Experimental study of thermal characteristics of ZrO$_2$/EG nanofluid for application of heat transfer

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Abstract
In thermal management system, nanofluids will act as robust elements in future for coolants. Nanofluids have remarkable potential during the heat transfer increase reported by researchers from all over the world. Nanofluids have attracted many researchers, and there have been tremendous advances because of the high thermal characteristics and possible applications in certain areas such as the transport sector, aerospace, medical regions, and microelectronics. This current study reports on the thermal characteristics of nanofluid based on ZrO$_2$/EG. The nanoparticles are characterized by XRD and SEM techniques. Nanofluid was prepared by a two-step method in ethylene glycol (EG) using ultra sonication. The thermal conductivity of ZrO$_2$/EG nanofluid was investigated experimentally at various volume concentrations (0.02–0.1vol. %) and temperature range between 35 and 55 °C. The enhancement in thermal conductivity was observed to be 26.2% at 0.1 vol. % which exhibits superior performance as compared to base fluid (EG). The results of the experiment were compared with the three most often utilized model in the literature. The behavior of ZrO$_2$/water-based nanofluid thermal conductivity, viscosity, and stability in various concentrations was studied.

Keywords Zirconia · Ethylene glycol · Nanofluid · Thermal conductivity · Viscosity · Stability

Abbreviations
K Thermal conductivity, W/m K
EG Ethylene glycol
XRD X-ray diffraction
SEM Scanning electron microscope
ZrO$_2$ Zirconium dioxide
T Temperature, °C
n Shape factor
t Time of flow, s
W Weight
ν Kinematic viscosity, cSt or mm$^2$/s
φ Volume concentration/volume fraction, %
ρ Density, kg/m$^3$

Introduction
As world competition increases, the industry needs to develop advanced heat transfer fluids that have considerably higher thermal conductivity than is currently available. The thermal conductivity of the heat transfer fluid plays an essential role in developing energy-efficient heat transfer equipment. However, inherently poor heat transfer fluids are the traditional heat transfer fluids such as ethylene glycol and water mixtures, ethylene glycol (EG), water, and oil.

Nanofluids are the most efficient fluids for heat transfer applications in transportation, electronic cooling, industrial cooling, aerospace, and defense cooling systems, and renewable energy (Kakac et al. 2002). To improve the convective heat transfer properties of conventional fluids, the fundamental concept is to improve the thermal conductivity of these base fluids. Numerous factors contribute to improving thermal conductivity such as volume fraction, particle size, shape, material, base fluid, temperature, Brownian motion,
and aggregation of nanoparticles (Simpson et al. 2019; Rajendiran et al. 2018). The influence of particle volume fraction on nanofluids thermal conductivity has received a lot of attention in the literature. Thermal conductivity and viscosity are also influenced by particle size and surfactant. According to the literature (Kim et al. 2007; Omrani et al. 2019; Kwek et al. 2010), an increase in nanoparticle size can increase or reduce thermal conductivity; however, the smaller nanoparticles had a higher thermal conductivity in the majority of studies. Furthermore, increasing the size of the nanoparticles reduces the viscosity of the nanofluid; but, as the nanoparticles get too large, the nanofluid becomes unstable, limiting the maximum size of nanoparticles. Thermal conductivity decreases as nanoparticle size grows due to a decrease in Brownian motion and a reduced surface area to volume ratio. Enhancing Brownian motion increases the thermal conductivity by providing more routes for heat transmission (Apmann et al. 2021).

Surfactants are utilized to make nanofluids more stable and avoid nanoparticle aggregation and deposition. Surfactants aid in increasing the thermal conductivity of the nanofluid at low concentrations, but they aid in decreasing it at high concentrations. A surfactant can negatively charge nanoparticles, causing them to reject each other, resulting in increased movement and particle collisions to transfer energy and lower nanofluid viscosity (Asadi et al. 2017).

The thermal conductivity of nanofluid is a property that can straightforwardly impact heat transfer ability of nanofluid (Choi 2008). A nanofluid is a fluid that contains nanometer-sized (1–100 nm) nanoparticles. These liquids are engineered nanoparticles’ colloidal suspensions in a base fluid. Superior thermophysical properties of nanofluid such as thermal conductivity, viscosity, and coefficients of convective heat transfer compared to base fluids (Kulkarni et al. 2008; Vajjha et al. 2010; Peyghambarzadeh et al. 2011; Leong et al. 2010).

A property that can have a direct impact on the heat transfer capacity of nanofluid is its thermal conductivity (Choi and Eastman 1995). The most common additives used in order to enhance thermal conductivity are the metal oxides (Al₂O₃, TiO₂, MgO, Fe₂O₃, SiO₂, CuO, ZnO), metal carbide (ACS, SiC), metals (Cu, Ag, Ni, Au), and the carbon (diamond, graphite,CNT, MWCNTs) (Sajid and Ali 2018). Researchers have been interested in zirconia (ZrO₂) due to its long-term thermal stability, mechanical strength, amphoteric behavior, stiffness, inert chemical existence, and lower cost of production (Sarfraz et al. 2020; Abd-Elwahed and Mesilhy 2020, Fiorati et al. 2021). It is used in catalysts, fuel cells, capacitors, batteries, fabrication of gas sensors, corrosion-resistant coatings, ceramics, and many other industrial applications (Colak 2021). As a result, researchers have focused on identifying novel nanoparticles in order to uncover likely nanoparticles that can increase the thermal properties and stability of the nanofluid in the system. Thus, this material was decided to test its ability to improve the heat transfer properties of the system.

Ettefaghi et al. (2013) studied the thermal properties by adding MWCNTs with a different concentration in engine oil. They found that thermal conductivity was 13.2% at 0.5wt%. It has been investigated that higher stability is achieved with lower concentration. Li et al. (2016) experimentally studied the silicon carbide (SiC) nanofluid thermal conductivity and viscosity dependent on motor coolants. They found that thermal conductivity was 53.81% at 0.5 vol.%. Maheshwary et al. (2017) have investigated TiO₂/water-based nanofluid’s thermal conductivity based on particle size, shape, and concentration. It was found that concentration is the main cause in the augmentation of thermal conductivity. Batmunkh et al. (2014) showed an intensification in the thermal conductivity from 0.619 to 0.627 W/mK at 40 °C with the addition of 0.5 wt.% Ag into 3 wt.% TiO₂/water nanofluid. Mukhbayar et al. (2013) have studied the enhancement of CNT surface properties by using silver nanoparticles. Volume concentration (0–3%) and temperature range 15–40 °C were used in the preparation of nanofluids. It was observed that improvement in thermal conductivity 14.5% contrasted with the base liquid. Hung et al. (2012) found that adding 1.5 wt.% Al₂O₃ nanoparticles to water improved heat transfer by 40%. It also demonstrated that lower operating temperatures result in better heat transfer performance. Guo et al. (2018) studied SiO₂/ (EG-Water) nanofluid’s thermal conductivity. They observed that the thermal conductivity of nanofluid increased with rising in temperature. Volume concentration is also found to be an important factor for the enhancement of thermal conductivity. Thrush et al. (2020) have studied the enactment of tribological applications and the stability of ZrO₂ nanofluids. The dispersion’s stability was tested over a period of 25 months to ensure that the nanoparticles did not clump together or settle out of the solution. It has been found that for concentration equal to or more than 0.1 wt.%, the tribofilm growth rate is swift and stable for more than 2 years. As a result, the tribological performance of ZrO₂ nanofluids has been reported as a function of nanoparticle concentration.

The available literature reveals that there have been few studies on the thermal conductivity and viscosity of ZrO₂/EG nanofluid. Mostly, concentration of the nanoparticles normally used in the preparation of the nanofluid is above 0.1 vol.%. When volume concentration of the nanoparticle increases in base fluid, then there is problem of clogging, sedimentation, and settling down the nanoparticle. Therefore, the objective of present work to study experimentally thermal characteristics of ZrO₂ nanoparticle has been suspended in base fluid ethylene glycol at lower volume concentrations, i.e., 0.02–0.1 vol. % with interval of 0.02 vol.% and temperature range between 35
and 55 °C. The results of the experiment were compared with the three most often utilized model in the literature.

**Preparation process of nanofluids**

The two-step approach for preparing nanofluids is the most often used in the literature (Suresh et al. 2011; Chen et al. 2011). Two-step methods are used in the current study for heat transfer purposes. The two-step method for the preparation of nanofluid is to be an economical method for mass production. In particular, Equations (1) calculated and re-evaluated the precise equilibrium of the nanoparticles to be used at five different volume concentrations of nanofluids 0.02%, 0.04%, 0.06%, 0.08%, and 0.1% (Kannaiyan et al. 2017):

\[
\text{%Volumeconcentration} = \left[ \frac{W_{np}}{\rho_{np}} + \frac{W_{EG}}{\rho_{EG}} \right] \cdot 100
\] (1)

To make sample nanofluids, 100 ml of the base fluid (ethylene glycol) was distributed in preweighed amounts of zirconia nanoparticle. After 30 min, the sample was stirred in a magnetic stirrer before it was placed 3 h in an ultrasound bath. Ultrasonic and mechanically agitated stirring are used to break the agglomeration of nanoparticles to keep them intact for a longer period of time.

**Measurement of thermal conductivity and viscosity**

Nanofluid’s thermal conductivity was evaluated by using the thermal property analyzer KD2 Pro (Decagon Devices, USA). The transient hot-wire method of functioning is used. Single-needle sensors assess thermal conductivity and resistivity, while dual-needle sensors measure thermal conductivity, volumetric specific heat capacity, resistivity, and diffusivity using this instrument. The accuracy of this device is ± 5.0%. ZrO$_2$/EG nanofluid’s thermal conductivity measurement device is shown in Fig. 1. To increase precision, the data was collected in triplicate, and the average value was utilized for analysis.

In this experiment, we use a Red wood viscometer to determine viscosity. A preset amount of fluid may flow through a capillary tube of specific dimensions in these viscometers under a predetermined set of parameters, and the flow rate at a certain temperature is measured. The viscosity of oil thus determined in the units is sometimes referred to as relative viscosity. As the instruments used are kinematic in the standard dimension of the oil in the centistokes, it can be calculated by using the following Eq. (2) as the oil passes through the standard orifice of the instrument:

\[
\nu = C \cdot t
\] (2)

where \( C = \text{viscometer constant} \) (value of \( C \) depends on \( t \)).

\[ K_{nf} = \frac{k_p + k_{bf} \times (n - 1) + (n - 1)(k_p - k_{bf})\varnothing}{k_p + k_{bf} \times (n - 1) - (k_{bf} - k_p)\varnothing} k_{bf} \] (3)

Maxwell (1891) model was utilized to ascertain nanofluids’ thermal conductivity:

\[ K_{nf} = \left[ \frac{k_p + 2 \times k_{bf} - 2 \times \varnothing (k_{bf} - k_p) \times k_{bf}}{k_p + 2 \times k_{bf} + \varnothing (k_{bf} - k_p) \times k_{bf}} \right] \] (4)

Yu and Choi (2003) was also utilized to determine thermal conductivity of the nanofluid:

\[ K_{nf} = \left[ \frac{k_p + 2 \times k_{bf} - 2 \times \varnothing (k_{bf} - k_p) \times (1 + \beta)^3}{k_p + 2 \times k_{bf} + \varnothing (k_{bf} - k_p) \times (1 + \beta)^3} \times k_{bf} \right] \beta = 0.1 \text{ was used by Yu and Choi for nanofluids.} \]

**Results and discussion**

**Characterization of sample**

The phase purity and crystallinity of ZrO$_2$ (Bruker AXS D8 advance) were depicted by powder X-ray diffractometer (PXRD). The PXRD data reveals the amorphous nature of ZrO$_2$ as displayed in Fig. 2. The as-synthesized ZrO$_2$ shows the characteristic peak at 2θ = 31.23° and 51.32°.
corresponding to (111) and (221) planes respectively depicting monoclinic phase of zirconia. The obtained XRD results are in agreement with JCPDS file no. 88–2390 of monoclinic ZrO$_2$ (Singh et al. 2015; Wang et al. 2014; Das et al. 2019) which were found to be quite similar to these diffraction peaks. Additionally, the peak broadening confirms the formation of small-size ZrO$_2$ nanoparticles. No other impurities were found in the XRD results.

A JEOL appliance has been used with the scanning electron microscope (SEM) (model JEOL 6380A) for identification of surface morphology. Figure 3 a SEM image indicates the formation of agglomerated ZrO$_2$ spherical nanoparticles. EDS analysis was carried out to confirm the element composition. Figure 3 b affirms the presence of Zr, O, C, and Cl, and no other extra peak was observed in EDS. The C peak observed in EDS is due to carbon tape used during sample preparation. However, the small Cl peak in EDS is observed, which might be due to trace amount of residual zirconium precursor used for the synthesis of ZrO$_2$ nanoparticles. The obtained results are in agreement with XRD data, confirming the formation of ZrO$_2$ nanoparticles without any impurities.

**Thermal conductivity and viscosity**

The thermal conductivity of ZrO$_2$/EG nanofluids was evaluated with varying volume concentrations of nanoparticles (0.02 to 0.1 vol. %) at temperatures ranging from 35 to 55 °C, as shown in Fig. 4. It reveals that nanofluids boost the thermal conductivity as their volume concentration and temperature rise. Thermal conductivity of the base fluid, ethylene glycol (EG), was first calculated (0.244 W/m–K), and then ZrO$_2$ nanoparticles were introduced to the base fluid (EG) in varied volume concentrations (i.e., 0.02 to 0.1 vol.%) at temperatures ranging from 35 to 55 °C.

In the analysis of the effect on thermal conductivity of nanofluid that five different volume concentration and temperature interval of 0.02% and 5 °C was taken. It shows an improvement in the thermal conductivity with increasing volume concentration and temperature. Because of the increase in Brownian movement and kinetic energy of particles, the thermal conductivity of nanofluids increases with temperature. An increment in Brownian movement takes into consideration more convection, prompting a higher thermal conductivity. An increment in the kinetic energy of particles implies more particles impacting, which increases heat transfer (Apmann et al. 2021).
Figure 5 illustrates the thermal conductivity of ZrO$_2$/EG nanofluid in aspects of volume concentration at different temperature. According to this figure, adding ZrO$_2$ nanoparticles to the base liquid leads to increases in thermal conductivity levels at any temperature, which is owing to intensification in thermophoresis of particles, Brownian motion, and particle collisions. Figure 6 shows the thermal conductivity of ZrO$_2$/EG nanofluid at various volume concentrations. It may be understood that with the increased volume of nanoparticles in base fluids, the thermal conductivity of all nanofluid has been improved. For different nanofluids, similar cases had been reported before (Paul et al. 2011; Mostafizur et al. 2014; Ijam et al. 2015).

A variety of parameters influence the thermal conductivity of nanofluids, including nanoparticle volume concentrations in base fluid, nanoparticle type and morphology, basic fluid type, base fluid temperature, and method of preparations (Murshed et al. 2008, 2005).

Nanofluids were computed using the following equation for thermal conductivity improvements (Senthilraja et al. 2015):

\[
\text{Thermal conductivity enhancement} \times 100 = \left( \frac{K_{nf} - K_{EG}}{K_{EG}} \right) \times 100
\]

Figure 7 shows the percent enhancement in the thermal conductivity of ZrO$_2$/EG nanofluids at different volume concentrations. Significant enhancement in the thermal conductivity was recorded for ZrO$_2$/EG nanofluids (5.73%, 10.24%, 14.34%, 20.08%, and 26.2%) for various volume concentrations of 0.02 vol. %, 0.04 vol. %, 0.06 vol. %, 0.08 vol. %, and 0.1 vol. % respectively, which exhibits superior performance as compared to base fluid (EG).

Thermal conductivity has been enhanced because of Brownian mobility and collisions between nanoparticles in base fluid (Hojjat et al. 2009). The thermal efficiency of the energy system is due to the large nanoparticles surface area per unit volume that allows more transfer of heat between solid particles and base fluids (Yin et al. 2018). Figure 8 illustrates the experimental viscosity of ZrO$_2$/EG nanofluid as well as base fluid. It has been revealed that when the temperature rises, the viscosity of nanofluid reduces. The viscosity of the nanofluid appears to decrease as the temperature rises between 35 and 55 °C. The reason is that when
The measured thermal conductivity values of ZrO₂/EG nanofluid were compared with the predicted values of existing models. Figure 9 compares these experimental values with predicted values using conventional models at different volume concentrations ranging between 0.02 and 0.1%.

For all volume concentrations, the experimental results of the nanofluid revealed higher thermal conductivities than the models developed by Hamilton-Crosser, Maxwell, and Yu and Choi. The thermal conductivity increases with increasing volume concentration, according to both experimental data and models. The anticipated models had not taken into consideration the impact of particle size and interfacial layer formed at the interface of the particle and fluid.

The zeta potential method determines the difference in potential between the bulk fluid and the stationary layer of fluid in contact with nanoparticles. To estimate formulation stability, zeta potential measurement was taken into consideration. Figure 10 shows the zeta potential of ZrO₂/EG nanofluid at various volume concentrations. The zeta potential method determines the difference in potential between the bulk fluid and the stationary layer of fluid in contact with nanoparticles. To estimate formulation stability, zeta potential measurement was taken into consideration (Sadeghi and Gholamhoseinpoor 2015). Figure 10 shows the zeta potential of ZrO₂/EG nanofluid at various volume concentrations. The stability of the prepared nanofluid at five different volume concentrations (0.02, 0.04, 0.06, 0.08, and 0.1 vol.%) was determined by a zeta potential measurement which is far from the isoelectric point (IEP).

Conglomeration occurs nearby the isoelectric point or pH value where the zeta potential becomes zero (Akhgar and Toghraie 2018). It shows that the zeta potential of the

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![Fig. 7 Enhancement of thermal conductivity (ZrO₂/EG nanofluid) at various volume concentration](image)

![Fig. 8 Viscosity of ZrO₂/EG nanofluid at different temperature](image)

![Fig. 9 Experimental thermal conductivity of ZrO₂/EG nanofluid compared to theoretical model at various volume concentration](image)
nanofluids verbalized in the work was observed to be around 50 mV which is revealing of good colloidal stability.

Higher zeta potential levels suggest more stable dispersion, while lower values indicate colloidal instability and particle aggregation (Wole-Osho et al. 2020). The nanofluid was shown to be stable after a week, with zeta potential values greater than 50 mV.

**Conclusions**

In this work, a KD2 Pro thermal property analyzer was used to estimate the thermal conductivity of ZrO$_2$/EG nanofluid with five different volume concentrations (0.02%, 0.04%, 0.06%, 0.08%, and 0.1%). Nanofluid was prepared by a two-step method in ethylene glycol (EG) using ultrasonication. Enhancement of thermal conductivity was obtained by 26.2% compared with base fluid ethylene glycol at 0.1 vol.%. The impact of concentration and temperature of nanoparticles on improvements in thermal conductivity was deemed. It shows that the enhancement in thermal conductivity of nanofluid is influenced by volume concentration and temperature. For all volume concentrations, the experimental results of the nanofluid revealed higher thermal conductivities than the predicted models’ value. A significant increase in thermal conductivity has been seen in nanofluids. Zeta potential method is used to formulate the stability of nanofluid and was found to be stable, with zeta potential values larger than 50 mV. As a result, ZrO$_2$ nanoparticles are likely to play a substantial role in heat transfer, and this aspect of nanofluid was further investigated. This reveals that nanofluids are the future generation’s most promising heat transfer fluids.

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**Competing interests** The authors declare no competing interests.

**Conflict of interest** The authors declare no competing interests.

**References**

Abd-Elwahed MS, Meselhy AF (2020) Experimental investigation on the mechanical, structural and thermal properties of Cu–ZrO$_2$ nanocomposites hybridized by graphene nanoplatelets. Ceram Int 46(7):9198–9206. https://doi.org/10.1016/j.ceramint.2019.12.172

Akhtar A, Toghaiea D (2018) An experimental study on the stability and thermal conductivity of water-ethylene glycol/TiO$_2$-MWCNTs hybrid nanofluid: developing a new correlation. Powder Technol 338:806–818. https://doi.org/10.1016/j.powtec.2018.07.086

Apmann K, Fulmer R, Soto A, Vafaei S (2021) Thermal conductivity and viscosity: review and optimization of effects of nanoparticles. Materials 14(5):1291. https://doi.org/10.3390/ma14051291

Asadi A, Asadi M, Siahmargoi M, Asadi T, Andarati MG (2017) The effect of surfactant and sonication time on the stability and thermal conductivity of water-based nanofluid containing Mg(OH)$_2$ nanoparticles: an experimental investigation. Int J Heat Mass Transf 108:191–198. https://doi.org/10.1016/j.ijheatmasstransfer.2016.12.022

Babar H, Sajid MU, Ali HM (2019) Viscosity of hybrid nanofluids: a critical review. Thermal Science, 23(3 Part B), 1713–1754. https://doi.org/10.2298/TSC181128015B

Batmunkh M, Tanshen MR, Nine MJ, Myekhlai M, Choi H, Chung H, Jeong H (2014) Thermal conductivity of TiO$_2$ nanoparticles based aqueous nanofluids with an addition of a modified silver particle. Ind Eng Chem Res 53(20):8445–8451. https://doi.org/10.1021/ie403712f

Chen RH, Phuc TX, Martello D (2011) Surface tension of evaporating nanofluid droplets. Int J Heat Mass Transf 54(11–12):2459–2466. https://doi.org/10.1016/j.ijheatmasstransfer.2011.02.016

Choi SU, Eastman JA (1995) Enhancing thermal conductivity of fluids with nanoparticles (No. ANL/MSD/CP-84938; CONF-951135–10). Argonne National Lab., IL (United States)

Choi SU (2008) Nanofluids: A new field of scientific research and innovative applications. https://doi.org/10.1080/01457630701850778

Colak AB (2021) Experimental study for thermal conductivity of water-based zirconium oxide nanofluid: developing optimal artificial neural network and proposing new correlation. Int J Energy Res 45(2):2921–2930. https://doi.org/10.1002/er.5988

Das RS, Warkhade SK, Kumar A, Wankhade AV (2019) Graphene oxide-based zirconium oxide nanocomposite for enhanced visible light-driven photocatalytic activity. Res Chem Intermed 45(4):1689–1705. https://doi.org/10.1007/s11164-018-3699-z
Ettedghchi E-O-L, Ahmadi H, Rashidi A, Nouralishahi A, Mohtasebi SS (2013) Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. 3Int Commun Heat Mass Transf 46:142–7. https://doi.org/10.1016/j.icheatmasstransfer.2013.05.003

Fiorati A, Florit F, Mazzci A, Buzzacarco S, Rossi B, Piazza R, Rota R, De Nardo L (2021) Dispersions of zirconia nanoparticles close to the phase boundary of surfactant-free ternary mixtures. Langmuir 37(14):4072–4081. https://doi.org/10.1021/acs.langmuir.0c03401

Guo Y, Zhang T, Zhang D, Wang Q (2018) Experimental investigation of thermal and electrical conductivity of silicon oxide nanofluids in ethylene glycol/water mixture. Int J Heat Mass Transf 117:280–286. https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.091

Hamilton RL, Crosser OK (1962) Thermal conductivity of heterogeneous two-component systems. Ind Eng Chem Fundam 1(3):187–191. https://doi.org/10.1021/i260003a005

Hoijat M, Etmed SG, Bagheri R, Thibault J (2009) The thermal conductivity of non-Newtonian nanofluids. In 8th World Congress of Chemical Engineering, Montreal, Canada

Hung YH, Teng TP, Teng TC, Chen JH (2012) Assessment of heat dissipation performance for nanofluid. Appl Therm Eng 32:132–140. https://doi.org/10.1016/j.applthermaleng.2011.09.008

Ijami A, Saidur R, Ganesan P, Golshieh AM (2015) Stability, thermophysical properties, and electrical conductivity of graphene oxide-deionized water/ethylene glycol based nanofluid. Int J Heat Mass Transf 87:92–103. https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.060

Kakac S, Liu H, Pramuanjaroekij A (2002) Heat exchangers: selection, rating, and thermal design. CRC press. ISBN 978-0-8493-0902-1. https://doi.org/10.1007/9781461503746

Kannaiyan S, Boobalan C, Umasankaran A, Ravirajan A, Sathyan S, Thomas T (2017) Comparison of experimental and calculated thermophysical properties of alumina/cupric oxide hybrid nanofluids. J Mol Liq 244:469–477. https://doi.org/10.1016/j.molliq.2017.09.035

Kim SH, Choi SR, Kim D (2007) Thermal conductivity of metal-oxide nanofluids: particle size dependence and effect of laser irradiation, 298–307. https://doi.org/10.1115/1.2427071

Kulkarni DP, Vajjha RS, Das DK, Oliva D (2008) Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant. Appl Therm Eng 28(14–15):1774–1781. https://doi.org/10.1016/j.applthermaleng.2007.11.017

Kwek D, Crivoi A, Duan F (2010) Effects of temperature and particle size on the thermal property measurements of Al2O3–water nanofluids. J Chem Eng Data 55(12):5690–5695. https://doi.org/10.1021/je1006407

Leong KY, Saidur R, Kazi SN, Mamun AH (2010) Performance investigation of an automotive car radiator operated with nanofluid-based coolants (nanofluid as a coolant in a radiator). Appl Therm Eng 30(17–18):2685–2692. https://doi.org/10.1016/j.applthermaleng.2010.07.019

Li X, Zou C, Qi A (2016) Experimental study on the thermo-physical properties of car engine coolant (water/ethylene glycol mixture type) based SiC nanofluids. Int Commun Heat Mass Transfer 77:159–164. https://doi.org/10.1016/j.icheatmasstransfer.2016.08.009

Mahbubul IM, Shahrus IM, Khaleduzzaman SS, Saidur R, Amalina MA, Turqut A (2015) Experimental investigation on effect of ultrasonication duration on colloidal dispersion and thermophysical properties of alumina–water nanofluid. Int J Heat Mass Transf 88:73–81. https://doi.org/10.1016/j.ijheatmasstransfer.2015.04.048

Maheshwary PB, Handa CC, Nemade KR (2017) A comprehensive study of effect of concentration, particle size and particle shape on thermal conductivity of titania/water based nanofluid. Appl Therm Eng 119:79–88. https://doi.org/10.1016/j.applthermaleng.2017.03.054

Maxwell JC (1891). Medium in which small spheres are uniformly disseminated. A treatise on electricity and magnetism, (part II).

Mostafizur RM, Bhuiyan MHU, Saidur R, Aziz AA (2014) Thermal conductivity variation for methanol based nanofluids. Int J Heat Mass Transf 76:350–356. https://doi.org/10.1016/j.ijheatmasstransfer.2014.04.040

Munkhbayar B, Tashen MR, Jeoun J, Chung H, Jeong H (2013) Surfactant-free dispersion of silver nanoparticles into MWCNT-aqueous nanofluids prepared by one-step technique and their thermal characteristics. Ceram Int 39(6):6415–6425. https://doi.org/10.1016/j.ceramint.2013.01.069

Murshed SMS, Leong KC, Yang C (2005) Enhanced thermal conductivity of TiO2-water based nanofluids. Int J Therm Sci 44(4):367–373. https://doi.org/10.1016/j.ijthermalsci.2004.12.005

Murshed SMS, Leong KC, Yang C (2008) Thermophysical and electrokinetic properties of nanofluids—a critical review. Appl Therm Eng 28(17–18):2109–2125. https://doi.org/10.1016/j.applthermaleng.2008.01.005

Omran AN, Esmaeilzadeh E, Jafari M, Behzadmehr A (2019) Effects of multi walled carbon nanotubes shape and size on thermal conductivity and viscosity of nanofluids. Diam Relat Mater 93:96–104. https://doi.org/10.1016/j.diamond.2019.02.002

Paul G, Philip J, Raj B, Das PK, Manna I (2011) Synthesis, characterization, and thermal property measurement of nano-Ag5Zn05 dispersed nanofluid prepared by a two-step process. Int J Heat Mass Transf 54(15–16):3783–3788. https://doi.org/10.1016/j.ijheatmasstransfer.2011.02.044

Peyghambarzadeh SM, Hashemabadi SH, Jamnani MS, Hoseini SM (2011) Improving the cooling performance of automobile radiator with Al2O3/water nanofluid. Appl Therm Eng 31(10):1833–1838. https://doi.org/10.1016/j.applthermaleng.2011.02.029

Rajendran G, Kuppusamy VB, Shanmugasundaram S (2018) Experimental investigation of the effects of sonication time and volume concentration on the performance of PVT solar collector. IET Renew Power Gener 12(12):1375–1381. https://doi.org/10.1049/iet-rpg.2018.5283

Sajid MU, Ali HM (2018) Thermal conductivity of hybrid nanofluids: a critical review. Int J Heat Mass Transf 126:211–234. https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.021

Sarafraz MM, Tiliî I, Tian Z, Khan AR, Safaei MR (2020) Thermal analysis and thermo-hydraulic characteristics of zirconia-water nanofluid under a convective boiling regime. J Therm Anal Calorim 139(4):2413–2422. https://doi.org/10.1007/s10973-019-08435-x

Sekhar YR, Sharma KV (2015) Study of viscosity and specific heat capacity characteristics of water-based Al2O3 nanofluids at low particle concentrations. J Exp Nanosci 10(2):86–120. https://doi.org/10.1080/17458080.2013.796595

Senthilraj S, Vijayakumar K, Gangadevi R (2015) A comparative study on thermal conductivity of Al2O3/water, CuO/water and Al2O3–CuO/water nanofluids. Dig J Nanomater Biostruct 10(4):1449–1458

Simpson S, Schelfhout A, Golden C, Vafaei S (2019) Nanofluid thermal conductivity and effective parameters. Appl Sci 9(1):87. https://doi.org/10.3390/app9010087

Singh BR, Shoba M, Khan W, Naqi AH (2015) Synthesis of graphene/zirconium oxide nanocomposite photocatalyst for the removal of rhodamineB dye from aqueous environment. J Alloy Compd 651:598–607. https://doi.org/10.1016/j.jallcom.2015.05.231

Suresh S, Venkitaraj KP, Selvakumar P, Chandrasekar M (2011) Synthesis of Al2O3–Cu/water hybrid nanofluids using two step method and its thermo physical properties. Colloids Surf, A 388(1–3):41–48. https://doi.org/10.1016/j.colsurfa.2011.08.005
Thrush SJ, Comfort AS, Dusenbury JS, Xiong Y, Qu H, Han X, Schall JD, Barber GC, Wang X (2020) Stability, thermal conductivity, viscosity, and tribological characterization of zirconia nanofluids as a function of nanoparticle concentration. Tribol Trans 63(1):68–76. https://doi.org/10.1080/10402004.2019.1660017

Vajjha RS, Das DK, Namburu PK (2010) Numerical study of fluid dynamic and heat transfer performance of Al2O3 and CuO nanofluids in the flat tubes of a radiator. Int J Heat Fluid Flow 31(4):613–621. https://doi.org/10.1016/j.ijheatfluidflow.2010.02.016

Wang X, Zhang L, Lin H, Nong Q, Wu Y, Wu T, He Y (2014) Synthesis and characterization of a ZrO2/gC3N4 composite with enhanced visible-light photoactivity for rhodamine degradation. RSC Adv 4(75):40029–40035

Wole-Osho I, Okonkwo EC, Kavaz D, Abbasoglu S (2020) An experimental investigation into the effect of particle mixture ratio on specific heat capacity and dynamic viscosity of Al2O3-ZnO hybrid nanofluids. Powder Technol 363:699–716. https://doi.org/10.1016/j.powtec.2020.01.015

Yin Z, Bao F, Tu C, Hua Y, Tian R (2018) Numerical and experimental studies of heat and flow characteristics in a laminar pipe flow of nanofluid. J Exp Nanosci 13(1):82–94. https://doi.org/10.1080/17458080.2017.1413599

Yu W, Choi SUS (2003) The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model. J Nanopart Res 5(1):167–171. https://doi.org/10.1023/A:1024438603801

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