Comparison of Heat Transfer and Fluid Dynamic Performance of Nanofluids

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ABSTRACT

Many recent studies have shown that nanofluids with metallic nanoparticles as suspension increase the thermal conductivity of base fluid by a substantial amount. First, we investigated the rheological properties of SiO_2, Al_2O_3 and CuO nanofluids at different volume percentages at varying temperatures. The fluids were tested over temperatures ranging from -35˚C to 50˚C. The viscosity trends showed the great influence of temperature on various nanofluids. Also, we investigated the particle diameter effect (20 nm, 50 nm, 100 nm) on nanofluid viscosity. Subsequent experiments were performed to investigate the convective heat transfer enhancement of nanofluids in a turbulent regime. During analysis of the convection coefficient, the measured viscosity values of the nanofluids were used as well as the thermal conductivity and specific heats were used from the available correlations in the current literature. Heat transfer coefficients of nanofluids increase with volume concentration, for example, a typical enhancement of a heat transfer coefficient of a 6% concentration of 45 nm CuO is about 54% at a Reynolds number of 8,000. Similar results were investigated for aluminum and silicon oxide nanofluids in ethylene glycol/water base fluid. Pressure loss was observed to increase with nanoparticle volume concentration and also with increasing particle diameter. It was observed that an increase in particle diameter increased the heat transfer coefficient. Applications of nanofluids will be in heating building and in automobiles in northern climates.

Keywords: nanofluid, heat transfer, fluid dynamics

1. INTRODUCTION

In the last decade, as energy costs have escalated rapidly, there is a need for new kinds of heating/cooling fluid which will increase the thermal efficiency of the system and thus reduce overall energy consumption. Nanofluids have attracted attention as a new generation of coolant for various industrial and automotive applications because of their excellent thermal performance [1]. Nanofluids are the dispersions of nanometer-sized particles (<100 nm) in a base fluid such as water, ethylene glycol or propylene glycol. Use of high thermal conductivity metallic nanoparticles (e.g., copper, aluminum, silicon) has the effect of increasing the thermal conductivity of such mixtures, thus enhancing their overall energy transport capability [2]. Eastman et al. [3] showed an increase of 40% in thermal conductivity with 0.3% (vol.) of copper nanoparticles in ethylene glycol.

In cold climates like those found in Alaska, Canada and circumpolar regions, heat transfer fluids regularly encounter very low temperatures, on the order of -40˚C. The commonly used mixture in cold climates is 60% by weight ethylene glycol and 40% water by weight [4]. This mixture's thermal performance could be enhanced by adding nanoparticles. We have measured the viscosity of ethylene glycol and water with copper oxide (CuO) [5], aluminum oxide (Al_2O_3) and silicon dioxide (SiO_2) nanoparticles has been investigated over a range of temperatures, from –35˚C to 50˚C.

A major goal of this study is to assess the effect of particle diameter and concentration on the thermal and hydraulic characteristics of SiO_2 nanofluids, on which very little data is available in the current literature. The reason we selected SiO_2 nanofluid is; it is one of the least expensive nanofluids and a small amount of increase in heat transfer will justify its use. The addition of these metallic particles would affect the rheology of this mixture. However, no rheological characteristics data is currently available for SiO_2 nanofluids at low temperatures in the literature. Investigating and reporting on the rheology & thermal characteristics of this nanofluid is very important to expanding its application in cold regions.

2. EXPERIMENTAL SET UP

An experimental apparatus was built to study the heat transfer and fluid dynamic characteristics of conventional ethylene glycol/water mixture and various nanofluids flowing through a tube. The experimental setup is shown in Fig. 1.

The heat transfer test section is a straight copper tube with outside diameter of 4.76 mm (3/16 inch) and a length of 1 m (3.28 ft). Six type-T (copper-constantan) thermocouples mounted on the tube surface along the length

measure the wall temperature. Two thermowells at the inlet and outlet of the test section measure the inlet and outlet temperature of the nanofluid. To attain the constant heat flux boundary condition, the test section is heated electrically by four strip heaters capable of delivering 1 kW each. A four-pass shell and tube counterflow heat exchanger cools the nanofluids to keep the inlet fluid temperature constant using water. A bypass valve controls the nanofluid circulation rate.

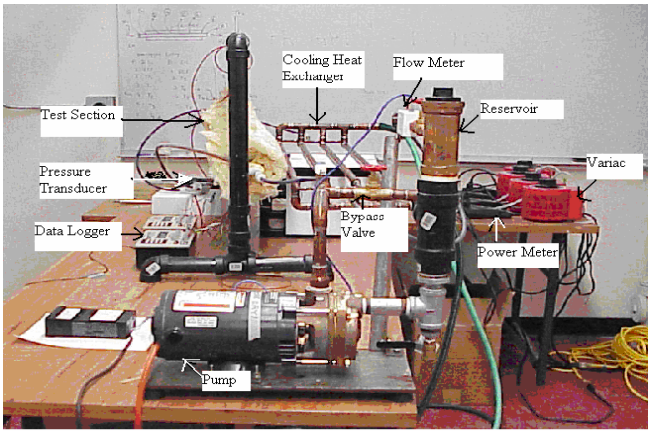

Fig. 1. Experimental set up to measure the convective heat transfer coefficient and pressure loss of nanofluids.

During experiments, the tube wall temperatures, fluid inlet and outlet temperatures, volumetric flow rate of the fluid and power supplied are measured. Using this data, the convective heat transfer coefficient of the nanofluid (h_{nf}) is determined as:

$$h_{nf} = \frac{q''}{T_w - T_f} \qquad (1)$$

where T_w is the average wall temperature and T_f is the average fluid temperature; q'' is the heat flux supplied to the test section. The heat provided by heaters can be equated to the heat gained by fluid flowing through the test section. It is given as:

$$q = \dot{m} C_{pnf} \Delta T_f \qquad (2)$$

where $\dot{m}$ is the mass flow rate, C_{pnf} is specific heat of nanofluid and ΔT_f is the difference between inlet and outlet temperature of the nanofluid. The specific heat of nanofluid, $C_{p_{nf}}$ is given by Choi et al. [6]

3. RESULTS

Several viscosity measurements were recorded at various shear rates at specific temperatures for each volume concentration of nanofluid. From these results the viscosity plot was generated which is shown in Fig. 2. This figure illustrates the dependence of viscosity on temperature of various nanofluids. At lower temperatures the viscosity is very high and it decreases exponentially with the increase in temperature.

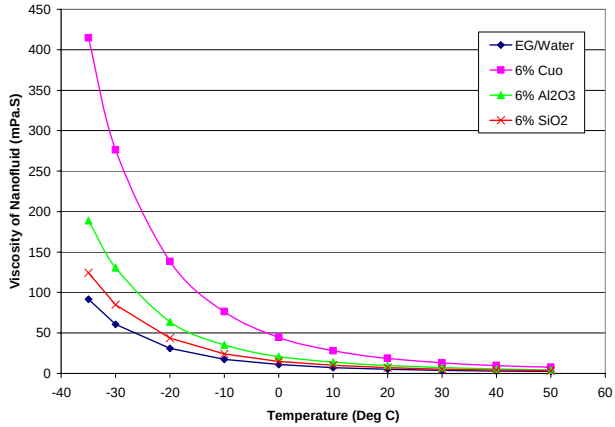

Fig. 2. The viscosity variation of various nanofluids with respect to temperature

From rheological measurements presented in Fig. 3 it was observed that the viscosity decreases with increase in particle size. Although not much information is available in the literature on the size effect of nanoparticles, it has been reported for micro-particle suspensions. In Cheremisinoff [8] it is reported that the viscosity decreases as the particle diameter increases in coal-oil mixtures.

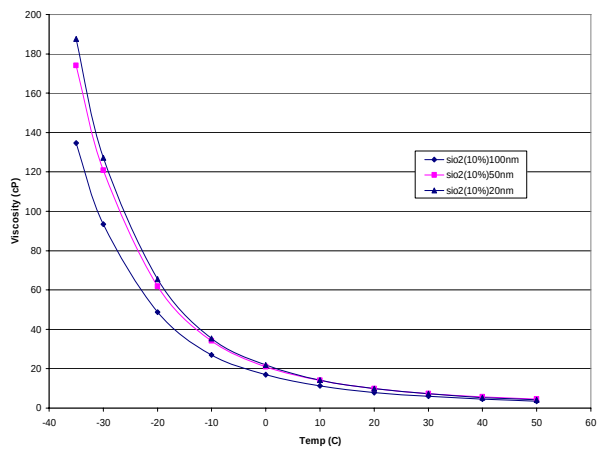

Fig. 3. Effect of particle diameter on viscosity for 10% SiO2 nanofluids.

Using equations (1) & (2), the heat transfer coefficient is calculated and plotted against the Reynolds number as shown in Fig. 4. Fig. 4 depicts that as the Reynolds number increases the heat transfer increases. Also for the same Reynolds number heat transfer for CuO nanofluid shows highest increase in heat transfer coefficient followed by Al_2O_3 and SiO_2 with respect to conventional glycol mixture. As a typical value, at a fixed Reynolds number of 8000, copper oxide, aluminum oxide and silicon dioxide exhibits 61%, 35% and 18% enhancement in heat transfer coefficient respectively. Although the heat transfer is enhanced, there is a penalty of increased pressure loss.

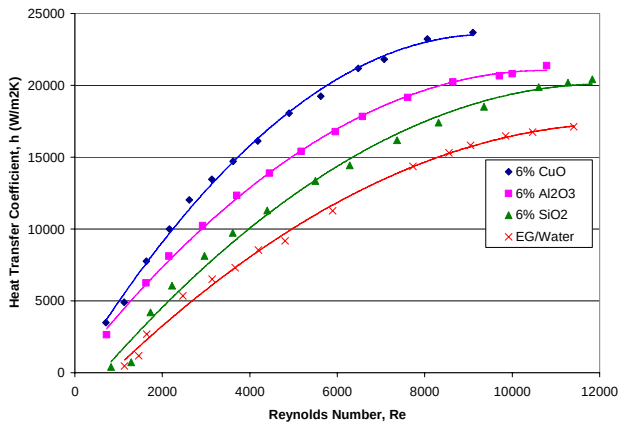

Fig. 4. Comparison of heat transfer coefficient of various nanofluids with respect to glycol/water mixture.

The pressure loss for various nanofluids are shown in Fig. 5. As the viscosity and density of the CuO nanofluid is higher the pressure loss associated with it is also higher for a fixed Reynolds number. Hence careful analysis should be done to balance the pressure loss and heat transfer performance while choosing the nanofluid for particular application.

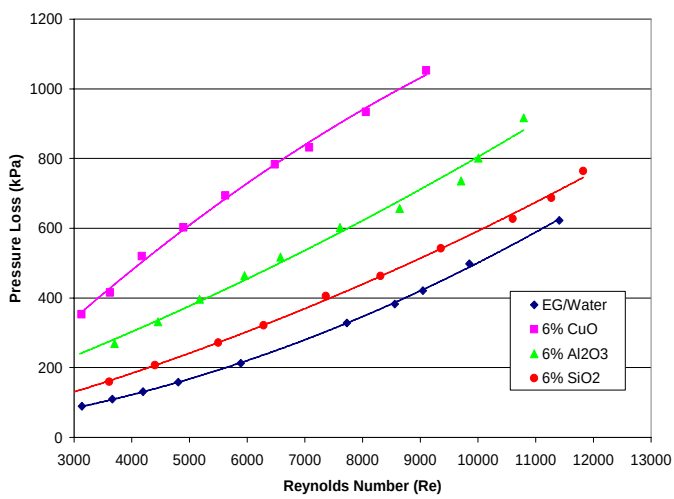

Fig. 5. Pressure loss of various nanofluids with respect to glycol/water mixture.

Fig. 6 show that the heat transfer coefficient increases with the size of particle. Similar observation was presented by Li & Xuan [9]. Nusselt number is directly proportional to Peclet number. As particle diameter increases the Peclet number increases giving rise to higher heat transfer coefficient. From Fig. 6 we determine that for a 6% concentration, the nanofluid with 100 nm particle diameter is capable of increasing the h by 12% at a Reynolds number of 10,000.

Fig. 7 establishes the effect of particle diameter on the pressure loss characteristics. Measurements show that as the particle size increases the pressure loss increases. At a Reynolds number of 10,000 the pressure loss for a nanofluid of 20 nm particle diameter and 6% concentration is 22% higher than the base fluid.

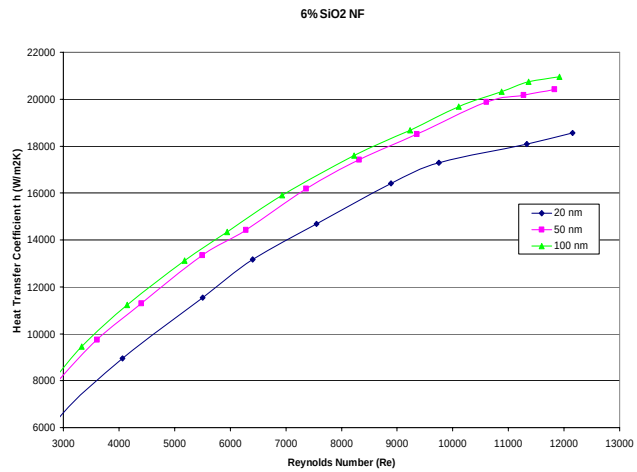

Fig. 6. Effect of particle diameter on heat transfer characteristics of 6% SiO_2 nanoparticles in ethylene glycol/water mixture.

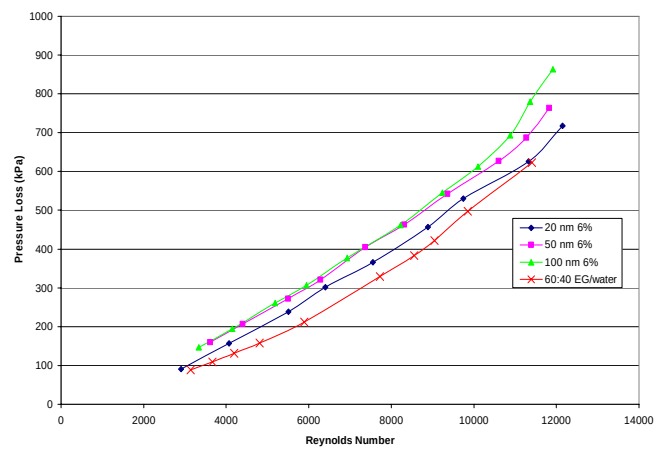

Fig. 7. Effect of particle size on pressure loss of 6% SiO_2 nanofluids.

4. APPLICATION OF NANAOFLUID IN HEATING BUILDING

In this case study, we have investigated the overall heat transfer coefficient of various nanofluids. To heat a building, we have assumed a typical rectangular plate fins bonded to copper tubes. Typical dimensions are given as: $A_{P,i}$ = 0.03536 m^2, $A_{P,o}$ = 0.03658 m^2, $A_{P,m}$ = 0.0375 m^2, A_F = 0.948 m^2, A_o = 0.09845m^2, $h_{c,o}$ = 57 W/m^{2}K and fin efficiency ϕ = 0.073. Table 1 depicts the various resistances and compared the overall heat transfer coefficient of various fluids with conventional ethylene glycol water mixture. Using nanofluids, the overall heat transfer coefficient increases for nanofluids. For the same thermal performance,

as the overall heat transfer increases, the surface area of the heating system will reduce. Reduction in area will be highest for copper oxide nanofluid followed by aluminum and silicon dioxide nanofluids.

Equation	60:40 EG/Water	6% Copper Oxide	6% Aluminum Oxide	6% Silicon Oxide
Reynolds Number	4000	4000	4000	4000
Inside heat transfer coefficient, h_i	3407	10,000	8,000	4,900
Inside Surface Resistance x 10E3 $R_i = A_o / A_i h$	8.17	2.78	3.475	5.67
Pipe Wall Resistance x 10E5 $R_P = A_o x_P / A_{P,m} k_P$	4.8	4.8	4.8	4.8
Fin Resistance x 10E3 $R_F = \frac{1}{h_{c,o}}(\frac{1-\phi}{\phi + A_{F,o}/A_F})$	6.16	6.16	6.16	6.16
Outside Surface Resistance x 10E3 $R_o = 1 / h_{c,0}$	17.5	17.5	17.5	17.5
Total Resistance x 10E3 $R_t = R_i + R_P + R_F + R_o$	31.88	26.48	27.175	29.37
Overall Heat Transfer Coefficient $U_o = 1 / R_t$	31.37	37.76	36.8	34.04
% Reduction in Area	……	20.37	17.3	8.5

Table 1. Comparison of overall heat transfer coefficient of various nanofluids with respect to ethylene glycol water mixture.

Various nanofluids are compared for the same heat transfer coefficient to investigate the effect on mass flow rate required for the same performance. Even though viscosity, density and pressure loss of nanofluid increases by addition of nanoparticles, the overall mass flow rate required will be reduced. This will result in power savings to pump the fluid. These results are shown in Table 2.

Type of Fluid Parameters	60/40 Eg/Water	6% Copper Oxide	6% Aluminum Oxide	6% Silicon Dioxide
Heat Transfer Coefficient (W/m2K)	14,400	14,400	14,400	14,400
Reynolds Number (Re)	8,000	3,600	4,500	6,290
Pressure Loss (kPa)	346	430	340	322
Viscosity (mPa.s)	1.1	2.27	1.41	1.17
Density (kg/m3)	1038	1366	1192	1116
Specific Heat (J/kgK)	3120	2339	2718	2821
Velocity (m/s)	2.12	1.5	1.33	1.65
Volumetric Flow Rate (10E+5 m3/s)	2.66	1.89	1.67	2.07
Power (W)	11.500	10.16	7.1	8.33
Power Advantage (W)	……	1.34	4.4	3.17
Power Advantage (%)	……	11.65	38.26	27.57
Mass Flow Rate (kg/s)	0.028	0.0258	0.0199	0.023
Reduction in Mass Flow Rate (%)	…….	6.495	27.904	16.333

Table 2. Comparison of mass flow rate of various nanofluids with respect to ethylene glycol water mixture.

5. CONCLUSIONS

1. Viscosity of nanofluid is a function of nanoparticle concentration, increasing with the concentration. This effect is more pronounced at sub-zero temperatures.
2. As particle size increases, the viscosity of nanofluids decreases.
3. Heat transfer coefficient of nanofluid increases with volume concentration. A typical value is about 16% at a concentration of 10% with 20 nm particle diameter at Re = 10,000.
4. Particle size influences the heat transfer coefficient, the larger the diameter, higher is the heat transfer coefficient.
5. Pressure loss is a function of the concentration, increasing with increasing concentration. This is because the viscosity increases with concentration.
6. With increase in the particle size the pressure loss increases.
7. Replacing the conventional ethylene glycol water mixture with nanofluids will reduce the size of the heating system.

6. REFERENCES

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