. 88–98, 2015.

[28] M. T. Nguyen, A. M. Aly, and S. Lee, "Natrual convection in a non-darcy porous cavity filled with Cu-water nanofluid using the characteristic-based split procedure in finite element method," *Numerical Heat Transfer, Part A*, vol. 67, pp. 224–247, 2015.

[29] I. US Research Nanomaterials, "Aluminum oxide (Al2O3) nanopowder water dispersion US7010." Online <http://www.us-nano.com/inc/sdetail/623>, 2014.

[30] L. S. Sundar, E. V. Ramana, M. K. Singh, and A. C. M. Sousa, "Thermal conductivity and viscosity of stabilized ethylene glycol and water mixture Al2O3 nanofluids for heat transfer applications: An experimental study," *International Communications in Heat and Mass Transfer*, vol. 56, pp. 86–95, 2014.

[31] Ashrae, *Ashrae Handbook Fundamentals*. American Society of Heating, Refrigerating and Air-conditioning Engineers, 2009.

[32] S. A. Adio, M. Sharifpur, and J. P. Meyer, "Investigation into effective viscosity, electrical conductivity and ph of γ - Al_2O_3 - glycerol nanofluids in Einstein concentration regime," *Heat Transfer Engineering*, vol. 36, no. 14, 2015.

[33] A. Y. Cengel, *Heat and Mass Transfer: A Practical Approach*. New York: McGraw-Hill, 2006.