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Experimental investigation of thermal conductivity and heat pipe thermal performance of ZnO nanofluids

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ABSTRACT

Nanofluids consisting of nanoparticles dispersed in heat transfer carrier fluid have received attention over the last view years for their enormous potential to improve the efficiency of heat transfer fluids. This work investigated the synthesis of ZnO nanoparticle-based thermal fluids prepared using a two-step process. Chemical precipitation was used for the synthesis of the ZnO powders, and ultrasonic irradiation was used to disperse the nanoparticles in ethylene glycol as the base fluid. The thermal conductivity enhancement of the nanofluid demonstrated a nonlinear relationship with respect to volume fraction and crystallite size, with increases in the volume fraction and crystallite size both resulting in increases in the working medium for a conventional screen-mesh wick heat pipe. The experiments were performed to measure the temperature distribution and thermal resistance of the heat pipe. The results showed temperature distribution and thermal resistance to decrease as the concentration and the crystallite size of the nanoparticle increased.

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1. Introduction

In recent times, there has been an urgent need in many industrial fields for a new cooling medium with significantly improved heat transfer performance compared to those currently available [1–3] and it is also well known that fluids typically have lower thermal conductivity compared to crystalline solids [4]. Therefore, fluids containing suspended solid particles can be reasonably expected to have higher thermal conductivities than pure fluids. The idea of using nanofluids, defined as liquids with nanometer-sized particle suspensions, was first introduced by Choi in 1995 [5]. It has been shown that when solid nanometer-sized particles are suspended in fluid, the enhancement of thermal conductivity can be significant. This enhancement can improve the efficiency of fluids used in heat transfer applications [6–9].

A wide variety of nanoparticles and base fluids that can be combined to formulate nanofluids have been evaluated over the last decade to determine the variation in thermophysical properties, with particular emphasis on measurements of thermal conductivity and viscosity [10-15]. A number of publications on the thermal properties of nanofluids consisting of metallic or nonmetallic nanoparticles have shown a large enhancement in the thermal conductivity of nanofluids. Eastman et al. [16] first reported the enhancement of thermal conductivity by 40% when 0.3 vol% Cu nanoparticles were dispersed in ethylene glycol. In addition, they reported that nanofluids consisting of 4 vol% of 36 nm CuO nanoparticles in distilled water exhibited as much as a 20% increase in effective thermal conductivity over that of the base fluid (distilled water) at room temperature. Similar behavior was also observed in another study of 33 nm Al₂O₃ nanoparticles dispersed in distilled water [17]. Moreover, it has been shown that the enhancement of thermal conductivity tends to increase with increased temperature. Das et al. [18] showed in their experiment using a temperature-oscillating technique that the thermal conductivity increased not only with increasing temperature but also with increasing particle volume fraction. Murshed et al. [19] studied the thermal conductivities of both rod-shaped and spherical-shaped TiO₂ nanoparticles dispersed in deionized water using a transient hot wire technique. Their results demonstrated that the thermal conductivity was influenced by the volume fraction as well as the shape and size of the particles. From the literature above, it is evident that fluids containing nanoparticles have substantially higher thermal conductivities than their base fluids

However, for heat transfer applications, the enhancement of thermal conductivity is not the only concern; the real worth of the

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Nomenciature					
λ	X-rav wavelength (Å)				
<d></d>	average crystallite size (nm)				
Δ. β	full-width at half maximum (rad)				
Θ, θ	diffraction angle (rad)				
2 Θ, 2 θ	x-ray diffraction peak position (degree)				
a, b, c	lattice parameter (Å)				
η	lattice strain				
F(R)	Kubelka–Munk function				
R	reflectance (%)				
Eg	energy gap (eV)				
$\kappa_{\mathbf{R}}$	relative values of thermal conductivity				
$R_{\rm e-a}, R_{\rm th}$	thermal resistance (°C/W)				
Т	temperature (°C)				
ΔT	temperature difference (°C)				
Q	input power (W)				
subscripts					
d	drying				
e	evaporator section				
a	adiabatic section				
e—a	between evaporator section and adiabatic section				
th	thermal				

nanofluid as a cooling medium can only be examined under convective conditions. Tsai et al. [20] synthesized gold (Au) nanoparticles of different sizes and dispersed these nanoparticles in an aqueous solution. The Au nanofluid was then employed as a working medium for a conventional circular heat pipe. The measured results showed that the thermal resistance of the heat pipe with the nanoparticle solution was lower compared to that with deionized water. Kang et al. [21] investigated the thermal performance of various particle sizes of silver (Ag) nanoparticles dispersed in deionized water using a grooved heat pipe. It was observed that when more Ag nanoparticles were dispersed in the deionized water, the increase in the heat pipe wall temperature was smaller than that for a pure water-filled heat pipe under various heat loads. In addition, maximum reductions of 50 and 80% of the thermal resistance were achieved when nanoparticle sizes of 10 and 35 nm, respectively, were added to the deionized water. Shafahi et al. [22,23] studied the thermal performance of CuO, Al₂O₃ and TiO₂nanofluids in cylindrical and flat-shaped heat pipes. They showed that the presence of nanoparticles in the working fluid led to a reduction in the speed of the liquid, a smaller temperature difference along the heat pipe and substantial enhancement in the thermal performance of the heat pipe.

The present work reports the synthesis of ZnO nanoparticles using a co-precipitation method and the dispersal of these nanoparticles in ethylene glycol without the addition of any surfactant. Nanoparticles were characterized by x-ray diffraction (XRD), energy dispersive x-ray (EDX), thermal analysis TG–DTA, UV–Vis spectroscopy and infrared absorption spectroscopy (FTIR). The observed structural and optical properties of the ZnO nanoparticles were determined to be correlated with those in the fluid samples by performing FTIR and UV–Vis measurements on the diluted ZnO nanoparticles in ethylene glycol. The thermal conductivity behaviors of the synthesized nanofluids were measured as a function of particle volume fraction. In addition, ZnO nanofluid was employed as the working fluid for a conventional screen-mesh wick heat pipe. In this experiment, the temperature distribution and the heat pipe thermal resistance were further investigated.

2. Experimental procedure

2.1. Synthesis of ZnO nanoparticles

For the synthesis of the undopedZnO nanoparticles in this study, ZnSO₄·7H₂O and 25% aqueous ammonia or NaOH were used, procured from Aldrich. All of the chemicals were GR grade without further purification. Analytical-grade ZnSO₄·7H₂O from Aldrich was dissolved in deionized water to obtain a final concentration of 0.1 M. In this solution, 0.1 M of NaOH solution was added gradually until the final pH of the solution reached 13. The solution was then stirred at a temperature of 80 °C for 30 min until a milky white solution was obtained. Subsequently, the solution was washed several times with deionized water and anhydrous alcohol to remove the by-product sodium sulfate (NaSO₄), and the solution was then filtered. The mixture was aged at room temperature for 24 h. To obtain different crystallite sizes, the mixture was dried at 200 or 600 °C for 4 h.

2.2. Characterization of ZnO nanoparticles

The structural characterization was conducted using a standard x-ray diffractometer (Philips PW1710) with monochromatic Cu–Ka $(\lambda = 1.54060 \text{ Å})$ radiation operated at 40 kV and 20 mA in the range of 10° to 80°. The calibration of the diffractometer was performed using Si powder. The XRD patterns of the nanoparticles were verified by comparison with the JCPDS data. The average size of crvstallites size <D> was estimated using the Scherrer peakbroadening method: $\langle D \rangle = 0.89 \ \lambda/\Delta \cos \Theta$, where Δ is the X-ray wavelength, Δ is line-broadening at half-height and Θ is the Bragg angle of the particles. The average crystallite size is obtained from the (002) peak, corresponding to the ZnO wurtzite structure. Elemental analyses of the samples were conducted through energy dispersive x-ray spectroscopy (EDX) using a scanning microscope. Simultaneous thermogravimetric and differential thermal analysis (TG–DTA) measurements were performed using a Setaram TAG 24. The samples were heated from room temperature up to 800 °C at 10 °C min⁻¹. To study the bonding configuration, infrared absorption measurements were performed using a Shimadzu Fourier transform spectrometer. Optical characterizations were performed by measuring the diffuse reflectance spectroscopy. All spectra were taken in the range of 200-800 nm using a Shimadzu UV-Vis spectrophotometer with an integrating sphere attachment and aSpectralon reflectance standard.

2.3. Synthesis of ZnO nanofluids

ZnO nanofluids were prepared using a two-step procedure by dissolving ZnO nanoparticles in ethylene glycol (EG) as the base fluid. As no surfactant was added in the preparation of the nanofluids, it is expected that the nanoparticles would form clusters in the nanofluid samples. To improve the dispersion of particles in the fluid samples, the nanofluids were stirred using a magnetic stirrer and sonicated using an ultrasonic processor under continuous pulse for 2 h. Five weight concentrations of nanofluids were prepared by dissolving 25, 50, 75, 100 and 500 mg of ZnO nanoparticles in 100 ml of ethylene glycol.

2.4. Measurement of thermal conductivity of the nanofluids

The thermal conductivity of the nanofluids was measured using a KD2 Pro thermal properties analyzer from Decagon Devices, Inc, which has a sensor with a length of 60 mm and a diameter of 1.28 mm. This KD2 thermal analyzer was used successfully by Wen and Ding [24] and Putra et al. [25] in their work with nanofluids and by other researchers [26]. The sensor must be inserted completely into the medium to obtain measurements. The interior of the sensor contains an integrated heating element and thermo-resistor, and it is connected to a microprocessor to control and conduct the measurements. The nanofluid sample was held in a glass beaker located in a thermostat bath to ensure that all of the measurements were at a constant temperature. At least five measurements were taken for each nanofluid to ensure the realiability of the measurements within 2%. The measurements were performed on the nanofluids at room temperature.

2.5. Measurement of ZnO nanofluid heat pipe thermal performance

The heat pipes used in our experiments were constructed using straight copper tubing with an outer diameter of 8 mm, an inner diameter of 7.44 mm and length of 200 mm. The wicks for each heat pipe were made from a stainless steel wire screen mesh with a wire diameter of 56.5 μ m and 67.42 strands per mm. The effect of fluid loading on the performance of the heat pipes was tested using pipes that each had four-layer screen-mesh wicks.

The experimental system (Fig. 1a) was composed of a cooling system, a test section, a power supply, a measurement system and a data acquisition system (National Instrument NI 9211). Heat was applied to the heat pipein a 60-mm-long evaporator section using a flexible electrical heater that was connected to the DC power supply. To minimize heat loss, the evaporator and adiabatic section were wrapped with several layers of glass wool and isolated using polyurethane. The condenser section of the heat pipe was inserted horizontally into the cooling chamber. The coolant circulated through the cooling chamber, where heat was removed from the condenser section to the thermostatic circulating bath (TCB). The TCB was set to the required temperature and held at a constant temperature throughout the tests.

The surfaces of the heat pipes tested here were equipped with five K-type thermocouples mounted along the wall to measure the surface temperature distribution in the evaporator, adiabatic and condenser sections (Fig. 1b). Three thermocouples were attached to the evaporator, two were attached to the adiabatic section and the others were attached to the condenser section. All thermocouples had diameters of 0.05 mm and were calibrated against a digital thermometer. The uncertainty in temperature measurements was ± 0.1 °C. The thermocouples were connected to a high-precision data acquisition system. The uncertainty of the geometrical size of the tested heat pipe was 0.5%. The maximum uncertainties of wall heat flux and the thermal resistance were within 2% and 3%, respectively.

3. Results and discussion

The typical XRD patterns of the nanoparticles dried at temperatures of 200 and 600 °C are shown in Fig. 2a. Structural changes in the nanoparticles could be observed with increasing drying temperature. The spectra are almost equal to the typical XRD spectra of ZnO nanoparticles reported from other experiments [27,28]. In all of the XRD patterns, nine peaks were observed at approximately 2 Θ = 32.12, 34.48, 36.6, 47.76, 56.84, 63.02, 66.95, 68.23 and 69.24, which correspond to the Bragg's reflection plane (100), (002), (101), (102), (110), (103), (200), (112) and (201), respectively. These peaks are in excellent agreement with the standard JCPDS file for ZnO and are indexed as the hexagonal



Fig. 1. a. Schematic of the experimental set-up for thermal performance of a heat pipe: 1. TCB; 2. Flow meter; 3. Thermometer; 4. Water reservoir; 5. Heat pipe; 6. Heater; 7. DAQ system; 8. Computer for data processing; 9. DC Power supply; 10. Insulating material; 11. Thermocouple. b. Thermocouple distribution on the tested heat pipe.



Fig. 2. a. XRD patterns of ZnO nanoparticles synthesized with different drying temperatures. b. EDX spectra of ZnO nanoparticles synthesized with a drying temperature of 600 $^\circ\text{C}.$

wurtzite structure of ZnO having space group P6_{3mc}. No other peaks related to the presence of impurities were found. The values of the lattice parameters calculated from the XRD data using the Rietveld refinement analysis are shown in Table 1. The lattice parameters increased from a = b = 3.218 Å and c = 5.155 Å to a = b = 3.233 Å and c = 5.173 Å as the drying temperature increased from 200 to 600 °C. These results are consistent with those of bulk ZnO [29]. However, a careful analysis of the peak positions suggested a small shift in the value toward a lower 2 Θ with increasing drying temperature, indicating the presence of compressive strain in the samples. It was also shown for all samples that the reflection peaks became sharper and that the full-width at half maximum (FWHM)

Table. 1

Lattice parameter, average crystallite size and strain of ZnO nanoparticles synthesized with different dry temperatures.

Dry temperature	Lattice parameters		Average crystallite size	Strain
<i>T</i> d (°C)	a = b (Å)	c (Å)	< <i>D</i> > (nm)	$\eta~(imes 10^{-2})$
200	3.218	5.155	18	2.724
600	3.233	5.173	23	2.264

decreased slightly with increasing drying temperature, indicating the enhancement of crystallinity. The average crystallite size and strain of the ZnO samples were calculated from the XRD data using the equation [30] $\beta \cos\theta = 0.89 \lambda/\langle D \rangle + \eta \sin\theta$, where λ , β , θ , η and $\langle D \rangle$ represent the wavelength of the X-ray radiation, FWHM, diffraction angle, strain and average crystallite size, respectively. Using this equation, we found that the average crystallite size increased from 18 to 23 nm, while the strain decreased as the drying temperature increased from 200 to 600 °C (Table 1). The results of the XRD measurements are consistent with the results obtained from the EDX spectra in Fig. 2b. In addition to an oxygen peak at 0.6 keV, Zn signals at approximately 1.01, 8.7 and 9.5 keV were observed, which are indicative of the successful synthesis of ZnO nanoparticles, as already confirmed by the XRD data.

To reveal any changes that occurred during thermal treatment of the precursor, TG-DTA analysis was carried out at atmosphere temperatures from room temperature to 600 °C in (see Fig. 3). According to the TG curve, the precursor lost its weight in two major steps. The first major step was in the temperature range below 100 °C and indicated a loss of 3.2 wt.%, revealing the dehydrogenation of surface-adsorbed water molecules. The second step of weight loss (2.6 wt.%), appearing in the range of 100-220 °C, could be associated with diffusion of OH⁻ ions or hydrogen atoms out of the ZnO network. A further outward diffusion of OH⁻ ions or H atoms was observed from the slight decrease of the TG curve at temperatures higher than 220 °C. The total weight loss in the entire thermal analysis study was less than 8 wt.%. indicating that the majority contributed to ZnO formation. The DTA curve of the precursor obtained during thermal treatment exhibited two endothermic peaks, corresponding to the two major weight loss steps of the TGA curve.

The structures of the samples were further investigated using infrared absorption measurements. Infrared spectra for samples prepared under various drying temperatures are plotted in Fig. 4. For both spectra, the background signal was subtracted from the original data. It can be observed that the intensity of the absorption peaks decreased with increasing drying temperatures. For all assynthesized samples, the strong absorption peaks in the range of 400–700 cm⁻¹ could be attributed to ZnO stretching modes [31]. These stretching modes are indicative of successful synthesis of nanocrystalline ZnO particles, as confirmed by XRD and EDX studies. Similarly, the observed absorption peaks at approximately 1646, 1390 and 1121 cm⁻¹correspond to the OH bending mode [32],C–OH plane bending and C–OH out-of-plane bending [32], respectively. The presence of hydrogen in the crystal growth



Fig. 3. TG-DTA curves of the ZnO precursor: (a) DTA and (b) TG.



Fig. 4. FTIR spectra of ZnO nanoparticles synthesized with different drying temperatures.

environment is not surprising, and it is very difficult to prevent its incorporation into the crystal during the process of crystal growth [33]. A broad band in the region of 2900–3700 cm⁻¹ could be explained as overlapping of physically absorbed water, O–H stretching modes and C–H stretching modes. C–H local vibrational modes between 2800 and 3100 cm⁻¹ have been observed in a number of semiconductors, such as amorphous silicon carbon (a-SiC:H) [34], GaAs [35] and GaN [36]. In these materials, the local vibrational modes are assigned to symmetric and antisymmetric C–H stretching modes.

Optical characterization was performed by measuring the diffuse reflectance spectroscopy. The spectra were taken in the range of 200-800 nm. Fig. 5 shows the diffuse reflectance spectra *R* as a function of wavelength for the samples shown in Fig. 2a. Because our samples were powders, the low reflectance values



Fig. 5. UV–Vis spectra of ZnO nanoparticles synthesized with different drying temperatures. The inset shows the correlated optical gap of the ZnO nanoparticles as a function of the drying temperature.



Fig. 6. a. FTIR spectra of the ZnO nanoparticles shown in Fig. 4 dispersed in ethylene glycol. The weight concentration and average crystallite size are indicated in the plot. b. UV–Vis spectra of the ZnO nanoparticles shown in Fig. 5 dispersed in ethylene glycol. The weight concentration and average crystallite size are indicated in the plot.

in our spectra indicate high absorption in the corresponding wavelength regions. The data collected at room temperature showed a clear difference between the samples in the region of 350-800 nm. The significance of this was more visible after applying the Kubelka–Munk function F(R) given by the relation $F(R) = (1 - R)^2/2R$, where R is the magnitude of reflectance [37]. The optical gap (inset of Fig. 5) was estimated from the diffuse reflectance spectra by plotting the square of the Kubelka-Munk function $F(R)^2$ as a function of energy. To obtain the optical gap, the linear part of the $F(R)^2$ curve was extrapolated until it intersected the energy axis. The optical gap of ZnO dried at 200 °C was determined by the above method to be 3.46 eV, which is slightly higher than that for bulk ZnO (3.34 eV) [37]. The corresponding optical gaps were noted to shift to lower energies with increasing drying temperature. This variation follows the strain data obtained from the analysis of XRD patterns in a direct relationship, indicating that the variation in the optical gap is related to structural changes resulting from the variation of drying temperature. Variations in the optical gap of ZnO have been observed by several authors



Fig. 7. Relative value of thermal conductivity as a function of weight fraction for ZnO dispersed in ethylene glycol. Lines are provided for visual guidance.

[28,38], some of whom explained the change in the optical gap on the basis of variation of the average crystallite size. This explanation is also consistent with our results obtained from the XRD spectra (Table 1).

To connect the observed structural and optical properties of the ZnO nanoparticles with those in the fluid samples, we performed FTIR and UV–Vis measurements on the diluted ZnO nanoparticles in ethylene glycol (ZnO/EG). Fig. 6 (a) shows infrared absorption spectra of ZnO/EG nanofluids with average crystallite sizes of 18 and 23 nm. The spectra of pure EG are also shown in the figure. Overall, the spectra of the ZnO/EG were similar to that of the base fluid (EG), indicating that the ZnO nanoparticles were well dispersed in their base fluid. Fig. 6(b) shows the UV–Vis absorption spectra taken from ZnO/EG plotted in Fig. 6(a). For the lowest concentrations (0.025 vol.%), the UV–Vis absorption spectra of ZnO/EG nanofluids with average crystallite sizes of 18 or 23 nm exhibited absorption peaks at approximately 348 or 359 nm, respectively. Increasing the concentrations of ZnO/EG results only



Fig. 8. Comparison between the measured thermal conductivity of the ZnO nanofluids in the present work and the results from other researchers.

in increase of absorption percentage, mainly for wavelength greater than 360 nm.

The thermal conductivity ratios of ZnO/EG nanofluids with average crystallite sizes of 18 and 23 nm were characterized and are plotted in Fig. 7. Thermal conductivity was measured immediately after stirring and sonicating the nanofluids. The relative values of thermal conductivity $\kappa_{\rm R}$ were obtained by dividing the effective thermal conductivity of the nanofluid by the value of the thermal conductivity of the base fluid. As expected, one can observe that the thermal conductivity increases with increasing volume fraction of the nanoparticles and with increasing average crystallite size. At lower particle concentrations, the conductivity ratio showed enhancements of approximately 5.3% or 7% at 0.025%, but these values increased to 14% or 15.5% at 0.5% for a ZnO/EG nanofluid with an average crystallite size of 18 or 23 nm, respectively. The experimental results showed a nonlinear relationship between the thermal conductivity and the particle volume fraction. However, in Fig. 8, it can be observed that the measured thermal conductivities are greater than those reported by other researchers [9,39], i.e., the thermal conductivities of the nanofluids increased nonlinearly as the particle volume fraction increased. It was also observed that for the nanofluid with an average crystallite size of 23 nm, the increase in conductivity was larger than that of the nanofluid with the smaller crystallite size.

The change in heat transfer rate through the heat pipe along with differences between the average temperatures of the evaporator and condenser are shown in Figs. 9 and 10 for ZnO nanofluids



Fig. 9. Average heat pipe temperature distributions for different weight fractions of ZnO nanoparticles synthesized with a drying temperature of 200 $^{\circ}$ C dispersed in ethylene glycol.



Fig. 10. Average heat pipe temperature distributions for different weight fractions of ZnO nanoparticles synthesized with a drying temperature of 600 $^{\circ}$ C dispersed in ethylene glycol.

with average crystallite sizes of 18 and 23 nm, respectively. For all measurements, the wall temperatures of the heat pipes decreased along the test section from the evaporator to the condenser section and increased with an increase in input power. As shown, the



Fig. 11. Thermal resistances of the heat pipes shown in Figs. 9 and 10. Lines are provided for visual guidance.

temperature distributions of the heat pipe containing ethylene glycol as a base fluid were 88.6, 84.6, 70.8, 67.9 and 28.7 °C, respectively. As the EG was replaced by 0.5 vol.% of ZnO/EG, the heat pipe wall temperature at the evaporator was significantly reduced from 86.6 to 80.7 °C or from 86.5 to 82.6 °C for ZnO nanofluids with average crystallite sizes of 18 or 23 nm, respectively. Figs. 9 and 10 demonstrate that as the volume fraction of ZnO nanoparticles increased, the heat pipe wall temperature became lower than that of the pipes filled with ethylene glycol. Upon dispersing more nanoparticles in the working fluid, the heat pipe wall temperature decreased more than that of a pure base fluidfilled heat pipe under various heat loads. These results indicate that utilization of the ethylene glycol-based ZnO (EG/ZnO) nanofluid as the working fluid enhanced the thermal performance of the heat pipe. In addition, it was also shown that both the volume fraction of nanoparticles and the average crystallite size of the nanoparticles influenced the reduction of the wall temperature in the evaporator section.

Based on the distribution of the wall temperature measurements, the thermal resistance between the evaporator section and the adiabatic section can be calculated using the equation $R_{\rm th} = \Delta T / \Delta T$ *Q*, where ΔT is the temperature difference between the evaporator and adiabatic sections and Q is the input power. As Fig. 11 shows, the thermal resistance of the heat pipe using ZnO/EG is lower than that of the heat pipe using pure EG. Overall, the thermal resistance of the heat pipe containing 23-nm-sized ZnO nanoparticle crystallites was lower than those using the smaller crystallite size ZnO (18 nm) or a higher input power. Increasing the volume fraction of the nanoparticles tended to decrease the thermal resistance even further. This finding indicates that nanoparticles play an important role in reducing the thermal resistance in the heat pipe, as the increase in the effective thermal conductivity of the working fluid in the heat pipe has a correlation to the thermal resistance of the heat pipe.

4. Conclusion

In the present study, we reported our experimental investigation on the effective thermal conductivities of ethylene glycol-based nanofluids containing low concentrations of ZnO nanoparticles. In addition, an experiment was performed to investigate the effect of nanoparticles in a nanofluid on the thermal performance of a screenmesh heat pipe. For these experiments, ZnO nanoparticles were synthesized using a co-precipitation method and were dispersed in ethylene glycol at concentrations from 0.025 to 0.5 vol.%. The properties of the ZnO nanoparticles were characterized by XRD, EDX, thermal analysis TG-DTA, UV-Vis spectroscopy and infrared absorption spectroscopy. The XRD patterns of the ZnO nanoparticles agreed well with the standard XRD pattern of ZnO with a hexagonal wurtzite structure. These results are consistent with the results obtained from EDX spectra. Moreover, all diffraction peaks revealed strong peak intensities, indicating that the produced ZnO particles had high crystallinity. The as-synthesized ZnO particles had average crystallite sizes of 18 or 23 nm. UV-Vis measurements showed a red shift in the optical absorption band with increasing average crystallite size. To connect the observed properties of the ZnO nanoparticles with those in the fluid samples, FTIR and UV-Vis measurements were conducted on the diluted ZnO nanoparticles in ethylene glycol. The thermal conductivity behaviors of the synthesized nanofluids were measured as a function of particle volume fraction. The experimental data revealed that nanofluids containing a small fraction of nanoparticles had higher thermal conductivities compared to the base fluid. The thermal conductivity increased significantly with increasing volume fraction of nanoparticles. It was also demonstrated that the crystallite size influenced the thermal

conductivity enhancement of the nanofluid. At lower particle concentrations, the conductivity ratio showed enhancements of approximately 5.3% until 15.5%. Moreover, it was found that the average crystallite size had an effect on the thermal conductivity. Thermal performance was evaluated with ZnO as the working fluid for a conventional screen-mesh wick heat pipe. In this experiment, both the temperature distribution and the heat pipe thermal resistance were evaluated, and the presence of nanoparticles in the working fluid led to a reduction of the heat pipe wall temperature. The heat pipe wall temperature at the evaporator was significantly reduced about 6 °C. In addition, it was observed that the temperature distribution and the size of the ZnO nanoparticles.

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