Research Article

Classical Behavior of Alumina (Al_2O_3) Nanofluids in Antifrogen N with Experimental Evidence

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A nanofluid is a suspension containing nanoparticles in conventional heat transfer fluids. This paper reports on an investigation of alumina (Al_2O_3) nanoparticles in Antifrogen N, also called AFN, which is a popular antifreeze coolant consisting primarily of ethylene glycol and other additives to impede corrosion. The base carrier fluid is 50% by weight of water and 50% by weight of AFN. We systematically measured the nanomaterials and heat transfer data of nanofluids for four different size particles, namely, 20, 40, 150, and 250 nm alumina particles. The pH of all the nanofluids is adjusted to have a stable dispersion. The material characterizations include SEM and DLS particle measurements. We measured thermal conductivity, viscosity, and heat transfer coefficient in developing flow of the nanofluids. We observed that these nanofluids behave as any other classical fluids in thermally developing flow and classical heat transfer correlations can be used to completely describe the characteristics of these nanofluids.

1. Introduction

Heat transfer fluids with enhanced cooling characteristics is a subject of active research in several laboratories [1]. Nanofluid is the dispersion of nanoparticles in conventional coolants [2, 3]. Numerous studies performed in our lab and elsewhere studied nanofluids prepared with coolants, such as water and ethylene glycol (EG) [4–10]. EG based nanofluids have a distinct advantage in cooling applications compared to water based coolant due to the possibility of operating these fluids down to -80°C [11, 12]. Antifrogen N (AFN) is a commercial coolant, which is a clear liquid with tinted pale yellow color and consists of monoethylene glycol as base component. Furthermore, AFN contains effective corrosion inhibitors and prevents scaling in commonly used metal surfaces in heat transfer equipment. It is used as a heat transfer medium for several applications, such as closed hot water heating systems and heat pumps and is widely used as cooling brine in industrial refrigeration equipment. AFN is a good freeze resistant coolant similar to EG. A mixture of AFN with water (minimum 20% by volume) can be used in a temperature

range of $+150^\circ\text{C}$ to -50°C . AFN is a commercial product of Clarinet and all the details were obtained from the published materials data sheet [13].

Alumina (Al_2O_3) nanoparticles are a preferred choice in preparing nanofluids due to the maturity of production on a large scale and lower cost and are environmentally friendly. Therefore, alumina based nanofluids are investigated extensively in many laboratories and are identified as one of the best candidates for a nanofluid based coolant [14]. Water based Al_2O_3 nanofluids are reported to show improved thermal performance (ranging from 2 to 10%) with a particle size of 40 nm [15, 16]. However, the conclusions in the literature seem not to agree with ethylene glycol as a base fluid. Timofeeva and coworkers [17] investigated different morphologies of Al_2O_3 nanoparticles in water-EG mixture as base fluid. They report a 15% increase in thermal conductivity with platelet Al_2O_3 nanoparticles (7% volume of solid content). The enhancement of thermal conductivity reduced to 3% when the alumina content is reduced to 1%. Maïga et al. showed reported heat transfer coefficient increase to 70% in a 7.5% volume of particles (roughly 22% by weight)

[18]. Similarly, Murshed et al. reported that 80 nm size Al_2O_3 nanoparticles dispersed in EG increased by only 3.5% and 6% in effective thermal conductivity for 0.5 vol % and 1 vol %, respectively [19]. Few other literatures presented comparable results that larger particle size in the EG based Al_2O_3 nanofluids gives more enhancement in thermal conductivity [20, 21].

Beck and coworkers [20–23] examined, theoretically and experimentally, the effect of particle size in water, EG, and water-EG mixtures. Their experimental results, measured at 25°C for 2 vol % and 3 vol % of 16 nm Al_2O_3 particles dispersed in ethylene glycol, showed thermal conductivity enhancement of 6% and 9%, respectively, whereas particles of 245 nm size with the same particle concentrations (2 vol % and 3 vol %) achieved 8% and 14% improvement in thermal performance [24]. Their second study for water EG mixture (50-50 vol %) based nanofluids have showed similar behavior; as the particle size increases from 10 to 50 nm, the thermal conductivity increases with higher solid content. For instance, 3 vol % Al_2O_3 particles with 10 and 50 nm in water EG mixture enhances the thermal conductivity ratio to 5% and 7% measured at room temperature [22, 23]. However, these investigations are not conclusive about the optimum particle size of a EG based nanofluid. Moreover, we have not found any published literature on an AFN based nanofluid, although this is the most commonly used coolant in the heat equipment industry.

The aim of this paper is to perform a systematic study of the influence of alumina nanoparticle size on the thermal performance of the nanofluid made with water and AFN mixture. Four different sizes of commercially available Al_2O_3 nanoparticles, namely, 20 nm (Disp-Al20), 40 nm (Disp-Al40), 150 nm (Disp-Al150), and 250 nm (Disp-Al250) particles, are selected for this study. To the best of our knowledge this is the first report of nanofluids prepared with water and AFN mixture as a base fluid. Thermal conductivity, viscosity, and forced convective heat transfer measurements were performed on these nanofluids.

2. Description of Experiments

The alumina (Al_2O_3) nanoparticles (Disp-Al20, Disp-Al40, Disp-Al150, and Disp-Al250) are procured from NanoPhase Nanoengineered Products, Romeville, IL, USA. Nanofluids are prepared by dispersing 9 weight % quantity of alumina nanoparticles into the base fluid (water-AFN 50/50 wt%). These mixtures were subjected to mechanical shaker for thirty minutes without any additives or surfactant and the pH of the solution is adjusted to a value of 8, to provide electrostatic dispersion strength for nanoparticles and to avoid agglomeration of the particles. The produced nanofluids remained stable for several hours on the shelf and no sedimentation has been observed during the flow measurements.

The thermal conductivity of the base fluid and the nanofluids are measured using a thermal property analyser based on hot wire method, KD2 Pro (Decagon Devices Inc.). A sample holder whose temperature is controlled with a thermal bath is used to improve the accuracy of the measurements. Each data point is acquired in an interval

of 15 minutes. An average of at least 50 measurement points is taken for each fluid. The relative viscosity of the nanofluids is measured using a rotational type viscometer. Forced convective heat transfer experiments are performed with the base fluid and the nanofluids. The heating section is a circular tube of nominal inner diameter of 4 mm and a length of 0.45 m. The inlet and outlet fluid temperature and the wall temperatures are measured (at regular intervals of 0.05 m) with thermocouples. The mass flow rate of the fluid pumped into the heated tube is also measured. The experimental setup details are described in this reference [25].

3. Results and Discussion

3.1. Physiochemical Characterizations. The morphology and particle size are characterized with a scanning electron microscopy (SEM), Zeiss Ultra 55. Figures 1(a)–1(d) show SEM micrographs of the four alumina powders (Disp-Al20, Disp-Al40, Disp-Al150, and Disp-Al250). The average particle size was measured with image J software using more than three hundred particles. The results are shown in Table 1. Figure 1(a) reveals spherical morphology of Disp-Al20 sample with an average particle size of $22 \text{ nm} \pm 12 \text{ nm}$. Few particles of the size in the range of 60 to 80 nm are also observed. Disp-Al40 sample also contains spherical particles with an average size of $52 \text{ nm} \pm 10 \text{ nm}$ as shown in Figure 1(b). However, the SEM micrographs of Figures 1(c) and 1(d) reveal irregular morphology and a wide distribution of primary particle size. It is important to note that SEM particle size analysis shows slight differences in particle size and morphology compared to the supplier quoted data.

Hydrodynamic (DLS) particle size is determined with Beckman Coulter Delsa NanoC setup. Figure 2 presents DLS particle size with the intensity distribution curves. DLS particle sizes for Disp-Al20 and Disp-Al40 nanofluids have shown narrow distribution over the range of 10 to 60 nm and 30 to 90 nm, respectively. DLS particle size is slightly bigger than the primary particle size and this increment is due to the interaction of solid and liquid content. DLS curves of Disp-Al150 and Disp-Al250 samples have shown wide distribution of particles, which correspond with the variance in size and the irregular morphology, as observed in SEM micrographs. Morphology, primary particle size, and average DLS size results are summarized in Table 1.

3.2. Thermophysical Properties. Figure 3 shows the ratio of thermal conductivity (TC) and viscosity of the four nanofluids to the base fluid of Antifrogen N and water mixture. Disp-Al20 Al_2O_3 nanofluid has the lowest increase in TC, about 3% with a large viscosity increase, 90% compared to the base fluid. TC enhancement in Disp-Al40 Al_2O_3 nanofluid is 6% while the viscosity increased to 50%. The viscosity of the nanofluids decreased with the increase in particle size. The thermal conductivity of Disp-Al150 nanofluid is the highest among all the measured nanofluids, about 11%. The thermal conductivity of Disp-Al250 actually decreases compared to Disp-Al150, which is due to the sedimentation of large particles. The measured values of thermal conductivity and viscosity are shown in Table 2.

FIGURE 1: SEM micrographs of (a) Disp-Al20, (b) Disp-Al40, (c) Disp-Al150, and (d) Disp-Al250 samples.

TABLE 1: Material properties of Al_2O_3 nanofluids.

Sample ID	Size (supplier)	SEM average particle Size	Morphology	DLS average particle Size
Disp-Al20	20 nm	22 ± 10 nm	Spherical	25 nm
Disp-Al40	40 nm	52 ± 10 nm	Spherical	50 nm
Disp-Al150	150 nm	165 ± 20 nm	Irregular	170 nm
Disp-Al250	250 nm	275 ± 25 nm	Irregular	285 nm

The effective specific heat capacity of the mixture is calculated based on the basic principle of the mixture rule as

$$c_{p,\text{mix}} = x c_{p,\text{particle}} + (1 - x) c_{p,\text{fluid}}. \quad (1)$$

$c_{p,\text{particle}}$ and $c_{p,\text{fluid}}$ are obtained from manufacturer specifications. The calculated specific heat capacity of the nanofluids is shown in Table 2. The specific heat capacity of the nanofluids is lower than the base fluid by about 7%.

3.3. Flow Experiments. Efficient heat transfer in the laminar flow occurs in the thermal entrance region. The objective of these flow experiments is to answer the question: Does the

addition of nanoparticles to a coolant alter the classical thermal behavior in a thermally developing flow? A correlation for the Nusselt number, Nu for laminar flow heat transfer in the thermal entrance regions, was provided by Incropera and DeWitt [26]:

$$Nu = 1.86 \left(\frac{\text{RePr}}{L/D} \right)^{1/3} \left(\frac{\mu}{\mu_o} \right)^{0.14}. \quad (2)$$

Flow experiments are performed in a test rig, the details of which are described in another publication of the author [25]. The length of the heated test section is 0.45 m and the inner diameter of the tube is 4 mm. The length of the entry region, L_{entrance} , before a temperature profile is fully established in the

TABLE 2: Thermophysical properties of the base fluid and nanofluids.

Properties	AFN/water	Disp-Al20	Disp-Al40	Disp-Al150	Disp-Al 250
Specific heat C_p (J/kgK)	3250	3037	3037	3037	3037
Viscosity μ (mPa·s)	4.513	8.345	6.864	6.583	5.936
Thermal conductivity k (W/m·K)	0.3887	0.3977	0.4119	0.4321	0.4125

FIGURE 2: DLS curves from Al_2O_3 nanofluid samples. FIGURE 3: Effect of particle size on thermal conductivity and viscosity of Al_2O_3 based NFs.

presence of a fully developed hydrodynamic boundary layer is

$$L_{\text{entrance}} = 0.05 \cdot D \cdot \text{Re} \cdot \text{Pr}. \quad (3)$$

The Reynolds number range of the tests is between 100 and 500 and the Prandtl number is between 37 and 43. Putting these figures into the above equation produces the limits for L_{entrance} between 0.74 and 4.3 m. As the length of the heated section in the test rig is 0.45 m it can be concluded that

the temperature profile is not fully developed in the test rig. This can be further checked by examining the temperature difference between the wall and the fluid. In the case of constant heat flux heat transfer the temperature difference between the tube wall and the fluid is constant when the temperature profile is fully developed. The measured temperature differences indeed do not stabilize along the length of the heated section.

Further analysis of the measurement data is based on the approach often used by heat exchanger designers to plot the data in a standard form, that is, of $\text{Log}_{10}(\text{Stanton Prandtl})^{2/3}$ against $\text{Log}_{10}(\text{Reynolds number})$. This has been done for the base fluid of Antifrogen N and for the four nanofluids tested. Figure 4(a) shows the data containing 50 points for the entire test results. The Antifrogen N and water base fluid results fall to the right of the graph as they have the highest Reynolds number due to a low viscosity. It is interesting to note that all the points for the four nanofluids and the base fluid fall on a single line indicating that it is the base fluid that is controlling the heat transfer. Any anticipated change in the heat transfer performance of the nanofluids due to a modification of the temperature profile, leading to a nonclassical behavior, is not apparent from this graph. The nanofluids are behaving as any classical fluid in the thermally developing flow. The equation of the line in Figure 4(b) can be expressed as

$$\text{Log StPr}^{2/3} = -0.6862 \text{Log Re} - 0.6761. \quad (4)$$

Substituting the definition of Stanton number into the above equation and using the value of $D = 0.004$ m and $L = 0.45$ m give a relation between Nu and Re:

$$\text{Nu} = 1.02 \text{Re}^{0.314} \left(\frac{\text{Pr}}{L/D} \right)^{1/3}. \quad (5)$$

This relation compares well to the Seider Tate equation for thermally developing flow given in (2). Therefore the experimental results confirm a classical relationship between Nusselt number and Reynolds number for nanofluids. The Nusselt number is plotted in Figure 4(b).

4. Conclusion

The following conclusions can be drawn from the systematic analysis of alumina nanofluids comprising Antifrogen N and water mixture as a basefluid.

- (i) The thermal conductivity enhancement decreases as the particle size decreases below about 170 nm. This finding is consistent with a decrease in the thermal conductivity of alumina nanoparticles with decreasing particle size, which can be attributed to phonon

FIGURE 4: Classical behavior of Al_2O_3 nanofluid; (a) Reynolds versus Nusselt number, (b) Reynolds versus Prandtl number.

scattering at the solid-liquid interface. Nanofluids with 285 nm size nanoparticles also show lower thermal conductivity enhancement, which could be attributed to the sedimentation of nanoparticles. Hence, there exists an optimum size of the nanoparticles for enhancement of thermal conductivity.

- (ii) The viscosity of nanofluids decreases with increasing particle size.
- (iii) Flow experiments in a developing flow show that the alumina nanofluids behave as a classical fluid. Any anticipated improvement in the heat transfer performance due to change in temperature profile in the developing flow is not observed in our experiments.

Notation

A: Area (m^2)
 v : Velocity (m/s)
 c_p : Specific heat at constant pressure ($\text{J/kg}\cdot\text{K}$)
 D : Diameter (m)
 h : Heat transfer coefficient ($\text{W/m}^2\cdot\text{K}$)
 k : Thermal conductivity ($\text{W/m}\cdot\text{K}$)
 L : Length (m)
 m : Mass flow rate (kg/s)
 Nu : Nusselt number, hD/k (—)
 Pr : Prandtl number, $c_p\mu/k$ (—)
 Q : Heat transfer rate (J/s , W)
 Re : Reynolds number, $\rho vD/\mu = m \cdot D/A \cdot \mu$ (—)
 St : Stanton number, $Nu/Re \cdot Pr$ (—)
 T : Temperature (K)
 ρ : Density (kg/m^3)
 μ : Viscosity ($\text{Pa}\cdot\text{s}$)
 x : Mass fraction of nanoparticles (—).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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