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Experimental Investigation on Free Convective Heat Transfer Performance of Oxide Nanofluids Along a Vertical Cylinder

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ABSTRACT

The multi criterion decision making (MCDM) method and experimental investigation on free convective heat transfer performance of oxide-based water nanofluids along a vertical cylinder are the two methods used to compare the performance in this paper. Al_2O_3, CuO, TiO_2, SiO_2, Fe_3O_4, and ZnO were the metal oxide nanoparticles used in the study to make water-based metal oxide nanofluids with volume fractions ranging from 0% to 1%. Two step method was used to create nanofluids. Thermo-physical properties like density, specific heat, viscosity, and thermal conductivity were measured after the various nanofluids were synthesized. Then, the performance of each nanofluid was evaluated based on various attributes using the weighted sum model (WSM) method, and the ranking of nanofluids was given. To begin, water served as the medium for free convection heat transfer experiments to validate the experimental setup. Free convection heat transfer experiments were carried out using metal oxide-based water nanofluids as mediums at volume fractions ranging from 0% to 1% for various heat inputs in the range of 30 W and 50 W. The heat transfer coefficient augments with percentage volume concentration up to 0.1 % for all types of nanofluids and then decreases until it reaches 0.6% volume fraction. Al_2O_3-water nanofluid performs better than other metal oxide nanofluids in both WSM and experimental methods.

Keywords: free convection, nanofluids, heat transfer, augmentation, thermal performance.

INTRODUCTION

Heat transfer has a substantial role in the life of any device which produces heat for the period of its operation. If the device is thermally well managed, it will have a longer life. It is not possible to employ external agencies like blowers or fans in all applications to cool the device by forced convection manner (Ghalambaz et al., 2019). In applications like nuclear cooling, heat transfer in double pane windows, electronic cooling, solar collectors etc., it offers only natural convection heat transfer. The fluid's flow rate is directly related to the magnitude of the natural convection heat transfer between a surface and a fluid (Anwar et al., 2020). The rate of heat transfer increases with flow. Since there are no blowers or fans used in natural convection, flow cannot be controlled externally. The fluid's dynamic balance of buoyancy and friction determines its flow. When the temperature difference between the fluid locations (one close to the hot surface and one away from it) is greater, buoyancy forces will be greater, and natural convection currents will be stronger, resulting in a higher heat transfer rate. Nanofluid is the new generation colloidal heat transfer liquid which exhibits superior thermo-physical properties (Zhang et al., 2021, Wisam et al., 2019, Nassima et al., 2021). By uniformly dispersing and maintaining a stable suspension of nanoparticles in carrier fluids, the primary goal of the synthesis of nanofluids is to achieve the highest possible thermal properties at a very low concentration. The nanofluids are now ready for use and more stable thanks to recent advancements in the production of nanoparticles.

Background of the work

Free convection is the most common method of heat transfer in many food heating and cooling applications. The process of sterilizing food in cans and freezing meat in still air or brine is controlled by free convection heat transfer [6]. Natural convection heat transfer using nanofluids especially in electronic cooling became very interesting topic of research these days. The articles published in this topic are exponentially increased over the last few years.

Ghalambaz et al. (2019) have chosen an enclosure with complex shape consisting of porous medium to study the heat transfer and flow characteristics of MgO-MWCNT/Ethylene Glycol hybrid nanofluid numerically. They identified that usage of hybrid nanofluids with two nanoparticles augments the heat transfer performance. Nusselt's number enhancement is 17% in case of glass ball and 15% in case of aluminum metal foam compared to base fluid i.e Ethylene glycol. Anwar et al. (2020) have conducted the numerical analysis of transient magneto hydrodynamic free convective flow of water – Cu, TiO_2, Al_2O_3 based nanofluids over a vertical plate of infinitely long in porous medium. Nussest number and skin friction coefficient are calculated at both isothermal wall and ramped wall and observed that high skin friction factor is attained at the wall and maximum rate of heat transfer is obtained for water-TiO_2.

Zhang et al. (2021) have numerically examined the free convective heat transfer using water – Cu nanofluid in a porous annulus. Heat transfer rate with streamlines and isotherms are obtained for nanoparticle size (10–90 nm dia), aspect ratio (1–10), porosity (0.1–0.9), Darcy number (10^{-4}–10^{-2}), Raleigh number (10^3–10^5). Wisam et al. (2019) have numerically investigated the free convective heat transfer in a porous square geometrical annulus with intervallic side wall temperature using water – Cu nanofluid as medium. Heat transfer rate with streamlines and isotherms are obtained for different volume fractions at Pr=6.2.

Nassima et al. (2021) have carried out numerical and analytical study of heat transfer performance on a porous metal cavity using two kinds of base fluids such as water and ethylene glycol and nanoparticles such as Cu, alumina, and titania and also varied the shape of the nanomaterial. They determined the effect of nanoparticle volume fraction on Nusselt number and observed a good heat transfer performance in case of water-Cu nanofluid. Hamza et al. (2019) have numerically analyzed natural convection performance in a heat exchanger in concentric cylindrical annulus by solving the governing equation using finite volume method. Streamlines and isotherms are presented for both water and various volume concentrations of water- Ag nanofluid.

Dey and Sahoo (2021) have experimentally investigated the natural convection heat transfer performance in a rectangular cross sectioned cavity using water – Alumina, ZnO nanofluid up to 0.05% volume fraction. They observed the convection loop for both pure water and nanofluids, but it took more time in case of water. Dey et al. (2023) have further studied flow visualization of Al_2O_3 and Fe_2O_3 nanoparticles in water. Under magnetic field Fe_2O_3 move in circular and Al_2O_3 move straight in static fluid. Suhaib et al. (2019) have prepared stable thermal oil-MWCNT nanofluid for investigating the heat transfer performance in a rectangular enclosure with an aspect ratio (A.R) of 4 for the mass concentration in the range of 0 to 1%. They observed the negative impact on heat transfer performance. Sharifpur et al. [10] have experimentally investigated the performance of natural convective heat transfer in a vertical squared cavity using water-ZnO nanofluids at volume concentrations of 0.1% to 1% and observed the maximum augmentation in Nu and heat transfer coefficient by 8.42% and 6.75% respectively.

Dorota Sawicka et al. (2021) have prepared Alumina based nanofluids at 0.01%, 0.1%, and 1% mass fractions using various base fluids with varied Prandtl number from 4.4 to 176. They observed enhancement in heat transfer at 0.1% and fall at 0.01% and 1% respectively. Abderrahmane Bairi et al. (2020) have prepared water-ZnO nanofluid at various volume fractions from 0 to 10% to investigate free convection heat transfer performance in a spherical porous enclosure experimentally. Maryam Torki et al. (2019) have investigated the heat transfer performance of water-Silica nanofluid in an inclined enclosure experimentally for different tilt angles and various volume concentrations. Maximum value of Nu is obtained for horizontal position and 0.5% volume concentration. Ravi babu et al. (2021) have synthesized transformer oil – Al_2O_3 nanofluid at various volume concentrations from 0% to 1%. They studied the effect of sonication time and moisture on stability, breakdown strength (voltage) and natural convection heat transfer coefficient and observed the highest performance at 0.1%. The summary of the studies reviewed from literature is represented in Table 1.

Many of the studies in literature review are limited to numerical studies on free convection heat transfer and very few researchers have done experimental studies on natural convection using nanofluids and that too their studies are concentrated mainly on rectangular enclosure geometries. So this factor motivated the authors to explore the natural convective heat transfer performance over a thin vertical slender cylinder using various oxide based nanofluids by taking water as base fluid.

Motivation and objectives of present study

Weighted sum model (WSM) technique is one of the simplest and most effective Multi Criterion Decision making (MCDM) techniques which is used to evaluate the performance of the number of alternatives and select the best possible option. It is the technique which is very much efficiently used for the applications like selection of solar panels, raw materials, the best possible place for establishing a power plant, tool materials etc. So, in this work, WSM method is used to rank the possible options of prepared oxide nanofluids and compare the same with experimental results. Experiments are to be conducted to know the performance of heat transfer of different oxide nanofluids at volume concentrations of 0% to 1%.

METHODOLOGY

In this study, various oxide based nanofluids like Al_2O_3, CuO, TiO_2, SiO_2, Fe_3O_4, ZnO were prepared by dispersing the nanosized particles of the said materials in the water as a two-step method. Nanoparticles were procured from Nanolabs, India in the size of 40 nm approximately with 99.5% purity. The quantity of nanoparticles was measured as per the volume fractions which is the ratio of the volume of the nanoparticles to the total volume of the nanoparticles and base fluid. After synthesizing the various nanofluids, thermo-physical characteristics like specific heat, density, thermal conductivity and viscosity were measured. Then using weighted sum model (WSM) method the performance of each nanofluid was evaluated based on various attributes and prepared the ranking of nanofluids. Similarly, experimentations were performed to know the performance of heat transfer and analyzed the results and related the results of WSM method and experimental results. The detailed block diagram of the procedure of the present work is depicted in Figure 1.

Preparation of nanofluid

The preparation of nanofluid was done as a two-step method and the primary step was synthesis of nanoparticles and later dispersion of oxide nanoparticles in water to prepare the oxide nanofluids. The mass of the nanoparticles dispersed in base fluid was calculated using Eq. 1. After dispersing nanoparticles, the mixture was added with sodium dodecyl sulfate (SDS)

Table 1. Summary of the various studies from literature review

S. No	Reference	Nanoparticle material	Base fluid	Geometry	Remarks
1	Ghalambaz et al., (2019)	MgO, MWCNT	EG	Complex shape	Numerical study
2	Anwar et al. (2020), Nassima et al. (2021)	Cu,TiO_2, Al_2O_3	Water	Vertical plate, metal cavity	Numerical study
3	Zhang et al. (2021), Wisam et al. (2019)	Cu	Water	Porous annulus, porous metal cavity	Numerical study
4	Hamza et al. (2019)	Ag	Water	Concentric cylindrical annulus	Numerical study
5	Debashis and Dibyanshu (2021)	ZnO, Al_2O_3	Water	Rectangular annulus	Experimental study
6	Debashis et al. (2023)	Fe_2O_3, Al_2O_3	Water	Rectangular annulus	Experimental study
7	Suhaib et al. (2019)	MWCNT	Thermal oil	Rectangular enclosure	Experimental study
8	Shafirpur et al. (2021), Abderrahmane et al. (2020)	ZnO	Water	Vertical square cavity, spherical enclosure	Experimental study
9	Sawicka et al. (2021)	Al_2O_3	Water	Vertical cavity	Experimental study
10	Maryam et al. (2019)	SiO_2	Water	Inclined enclosure	Experimental study
11	Ravi babu et al. (2021)	Al_2O_3	Transformer oil	Vertical cylinder	Experimental study

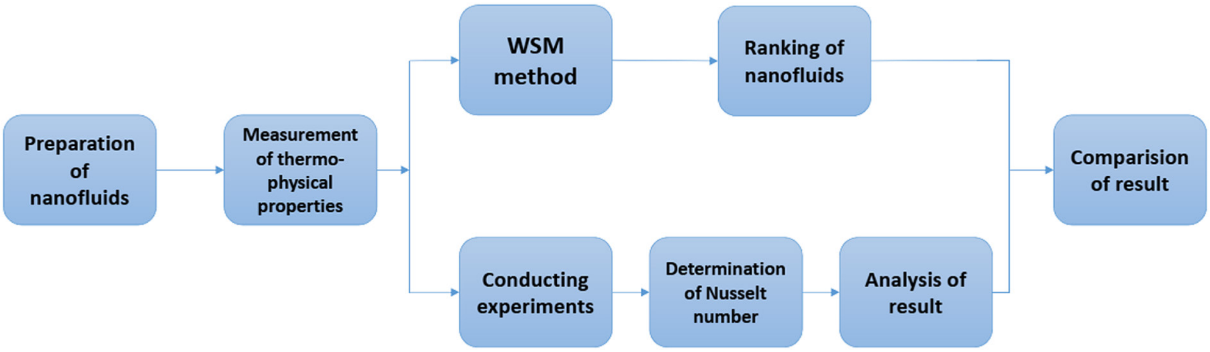

Figure 1. Block diagram represents methodology of the work

surfactant in the quantity of 10th of nanoparticles quantity. Then after stirring with a magnetic stirrer for 30 minutes, ultra- sonication treatment was performed at 20 kHz frequency using ultrasonic sonicator. Sonication was performed for 3 hours for getting homogenous mixture with a pause of 5 minutes to avoid over heating of the system. The Al_2O_3, CuO, TiO_2, SiO_2, Fe_3O_4, ZnO – water oxide nanofluids were synthesized for various volume fractions ranging from 0% to 1% respectively. Systematic sequential steps of preparing the nanofluids is shown in Figure 2. After synthesizing the nanofluids, thermo-physical characteristics like specific heat, density, thermal conductivity and viscosity were measured.

$$\text{Volume fraction} = \frac{V_{np}}{V_{np}+V_{bp}} \tag{1}$$

WSM method

Metal oxide nanoparticles Al_2O_3, CuO, TiO_2, SiO_2, Fe_3O_4, and ZnO are considered in the current study for ranking using WSM technique. Thermo-physical properties such as thermal conductivity (W/mK), specific heat (J/kg.K), density (kg/m^3), and volumetric expansion coefficient (K^{-1}), zeta potential (mV) play an important role in performance fulfillment of nanofluids. Nanoparticle cost is also important when choosing a nanoparticle material. Therefore, these parameters are used as attributes in this study. The higher the density of the nanoparticles, the lower the performance of the nanoliquid as the particles settle in the base liquid. Among these parameters, nanoparticle density and cost are considered unfavorable attributes, while the others are considered favorable attributes, resulting in improved nanofluidic performance. The thermo-physical properties of nanoparticles to be given grade using the WSM technique and are summarized Anwar et al. (2020); Debashis and Dibyanshu (2021); Debashis et al. (2023); Shafirpur et al. (2021) and shown in Table 2.

Convert the thermo-physical properties of the nanoparticles shown in Table 1 to a five-step scale as 1 for low, 2 for average, 3 for high, 4 for very high, 5 for exceptionally high (Rao, 2007). Create a decision matrix by assigning appropriate values

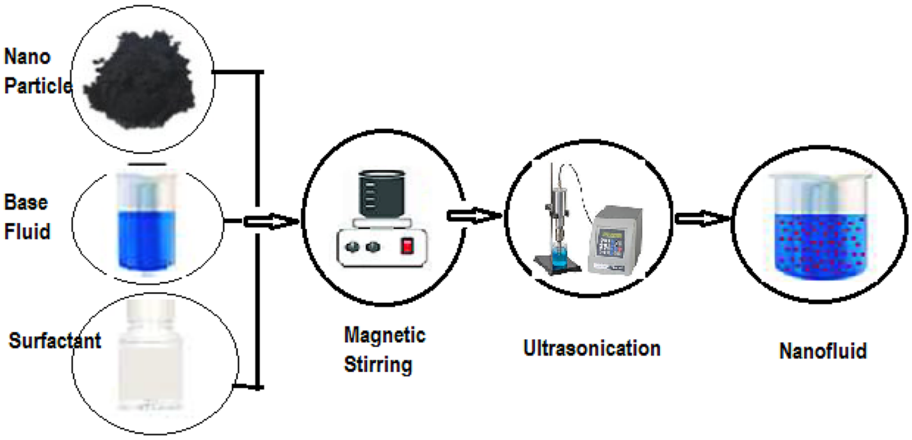

Figure 2. Progressive steps of synthesizing nanofluid

Table 2. Thermo-physical properties of Nano particles to be ranked

Type of particle	P (kg/m^3)		Cp (J/kg.K)		K (W/mK)		β X 10^{-5} (K^{-1})		Z (mV)		C (Rs)	
Al_2O_3	3970	3	765	4	40	4	0.85	2	50	4	3719	3
CuO	6320	5	531.8	3	76.5	5	0.85	2	25.5	2	6575	5
TiO_2	4230	3	686.2	3	8.95	2	0.9	2	46	4	5905	4
SiO_2	2650	2	745	4	1.38	1	45.26	3	49	4	3988	3
Fe_3O_4	5170	4	670	3	6	2	1.3	2	27.8	2	3903	3
ZnO	5100	4	514	2	29	3	4.77	2	35	3	3837	3

using a 5-point scale. Identify favorable properties that improve nanofluid performance and unfavorable properties that reduce performance and increase cost. Prepare a normalized decision matrix using (Min Aij)/Aij for non-preferred attributes and (Aij)/(Max Aij) for preferred attributes, where Aij refers to the value of the "i"th attribute and the "j"th to the nanoparticle. Assign weights to attributes based on their importance and impact on nanoliquid performance and cost. Multiply the attribute weights by the normalized decision matrix to prepare the normalized weighted decision matrix. Grade the attributes based on its overall performance (Ravi Babu et al. (2021); Dharmalingam et al. (2023); Mohd et al. (2020); Dubey et al. (2021)). The stepwise sequential steps are shown in Figure 3.

The decision matrix was created by giving appropriate values on a scale of 1–5 and is displayed in a Table. 2. Since CuO has a very high density compared to the other Nano particles, it was given 5, while Fe_2O_3 and ZnO materials were assigned 4, and Al_2O_3 and TiO_2 were assigned 3 and SiO_2 was given 2. Regarding specific heat, no material has a much higher value, with values of 4 for Al_2O_3, SiO_2, 3 for CuO, TiO_2, and Fe_3O_4, and 2 for ZnO were given. CuO has a thermal conductivity value of 5 because it has an extremely high thermal conductivity when compared to other materials. 4 is provided for Al_2O_3 because it has strong thermal conductivity. Because no material has an extremely high thermal expansion coefficient, only 2 and 3 are allocated. Al_2O_3, TiO_2, SiO_2 are allocated a zeta potential of 4, ZnO is assigned a zeta potential of 3, while CuO and Fe3O4 are assigned a zeta potential of 2. CuO has a greater cost and is awarded a value of 5, whereas TiO_2 is assigned a value of 4, and other materials are assigned a value of 3.

Table 3 shows a normalized decision matrix. However, it is important to emphasize that the relative importance values ascribed to the traits are purely subject to the decision maker's discretion. The relative weights for density, specific heat, thermal conductivity, volumetric expansion coefficient, zeta potential, and cost of the nanoparticles are 0.1, 0.15, 0.45, 0.05, 0.1, and 0.15, respectively. These weights are assigned based on the relevance of thermo-physical properties in determining the thermal performance and cost of the nanofluid. According to the overall performance of the normalized and weighted choice matrix, Al_2O_3 is the best potential alternative among the nanoparticles chosen for the study.

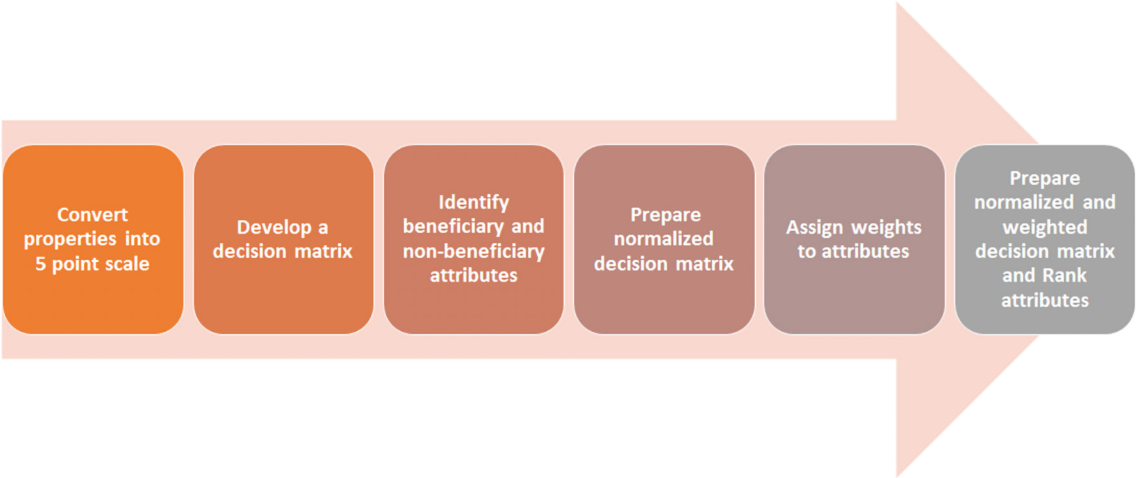

Figure 3. Sequential steps in WSM methodology

Table 3. Normalized & weighted decision matrix

Type of particle	P (kg/m^3)		Cp (J/kg.K)		K (W/mK)		$\beta \times 10^{-5}$ (K^{-1})		Z (mV)		C (Rs)		Overall performance	Rank
Relative weights	0.1		0.15		0.45		0.05		0.1		0.15			
Al_2O_3	0.6	0.06	1	0.15	0.8	0.36	0.66	0.033	1	0.1	1	0.15	0.859	1
CuO	1	0.1	0.75	0.1125	1	0.45	0.66	0.033	0.5	0.05	0.6	0.09	0.7755	2
TiO_2	0.6	0.06	0.75	0.1125	0.4	0.18	0.66	0.033	1	0.1	0.75	0.11	0.604	5
SiO_2	0.2	0.02	1	0.15	0.2	0.09	1	0.05	1	0.1	1	0.15	0.64	4
Fe_3O_4	0.8	0.08	0.75	0.1125	0.4	0.18	0.66	0.033	0.5	0.05	1	0.15	0.5755	6
ZnO	0.8	0.08	0.5	0.075	0.6	0.27	0.66	0.033	0.75	0.05	1	0.15	0.653	3

EXPERIMENTAL SETUP

Establishment of an experimental set up was done as per the dimensions shown in schematic diagram. After synthesizing the oxide based nanofluids at 0 to 1% concentrations of volume, experiments were conducted using the experimental set up [14] shown in Figure 4 to investigate the performance of free convective heat transfer using oxide based nanofluids along a vertical cylinder. Experimental set up consists of electric heater, data acquisition system to indicate the temperatures, input voltage and power, vertical cylinder in a square cross sectioned test enclosure where nanofluid was filled in, thermocouples (6 no's of Cr-Al type), an outer shell with cooling water circulation. Thermocouples were brazed to vertical slender cylinder to recognize its surface temperature at six different locations spaced uniformly. To minimize the conduction heat loss between heater and vertical cylinder, it was completely filled with Magnesium Oxide. Test liquid (water or water based nanofluid) was completely filled till the vertical cylinder is completely drowned. The circulation of cooling water was done at the rate of 1.43 lit/m to 2.23 lit/m for the heat input range of 30 W and 50 W in order to attain steady state conditions.

Near the experimental set up, no fans were in operation while doing the experiments in order to ensure free convection conditions prevailed. Experiments were performed for different heat fluxes or heat inputs by adjusting dimmer stat (variac). These heat inputs were taken in the range between 30 W to 50 W. Firstly, free convection heat transfer experiments were performed by taking water as medium to validate the experimental set up.

Determination of heat transfer performance

All the temperatures of surface of vertical cylinder were noted down where thermocouples are located and also fluid temperature at the middle point level of the cylinder. After noting down the temperatures the film temperature was calculated from Eq. 2.

$$\text{Film temperature} = T_{film} = \frac{T_s + T_f}{2} \tag{2}$$

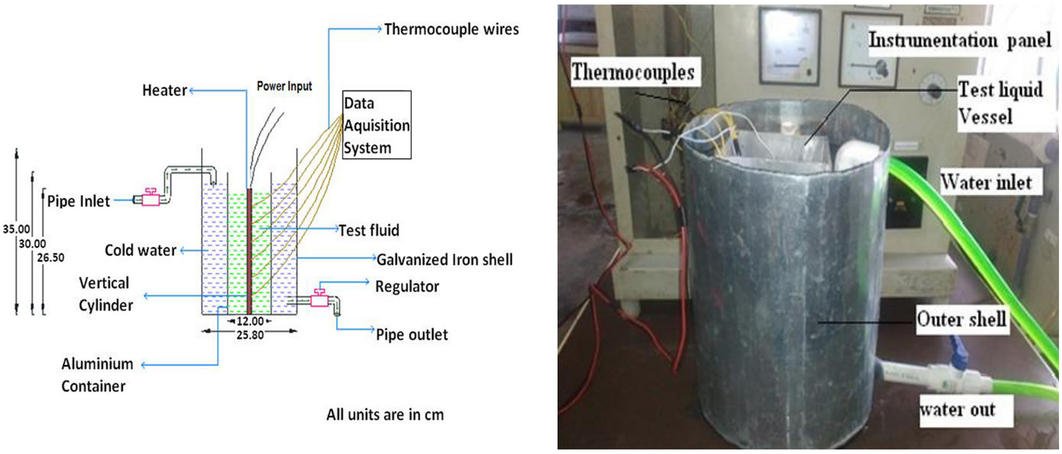

Figure 4. Schematic diagram and picture of experimental set up

The average heat transfer coefficient was determined using the formula represented in Eq. 3.

$$\text{Average heat transfer coefficient } h_{avg} = \\ = \frac{Q}{A\,(T_s - T_f)}\ W/m^2.K \quad (3)$$

Thermo-physical characteristics of water and prepared nanofluids, like thermal conductivity, specific heat, density, and viscosity were measured.

RESULTS AND DISCUSSION

To validate the experimental set up, first experiments were performed by taking water as medium and determined the Rayleigh number as the product of Grashof number and Prandtl number which is shown in Eq. 4. Later, Nusselt number was determined using Eq. 5.

$$\text{Rayleigh Number } Ra = Gr.Pr = \frac{g\beta L^3 \Delta T}{\vartheta^2}\frac{\mu C_P}{K} \quad (4)$$

$$\text{Nusselt number Nu} = \frac{hL}{K} \quad (5)$$

Figure 5 shows the comparision of Nusselt number which was calculated as a function of Raleigh number. The calculated Nusselt number from the present study is compared with standard Mc. Adams equation of natural convection for turbulent flow. It is fairly in concurred with the standard equation and within the limits of ± 2% deviation. A regression equation is also presented.

After validating the investigational set up, free convective heat transfer experiments were conducted by taking metal oxides Al_2O_3, CuO, TiO_2, SiO_2, Fe_3O_4, and ZnO based water nanofluids were taken as mediums at volume fractions from 0% to 1% for various range of heat inputs between 30 W and 50 W. heat transfer coefficient was calculated for the heat inputs 30 W to 50 W, various volume fractions of water-oxide nanofluids. Figure 6 shows the variation of heat transfer coefficient (HTC) with volume fraction %. Heat transfer coefficient is augmented with increase in volume concentration up to 0.1% for all types of nanofluids and then seen deterioration till 0.6 % volume fraction. Water-Al_2O_3 nanofluid exhibits better performance compared to other oxide based nanofluids. Then CuO, ZnO, SiO_2, TiO_2, Fe_2O_3 follows.

As the Nusselt number is the function of Rayleigh number and in turn it is the function of Thermal conductivity, density, dynamic viscosity, specific heat, etc. and among these thermo-physical properties, thermal conductivity and viscosity are the main properties which alter the heat transfer performance. Figure. 7 shows the graph drawn between effective thermal conductivity and % volume fraction, effective thermal conductivity is the ratio of the thermal conductivities of nanofluid and base fluid. With increase in percentage volume fraction of the nanofluid, thermal conductivity of nanofluid increases so the effective

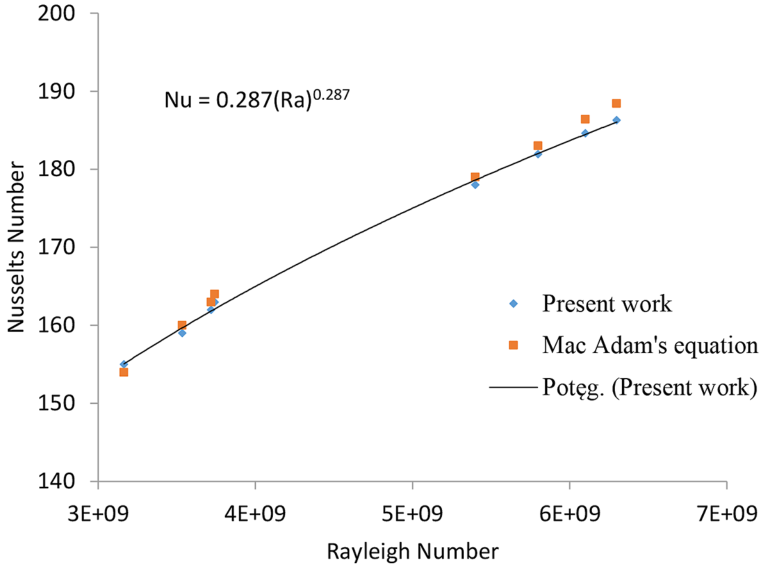

Figure 5. Validation of present free convection along vertical cylinder experimental set up

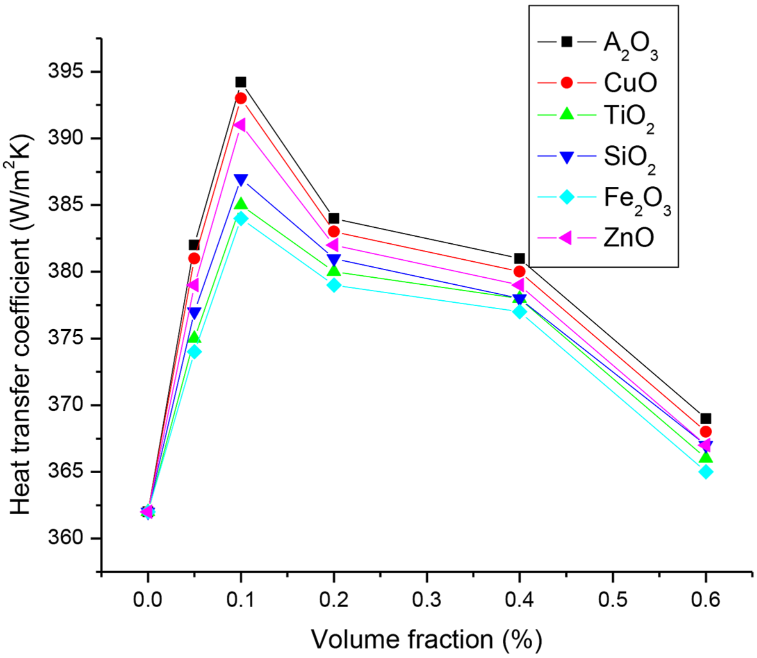

Figure 6. Heat transfer coefficient variation with percentage volume fraction (%) for various nanofluids at 50 W heat input

thermal conductivity is increased. Effective thermal conductivity is compared with the previous studies from literature and shown in the *Figure* 7 and it is fairly in the allowable acceptance of deviation i.e ± 4.85%.

Figure 8 shows the graph drawn between effective dynamic viscosity and % volume fraction, effective dynamic viscosity is the ratio of the viscosities of nanofluid and base fluid. With increase in percentage volume fraction of the nanofluid, viscosity of nanofluid increases so the effective viscosity is increased. Effective viscosity is compared with the previous studies from literature and shown in the Figure. 8 and is within the acceptable deviation of ± 3.68%. To improve the heat transfer coefficient, thermal conductivity of the nanofluid should be high and viscosity should be low. If the viscosity is more, this will affect the natural convection flow along the vertical cylinder and in the test enclosure.

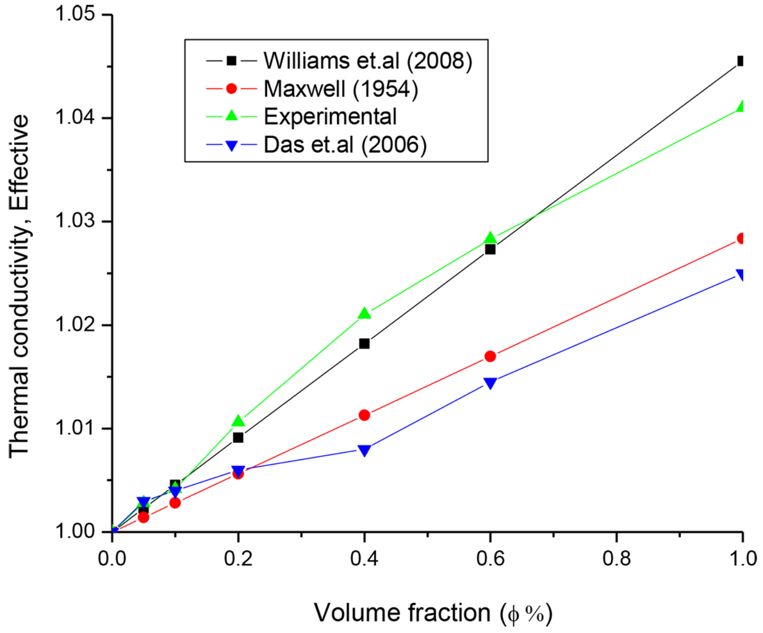

Figure 7. Comparision of deviation of thermal conductivity (effective) with % volume fraction

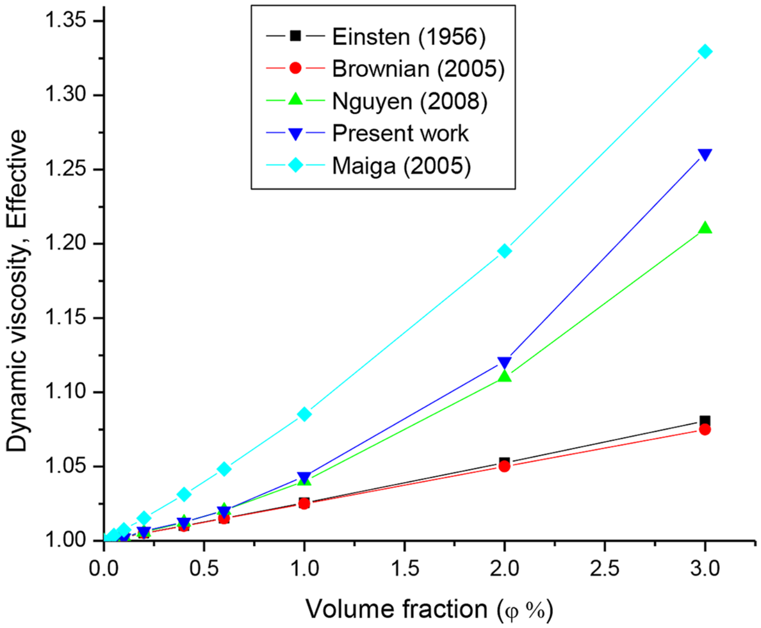

Figure 8. Comparison of deviation of dynamic viscosity (effective) with % volume fraction

It is observed the similar trend in both WSM method and experimental method for selecting the best possible option of nanofluid among other oxide based nanofluids. In both methods, Al_2O_3-water nanofluid stood the best among others.

Limitations of experimental study

Long term stability of the nanofluid is the primary concern even though it gives better performance in the short run. This study did not concentrate on the examination of the effect of time on nanofluid performance and also did not aim at determining the corrosion effect on the surface of slender cylinder. The study may be later expanded by doing studies for altered time periods to determine the influence of time on stability and thermal performance.

CONCLUSIONS

In this paper, free convective heat transfer performance of oxide based water nanofluids along a vertical cylinder was investigated experimentally as well as multi criterion decision making (MCDM) technique. Metal oxide nanoparticles taken for the study were Al_2O_3, CuO, TiO_2, SiO_2, Fe_3O_4, and ZnO for preparing water based metal oxide nanofluids at percentage volume fractions from 0% to 1%. Nanofluids were synthesized using two step method. After synthesizing the various nanofluids, thermo-physical characteristics like density, specific heat, viscosity, thermal conductivity were measured. Then using weighted sum model (WSM) method the performance of each nanofluid was evaluated based on various attributes and prepared the ranking of nanofluids.

Firstly, free convection heat transfer experiments were performed by taking water as medium to validate the experimental set up. After validating the investigational set up, free convection heat transfer experiments were conducted by taking metal oxides Al_2O_3, CuO, TiO_2, SiO_2, Fe_3O_4, and ZnO based water nanofluids were taken as mediums at volume fractions from 0% to 1% for various heat inputs between 30 W and 50 W. Heat transfer coefficient is augmented with increase in volume concentration up to 0.1% for all types of nanofluids and then seen deterioration till 0.6 % volume fraction. In both WSM and experimental methods, Al_2O_3-water nanofluid exhibits better performance among other metal oxide nanofluids.

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