

Thermal conductivity enhancement of ZnO nanofluid using a one-step physical method

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ABSTRACT

In the present work, an ethylene-glycol (EG) based nanofluid containing ZnO nanoparticles was prepared by a one-step physical method known as pulsed-wire evaporation (PWE). The structural properties of the ZnO nanoparticles were studied by X-ray diffraction method and high-resolution transmission electron microscopy. The thermal conductivity of the EG-based ZnO nanofluid at a higher concentration exhibited temperature-dependency due to the clustering and aggregation of nanoparticles in the fluid. Moreover, the experimentally measured value of the thermal conductivity was higher than the theoretically calculated value based on the Hamilton–Crosser model. From an analysis of the rheological behavior, it was found that all of the nanofluids showed Newtonian behavior. The viscosity increment did not show temperature-dependency, and its value increased with the ZnO volume fraction at a fixed temperature.

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1. Introduction

Nanofluids, dispersions of nanoparticles in fluids, have attracted much attention as potential heat transfer fluids because their effective thermal conductivity is significantly greater than the thermal conductivity of the base fluid [1–7]. There are two methods for the synthesis of a nanofluid: a two-step process and a one-step process. The two-step process involves preparing nanoparticles and then dispersing them in a fluid. The one-step method simply involves dispersing nanoparticles in the fluid simultaneously with the synthesis of the nanoparticles. Compared to the two-step method, the one-step process has many advantages, such as a smaller particle size, less contamination of the particle surface, and high dispersion stability.

However, the one-step process only produces nanofluids in small quantities and the produced nanofluid is expensive. Furthermore, the volume concentration of nanoparticles is much more limited with the one-step process compared to the two-step technique. To overcome the above weaknesses of the one-step process, the pulsed-wire evaporation (PWE) method [8–12] was used for the synthesis of a nanofluid in the present work. The PWE method is a gas condensation process that is used for the synthesis of nanoparticles with high efficiency and a high production rate. Various metal and oxide nanoparticles can be prepared by changing the starting

wire and the gas atmosphere. In particular, the product mass of the nanoparticles can be easily controlled by changing the wire explosion number.

In this work, a modified PWE method was applied to prepare EG-based ZnO nanofluid with various particle concentrations. With a rotary chamber of which the inner wall is covered by EG and a nozzle spray system, nanoparticles synthesized by the wire explosion method came into direct contact with EG without surface contamination. The structural properties of the ZnO nanoparticles were studied by the X-ray diffraction (XRD) method and high-resolution transmission electron microscopy (HRTEM). The thermal conductivity and viscosity of the prepared nanofluid were experimentally measured as functions of the ZnO volume concentration and temperature. In addition, the experimental value of the thermal conductivity was compared with the theoretical value of the Hamilton–Crosser model.

2. Experiments

EG-based ZnO nanofluid was prepared using the one-step PWE method. The apparatus used consists of four main components: a high-voltage DC power supply, a capacitor bank, a high-voltage gap switch, and an evaporation/condensation chamber. Pure Zn (>99.9%) wire with a diameter of 0.5 mm was used as the starting material, and the feeding length of the wire into the reaction chamber was 100 mm. When a pulsed high-voltage of 26 kV is driven through a thin wire, the non-equilibrium overheating induced in the wire makes the wire evaporate into plasma within several

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micro-seconds. The high-temperature plasma is then cooled by an interaction with an argon–oxygen mixed gas and condensed into small-size particles. The synthesized nanoparticles come into direct contact with the EG inside the chamber wall, and the EG-based nanofluid containing ZnO nanoparticles is finally obtained without any surface contamination. The concentration of the ZnO nanoparticles in the EG was controlled here via the wire explosion number. A schematic diagram of the PWE apparatus can be found in the literature [11].

The structural properties of ZnO nanoparticles were studied by XRD with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) and HRTEM. The thermal transport properties, including the thermal conductivity and viscosity, were measured as functions of the ZnO concentration and temperature. The thermal conductivity of the ZnO nanofluid was estimated by a hot wire method (LAMBDA, F5, Germany). A temperature-controlled bath was used to ensure a constant temperature. All of the nanofluids were prepared with a sufficient duration of sonication, so that the nanoparticles were well suspended with minimum coagulation. Placing the sample cup of the nanofluid inside a circulating thermal bath provided the tested temperature range of 20–90 °C with $\pm 0.01 \text{ }^\circ\text{C}$ accuracy at each specified temperature. After measuring the thermal conductivity of the nanofluid, the sample cup and platinum wire were washed several times with acetone and distilled water.

The viscosity of the EG-based ZnO nanofluid was measured using a viscometer (LV DV-II+ Brookfield Programmable Viscometer, USA) over a shear rate range of 2.45–300 s $^{-1}$ (a rotational speed of 2–245 rpm) in a temperature range of 20–80 °C. A S00 spindle was used with this viscometer and was calibrated using Brookfield standard fluid. The volume concentrations of ZnO nanoparticles were 0.5, 1.0, 2.0, 3.0, 4.0, and 5.5 vol.% and the size of the ZnO nanoparticles was smaller than 100 nm. Due to the limitation of the measurement range of the instrument, the present work did not cover a wide range of shear rates. To ensure the reliability of the experimental results of the thermal conductivity and viscosity, the measurements were repeated five times.

3. Results

A crystalline phase of the ZnO nanopowder synthesized by PWE method was confirmed by an XRD investigation, as shown in Fig. 1. The figure clearly shows that the XRD pattern has intense peaks which can be indexed as a monoclinic structure of ZnO (JCPDS card No. 036-1451). No impurity or other oxide peaks were observed in the XRD pattern. Fig. 2 shows a typical TEM image of the ZnO

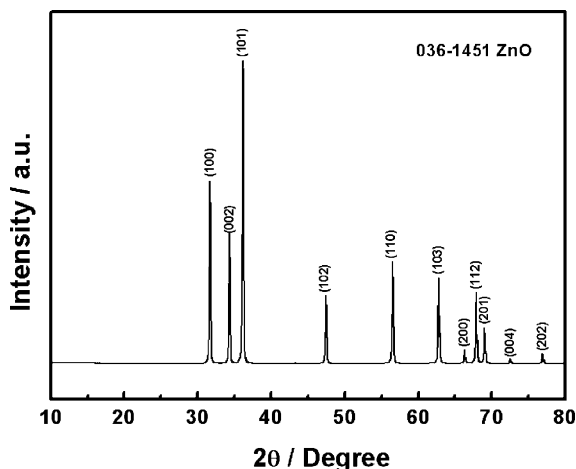


Fig. 1. X-ray diffraction (XRD) patterns of ZnO nanoparticles synthesized by the pulsed-wire evaporation (PWE) method.

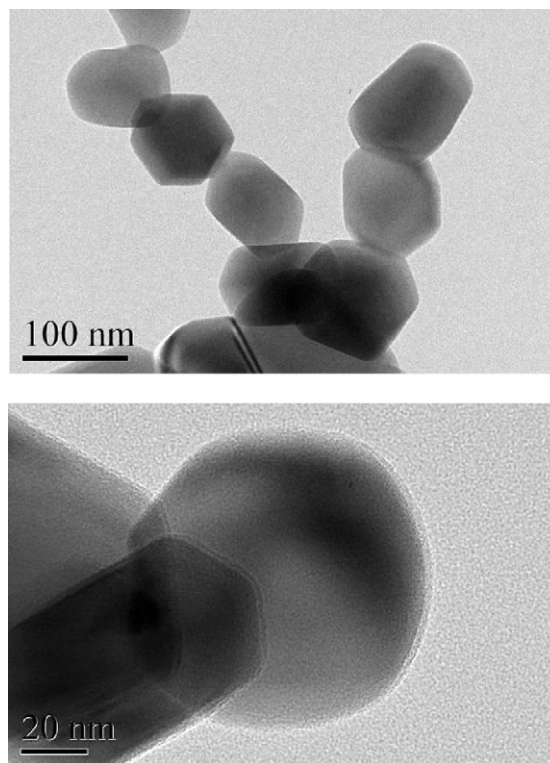


Fig. 2. Transmission electron microscopy (TEM) image of ZnO nanoparticles synthesized by the pulsed-wire evaporation (PWE) method.

nanoparticles synthesized by the PWE method. It was observed that the ZnO nanoparticles have spherical and rectangular shapes with a size smaller than 100 nm.

Fig. 3(a) and (b) illustrates the absolute value of thermal conductivity and the thermal conductivity enhancement as a function of temperature for each volume concentration of ZnO nanofluid, respectively. The enhanced ratios are nearly constant for the ZnO nanofluids with concentrations smaller than 3.0 vol.%. On the other hand, the thermal conductivity enhancement of the ZnO nanofluids at 4.0 and 5.5 vol.% increased as the temperature increased. It is well known [3,5,7,13,14] that the thermal conductivity increases with an increase in the temperature and as the nanoparticle size decreases due to the active Brownian motion of the nanoparticles. It was also reported [15–19] that the formation of clusters or aggregates in the fluid enhances the thermal conductivity of the fluid, as the heat transport can be much faster along the back bone of the clusters. In particular, clustering of the nanoparticles occurs more actively in a fluid with a higher concentration and at a higher temperature.

In the present work, because only ZnO nanofluids with a higher concentration showed temperature-dependency of the thermal conductivity characteristics, it is reasonable to conclude that the thermal conductivity enhancement with temperature for ZnO nanofluid at a higher concentration is attributable to the aggregation of ZnO nanoparticles, not to the active Brownian motion. To confirm whether the aggregation of ZnO nanoparticles is reversible or not, a reproducibility test of the thermal conductivity was conducted. The thermal conductivity measurement was repeated after sonication of the ZnO nanofluid for 10 min. The resulting values of thermal conductivity coincided with the previous values within an error range of $\pm 5\%$, suggesting that the aggregation of ZnO nanoparticles is reversible.

Fig. 3(c) depicts the enhanced thermal conductivity as a function of the ZnO volume concentration. The experimental values of the thermal conductivity for the 0.5 and 1.0 vol.% ZnO

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