EFFECT OF NANOPARTICLES CONCENTRATION ON THERMAL CONDUCTIVITY OF SRAL$_2$O$_4$-WATER BASED NANOFLUIDS

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A B S T R A C T

Surfactant free stable $SrAl_2O_4$-water based nanofluids were prepared by two step method. The $SrAl_2O_4$ nanoparticles were synthesized by solid state diffusion method. The influence of $SrAl_2O_4$ nanoparticles concentration (0.01-0.05 M) on thermal conductivity of nanofluid was studied in the temperature range 30-80 °C. While the viscosity and average hydrodynamic radius of suspension increases with nanoparticle concentration. The enhancement in thermal conductivity of $SrAl_2O_4$-water based ceramic nanofluids increased smoothly with nanoparticle concentration. The nearly 68% enhancement is observed in 0.05 M $SrAl_2O_4$-water based ceramic nanofluid at 80 °C.

Keywords: Thermal conductivity, $SrAl_2O_4$, Ceramic nanofluids

Introduction

Escalation of heat transfer capacity of nanofluids has gained scientific importance, for various modern applications in the context of thermal engineering such as heat exchanger, coolant and refrigerant [1, 2]. For optimum application of nanofluid in thermal engineering, lower viscosity and high thermal conductivity are the desirable thermo-physical parameters [3, 4]. In most of the recent attempts regarding the enhancement of thermal conductivity is accompanied by concentration of nanoparticles [5], shape of nanoparticles [6, 7] and particle size [8].

Buschmann et al demonstrated the enhancement of thermal conductivity and heat transfer by using ceramic nanofluid. The result of this study suggests that heat transfer is enhanced in the thermal entrance region of laminar pipe flow [9]. The ceramic nanofluid mainly dominated by Al_2O_3 based nanofluid. Sarojini et al investigated the electrical properties of ceramic and metallic nanofluids. Comprising Cu, Al_2O_3 and CuO. This study concludes that enhancement mechanism for electrical conductivity is entirely diverse from that of thermal conductivity in nanofluids [10].Tavman et al report the variation of thermal conductivity of ceramic nanofluid based on Al_2O_3-water system. Finding of this research clearly indicates that effective thermal conductivity of nanofluids increase as a function of concentration of the particles but not anomalously [11]. Xie et al studied the enhancement of thermal conductivity by using Al_2O_3 nanoparticles. This study shows that suspension containing a minute amount of Al_2O_3, have considerably higher thermal conductivity than the base fluid [12].

A mathematical model for thermal conductivity enhancement due to dispersion of nanoparticles in base fluids was firstly attempted by Maxwell for statically homogenous and spherical particles of uniform size. The thermal conductivity of liquid-solid suspensions of monodisperse with low volume- fraction and spherical particles explained by static model of Maxwell through relation (Eq.(1)),

$$\frac{K_{nf}}{K_{bf}} = 1 + \frac{3(K_p / K_{bf} - 1)\varphi}{(K_p / K_{bf} + 2) - (K_p / K_{bf} - 1)\varphi} \quad (1)$$

According to this model, enhancement of thermal conductivity in nanofluids as a function of concentration of nanoparticles attributed to formation quasi-convection small regions in nanofluid. This model is valid for nearly spherical nanoparticles. Therefore, it is necessary to developed model for non-spherical nanoparticles. Lu-Lin model extends idea of Maxwell model for non-spherical nanoparticles, which relates as follows (Eq.(2)),

$$\frac{K_{nf}}{K_{bf}} = 1 + (K_p / K_{bf})\varphi + b\varphi^2 \quad (2)$$

The main accomplishment of this model is that prediction of thermal conductivity is independent of particle shape [13]. There are relatively few experimental reports present on ceramic nanofluids in literature of materials science. To the best of our knowledge, there are no direct reports on $SrAl_2O_4$-water based nanofluid exploring the thermophysical properties.

Inspiring from above discussion, in the present work we planned to study the thermal properties of $SrAl_2O_4$-water based nanofluid as a function of concentration and particle size. The two-step method was adopted for the preparation of ceramic nanofluid. To alter the particle size, probe sonication process was employed to nanofluid. The $SrAl_2O_4$ nanoparticle for this experimentation was synthesized by solid state diffusion method.

Experimental

$SrAl_2O_4$ nanoparticles were synthesized by solid state diffusion method. The aluminum nitrate ($Al(NO_3)_3$) and strontium nitrate ($Sr(NO_3)_2$) were used as starting chemicals of analytical grade quality with purity 99.99%. Firstly, $Al(NO_3)_3$ and $Sr(NO_3)_2$ were taken in proper stoichiometric ratio in methanol followed by crushing process of 30 minute, in order to make homogeneous mixture of precursors. After this step, mixture was placed in hot air oven for 50°C for overnight to remove methanol completely. Subsequent to this procedure, the dry powder of precursors was heated in stepwise manner at 250 °C, 500 °C, 750 °C and 1000 °C. For each step the pre-decided temperature was maintained for 2 h. The as-obtained final product appears white in color with rough touch. This power was probe sonicated for 15 minutes with 20 Watt, 80% pulse mode.

The structural purity of as-obtained power was confirmed by using X-Ray Diffraction (XRD) analysis on Rigaku Miniflex-II, X-Ray diffractometer. Field Emission-Scanning Electron Microscope (FE-SEM) was used to study surface morphology of as-synthesized nanoparticles and to ascertain the presence of nanoparticles using JEOL JSM-7500F microscope maintained at an accelerating voltage of 15 kV. The probe sonicator (PCi, 750-F) was used to alter particle size of synthesized materials. The thermal conductivity of samples was measured by using the equipment KD2, Decagon Devices, which works on the principle of hot-wire method. The hydrodynamic particle size distribution of as-synthesized $SrAl_2O_4$ nanoparticles was determined by NanoZS, Malvern. The viscosity was estimated using digital viscometer LVDV-II +Pro, Brookfield Engineering.

The two-step method was adopted for the preparation of $SrAl_2O_4$-water based ceramic nanofluids. It is very well known that $SrAl_2O_4$ ceramic nanoparticles are not soluble in water readily, so the probe sonicatination of 20 Watt applied to the suspension containing $SrAl_2O_4$ nanoparticles. The double distilled water was used as base fluid for this work. In order to study the effect of prolonged ultrasonication time on thermal conductivity of $SrAl_2O_4$-water based ceramic nanofluids, the sample with molar ratio 0.05 M probe-sonicated for different interval of time.

Results & Discussion

As discussed in introduction section, we report the nearly linear enhancement of thermal conductivity of nanofluids as a function of molar concentration of $SrAl_2O_4$ ceramic nanoparticles.Figure 1 depicts the XRD pattern of $SrAl_2O_4$ ceramic nanoparticles ultrasonicated for 15 minutes synthesized by solid-state diffusion method. The peak position and relative peak intensity of $SrAl_2O_4$ ceramic nanoparticles (Figure 1) confirms the structural purity of the product, also XRD pattern in accordance with JCPDS No. 34-0379. The diffraction peaks clearly show that $SrAl_2O_4$ ceramic nanoparticles exhibits pure monoclinic phase, with lattice constants are a = 8.442 Å, b = 8.822 Å, c = 5.160 Å, β = 93.415°. The average crystallite size of as-synthesized $SrAl_2O_4$ nanoparticles estimated by using Debye-Scherer Eq. (3) [14, 15],

$$D(nm) = \frac{K\lambda}{\beta \cos\theta} \quad (3)$$

Where, D is average crystallite size (nm), k is a shape factor with value 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 diffraction peak angle. The width of the diffraction peak is depending on nature of instrument and sample. Thus, it is necessary to avoid width contributed by instrument. The contribution in width is determined by reference material that is single crystal silicon. By adopting this approach, instrument-corrected broadening (β) of SrAl2O4 ceramic nanoparticles was computed using the relation Eq. (4) [16],

$$\beta^2 = (\beta)^2_{measured} - (\beta)^2_{\text{int}\,rumental} \qquad (4)$$

Through this treatment average crystallite size of $SrAl_2O_4$ ceramic nanoparticles was found to be 37.2 nm.

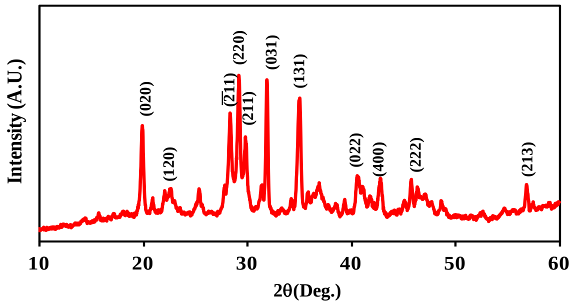

Figure 1. Powder X-Ray diffraction pattern of $SrAl_2O_4$ particles ultrasonicated for 15 minutes.

Figure 2 represents the FE-SEM image of $SrAl_2O_4$ particles ultrasonicated for 15 minutes. The complete region of FE-SEM image shows that particles acquire almost irregular morphology. The average crystallite size estimated using XRD analysis is nicely supported by FE-SEM study. As the solid state diffusion is high temperature process, the resultant particles acquires particle size in micrometer range. But, the application of probe sonication of 15 minite (20 watt), rapidly reduce the average crystallite size of resultant product.

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The FE-SEM image shows that small amount of agglomeration is present in final product.

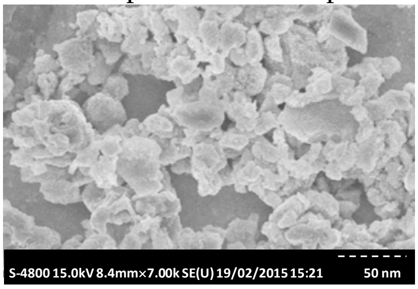

Figure 2. Scanning electron micrograph of $SrAl_2O_4$ particles ultrasonicated for 15 minutes.

Figure 3 (a) and (b) shows the variation of viscosity and average hydrodynamic diameter with molar concentration of $SrAl_2O_4$ nanoparticles at room temperature (303 K). Molar concentration of nanoparticle in base fluid is another important parameter, which directly influences the viscosity of nanofluids and thermal properties also [17]. The viscosity of $SrAl_2O_4$-water based ceramic nanofluids increases by increasing molar concentration of nanofluids. The hydrophilic metal oxides in polar solvent exhibited strong hydrogen bonds with water molecules, which results in the increase of viscosity [18]. In fact, still no model satisfactory predicts the viscosity of nanofluids precisely over broad range of concentration of nanoparticle [19]. The average hydrodynamic diameter of $SrAl_2O_4$-water based ceramic nanofluids increases with molar concentration (Figure 3 (b)). This increases in value of average hydrodynamic diameter assigned to increase in weakly associated diffusion layers to core nanoparticles. Therefore, as the molar concentration of $SrAl_2O_4$ nanoparticles increases, the number of diffusion layers also increases

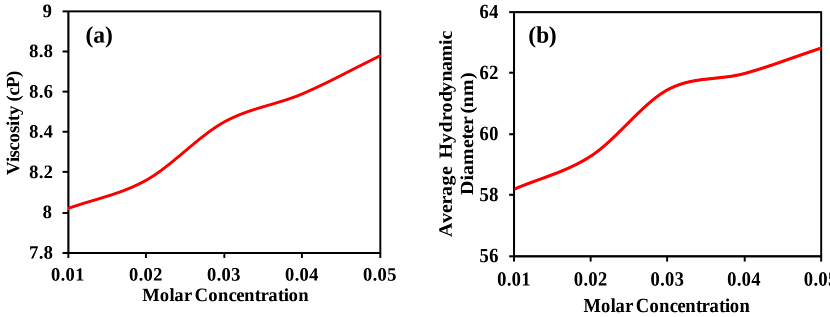

Figure 3. Influence of molar concentration on (a) viscosity and (b) average hydrodynamic diameter.

Now days, nanofluids becomes very important class of materials science for thermal engineering applications. For thermal engineering application, control over thermal conductivity of fluid is very necessary. The thermal conductivity of base fluid is easily altered by concentration of nanoparticles. Several recent reports in materials science show that thermal conductivity of nanofluids is sensitive to concentration of nanoparticles [20-23]. Figure 4 shows the variation of $SrAl_2O_4$-water based ceramic nanofluids with temperature. It is evident that magnitude of thermal conductivity of nanofluids increases with increase in molar concentration of $SrAl_2O_4$ nanoparticles over base fluid. This trend is observed over entire temperature range (30-50 °C). The linear increase in $SrAl_2O_4$-water based ceramic nanofluids with increasing molar concentration point out that well dispersed nature of nanoparticles in the nanofluid. The thermal conductivity of 0.5 M $SrAl_2O_4$-water based ceramic nanofluid sample enhanced by nearly 68% over base fluid.

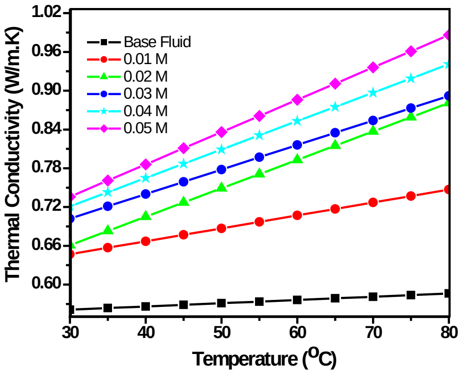

Figure 4. Influence of temperature on thermal conductivity of $SrAl_2O_4$-water based ceramic nanofluids as a function of molar concentration.

The enhancement of thermal conductivity is attributed to formation of microconvection regions caused by Brownian motion. Brownian motion is thermally triggered phenomenon, which results in enhancement of thermal conductivity. The terminal settling velocity (ut) of particles is given by (Eq.(5)),

$$u_t = \frac{g d_p^2 (\rho_n - \rho_b)}{18\mu} \quad (5)$$

Where, ut is terminal settling velocity of particles, dp is particle size of suspended nanoparticles in base fluid, ρn is density of nanofluid, ρb is density of base fluid and μ is viscosity.

The Brownian velocity (uB) for nanoparticles in suspension is given by (Eq.(6)),

$$u_B = \frac{2K_B T}{\pi \mu d_p^2} \quad (6)$$

Where, KB is Boltzmann constant, T is temperature, μ is viscosity and dp is particle size of suspended nanoparticles in base fluid.

The terminal setting velocity and Brownian velocity for 0.05 M $SrAl_2O_4$-water based ceramic nanofluids was found to be 1.349×10^{-15} m/s and 0.021×10^{-5} m/s, respectively. The Brownian velocity is much greater than terminal setting velocity, which indicates that prepared nanofluids are stable.The thermal conductivity ratio is measure of heat transfer due to added nanoparticles. The thermal conductivity ratio is determined by relation (Eq.(7)),

$$k_{ratio} = \frac{k_{nanofluid}}{k_{basefluid}} \quad (7)$$

Where, $k_{nanofluid}$ is thermal conductivity of nanofluid and $k_{basefluid}$ is thermal conductivity of base fluid. The values of thermal conductivity ratio are listed in Table 1. The critical observation of Table 1, indicates that thermal conductivity ratio increases as a function of temperature. Whereas for fixed temperature, the thermal conductivity ratio of nanofluid samples increases with increasing molar concentration. The value of thermal conductivity ratio greater than unity indicates that enhanced heat transfer is attributed to addition of $SrAl_2O_4$ nanoparticle.

Table 1. Thermal conductivity ratio (k_{ratio}) values for $SrAl_2O_4$-water based ceramic nanofluids as a function of molar concentration.

Temperature (°C)	K_{ratio}				
	0.01 M	0.02 M	0.03 M	0.04 M	0.05 M
30	1.152	1.177	1.250	1.284	1.311
40	1.178	1.245	1.306	1.351	1.388
50	1.202	1.311	1.362	1.416	1.463
60	1.227	1.376	1.416	1.480	1.537
70	1.250	1.440	1.469	1.543	1.610

Conclusion

In summary, we successfully synthesized $SrAl_2O_4$ ceramic nanoparticles and prepared its nanofluid by two step method in water as base fluid. The structural purity of $SrAl_2O_4$ ceramic nanoparticles is confirmed by XRD analysis. The results of thermal conductivity measurement of $SrAl_2O_4$-water based ceramic nanofluids as a function of nanoparticle concentration showed that for 0.05 M $SrAl_2O_4$-water based system shows enhancement in thermal conductivity of nearly 68 % at 80 °C.

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