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Research Paper

A comprehensive study of effect of concentration, particle size and particle shape on thermal conductivity of titania/water based nanofluid

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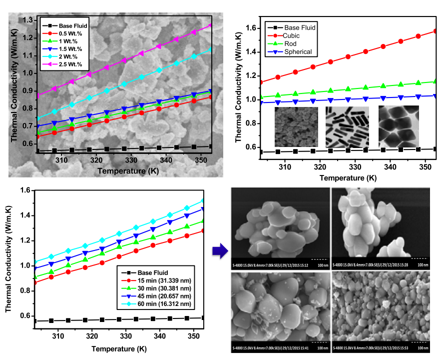
HIGHLIGHTS

- Thermal conductivity of titania/water nanofluid analyzed for concentration, particle size and shape.
- Concentration factor contributes 69.23% in enhancement of thermal conductivity.
- Particle size contributes 24.85% in enhancement of thermal conductivity.
- Shape factor contributes 5.54% in enhancement of thermal conductivity.
- Further optimization is possible with proper combination of above three parameters.

GRAPHICAL ABSTRACT



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ABSTRACT

Detailed experimental study is performed to investigate the effect of concentration, particle size and shape on thermal conductivity of TiO_2-water based nanofluid. In this work, nanofluid is prepared by two step method in water using probe sonicator. TiO_2-water nanofluid is prepared at 0.5–2.5 wt.% of concentration with an interval of 0.5 wt.% and its thermal conductivity is measured in the temperature range of 303–353 K. An increase in thermal conductivity is noticed with concentration of TiO_2 nanoparticles in base fluid (water). Further, thermal conductivity is increased by reducing particle size of TiO_2 in nanofluid using probe sonication process. Also, increase in thermal conductivity is also achieved by changing the shape of TiO_2 nanoparticles. The cubic shaped (2.5 wt.%) TiO_2-water based nanofluid indicated highest thermal conductivity. This study concludes that out of all three parameters (concentration, particle size and shape), concentration has significant effect on the thermal conductivity of TiO_2-water based nanofluid.

1. Introduction

Nanofluid is an emerging branch of nanotechnology, which may resolve some major difficulties in the area of thermal engineering [1]. Nanofluid is a contaminated suspension of nanosize particles in base fluid. Nanosize particles may be metal oxide, metal sulfide, carbides, nitrides and carbonaceous materials like carbon nanotubes, graphene, fullerene etc. Nanofluid plays an important role for effective heat transfer [2]. Other than material types, several factors such as concentration, particle size, shape, viscosity, Brownian motion, pH value, particle agglomeration etc. show significant

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influence on heat transfer performance of nanofluids [3]. Beside, all these factors, choice of nanomaterial is also an important issue. The nanoparticles required for dispersion in base fluid must be safe chemically and environmentally. In this context, TiO_2 is an appropriate material for the preparation of nanofluid. The heat transfer performance of TiO_2 nanofluid in water–ethylene glycol mixture is significantly sensitive to the thermal properties, concentration, temperature, and Reynolds number of TiO_2 nanofluids [4]. Hedayatia et al. [5] have studied the forced convection of laminar TiO_2–water nanofluid flow in a parallel plate microchannel. The non-uniform viscosity and thermal conductivity is explained using modified Buongiorno model. Khedkar et al. [6] have measured the thermo-physical properties (thermal conductivity and viscosity) of TiO_2–ethylene glycol nanofluid. Their study shows that the addition of nanoparticles to base fluids substantially increases thermal conductivity as compared to viscosity at higher volume fraction. Barzegarian et al. [7] have studied the heat transfer and pressure drop characteristics of brazed plate heat exchanger using TiO_2–water nanofluid. The convective heat transfer coefficient increases with Reynolds number and weight concentration of nanoparticles. The TiO_2/water nanofluid has been utilized in plate heat exchanger for dairy industries [8]. The summary of reports conclude that TiO_2 nanofluid with wt.% of concentration 0.25, 0.35 and 0.8% has higher heat transfer rate which results in better performance of plate heat exchanger. Chen et al. [9] propose a methodology for prediction of thermal conductivity of nanofluids based on rheology. Their approach identifies four types of nanofluids made of TiO_2 nanoparticles and TiO_2 nanotubes dispersed in water and ethylene glycol. Sen et al. [10] have studied the electrochemical activity of TiO_2 nanofluids by surface modification approach. The significant effect is observed on the viscosity and thermal conductivity of the resulting nanofluids.

To the best of author's knowledge, existing studies related to TiO_2 nanofluids suggest that no comprehensive and unifying study covering parameters like concentration, particle size and shape is present in the literature of thermal engineering. Based on the above literature survey, it was planned to investigate effect of concentration, particle size and particle shape on thermal conductivity of titania/water based nanofluids. In this investigation, two-step method was used to prepare TiO_2-water based nanofluid of different concentration, particle size and shape. Probe sonication method was used for reducing particle size. Further, obtained results were compared with recent reports present in literature of thermal engineering.

2. Experimentation

2.1. Materials

Titanium dioxide (TiO_2) required for present work was purchased from Sigma-Aldrich (India) of analytical grade. The purchased TiO_2 was used without any further purification for experimentation. The deionized water of resistivity not less than 0.18 MΩ m was used as base fluid for the preparation of nanofluids.

2.2. Characterization of nanoparticles

The X-ray diffraction (XRD) analysis was carried out to verify the structural purity of used TiO_2 nanoparticles. The XRD analysis was performed on Rigaku, Miniflex-II (Japan) X-ray diffractometer in the 2θ range 20–70° with step height 0.02°. This technique was also used to confirm particle size of TiO_2 nanoparticles.

The particle size of TiO_2 nanoparticles was determined by using the Debye-Scherrer equation (Eq. (1)) [11],

$$D = \frac{K\lambda}{\beta Cos\theta} \tag{1}$$

where D is average particle size, K is a shape factor (K = ~0.89), λ is the wavelength of X-ray source (λ = 1.540 Å), β is the full width at half maxima, and θ is the peak position angle.

The scanning electron microscopy (SEM) technique was employed to analyze morphology, particle size, and shape of TiO_2 nanoparticles dispersed in the base fluid. The SEM images of TiO_2 nanoparticles were captured using the SEM set up of JEOL JSM-7500F. The ultraviolet–visible (UV–VIS) absorption spectra of nanofluids were acquired using Agilent Cary 60 UV–VIS spectrophotometer to study absorption shift.

2.3. Formulation of nanofluid

In order to study the effect of concentration, particle size and shape of TiO_2 nanoparticles on thermal conductivity of nanofluids, two-step method was used to formulate nanofluid with assistance of probe sonication. To study concentration effect, five different nanofluid systems were prepared by altering TiO_2 concentration from 0.5 to 2.5 wt.% with interval of 0.5 wt.%. The upper limit of concentration was decided by studying various models namely Einstein model, Hamilton-Crosser model and Maxwell model. According to these models, non-interacting particle suspension in base fluid is formed only below 2.5% of concentration. The required wt.% of the TiO_2 nanoparticles was computed using the relation (Eq. (2)) [12],

$$\%\ \text{Volume Fraction} = \frac{\frac{W_{TiO_2}}{\rho_{TiO_2}}}{\frac{W_{TiO_2}}{\rho_{TiO_2}} + \frac{W_{Water}}{\rho_{Water}}} \tag{2}$$

where W_{TiO2}, ρ_{TiO2}, W_{water} and ρ_{water}, are weight of TiO_2 nanoparticles, density of TiO_2 nanoparticles, weight of base fluid (Water) and density of base fluid (Water), respectively.

The effect of particle size on thermal conductivity of nanofluids was analyzed for 2.5 wt.% of TiO_2 concentration. The change in particle size was achieved by giving different time interval (15, 30, 45 and 60 min) of probe sonication to nanofluid containing TiO_2 nanoparticles. Similarly, the effect of shape on thermal conductivity of nanofluid was investigated for cubic, spherical and rod shaped TiO_2 nanoparticles. Three different nanofluids were prepared by dispersing 2.5 wt.% of TiO_2 nanoparticles of each shape in base fluid followed by gentle probe sonication of 5 min. In all cases, no particle dregs were observed up to 2 months. The hydrodynamic radius of dispersed nanoparticle was measured using dynamic light scattering technique (NanoZS, Malvern) for the analysis of stability of nanofluids. The hydrodynamic radius data was used to compute settling velocity and Brownian velocity.

2.4. Characterization of nanofluid

The viscosity of TiO_2-water based nanofluids of different concentration, particle size and shape was determined using AR-1000 Rheometer, TA Instrument (Accuracy = ±0.05%). The viscosity of TiO_2-water based nanofluids was determined using relation (Eq. (3)) [13],

$$\mu = \frac{\tau}{\gamma} \tag{3}$$

where μ is the viscosity of nanofluid, τ is the shear stress and γ is the shear strain. The temperature difference was measured using thermocouple with accuracy of ±0.1 °C. Firstly, rheometer was calibrated for base fluid i.e. water in the temperature range of 300–360 K. All measurements of viscosity were performed at different shear rates from 18.34 S^{-1} to 1949 S^{-1}.