Investigation of Thermal Conductivity and Convective Heat Transfer Coefficient of Water-Based ZnO Nanofluids

Sayyadnejad, Saeed
Department of Mechanical Engineering, College of Engineering, Yazd Science and Research Branch, Islamic Azad University, Yazd, I.R. IRAN

Rashidi, ALimorad*+
Nanotechnology Research Center, Institute of Petroleum Industry (RIPI), Sport Azadi Complex, Tehran, I.R. IRAN

Mirjalily, Seyed ALi Agha
Department of Mechanical Engineering, Yazd Branch, Islamic Azad University, Yazd, I.R. IRAN

ABSTRACT: *Nanofluids are stable suspensions of nanoparticles in a conventional fluid. They have shown superior potential in heat transfer enhancement. In this research, ZnO/water nanofluids were prepared at various concentrations from 0.2 to 1.5vol%, and their thermal conductivity was measured. The results showed that the thermal conductivity of ZnO/water nanofluids depends on particle concentration and increases non-linearly with the volume fraction of nanoparticles. The effects of particle size and temperature on the thermal conductivity were also investigated at 1.5vol%. The results indicated that thermal conductivity enhanced with decreasing particle size and increasing with temperature. For nanofluids containing 10-15 nm and 45-50 nm particle sizes, the enhancements were 26.3 and 22.8% at 40ºC, respectively. In this research, the convective heat transfer coefficient of ZnO/water nanofluids with the above particle sizes was also measured under laminar flow in a horizontal tube heat exchanger. It was observed that both nanofluids showed higher heat transfer coefficients compared to the base fluid at a constant concentration (1.5 vol%). For nanofluids with 10-15 nm and 45-50 nm particle sizes, the average heat transfer coefficient enhancement was 18.1 and 14.9% at Re=1115, respectively.*

KEYWORDS: *Nanofluid, Thermal conductivity; Heat exchanger; Laminar flow; Convective heat transfer; ZnO nanoparticles.*

INTRODUCTION

One of the most important ways to enhance the thermal performance of cooling or heating equipment such as heat exchangers and electronic devices are to use heat transfer fluids with high thermal properties. Conventional fluids, including water, Ethylene Glycol (EG), and oil, have been widely used as heat transfer fluids in different types of heat exchangers for several decades. These fluids have poor thermal properties compared to those of most solid materials. Researchers have improved the thermal conductivity of conventional fluids by adding millimeter or micrometer-sized metallic particles to them, which were named micro fluids. Disadvantages of macro fluids such as instability, sedimentation of large particles, corrosion and clogging of flow channels, and also pressure drops [1-3] led to the introduction of nanofluids as new fluids for heat transfer by *Choi* in 1995 [4].

Nanofluids are stable suspensions of solid particles with diameters below 100 nm in a conventional fluid. The small diameters and very large specific surface areas of nanoparticles not only increase the stability and thermal properties of nanofluids but also decrease the above-mentioned problems often associated with micro fluids. Long–term stability and anomalous enhancement of thermal performance of nanofluids led to a number of studies on these fluids [5-10]. It has been found that the thermal conductivity and convective heat transfer coefficient of nanofluids are notably higher than those of base fluids [11-15].

Among the metal oxides nanofluids, alumina (Al_2O_3), copper oxide (CuO), and titanium oxide (TiO_2) are the most common particles whose thermal properties such as thermal conductivity and heat transfer coefficient have been widely investigated by many researchers[8, 12, 16, 17]. Studies on the thermal performance of ZnO/water nanofluids compared to those of the above-mentioned nanofluids are limited [14,18 - 20]. Most of the studies on ZnO nanofluids have been carried out on ZnO/EG ones [21-25].

In this research, the effects of different nanoparticle concentrations, particle size and temperature on the thermal conductivity of water-based ZnO nanofluids have been investigated. Furthermore, the convective heat transfer coefficient of ZnO/water nanofluids has been measured under laminar flow in a horizontal tube heat exchanger. The effects of particle size and Reynolds number on the heat transfer coefficient have also been investigated.

EXPERIMENTAL SECTION

Materials

Deionized water, ZnO nanoparticles, and a terpolymer dispersant were used to prepare nanofluids. ZnO nanoparticles with 10-15 and 45-50 nm and density of 5.106 g/cm^3 were supplied from Nanoshel Company (USA, Indian branch). The three functional groups terpolymer containing polyacrylic acid-based dispersant (Acumer^{TM} 3100) was purchased from Rohm and Haas Company (Germany) to prevent the agglomeration of ZnO nanoparticles in the base fluid. This is a carboxylate/sulfonate/nonionic functional terpolymer with an average molecular weight of 4500.

Preparation and characterization of nanofluids

ZnO/water nanofluids were prepared at various concentrations of nanoparticles from 0.2 to 1.5% volume fractions in Deionized Water (DW) containing terpolymer dispersant. The weight ratio of nanoparticles to dispersant was fixed at 1:0.5, following the optimization experiments. To prepare stable nanofluids, at first, nanoparticles were suspended into base fluid using a high speed shearing mixer (IKA, Ultra-Turrax T25, Germany) at approximately 13500 rpm for 10 min. Then, an ultrasonic disruptor (24KHZ, 400W, Hielscher GmBH, model UP 400S) was used to sonicate the suspended solution continuously for about 1 hour in order to improve the uniform dispersion of nanoparticles and break down the agglomerated particles in the base fluid.

The Zeta potential of nanofluids was measured at 25 ± 0.1ºC using Zetasizer (Nano ZS, Malvern Instrument Inc., UK) to investigate the stability of particles in suspensions. The thermal conductivity of ZnO/water nanofluids was measured by KD2 thermal analyzer (Decagon – Devices, Inc. USA), which is based on the transient hot-wire method. The KD2 analyzer with an accuracy of ± 5% from 0.2-2 W/(m.K) and ± 0.01% from 0.02-0.2 W/(m.K) was calibrated by distilled water before any set of measurements. In order to investigate the effect of temperature on the thermal conductivity of nanofluids, a circulating bath (PolyScience, model 9712, USA) was employed, which was able to maintain temperature uniformity within ±0.1ºC during measurements. The dynamic viscosity and density of nanofluids were measured at bulk temperature using a viscometer and densitometer (DMA 602, Anton Paar Inc. USA).

Experimental set-up

The experimental setup for measuring the convective heat transfer coefficient of ZnO/water nanofluids in the

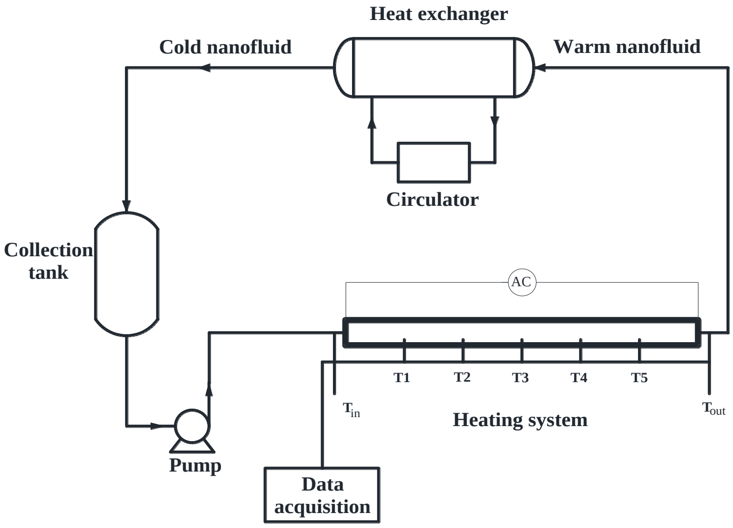

Fig. 1: Schematic diagram of experimental set-up.

laminar flow regime is shown schematically in Fig. 1. It consists of a test section, a pump, a shell and tube heat exchanger and a three lit collection tank. The test section is a horizontal circular copper tube with an 11.42 mm inner diameter and 793 mm length. The tube surface was electrically heated by an AC Power supply to generate constant heat flux (6430 w/m^2) and is thermally insulated by an about 150 mm thick blanket to minimize the heat loss from the tube to the ambient temperature. To measure the wall temperature of the copper tube, five calibrated K-type thermocouples with a standard error of ± 0.75%T from -62 to 125oC are soldered on the test section at axial positions in mm of 55 (T1), 220 (T2), 390 (T3), 565 (T4), and 735 (T5) from the inlet of the test section. Two K-type thermocouples are inserted into the flow at the inlet and outlet of the test section for measuring the bulk temperatures of nanofluids. The laminar flow rates are controlled by a pump (HV–77921-40). There is a three-way valve in the flow loop for flow rate calibration. To preserve a constant temperature at the inlet of the test section, the heated fluids return to the collection tank passing through a cooling unit, which is a shell and tube heat exchanger.

To establish various laminar flows, volumetric flow rates of 0.56, 0.83, and 1.1 lit/min were fed to the system, and the temperatures during experimental runs were recorded with a data acquisition system. The heat transfer rate (*q*) from the tube wall to the nanofluid and constant heat flux (*q''*) were obtained as follows:

$$q = m \cdot C_P \left(T_{in} - T_{out}\right) \tag{1}$$

$$q'' = q / \pi \cdot D \cdot L \tag{2}$$

Where *m*, *D*, and *L* are the mass flow rate, the inner diameter of the tube, and length of the tube, respectively. The local heat transfer coefficient *h(x)* was calculated by:

$$h(x) = q'' / \left(T_w(x) - T_f(x)\right) \tag{3}$$

Where $T_w(x)$ and $T_f(x)$ are the local wall and fluid temperature, respectively. $T_f(x)$ is evaluated from the heat balance energy [26,27] given below:

$$T_f(x) = T_{in} + \left(q''.P.x / m.C_P\right) \tag{4}$$

Where *P* and *Cp* are the surface perimeter and the specific heat of the nanofluid. The specific heat of nanofluid was calculated [27] by:

$$\left(\rho C_P\right)_{nf=} (1-j)\left(\rho C_P\right)_{bf} + j\left(\rho C_P\right)_{np} \tag{5}$$

Where φ is the volume fraction of nanoparticles in a nanofluid?.

RESULTS AND DISCUSSION

The effect of nanoparticle concentration on the thermal conductivity

Fig. 2 shows the effect of nanoparticle (10-15nm) volume fraction on the thermal conductivity enhancement of ZnO/water nanofluids at different temperatures.

Table 1: The highest thermal conductivity enhancement for ZnO nanofluids.

Reference	Base fluid	Particle size (nm)	Concentration (vol%)	Thermal conductivity enhancement (%)
Yu et al. 2009	EG	10-20	5.0	26.5
Lee et al. 2012(90ºC)	EG	<100	5.0	23
Saleh et al. 2013	EG	23	0.5	15.5
Jeong et al. 2013	DW	20-40	5.0	16.0
Chaitanya et al. 2018	DW	<100	1.5	11.5
Topuz et al. 2020 (40ºC)	DW	18	0.5	3.9
Present work (40ºC)	DW	10-15	1.5	26.3
Present work (40ºC)	DW	45-50	1.5	22.8

Fig. 2: Thermal conductivity ratio of ZnO/water nanofluids as a function of volume fraction.

According to Fig. 2, the thermal conductivity ratio of nanofluids depends on particle concentration and increases with an increase in the volume fraction of nanoparticles at different temperatures. For example, for nanofluids at 0.2 and 1.5 vol%, thermal conductivities were enhanced by 15.0 and 24.6% at 30ºC, respectively. From Fig. 2, it is clear that the relation between thermal conductivity enhancement and ZnO nanoparticle concentrations is non-linear, as reported by other researchers for nanofluids [21,24,28].

Table 1 shows the highest thermal conductivity enhancement for ZnO nanofluids prepared by the two-step method. According to Table 1, the thermal conductivity value in the present work is higher than that previously reported and is similar to the value obtained by *Yu et al.* [21]. Comparison of thermal conductivity enhancement in the present study with that obtained by *Jeong et al.* [18], in which the nanofluid was also prepared in deionized water containing dispersant (ammonium polymethacrylate), indicates that a significant enhancement of thermal conductivity is achieved in the present work in spite of the lower concentration of the ZnO nanoparticles. The observed difference could be due to the physical treatment technique used in this study, which was an ultrasonic disruptor. To prepare nanofluids, *Jeong et al.* employed a stirrer, the mechanical energy of which is not sufficient to break down the initial particle clusters in the base fluid compared with an ultrasonic disruptor [29,30].

The effect of dispersant concentration on the thermal conductivity.

Zinc oxide nanoparticles are not easily dispersed in water due to their high surface energy, which causes the agglomeration of particles. Therefore, it is required to use a suitable dispersant for preparing stable suspension. It was found that acrylic acid-based polymers can be used as ZnO nanoparticle dispersants in water-based nanofluids [18,31,32]. The thermal conductivity ratio of ZnO/water nanofluids (0.5vol%) at different temperatures and concentrations of Acumer 3100 dispersant has been shown in Fig. 3. The result indicates that the thermal conductivity ratio decreases with increasing dispersant concentration at 15, 20, and 30ºC. For example, thermal conductivity enhancement at dispersant concentrations of 0.5 and 2.0 are 16.9 and 10.5% at 30ºC, respectively. According to this result, the optimizing concentration of Acumer 3100 dispersant can be half of the nanoparticle weight.

In general, a nanofluid with a zeta potential absolute value larger than 30mV is considered to have good stability [13]. Zeta potential of nanofluids with dispersant (half of the nanoparticles weight) and without dispersant

Table 2: Zeta potential of ZnO/water nanofluids with and without dispersant.

nanofluid	Without dispersant	With dispersant after preparation	With dispersant 4 days later
Zeta potential(mV)	-19.0	-35.4	-33.5

Fig. 3: Effects of dispersant concentration on the thermal conductivity at different temperatures.

Fig. 4: Effect of elapsed time on thermal conductivity of ZnO/water nanofluid (10-15 nm).

for the 1.5 vol% of ZnO nanoparticles (10-15 nm) have been shown in Table 2. According to Table 2, zeta potential values of nanofluid without dispersant were found to be –19.0 mV, which indicated that the nanofluid was unstable, while the absolute value for nanofluids with dispersant after preparation and four days later were found to be -35.3 and -33.5 mV, respectively showing that the nanofluid was stable with elapsed time.

The effect of elapsed time on thermal conductivity was also investigated for nanofluids 15 days after preparation at different concentrations at 30ºC. The results have been shown in Fig. 4.

According to Fig.4, the thermal conductivity of nanofluids decreases with elapsed time, which indicates that ZnO nanoparticles slowly agglomerate over time. A similar trend was observed in nanofluids by other researchers [28,30,33].

The effects of particle size and temperature on the thermal conductivity

Fig. 5 presents the effect of particle size on the thermal conductivity ratio of ZnO/water nanofluid for 1.5vol% at different temperatures. The results clearly indicate that the thermal conductivity ratio is enhanced with decreasing particle size. For ZnO nanofluids containing 10-15 and 45-50 nm particle sizes, the enhancements were 26.3 and 22.8 % at 40ºC, respectively. This is similar to previous reports about nanoparticles size [34-36]. For example, Vajjha and Das [37] investigated the effect of particles size on the thermal conductivity ratio for two ZnO nanoparticles (29,77 nm) in EG/water (40:60) base fluid. Their experimental results demonstrated that as particle size decreases, the thermal conductivity ratio of nanofluids increases, which is similar to our results. It is believed that the Brownian motion of nanoparticles is one of the key factors to enhance the thermal conductivity of nanofluids [38]. The Brownian motion in smaller particles is stronger than that in larger ones, so the nanofluids with smaller particles show higher thermal conductivity ratio enhancement.

From Fig. 5, it is apparent that for both ZnO nanofluids, the thermal conductivity ratio slightly enhances with increasing the temperature as reported for nanofluids in the literature [22,23,39]. For example, this was 22.8 and 25.0% for ZnO/water nanofluid with 10-15 nm particle sizes at 15 and 60 ºC, respectively. It is well known that the Brownian motion intensifies with increasing temperature, which results in the thermal conductivity enhancement of nanofluids.

Heat transfer coefficient of ZnO/water nanofluids

Fig. 6 shows the local convective heat transfer coefficient of ZnO/water nanofluids at a constant concentration (1.5vol%) for 10-15 and 45-50 nm particle

Fig. 5: Thermal conductivity ratio with temperature for ZnO /water nanofluids at different particle sizes.

sizes at various axial locations in laminar flows at different Reynolds numbers. From Fig. 6, it was found that the heat transfer coefficient of both nanofluids is higher than that of the base fluid, and it decreases with axial distance from the entrance region of the test section. For example, at X=55 mm, for 10-15 nm nanofluid at Re=1115, the enhancement is 32.7%, while at X=390 mm, it is 10.9 %. In fact, at the beginning of the test section, the thickness of the thermal boundary layer is very low. Therefore the thermal resistance reduces, and the heat transfer coefficient increases. With the movement of the nanofluid along the axial direction of the test section, the boundary layer becomes developed, and the thermal resistance enhances, which results in decreasing the heat transfer coefficient. This finding of greater enhancement of the heat transfer coefficient at the entrance region agrees with the reported investigations for nanofluids [27,40]. Comparison of Fig. 6a with Figs. 6b-c indicates that the trend of the local heat transfer coefficient for ZnO/water nanofluids is similar at different Reynolds numbers (1115, 1650, 2190) in laminar flow conditions, but it increases with increasing the Reynolds number.

From Fig. 6, it was furthermore found that the nanofluid with a smaller particle size shows a higher local heat transfer coefficient enhancement. For instance, at x=55 mm, this was 32.7 and 26.2% at Re=1115 for nanofluids with 10-15 and 45-50 nm, respectively. A similar result was found for Al_2O_3/water nanofluids containing 45 and 150 nm particle sizes by *Anoop et al.,* who investigated the local heat transfer coefficient enhancement for both nanofluids under laminar flow conditions (Re=1550) in a horizontal tube heat exchanger[27].

Fig. 6: Local heat transfer coefficient of ZnO/water nanofluids.

Fig. 7 demonstrates the average heat transfer coefficient of ZnO water nanofluids as a function of the Reynolds number for two different particle sizes at a fixed concentration (1.5vol%). The results indicate that this is enhanced by increasing the Reynolds number and decreasing the particle size. The average heat transfer coefficient ratio for nanofluids with10-15 and 45-50 nm

Fig. 7: Heat transfer coefficient of ZnO/water nanofluids as a function of the Reynolds number.

particle sizes at Re=1115 were found to be 18.1% and 14.9 % higher than that of the base fluid, respectively. There is no experimental data in the literature on the heat transfer coefficient of ZnO/water nanofluid in horizontal tube heat exchangers to compare with those of the present work, but such behavior has been observed for water-based functionalized multi-walled carbon nanotubes by *Amrollahi et al.* [26] and *Meibodi et al*. [41].

CONCLUSIONS

In this research, stable water-based ZnO nanofluids at different concentrations were prepared, and the effects of dispersant concentration, elapsed time, volume concentration, particle size, and temperature on thermal conductivity were investigated. The effects of particle size and Reynolds number on the local and average convective heat transfer coefficient were also studied under laminar flow conditions. Some important conclusions have been drawn as follows:

● The thermal conductivity ratio of ZnO/water nanofluids enhances non-linearly by increasing the volume fraction of nanoparticles. For nanofluids with particles size 10-15 nm at 0.2 and 1.5vol%, thermal conductivities were enhanced by 15.0 and 24.6% at 30ºC, respectively.

● The dispersant concentration could play a key role in the thermal conductivity enhancement and stability of ZnO/water nanofluid. The optimizing concentration of the Acumer 3100 dispersant can be half of the nanoparticle weight.

● The thermal conductivity ratio of ZnO nanofluids slightly decreased 15 days after preparation, which indicates that ZnO nanoparticles slowly agglomerate over time.

● It was clearly observed that the thermal conductivity ratio slightly enhanced with increasing the temperature. For ZnO nanofluid (1.5 vol%) with 10-15 nm particle size at 15 and 60oC, the enhancements were 22.8 and 25.0%, respectively.

● The thermal conductivity ratio is enhanced with decreasing particle size. For ZnO nanofluids containing 10-15 and 45-50 nm particle sizes, the enhancements were 26.3 and 22.8 % at 40oC, respectively.

● The local heat transfer coefficient of ZnO/water nanofluid decreases with axial distance from the entrance region of the test section.

● The average heat transfer coefficient of ZnO nanofluids is enhanced by increasing the Reynolds number and decreasing the particle size. For nanofluids (1.5 vol%) with 10-15 nm and 45-50 nm particle sizes, the average heat transfer coefficient enhancements were 18.1 and 14.9% at Re=1115, respectively.

Nomenclature

C_p	Heat capacity, kJ/kgK
D	Tube inner diameter, m
H	Convective heat transfer coefficient, W/m^2K
k	Thermal conductivity, W/mK
L	Tube length, m
m	Mass flow rate, kg/S
P	Tube surface perimeter, m
q"	Heat transfer rate, W
q	Heat flux, w/m^2
Re	Reynolds number
T_w	Tube wall temperature, ºC
T_f	Fluid temperature, ºC

Greek symbols

φ	Nanoparticle volume fraction
P	Density, kg/m^3

Subscripts

bf	Base Fluid
in	Inlet
nf	Nanofluid
np	Nanoparticles
out	Outlet

Received : Jun. 21, 2021 ; Accepted : Nov. 22, 2021

REFERENCES

[1] Khanafer K., Vafai K., Lightston M., Buoyancy-Driven, *Int. J. Heat Mass Transfer*, **45(19)**: 3639-3653 (2003).

[2] Wu D., Zhu H., Wang L., Liu L., Critical Issues in Nanofluids Preparation, Characterization and Thermal Conductivity, *Curr. Nanosci.*, **5**: 103-112 (2009).

[3] Hajian R., Layeghi M., Abbaspour Sani K., Experimental Study of Nanofluid Effects on the Thermal Performance with Response Time of Heat Pipe, *Energy Convers. Manage.*, **56**: 63-68 (2012).

[4] Choi S.U.S., "Enhancing Thermal Conductivity of Fluids with Nanoparticles, Developments and Application of Non-Newtonian Flows", FED-V. 231/MD-Vol. **66**: 99-105 (1995).

[5] Eastman J. A., Choi S.U.S., Thompson L.J., Lee S., "Enhanced Thermal Conductivity Through the Development of Nanofluids", *Proceedings of Materials Research Society Symposium*, **457**: 3-11 (1997).

[6] Lee S., Choi S.U.S., Li S., Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles, *J. Heat Transfer*, **121**: 280 (1999).

[7] Ghadimi A., Saidur R., Metselaar H.S.C, A Review of Nanofluid Stability Properties and Characterization in Stationary Conditions, *Int. J. Heat Mass Transfer*, **54**: 4051-4068 (2011).

[8] Kiani H., Nadooshan A.A., Thermal Performance Enhancement of Automobile Radiator Using Water-CuO Nanofluid: An Experimental Study, *Energy Equip. Sys.*, **7(3)**: 235-248 (2019).

[9] Awais M., Ullah N., Ahmad J., Sikandar F., Ehsan M.M., Salehin S., Bhuiyan A.A., Heat Transfer and Pressure Drop Performance of Nanofluid: A State-of-the-Art Review, *Int. J. Thermofluids*, **9**: 100065 (2021).

[10] Maghrabie H.M., Elsaid K., Sayed E.T., Abdelkareem M.A., Wilberforce T., Ramadan M., Olabi A.G., Intensification of Heat Exchanger Performance Utilizing Nanofluids, *Int. J. Thermofluids*, **10**: 100071 (2021).

[11] Eastman J.A., Choi S.U.S., Li S., Yu W., Thompson L.J., Anomalously Increased Effective Thermal Conductivities of Ethylene Glycol–based Nanofluids Containing Copper Nanoparticles, *Appl. Phys. Lett.*, **78**: 718 (2001).

[12] Kong M., Lee S., Performance Evaluation of Al_2O_3 nanofluid as an Enhanced Heat Transfer Fluid, *Adv. Mech. Eng.*, **12(8)**: 1-113 (2020).

[13] Lee J.H., Hwang K.S., Jang S.p., Lee B.H., Kim J.H., Choi S.U.S., Choi C.J., Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al_2O_3 Nanoparticles, *Int. J. Heat Mass Transfer*, **51**: 2651-2656 (2008).

[14] Topuz A., Erdogan B., Aycon O., "Determination and Measurements of Some Thermophysical and Properties of Nanofluids and Comparison with Literature Studies", *Thermal Science*, OnLine-First Issue, 239(2020).

[15] Javadi F.S., Sadeghipour S., Saidur R., Boroumandjazi G., Rahmati B., Elias M.M., Sohel M.R., The Effects of Nanofluid on Thermophysical Properties and Heat Transfer Characteristics of a Plate Heat Exchanger, *Int. Commun. Heat Mass Transf.*, **44**: 58-63 (2013).

[16] Zeinali Heris S., Etemad S. Gh., Nasr Esfahany M., Experimental Investigation of Oxide Nanofluids Laminar Flow Convective Heat Transfer, *Int. Commun. Heat Mass Transf.*, **33**: 529-535 (2006).

[17] Alizadeh R., Karimi N., Arjmandzadeh R., Mehdizadeh A., Mixed Convection and Thermodynamic Irreversibilities in MHD Nanofluid Stagnation-point Flows over a Cylinder Embedded in Porous Media, *J. Therm. Anal. Calorim.*, **135**: 489-506 (2019).

[18] Jeong J., Li C., Kwon Y.H., Lee J., SH. Kim S.H., Yun R, Particle Shape Effect on the Viscosity and Thermal Conductivity of ZnO Nanofluids, *Int. J. Refrig.*, **36**: 2233-2241 (2013).

[19] Chaitanya Lahari M.L.R., Sesha Talpa Sai P.H.V., Swamy K.S.N., Krishnamurthy N., Sharma K., "Investigation on Heat Transfer Properties of Water Based TiO_2–ZnO Nanofluids", *IOP Conf. Ser. Mater. Sci. Eng.*, **455**:12092 (2018).

[20] Ahmad M.A., Abubakar M., Ghani M.U., Zafar M.A., Abdullah M., Experimental Study of Heat Transfer Enhancement by Using ZnO and Al_2O_3 Water Based Nanofluids in Car Radiator, *Int. Res. J. Eng. Tech.*, **4(11)**: 740- 744 (2017).

[21] Yu W., Xie H., Chen L., Li Y., Investigation of Thermal Conductivity and Viscosity of Ethylene Glycol Based ZnO Nonofluid, *Thermochim. Acta*, **491**: 92-96 (2009).

[22] Kole M., Dey T.K., Effect of Prolonged Ultrasonication on the Thermal Conductivity of ZnO-ethylene Glycol Nanofluids, *Thermochim. Acta*, **535**: 58-65(2012).

[23] Lee G.J., Kim C.K., Lee M.K., Rhee C.K., Kim S., Kim C., Thermal Conductivity Enhancement of ZnO Nanofluid Using a One-step Physical Method, *Thermochim. Acta*, **542**:24-27(2012).

[24] Saleh R., Putra N., Parkoso S.P., Septiadi V.N., Experimental Investigation of Thermal Conductivity and Heat Pipe Thermal Performance of ZnO Nanofluids, *Int. J. Therm. Sci*., **63**: 125-132 (2013).

[25] Li H., He Y., Hu Y., Jiang B., Hang Y. Thermophysical and Natural Convection Characteristics of Ethylene Glycol and Water Mixture Based ZnO Nanofluids, *Int. J. Heat Mass Transfer*, **91**: 385-389 (2015).

[26] Amrollahi A., Rashidi A.m., Lotfi R., Emami Meibodi M., Kashefi K., Convection Heat Transfer of Functionalized MWNT in Aqueous Fluid in Laminar and Turbulent Flow at Entrance Region. *Int. Commun. Heat Mass Transf.*, **37**: 717-723 (2010).

[27] Anoop KB, Sundararajan T., Das S.K., Effect of Particle Size on the Convective Heat Transfer in Nanofluid in the Developing Region, *Int. J. Heat Mass Transfer*, **52**: 2189-2195 (2009).

[28] Karthikeyan N.R., Philip J., Raj B.V., Effect of Clustering on the Thermal Conductivity of Nanofluids, *Mater. Chem. Phys*., **109**: 50-55 (2008).

[29] Hwang Y., Lee J.K., Lee J-K., Jong–Ku J., Young-Man C., Cheong S-I., Ahn Y.C., Kim S.H., Production and Dispersion Stability of Nanoparticles in Nanofluids, *Powder Technol*., **186**: 145-153(2008).

[30] Amrollahi A., Rashidi A.M., Emami Meibodi M., Kashefi K., Conduction Heat Transfer Characteristics and Dispersion Behavior of Carbon Nano Fluids as a Function of Different Parameters, *J. Exp. Nanosci*., **4(4)**: 347-363(2009).

[31] Tang E., Cheng G., Ma X., Pang X., Zhao Q., Surface Modification of Zinc Oxide Nanoparticle by PMAA and its Dispersion in Aqueous System, *Appl. Surf. Sci.*, **252**: 5227-5232(2006).

[32] Chung S.J., Leonard J.P., Nettleship I., Lee J.K., Soong Y., Martello D.V., Chyu M.K., Characterization of ZnO Nanoparticle Suspension in Water: Effectiveness of Ultrasonic Dispersion, *Powder Technol.*, **194**: 75-80(2009).

[33] Ghozatloo A., Shariaty–Niassar M., Rashidi A.M., Preparation of Nanofluids from Functionalized Graphene by New Alkaline Method and Study on the Thermal Conductivity and Stability, *Int. Commun. Heat Mass Transf.*, **42**: 89-94(2013).

[34] Minista H.A., Roy G., Nguyen C.T., Doucet D., New Temperature Dependence Thermal Conductivity Data for Water-based Nanofluids, *Int. J. Therm. Sci.*, **48:** 363-371(2009).

[35] Teng T.P., Hung Y.H., Teng T.C., Moa H.E., Hsu H.G., The Effect of Alumina/water Nanofluid Particle Size on Thermal Conductivity, *Appl. Therm. Eng.*, **30**: 2213 – 2218 (2010).

[36] Patel H.E., Sundararajan T., Das S.K., An Experimental Investigation into the Thermal Conductivity Enhancement in Oxide and Metallic Nanofluids, *J. Nanopart. Res.*, **12**: 1015-1031(2010).

[37] Vajjha R.S., Das D.K. Experimental Determination of Thermal Conductivity of Three Nanofluids and Development of New Correlations, *Int. J. Heat Mass Transfer*, **52**: 4675-4682(2009).

[38] Li C.H., Peterson G.P., Mixing effect on the Enhancement of the Effective Thermal Conductivity of Nanoparticle Suspensions (Nanofluids), *Int. J. Heat Mass Transfer*, **50:** 4668-4677 (2007).

[39] Singh R.P., Sharma K., Tiwari A.K. An Experimental Investigation of Thermal Conductivity of TiO_2 Nanofluid: Proposing a New Correlation, *J. Sci. Ind. Res.*, 78: 620-623 (2019)

[40] Wen D., Ding D., Experimental Investigation into Convective Heat Transfer of Nanofluid at the Entrance Region under Laminar Flow Conditions, *Int. J. Heat Mass Transfer*, **47**: 5181-5188(2004).

[41] Emami Meibodi M., Vafaie–Sefti M., Rashidi A.M., Amrollahi A., Tabasi M., Sid Kalal H., The Role of Different Parameters on the Stability and Thermal Conductivity of Carbon Nanotube/water Nanofluids, *Int. Commun. Heat Mass Transf.*, **37**: 319-323(2010).