

Thermal evaluation of water-based alumina nanofluid in an electronic heat sink application

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Abstract. An experimental study was conducted to investigate the thermal performance of a water-based Al_2O_3 nanofluid in an electronic heat sink application. Heat transfer tests were carried out using 20 nm alumina particles at a concentration of 5% by mass, and a coolant temperature ranging from 47 to 57 °C. The results were compared to a baseline case using deionized water as a coolant. Thermal conductivity and viscosity tests conducted on alumina nanofluids show both parameters increase with nanoparticles mass concentration. Alumina nanofluid with 5% nanoparticles mass concentration behaves as a shear thinning fluid. Tests conducted on an electronic heat sink show heat flux and coolant heat transfer coefficient increase with bulk mass flow rate. Compared to cooling by deionized water, the average increase in the heat transfer coefficient using water-based alumina nanofluid as a coolant was about 20%, while the average increase in heat flux was about 24%. An additional decrease in the heated wall cross-section temperature between 4.1 and 4.9 °C is also seen. For the same pumping power, the presence of nanoparticles in the base fluid is shown to have a significant effect on the increase in heat transfer coefficient.

1. Introduction

With the ever increasing demand for cooling power in electronic devices, huge efforts have been devoted to their heat transfer enhancement. Research conducted during the last few years have shown significant improvements in the thermal properties of conventional heat transfer fluids by the addition of nanoparticles to the base fluids. Tests conducted on water-based Al_2O_3 nanofluids have shown enhancement in thermal conductivity that varied from a modest 1.4% at 0.3% volume concentration with 30 nm particles [1], to 10% at 3% volume concentration with 43 nm particles [2], to 24% at 4% volume concentration with 33 nm particles [3], to 30% at 18% volume concentration with 36 nm particles [4], and to a considerable enhancement of 88% at 12% volume concentration with 75 nm particles [5]. It is clearly evident in those studies that the bulk fluid thermal conductivity in general increases with the increase in nanoparticles volume concentration. In their 2009 publication, Buongiorno et al. [6] reported on an international nanofluid property benchmark exercise that was conducted by 34 organizations participating from around the world. Thermal conductivity of different nanofluids was measured at temperatures ranging from 20 to 30 °C. The nanofluids that were tested included alumina, gold, silica and Mn-Zn ferrite nanoparticles. Measurement techniques consisted of KD2 thermal properties analyzer, custom thermal hot wire, steady state parallel plate, and other techniques. The findings by the researchers showed the bulk fluid thermal conductivity enhancement

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increased with the increase in particle loading and particle aspect ratio. Thermal conductivity measurements from most organizations showed a deviation within $\pm 5\%$ from the sample average. When the results from KD2 and custom hot wire measurement techniques were compared, they showed that for the majority of the tested fluids KD2 thermal conductivity measurements were lower than those by custom hot wire technique.

The benefit of using nanofluids in heat exchanger applications have been investigated by several researchers. In the cooling of a microchannel heat sink, Ijam et al. [7] has shown that adding Al_2O_3 nanoparticles to water at 4% volume concentration improved the heat flux by about 3 %, and by about 17.3% when the particle volume concentration was 0.8%. Ijam and Saidur [8] also showed that the addition of SiC nanoparticles to water at 4% volume fraction resulted in an improvement between 7.3 to 12.4% in heat flux. Selvakumar and Suresh [9] studied the performance of CuO water-based nanofluid in an electronic heat sink. Their study revealed a 29% improvement in heat transfer coefficient for 0.2% volume fraction of CuO in deionized water. Hashemi et al. [10] studied heat transfer enhancement in a nanofluid-cooled miniature heat sink application. Their study showed an enhancement in the heat transfer coefficient by about 27% when using SiO_2 at a concentration of 5% concentration by volume. Khedkar et al. [11] studied the heat transfer in a concentric tube heat exchanger with different volume fractions of water-based Al_2O_3 nanofluids. It was observed that at 3% volume fraction, the optimal overall heat transfer coefficient was about 16% higher than water. Sun et al. [12] analyzed the flow and convective heat transfer characteristics of Fe_2O_3 water-based nanofluids inside inner grooved copper and smooth copper tubes. For the same mass fraction of Fe_2O_3 nanoparticles, the convective heat transfer coefficient was better in the inner grooved copper tube than in the smooth copper tube. The enhancement in heat transfer coefficient associated with the inner grooved copper tube was about 33.5% for Fe_2O_3 mass concentration of 0.4%. All of the above researchers have examined the effect of nanoparticles concentration on heat transfer enhancement, and have studied different types of nanoparticles. However, there are contradictory conclusions on the heat transfer enhancement at lower nanoparticle concentrations among different researchers. Also, still limited research studies have been conducted on the evaluation of alumina nanofluid properties and their performance in heat sink applications. The current study aims at investigating some of these issues by analyzing both the thermal and rheological properties of water-based alumina nanofluids, and the heat transfer enhancement in electronic cooling.

2. Experimental Setup

A closed-loop cooling system using block heat exchangers was built to evaluate the heat transfer performance associated with the use of a water-based nanofluid with alumina particles as a cooling fluid. A general picture of the experimental setup is shown in figure 1a. The nanofluid was prepared by mixing alumina nanoparticles with 20 nm average size in deionized water for a suspension concentration of 5% by mass (1.3% by volume). The suspension was thoroughly mixed using a high-speed mixing device for about 30 minutes before tests were carried out.

A digital geared-pump (Cole Parmer model no. 75211-30) was used to pressurize the nanofluid for circulation in the closed-loop system. Two block heat exchangers were used in the system: one to heat the nanofluid (HXR1), and the other to cool the fluid (HXR2). The interior of the block heat exchanger is shown in figure 1b. The heat exchanger has 10 channels through which the cooling fluid travels back and forth as it transfers heat through its walls. The heat exchanger that was used to heat the nanofluid sat on top of a 500 W plate heater (Omega model no. WS-605) separated by a 6.2 mm thick aluminium plate. A temperature control system (Omega model no. CN-63200-DC1-AL) was used to control the input heat to the base plate of the heat exchanger. The heat exchanger that was used for cooling the nanofluid sat approximately five inches above the base of the closed-loop system, and was encased in a fibreboard fan shroud. Two cooling fans rated at 120 cfm each were used to cool the upper and lower surfaces of this heat exchanger. Water pressure gauges were installed at the inlet and exit sides of the heat exchangers, while a flow rate meter was installed at a close proximity to the pump exit. Once the fluid exited HXR2 it flowed into a 2-litres reservoir tank made of clear acrylic

material. A compact digital mixer (Cole Parmer model no. EW-50006-01) system providing a top speed of 2,500 rpm was embedded in the tank. To achieve closed-loop circulation, the outlet from the reservoir tank fed directly into the pump inlet.

Eight thermocouples of type K were embedded at various locations to record the temperature variation throughout the system. The locations of the thermocouples were: Inlet and outlet sides to HXR1, inlet and outlet sides to HXR2, fluid reservoir tank, upper and lower surfaces of the aluminium base plate for HXR1, and ambient air. All thermocouples were connected to a data acquisition device (Omega OMB-CHARTSCAN-1400) that recorded the temperatures at a sampling rate of 1 data point per second. Heat transfer tests were conducted using 20 nm alumina particles in deionized water base at a concentration of 5% by mass, and results were compared to a baseline case consisting of deionized water.

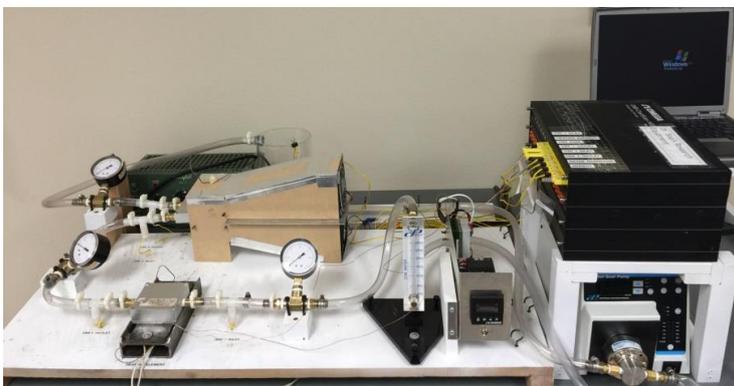


Figure 1a. Experimental setup of the electronic heat sink system.

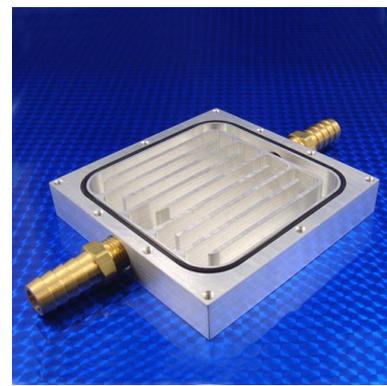


Figure 1b. Block heat exchanger.

Thermal conductivity of various concentrations of Al_2O_3 in deionized water was measured using a KD2 Pro thermal properties analyzer by Decagon Devices. Details about the design and working of the KD2 Pro device can be found in the operator's manual [13]. The analyser consists of a microcontroller with several needle sensors that can be used. KS-1 sensor needle was selected to determine the thermal conductivity of the nanofluids. The needle contains both a heating element and a thermistor. The needle, 1.3 mm in diameter and 6 cm long, was inserted vertically (to minimize natural convection) inside a test tube containing the nanofluid sample (figure 2). Heat was applied to the single needle for a short duration of time, and the temperature was monitored in the needle for an additional time after heating was turned off. The total time duration for each test was about 1 minute. The fluid sample was heated by a temperature-controlled water bath that was insulated from the surroundings. Tests were carried out after the desired steady state temperature of the fluid was reached. KD2-Pro thermal conductivity measurements are sensitive to temperature changes, and for this reason all measurements were done in a water bath. To eliminate forced vibration in the fluids, tests were carried out in the quiet evenings on a specially built vibration isolation table and away from environmental disturbances that are caused by systems such as HVAC, fans, electronic devices, and daily people activity. Repeated test measurements were performed on each nanofluid sample, and averaged thermal conductivity values were obtained.

Rheology tests were also conducted on the prepared nanofluid using a specially built UL adapter attached to LVDV-II+Pro Brookfield digital viscometer (figure 3). The UL adapter consists of a precision cylindrical spindle rotating inside an accurately machined tube that contains the 16 ml fluid test sample. A water jacket for accurate temperature control surrounds the tube.

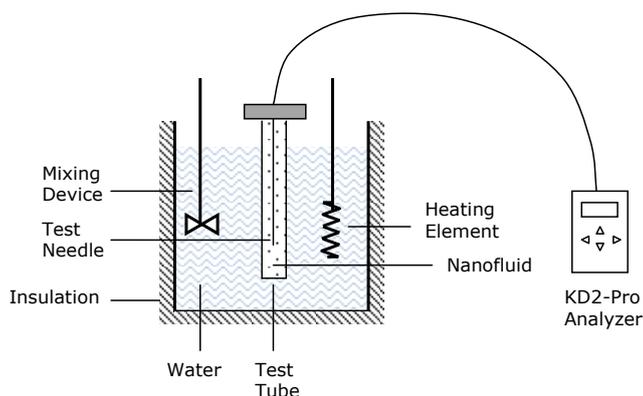


Figure 2. Experimental setup for thermal conductivity analysis.



Figure 3. LVDV-II+Pro viscometer (UL adapter).

3. Results and Discussion

3.1. Property measurements

Nanofluid test samples using 20 nm alumina particles of various concentrations were prepared and tested in a laboratory experimental setup for the determination of thermal conductivity. Figure 4 shows the average thermal conductivity of Al_2O_3 suspensions in deionized water. Tests were carried out at 46 °C, and for nanoparticles concentrations ranging from 0 to 40% by mass. Tests reveal that the thermal conductivity of the nanofluid increases with the increase in Al_2O_3 mass concentration.

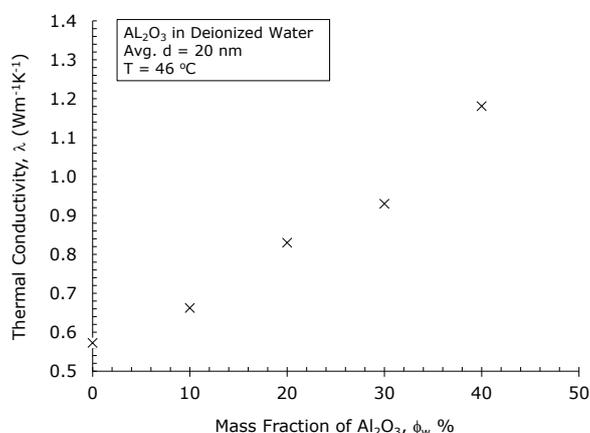


Figure 4. Nanofluid thermal conductivity versus mass fraction of Al_2O_3 .

Rheological tests were also conducted on nanofluid test samples for concentrations of 2.5 and 5% by mass. Rheological properties were conducted using UL adapter attached to LVDVII+Pro viscometer. Suspensions were mixed thoroughly using a high-speed agitator for about 30 minutes before the viscosity tests were carried out. Tests were performed at an average temperature between 48 and 49 °C for alumina in deionized water, and at 44.5 °C for deionized water. Figure 5 shows the variation in the nanofluids and deionized water viscosity as function of the shear rate. The figure shows a decrease in viscosity with the increase in shear rate for the nanofluid having 5% mass concentration (i.e., shear thinning fluid), and an increase in viscosity for the nanofluid having 2.5% mass concentration (i.e., shear thickening fluid). Figure 6 shows the fluids shear stress as function of shear rate. An almost linear relationship is shown for the deionized water (revealing Newtonian behavior), while the nanofluids show non-linear relationships (revealing non-Newtonian behavior).

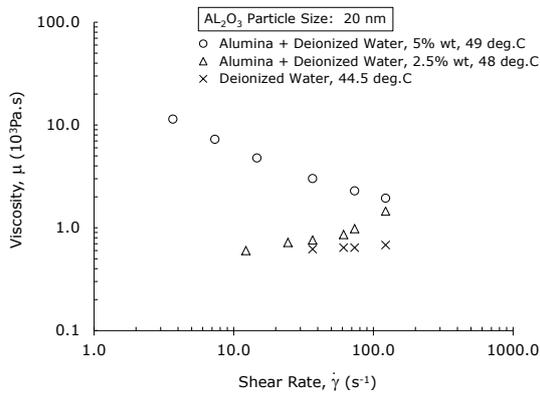


Figure 5. Viscosity versus shear rate.

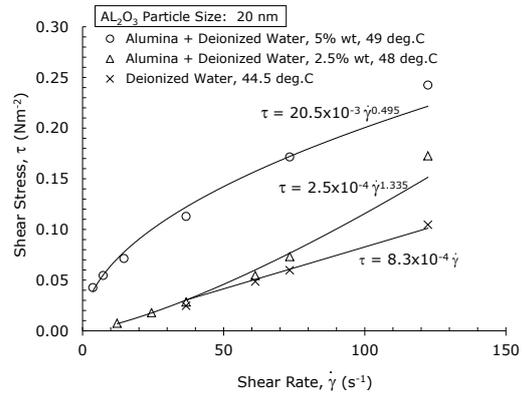


Figure 6. Shear stress versus shear rate.

The relationship between nanofluids shear stress and shear rate is best expressed by power law model:

$$\tau = K\dot{\gamma}^n \quad (1)$$

where K is a consistency coefficient and n is the power law index of the flow. n can be experimentally determined from the slope of the double logarithmic plot for the viscometer motor torque, T_m , versus spindle angular velocity, ω :

$$n = \frac{d \ln T_m}{d \ln \omega} \quad (2)$$

n is less than 1 for shear thinning fluids, greater than 1 for shear thickening fluids, and equal to 1 for Newtonian fluids. The apparent viscosity of the power law fluid, μ_{ap} , is expressed as:

$$\mu_{ap} = K\dot{\gamma}^{n-1} \quad (3)$$

Based on the shear stress versus shear rate data of figure 6, the alumina nanofluid having 5% mass concentration yields the following relationship at the operating temperature of 49 °C:

$$\tau = 20.5 \times 10^{-3} \dot{\gamma}^{0.495} \quad (4)$$

while the nanofluid having 2.5% mass concentration yields the following relationship:

$$\tau = 2.5 \times 10^{-4} \dot{\gamma}^{1.335} \quad (5)$$

Since the alumina nanofluid is a time-independent non-Newtonian fluid, its shear rate at the tube wall can be expressed by [14]:

$$\dot{\gamma} = \frac{8V}{D} \left(\frac{3n+1}{4n} \right) \quad (6)$$

where V is the speed of the flow, and D is the tube inner diameter.

3.2. Heat transfer measurements

Heat transfer tests were carried out on the electronic heat sink system using water-based alumina nanofluid with a mass concentration of 5% as a cooling fluid, and the results were compared to that of a cooling fluid consisting of deionized water alone. The plate heater was set to constant temperature of 91 °C, and the coolant flow rate was varied between 7.8 and 16.1 cm³s⁻¹. Interface temperatures,

and heat exchangers inlet and outlet temperatures were recorded once steady state temperature in the system was reached. The steady state temperature of the coolant associated with the different flow rates ranged from about 47 to 57 °C. The total volume of the coolant in the system was 2 litres. To minimize the precipitation of nanoparticles in time, a stirring device embedded in the reservoir tank was turned on for the duration of the test. The heat flux supplied by the electric heater at the base plate of HXR1, q'' , is determined from the temperature variation, ΔT , across the plate wall thickness:

$$q'' = \frac{q}{A} = \lambda_p \frac{\Delta T}{\Delta x} \quad (7)$$

where λ_p is the thermal conductivity of the plate, Δx is the plate thickness, and A is the surface area. The heat transfer coefficient associated with the coolant in the heat exchanger, h_c , is calculated as:

$$h_c = \frac{q''}{T_i - T_f} \quad (8)$$

where T_i is the heat exchanger base plate interface temperature (interface between the heat exchanger bottom surface and the base plate top surface), and T_f is the bulk mean temperature of the cooling fluid in HXR1. The pumping power of the bulk fluid, P_{power} , is calculated as:

$$P_{power} = \dot{V} \Delta P \quad (9)$$

where \dot{V} is the bulk fluid volumetric flow rate, and ΔP is the fluid pressure drop.

Figures 7 and 8 show the wall heat flux (at the base of HXR1) and the coolant heat transfer coefficient as function of the bulk mass flow rate for the case of water-based alumina nanofluid and deionized water, respectively. The average nanoparticle size is 20 nm, and the alumina suspensions mass concentration is 5%. The wall heat flux and coolant heat transfer coefficient are shown to increase with the increase in bulk mass flow rate. A comparison of the results between figures 7 and 8, show water-based alumina nanofluid to have higher values for both the wall heat flux and the heat transfer coefficient. An average increase by about 24% is seen in the wall heat flux for the case of water-based nanofluid compared to the case of deionized water. The heat transfer coefficient is also shown to increase by about 20% for the case of water-based nanofluid.

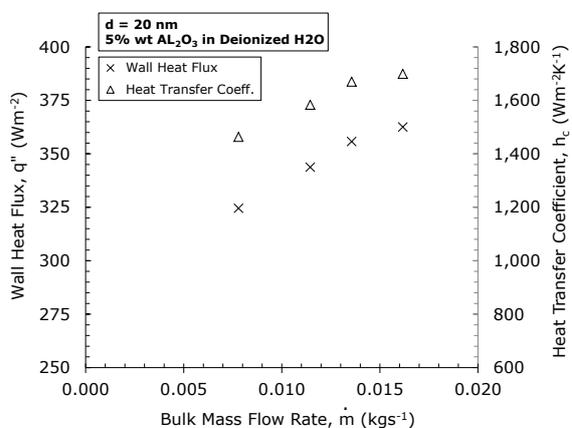


Figure 7. Wall heat flux versus bulk mass flow rate (5% by mass AL₂O₃).

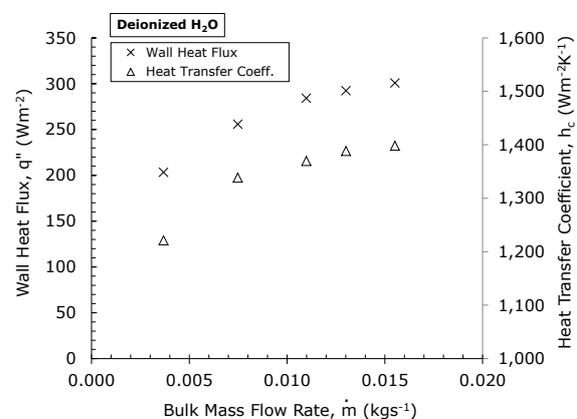


Figure 8. Wall heat flux versus bulk mass flow rate (Deionized water).

Figure 9 shows the decrease in the heated wall cross-section temperature (at the base of HXR1) as function of bulk mass flow rate. For the considered flow rates, the decrease in temperature ranged from 23.7 to 25.8 °C for the nanofluid test case, while it ranged from 18.8 to 21.7 °C for the deionized water test case. Figure 9 clearly shows an additional temperature drop (i.e., enhancement) between 4.1 and 4.9 °C when alumina nanofluid instead of deionized water is used as a coolant.

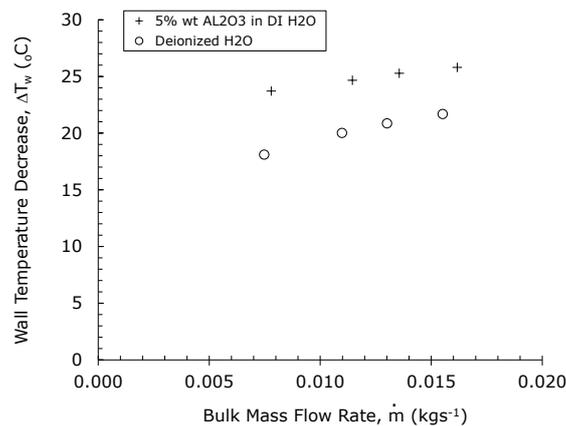


Figure 9. Decrease in wall temperature versus bulk mass flow rate.

Figure 10 shows the pressure drop across HXR1 heat exchanger as function of the bulk mass flow rate. The pressure drop is shown to increase with mass flow rate and with the addition of nanoparticles to the base fluid. The relationship between bulk fluid heat transfer coefficient and pumping power is shown in figure 11. The increase in heat transfer coefficient is shown to occur at the expense of pumping power increase. But for the same pumping power, the presence of nanoparticles in the base fluid is shown to have a significant effect on the increase in heat transfer coefficient, and therefore cooling efficiency.

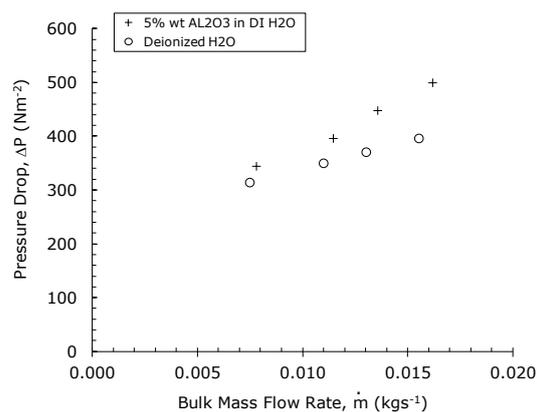


Figure 10. Pressure drop versus bulk mass flow rate.

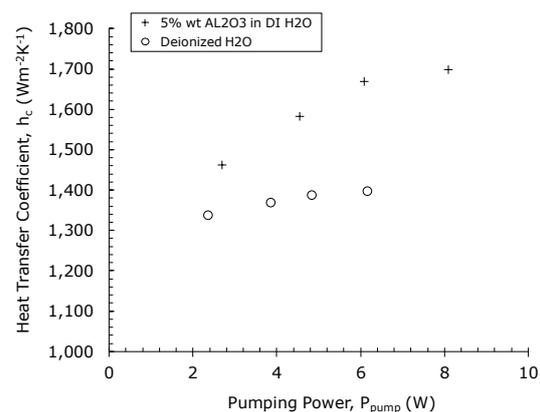


Figure 11. Heat transfer coefficient versus pumping power.

4. Conclusion

An experimental study was conducted to investigate the thermal performance of a water-based alumina nanofluid in an electronic heat sink application. Tests were carried out on two cooling fluids: One consisting of 20 nm alumina particles in deionized water at a concentration of 5% by mass, and the other consisting of deionized water. The alumina suspension particles were thoroughly mixed using high speed mixing device for 30 minutes before the start of each test, and in the coolant reservoir during the test. The coolant flow rate ranged from 7.8 to 16.1 cm³/s, and the steady state temperature of the coolant ranged from 47 to 57 °C when the plate heater was set to 91 °C. Thermal conductivity and viscosity tests were also conducted on the heated fluids. Nanofluids thermal conductivity and viscosity were shown to increase with the increase in nanoparticles mass concentration. Alumina nanofluid with 5% nanoparticles mass concentration behaved as a shear thinning fluid. Tests on the electronic heat sink system showed wall heat flux and coolant heat transfer coefficient increased with bulk mass flow rate. An average enhancement of about 20% in heat transfer coefficient and 24% in heat flux were seen when nanoparticles were added to the base fluid. Results also show an additional decrease between 4.1 and 4.9 °C in the heated wall cross-section temperature. For the same pumping power, the presence of nanoparticles in the base fluid is shown to have a significant effect on the increase in heat transfer coefficient.

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