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Research Article

Thermophysical Properties of Copper and Silica Nanofluids in Glycerol-Water Mixture Base Liquid

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ABSTRACT

Thermophysical properties of copper and silica nanoparticles dispersed in glycerol-water mixture as base liquid are determined experimentally. Cu and SiO_2 nanoparticles are mixed in a glycerol-water mixture of 30:70 ratio by volume. Three concentrations of 0.2%, 0.6%, and 1.0% are prepared and viscosity (μ), thermal conductivity (k), specific heat (Cp), and density (ρ) are determined in the temperature range of 20°C - 80°C using Brookfield Viscometer and TPS500S thermal constants analyzer. Nanofluid viscosity and density increased with particle concentration and decreased with temperature. The 'k' of nanofluids increased with temperature and particle concentration. Specific heat, 'C_p' of nanofluids reduced with volume concentration and enhanced with temperature. Maximum viscosity is observed for 1.0% Cu and SiO_2 nanofluids at 20°C and is 3.615 cP and 4.334 cP respectively against the base liquid viscosity of 3.040 cP at the same temperature. Thermal conductivity is maximum for 1.0% concentration at 80°C measured to be 0.843 W/m.K , 1.005 W/m.K for SiO_2 , Cu nanofluids whereas the base liquid thermal conductivity is 0.461 W/mK. The specific heat of Cu and SiO_2 nanofluids for 0.2% concentration at 20°C is 3432 J/kg K , 3468 J/kg K which increased to 3598 J/kg K , 3652 J/kg K at 80°C. The 'density'(ρ) of Cu and SiO_2 nanofluids of 1.0% concentration at 20°C, is computed to be 1102 kg/m^3 and 1057 kg/m^3 which decreased to 1089 kg/m^3 and 1028 kg/m^3 respectively at 80°C.

Keywords: Base liquid; Glycerol water mixture; Cu and SiO_2 Nano fluids; Thermal conductivity (k); Viscosity (μ); Density (ρ); Specific heat (Cp)

INTRODUCTION

Thermophysical properties of some conventional heat transfer fluids like water, glycerol, ethylene glycol, engine oil, propanol, etc., can be improved significantly by dispersing metal or metal oxide nanoparticles in small quantities. Determination of thermal properties of these characteristic fluids, called 'nanofluids' became necessary to understand their heat transfer and thermal transport capabilities. Attempts were made in the early years to enhance the thermal conductivity (TC) and convective heat transfer coefficient (HTC) using micro-sized particles. It had major drawbacks of causing erosion of the components due to abrasive action of the particles and rapid sedimentation resulting in clogging, fouling, and increased pressure drop. Nanometer size particles have higher thermal conductivity and viscosity overcoming drawbacks observed with micron-sized particles. Maxwell developed a predictive theory for computing TC of colloidal fluids using effective medium theory. Most of the subsequent studies with nanofluids reported substantially higher enhancement than the values estimated with Maxwell's relation which resulted in the development of new predictive models [1-5]. Studies were undertaken to determine thermophysical characteristics with Al_2O_3, SiO_2, TiO_2, ZnO, CuO, Cu, Ag, Al, Au, Fe, CNT, etc., nanoparticles dispersed in oils, water, EG, water, and glycerol, etc. Significant enhancement of thermal properties using various nanofluids was reported. Further studies were undertaken with nanoparticles mixed in base fluid mixtures of EG- water in 60:40 and 40:60 ratios to explore the potential of the nanofluids [6-9].

Viscosity and thermal conductivity

Masuda et al. [3] determined the viscosity (VST), thermal conductivity (TC) of water based Al_2O_3/13nm ; SiO_2/12nm nanofluids for a range of volume concentration of 1.30 to 4.30% and 1.10-2.40% respectively in the temperature range of 31-86°C.

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A viscosity enhancement of 300 and 200 percent and thermal conductivity enhancement of 32.4 and 1.1% for Al_2O_3 and SiO_2 respectively were reported. Pak and Cho [10] experimented with Al_2O_3 with 13nm and TiO_2 with 27nm nanofluids in water for volume concentrations of 0.99-10% and reported viscosity enhancement of 150 and 200 percent at 25°C. Heris et al. [11] used water-Al_2O_3/20nm; CuO/29nm nanofluids for particle loading of 0.2-3.0% and observed maximum viscosity enhancement of 40 and 60 percent respectively at 24°C. Azmi et al. [12] used SiO_2/50nm in water up to 4.0 volume concentrations and observed viscosity enhancement of 49% at 30°C.

Namburu et al. [13,14] experimented with 0.6-12% concentrations of CuO/29nm in water and obtained a maximum viscosity enhancement of 350% at 35°C. They also dispersed SiO_2 particles of 29, 50, and 100nm size in EG-water in the wt. ratio 60:40 to measure viscosity and specific heat in temperature ranging from -30-50°C. The viscosity of SiO_2 nanofluids enhanced with concentration at about 1.8 times compared to the base liquid and decreased exponentially with temperature. For the same volumetric concentration of 8% viscosity increment was more for lower particle diameter. With a 10% concentration of SiO_2 the specific heat was 12% lower than base liquid.

Azmi et al. [15] prepared TiO_2/22nm nanofluids in water for concentrations up to 3.0% and obtained a 7% enhancement in peak thermal conductivity at 30°C. Lee et al. [16] prepared CuO/23.6 nm in water-EG mixture in concentrations from 1.0 to 4.0% and observed 23% highest enhancement in 'k' at room temperature. Wang et al. [17] prepared nanofluids of CuO/23 nm in water-EG; vol. concentrations of 6.20 to 14.80% ; and reported a peak enhancement in 'k' of 54% measured at ambient conditions.

Cu with high thermal conductivity of 383W/mK can contribute to enhancement in 'k'. Xuan et al. [18] conducted experiments with Cu nanoparticles dispersed into transformer oil for 2 and 5 vol% and water with 5vol%. Laurate salt was used in different percentages to mend the stability of the suspension and concluded that an addition of 9% salt by weight yields good stability of water-Cu nanofluids. Cu particles of less than 100nm size were used to measured thermal conductivity for nanofluids at ambient temperature by transient hot-wire technique. The thermal conductivity ratio for water-Cu suspension varied in the range between 1.24 and 1.78 with increasing nanoparticle volume fraction between 2.5% and 7.5%.

In another work, Eastman et. al [19] described a 40% enhancement in 'k', measured at ambient temperature with Cu of size smaller than 10nm in base liquid EG for particle loading of less than 1%. Copper Oxide nanoparticles of 29nm size were dispersed in EG by Liu et al. [20] to a maximum volume fraction of 5%. The maximum improvement of 22.4% in thermal conductivity was reported at room temperature. Garg et al. [21] synthesized copper nanofluids in base liquid EG and measured the rheological and thermal properties. Cu particles of 200nm size were synthesized and thereafter the TC was determined at ambient temperature. Experimental thermal conductivity was found to be twice the predicted values with Maxwell's relation. Viscosity values predicted using Einstein's law of viscosity were 4 times lesser than experimental data. They also reported measured values of TC were observed to be lesser than the values reported by Eastman [19].

It was also reported that silica-based ceramic materials nanoparticles can exhibit higher thermal stability and low density and also chemically inert. However, its thermal and electrical conductivity is lower as compared to metal nanoparticles. Still, silica nanofluid is the best choice for heat transfer because of its high thermal stability, wear, and corrosion resistance. Silica nanoparticles are also comparatively less expensive and environmentally friendly. Bobbo et al. [22] discoursed the 'k' and viscosity of water-based silica nanofluid prepared with 22nm size particles. They observed a significant shift in the exotherm of silica nanofluids shifted from Newtonian behavior and observed shear-thinning, as the nanoparticle concentration increased from 16 to 31% by volume. Zyla and Jacek et al. [23] conducted thermal conductivity measurement experiments with water-based SiO_2 nanofluids of 7-14 nm size at 25°C. They reported a thermal conductivity followed by a viscosity enhancement ratio of 1.03 and 1.39 respectively with 2.6% vol. concentration.

Akilu et al. [24] contrasted the viscosity along with 'k' of non-porous EG and glycerol-based silica /15-22nm nanoparticles, in the concentrations of 0.5-2.0% and measured properties for range over 30-80°C. Enhancement of 'k' of SiO_2 at 2.0% concentration was reported to be 6.1% and 11.5% in base liquid EG and G respectively at 80°C. A reduction in viscosity of 95% and 80% for SiO_2 nanofluid was observed in base liquids Glycerol and EG respectively. Sharifpur et al. [25] reported the TC of Al_2O_3 nanofluid in base liquid glycerol over a temperature range of 20 to 45°C. An increment of 19.5% in TC with 31nm size Al_2O_3 nanoparticles at a 4% volume fraction. The temperature has revealed no substantial influence on the range of studies undertaken by them. Harikrishnan et al. [26] has investigated the thermophysical properties of CuO nanoparticles. A mixture of glycerol water in a 20:80 by weight is considered in this work. The thermal conductivity enhancement of 40.24% is reported with a 1% weight concentration.

Specific heat and density

Limited works are reported on the determination of 'Cp' and 'ρ' of nanofluids in different base liquids at different temperatures. Akilu et al. [27] conducted experiments using 21nm size SiO_2 -Glycerol, SiO_2-EG, and SiO_2 - Glycerol and EG mixture of 60:40 by mass ratio. They used 1.0-4.0% volume concentrations and measured the specific heat at the temperatures of 25°C and 50°C. it was found that by adding nanoparticles specific heat reduced. At 4.0% concentration and 25°C the decrement of specific heat of glycerol/EG mixture based SiO_2 nanofluid is higher compared to EG and Glycerol based SiO_2 nanofluids. Chieruzzi et al. [28] reported the same trend and attributed it to Brownian motion. They also assumed accumulation of nanoparticles, and molecular nano-layering as the probable reasons. They predicted that through mixing and uniform distribution of particles in nanofluid will form a solid like structure round about the particles and this was the major contributor to the variations in 'C_p'. Shin and Banerjee [29] concluded that the ordered layering of molecules over the interface of liquid-solid leads to an increase of 'C_p'. Vajjha and Das [30] measured the 'C_p'of water-based SiO_2/20nm nanofluids of φ= 2.0% to 10% ; T= 20-90°C; and developed a generalized regression equation to compute 'C_p' by considering the 'C_p' of both particles along with base liquid. This equation was valid up to the concentrations of 10% for T= 20-90°C with a deviation upto 3.1%.

In another work, Vajjha et al [31] experimentally determined the density of Al_2O_3/44nm in different concentrations ranging from 1%-10% in the temperature range of 0°C-50°C. They reported 'ρ' reduced with 'T' and enhanced with 'φ'. Compared to the data of Pak & Cho [10] the maximum deviation in the measured values was 1.2%. The density of Al_2O_3 –propanol nanofluids was measured by Sommers and Yerks [32]. They used two different methods to measure the density to compare the values. In the first method-specific gravity was measured using a hydrometer and then density was calculated. In the second method, sample with known volume is taken and the weight is measured and density is computed. They reported a near-linear relationship between particle concentration and density.

Base liquid

Properties of base liquid greatly influence the thermophysical properties of nanofluids like viscosity, thermal stability, 'C_p', 'k', density, freezing point, and boiling point, etc. Effectiveness of any nanofluid depends on the base liquid properties and the physical properties of the nanoparticles mixed in it. Water is a better choice for heat transfer applications because of its cheaply available. It is having higher specific heat, and low viscosity due to which power required to pump will be lower. Drawback with water is its boiling point is low at 100°C and causes rusting of the equipment. To overcome the limitations EG is mixed with water. This will result in an increased boiling point with moderate specific heat and viscosity of the mixture. Reasonable amount of works reported on determination of TC and VST using different nanoparticles in a base liquid water-EG mixture.

However, EG is flammable and ingestion of certain amounts can be fatal. Therefore, it is important to select an alternate working fluid that is miscible with water and offsets the limitations of EG. Glycerol was in use since the 1930s and was identified as a good candidate to replace toxic EG. Glycerol is relatively cheaper, non-toxic, non-hazardous as it is a bioproduct. Glycerol has a higher 'k' (0.285 W/mK) and boiling point compared to EG (0.258 W/mK). ASTM international committee examined glycerine as an 'anti-freeze fluid' for industrial applications. Glycerol, not only more environmentally friendly than EG but will sustain as liquid at lower temperatures (boiling point of glycerol 290°C and freezing point of -35°C approximately). It is resistant to oxidization as compared to other coolants such as oils.

Glycerol is thoroughly miscible in water; the net viscosity enhancement is not significantly higher than EG-water mixtures of 40:60 and therefore the pumping power required is less. Thermal transport properties can be further improved by adding nanoparticles of higher thermal conductivity and good stability [27]. The Molecular Dynamic (MD) simulations undertaken by Baz et al. [33] show that "at higher water content, glycerol–glycerol hydrogen bonds are replaced by glycerol–water hydrogen bonds indicating the formation of an aqueous solution accompanied by a strong decrease of the shear viscosity". Akinkunmi et al. [34] have undertaken MD simulations on water glycerol mixtures between 210-460 K to determine thermodynamic properties viz., density, isobaric specific heat, diffusion coefficient, etc.

Based on studies undertaken with glycerol-water mixtures, it is intended to use base liquid of glycerol-water in 30:70 ratio by volume, referred to as GW70, in this work. It can be a good choice as working fluids that can have advantageous thermal properties as compared to EG-water at 40:60 ratio without significantly increasing the VSTof the base liquid.

Most of the studies on VST and 'k' are reported for water, EG; their mixtures as the base liquid for various particle concentrations. Experimental determination of 'C_p' and 'ρ' of the nanofluids is scarce in literature. Also, extremely limited data is available for the thermal properties of nanofluids in base liquid glycerol and more so with glycerol-water mixtures. Hence, the determination of the thermophysical properties ; 'μ', 'k', 'C_p', and 'ρ' ; for both Cu and SiO_2 is essential for the estimation of HTC. The three times higher viscosity of GW70 base liquid as compared to water is expected to contribute to the higher stability of nanofluids. Thermophysical characteristics of Cu and SiO_2 nanofluids in a combination of GW70 have not been reported in the literature to the best of author's knowledge, thus the current investigation.

MATERIALS AND METHODS

Preparation of Cu and SiO_2 nanofluids

Cu and Silica nanoparticles and glycerol purchased from Sigma Aldrich are used in the preparation of the base liquid. The base liquid is prepared in a mixture of glycerol (G) and distilled water (W) in 30:70 ratio by volume and referred to as GW70. A two-step dispersion synthesis process is adopted for mixing of nanofluids in GW70 base liquid in the absence of surfactant. Cu and SiO_2 nanofluids in concentrations of 0.2%, 0.6%, and 1.0% by volume are prepared. Uniform dispersion of the nanofluids is ensured by magnetic stirring the mixture for one hour followed by high-frequency ultrasonication for two hours duration.

Field emission scanning electron microscopy (FESEM) is used to determine the shape and size of Cu and SiO_2 nanoparticles, as illustrated in Fig. 1(a) and 1(b). Spherical-shaped nanoparticles of Cu and silica with average sizes of 25 nm and 22 nm can be found in accordance with the vendors specifications. The corresponding EDX spectra are also illustrated in Fig. 2(a) and 2(b) which indicate the elemental structure of both Cu and SiO_2 nanoparticles. XRD peaks with corresponding crystalline values are also shown in fig. 3(a) and 3(b)for Cu and SiO_2 nanoparticles. XRD pattern for Cu and SiO_2 nanoparticles is determined using a powder X-ray diffractometer with a diffraction angle (2 thetas) between 0 and 80 degrees. Broadenings of the peaks due to the nanocrystalline size of the particles can be observed. Three peaks belonging to the copper crystalline phase are predominantly appearing at (111), (200), and (220) whereas the planes of silica appear at (101), (200), and (220) peaks. Both EDX and XRD pattern shows no impurities other than Cu and Silica. Table 1 shows the properties of nanoparticles and base liquid at 20°C.

Table 1: Nanoparticles & base liquid properties at 20oC

Characteristics	Cu	SiO2	Water	Glycerol
Purity (%)	99.99	99.99	-	99.5
Colour	red	white	-	colour-less
Particle size (nm)	25	22	-	-
Thermal conductivity (w/mK)	383	1.4	0.613	0.2886
Specific heat (J/kgK)	386	745	4181	2416
Density (kg/m3)	8954	2220	998.9	1261

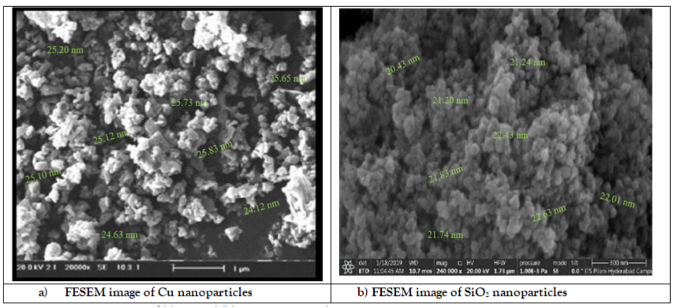

Figure 1: FESEM images of (a) Cu and (b) SiO_2 nanoparticles.

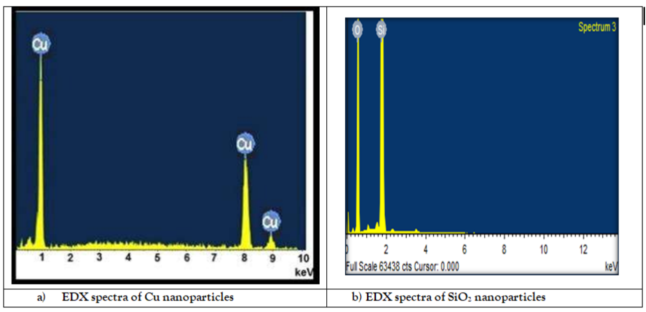

Figure 2: EDX spectra of Cu and SiO_2 nanoparticles.

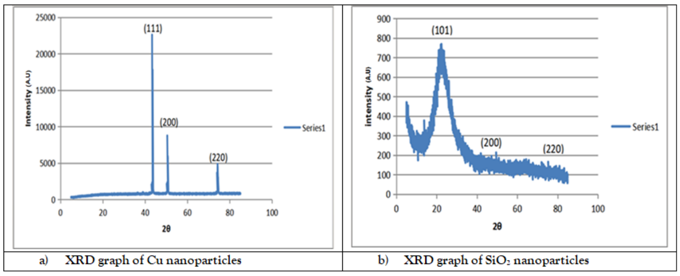

Figure 3: XRD graphs of Cu and SiO_2 nanoparticles.

Determination of thermal conductivity

The Brookfield LVDV -2 Viscometer, depicted in Fig.4, is used to determine the nanofluid's dynamic viscosity. It comprises of a UL adapter and a spindle with a spring for measuring torque generated by spindle rotation. Variable spindle speeds can be set in this instrument ranging from 0.01 to 250 rpm. The temperature of the sample in the chamber can be controlled by circulation in a water bath. The device has many features like auto zero set up and can be calibrated using a fluid with known or standard values such as EG or Glycerol. Viscosity measurements in the range of 1 and 106 mPa.s can be measured using this instrument. The viscosity of Cu and SiO_2 nanofluids was investigated in this work at temperatures ranging from 20 to 80 degrees Celsius. Lahari et al. [35] reported specifications and more information regarding the LVDV-2 type Viscometer.

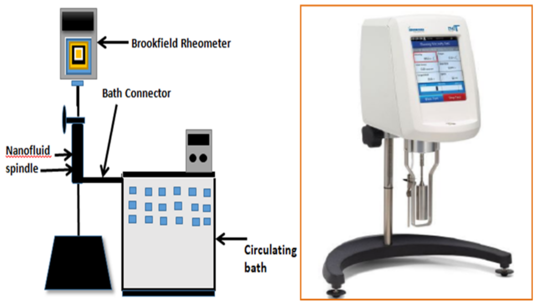

Figure 4: Experimental set up of Brookfield LVDV-2 Viscometer.

The dynamic viscosity of nanofluids was evaluated against shear rates up to 300 s^{-1}, and it was found that the dynamic viscosity remained constant, for all volume concentrations of nanofluids, as the shear rate increased this trend is shown in Fig.5 for 0.2% concentration of SiO_2 and Cu nanofluids at 20°C and 80°C. This shear independent behavior of the fluid confirms Newtonian fluid behavior and in good agreement with published works [10].

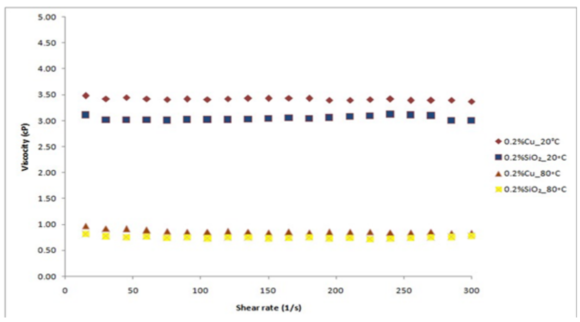

Figure 5: Variation of dynamic viscosity with shear rate.

Determination of thermal conductivity

The thermal conductivity, 'k,' is measured using a TPS-500-S analyzer. It is based on the Transient Plane Source (TPS) theory. It is used to determine the thermal conductivity, thermal diffusivity, and specific heat capacity of nanofluids all at the same time.In this system, a sensor is suspended proportionally in the cylindrical container that holds the sample fluid. This sensor can be used both as the heating element and for temperature measurement. Constant current is applied to the sensor and the time evolution of its electrical resistance because of enhancement in the temperature is measured. The temperature of this thin platinum wire rises with time by increasing its applied voltage. It produces a consistent heat flow per unit of wire length. These measured values of resistance and heat flux are be used to calculate the 'k', 'C_p', and diffusivity of the fluid. A platinum sensor is used because of its resistance to temperature for a wide range. The temperature of the sample is consistently varied in the necessary range of 20°C to 80°C using a constant temperature bath.Fig. 6 shows the experimental setup of the TPS 500 S Hot Disk Thermal Constants Analyzer. This instrument requires a small quantity of 5- 10 ml liquid sample for measurement of thermal properties. It consists of a single needle-type sensor made of platinum wire. The system is equipped with built-in software that captures the data of time & temperature. Before any measurement, the instrument is calibrated with the standard glycerol. The needle of the sensor is placed in a vial provided to fill with the sample and measurements are taken after the sample has attained a temperature of equilibrium. To eliminate any measurement mistakes, three measurements are taken for each sample and the mean result is used.The instrument is calibrated to keep the deviation within ±2.0%. Readings are taken in the temperature range of 20 -80°C. Technical specifications of the TPS-500S hot disc analyzer are shown in Table 2.

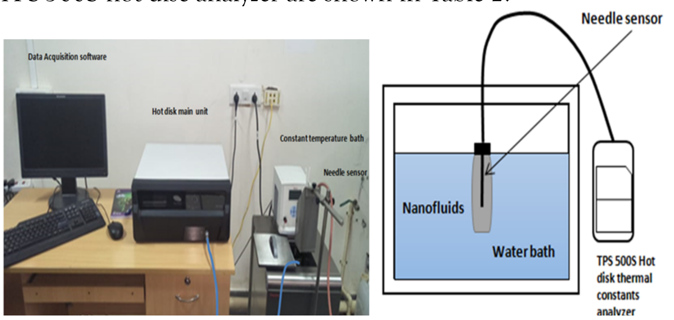

Figure 6: TPS 500 S Hot Disk Thermal Constants Analyzer.

Table 2: Specifications of TPS 500 S hot disk thermal constants analyzer (Source- TPS-500S manual)

Thermal Conductivity:	0.03 to 100 W/mK
	5 to 200 W/mK using slab or one-dimensional methods
Thermal Diffusivity:	0.02 to 40 mm²/s.
	2 to 100 mm²/s using slab or one-dimensional methods
Specific Heat Capacity:	Up to 5 MJ/m³K
Measurement Time:	2.5 to 2560 seconds
Reproducibility:	2% (thermal conductivity)
	10 % (thermal diffusivity, sensor radius 6.4 mm)
	12 % (specific heat per unit volume, sensor radius 6.4 mm)
Accuracy:	Better than 5 % (thermal conductivity)
Temperature Range:	-100°C to 200 (300* with attachment) °C
Core Instrument:	Ambient
With Oven:	Up to 200 (300*with attachment) °C
With Circulator:	-35°C to 200°C
Power Requirements:	Adjusted to the line voltage in the country of use
Smallest Sample	3 mm × 13 mm diameter or square for bulk testing
Dimensions:	2 mm × 8 mm diameter or square for bulk testing
	0.1 mm × 12 mm diameter or square for slab testing
	10 mm × 5 mm diameter or square for one-dimensional testing
Sensor Types Available:	Kapton sensors: 7577, 5465, 5501
	Teflon sensors: 7577, 5465, 550

Measurement of specific heat

The 'specific heat (C_p) and 'thermal diffusivity' (α) values of nanofluids are obtained from TPS 500 S model hot disk thermal constants analyzer. The container that holds the nanofluid is heated to the desired temperature using a circulating bath. The increase in temperature is monitored by the data from the sensor. Data logger captures the temperature data in intervals of 5 seconds and the algorithm provided will give the specific heat capacity and thermal diffusivity values simultaneously along with the thermal conductivity values. The instrument is calibrated by measuring the specific heat of pure water whose value is known. Water with known mass is taken in the container and constant power input is supplied and specific heat values are measured using Eq. (1).

$$Q=m\,(C_p)\Delta T \qquad (1)$$

Where Q represents the heat energy input (J), m represents the mass of water (kg), C_p represents the specific heat (J/kg K), and ΔT represents the temperature differential (K).

Specific heat of nanofluids is estimated using the theoretical equations available in the literature. According to the law of mixtures, Pak & Cho [10] provided Eq. (2), and Xuan et al. [36] presented Eq. (3), presuming equilibrium state between the dispersed nanoparticles and the base liquid phases.

$$C_{pnf}=\varphi C_p+(1-\varphi)\, C_{p.bf} \qquad (2)$$

$$C_{pnf}=(\varphi\, (\rho C_p)_p+(1-\varphi)\, (\rho C_p)_f)/(\varphi\rho_p+(1-\varphi)\, \rho_{bf}) \qquad (3)$$

Where C_p denotes specific heat and φ denotes particle concentration; the subscripts p and bf denote particle and base fluid, respectively.

Estimation of density

The density depends on nanofluid concentration. Because solids have a higher density than liquids, the density of nanofluids rises with concentration. Using Eq. 1, Experimental data of thermal diffusivity, Sp. heat, and thermal conductivity (k) are used to determine the density of the base liquid and nanofluids using Eq. (4).

$$\rho=(\alpha.C_p)/k \qquad (4)$$

In the lack of proper experimental data, the law of mixtures, as given by Eq. (5), is commonly used by researchers to estimate density. The present experimental data estimated with Eq. (4) for nanofluid is found to be consistent with the values computed with the law of mixtures given by Eq. (5)

$$p_{nf}=(1-\varnothing)\rho_{bf}+\varnothing\rho_s \qquad (5)$$

Where, ρ_{nf}, ρ_{bf} and ρ_s represent the density of the nanofluid, base liquid, & solid particles ; and $\varnothing$ its volume fraction.

RESULTS AND DISCUSSION

Viscosity of Cu and Silica Nanofluids

GW70 experimental viscosity data GW70 shown in Fig. 7. The data is compared with the values estimated with the theoretical model developed by Cheng [37] valid for aqueous mixtures. The viscosity of GW mixture for φ= 0 – 100% ; T= 0-100°C in power form can be estimated with Eqs. (6) – (11).

$$a = 0.705 - 0.0017T \qquad (6)$$

$$b = (4.9 + 0.036T)a^{2.5} \qquad (7)$$

$$\alpha = 1 - C_m + \frac{abC_m(1-C_m)}{aC_m+b(1-C_m)} \qquad (8)$$

$$\mu_w = 1.790exp\left(\frac{(-1230-T)T}{36100+360T}\right) \qquad (9)$$

$$\mu_g = 12100exp\left(\frac{(-1233+T)T}{9900+70T}\right) \qquad (10)$$

$$\mu_{gw} = \mu_w^{\alpha}\, \mu_g^{1-\alpha} \qquad (11)$$

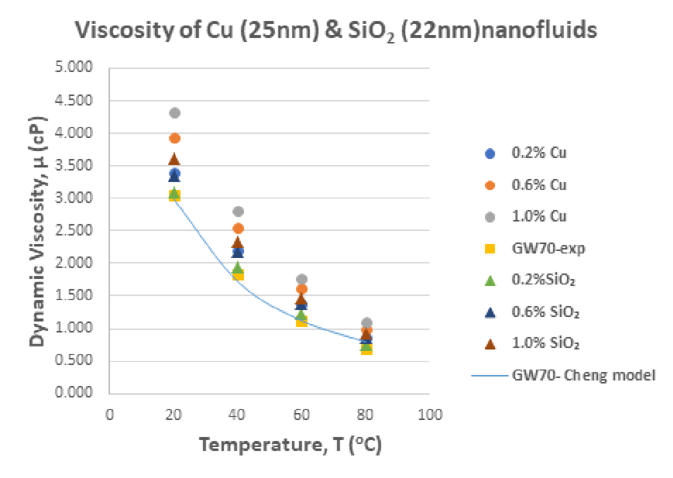

Figure 7: Viscosity of GW70 base liquid and nanofluids

Where a, b are coefficients; g and w represent glycerol and water, α is the weighing factor in the range of 0 to 1; C_m is glycerol concentration in mass. The viscosity of glycerol μ_g is obtained in centipoise (or 0.001Ns/m²) and T is in °C. Empirical data deviated to a maximum of 14% with the computed values using Eqs. (6) – (11).

Fig. 7 illustrates experimental viscosity variation of Cu and SiO_2 nanofluids along with GW70 base liquid against temperature. The viscosity of nanofluids is seen to rise with particle volume concentration and decrease with temperature in the studied range of 20-80°C. At elevated temperatures, intermolecular distance from each other increases causing decreased viscosity. Viscosity data of Cu and SiO_2 nanofluids compared to base liquid for different concentrations and temperatures are shown in Table 3. At 20°C and 0.2% concentration, the enhancement in viscosity is 11.88% and 1.46% for Cu and SiO_2 nanofluids respectively. The increase in viscosity for Cu and SiO_2 nanofluids at 1.0% vol. concentration at 20°C is 42.58% and 18.93% higher to the GW70 as shown in Table 3.

Table 3: Viscosity enhancement percentage of Cu and SiO_2 nanofluids.

Temperature/ Concentration	20°C	40°C	60°C	80°C
0.2% Cu	11.88	20.11	24.3	28.14
0.6% Cu	29.28	38.36	44.35	47.37
1.0% Cu	42.58	52.76	59.17	63.41
0.2% SiO_2	1.46	5.16	9.32	12.12
0.6% SiO_2	10.43	18.12	22.7	26.53
1.0% SiO_2	18.93	27.03	31.76	35.69

Jensen et al. [38] observed that “water acts as a lubricant, softening the hydrogen bonding which contributed to the macroscopic viscosity of the glycerol-water mixture”. Takamura et al. [39] observed that “the increase in viscosity of glycerol-water mixtures with the addition of glycerol is highly non-linear" and the variation in the aqueous phase was over three orders of magnitude. Viscosity is reported to be independent of the material and increase with concentration, decrease with raise in 'T' and 'φ'. Machrafi [40] reported that the 'ρ'of the nanoparticles, nanofluid, base fluid influences the nanofluid VST. The average particle size of Cu and SiO_2 considered in this work are 25nm and 22nm respectively. The density of Cu is 8954 kg/m^3 while that of SiO_2 is 2220 kg/m^3. The viscosity of Cu and SiO_2 nanofluids is shown to differ dramatically due to considerable variances in particle density.

Viscosity data of Cu and SiO_2 nanofluids in GW70 base liquid is not available in published works for comparison. Azmi et al [41] measured the VST of water-EG in 60:40 as a base liquid at 20°C to be 3.0cp. The viscosity of Al_2O_3/13nm nanofluid undertaken by Azmi et al. is taken for comparison which is shown in Fig. 8. It can be seen that VST of Cu is higher to SiO_2. The Al_2O_3 (13nm) VST is greater which might be due to the smaller size of the particle at 20°C and 40°C.

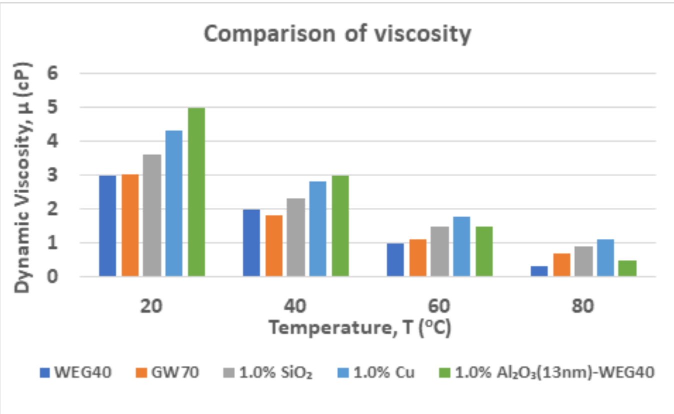

Figure 8: Comparison of viscosity with Al_2O_3/13nm in WEG40.

Thermal conductivity-Copper and SiO_2 Nanofluids

The TC of the base liquid GW70, Cu, and Silica nanofluids are measured at T= 20-80°C. The experimental 'k' data obtained for the base liquid GW70 mixture is compared to computed values using Fillipov model.

Fillipov [42] proposed a linear mixture model to predict TC of aqueous mixes of glycerol and water given by Eqs. (12) and (13)

$$k_{gw}=k_g\,C_g+k_w\,C_w-\propto C_g\,C_w \qquad (12)$$

$$\propto = C_a\,|k_w-k_g| \qquad (13)$$

Where

$$k_g=0.281+0.0001T \qquad (14)$$

$$k_w=0.56112+0.00193T-0.00000260152749T^2-0.0000000608803T^3 \qquad (15)$$

k is thermal conductivity; g and w stand for glycerol and water. Cg and C_w is the concentration of the glycerol and water in weight fraction. The weight fraction for 30% by volume of glycerol is 0.3511. The value of the constant C_a for aqueous solution vary between 0.3 to 0.7. The value of the constant C_a in Eq. 13 is taken as 0.3.

Enhancement of 'k' with temperature and concentration shown in Fig.9. The 'k' of GW70 base liquid is 0.461 W/mK at 20°C which increased to 0.493 W/mK and 0.588 W/mK for SiO_2 and Cu nanoparticles at 0.2% concentration. The thermal conductivity increases further to 0.616 W/mK and 0.734 W/mK when T = 80°C.TC of 1.0% SiO_2 and Cu nanofluids is determined to be 0.843 W/mK and 1.005 W/mK at 80°C. The variation of TC of Cu, SiO_2, nanofluids, for φ= 0.2, 0.6, and 1.0 %, along with base liquid GW70 mixture against temperature is illustrated in Fig.9. The experimental data is found closer to estimated values of Eqs. (12) – (13) for the base liquid and highest difference is 0.28%.

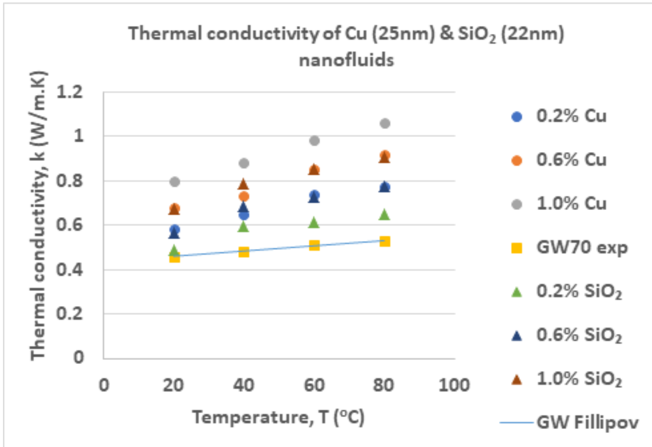

Fig 9: Variation of thermal conductivity with temperature and comparison of base liquid thermal conductivity with Fillipov model [42]

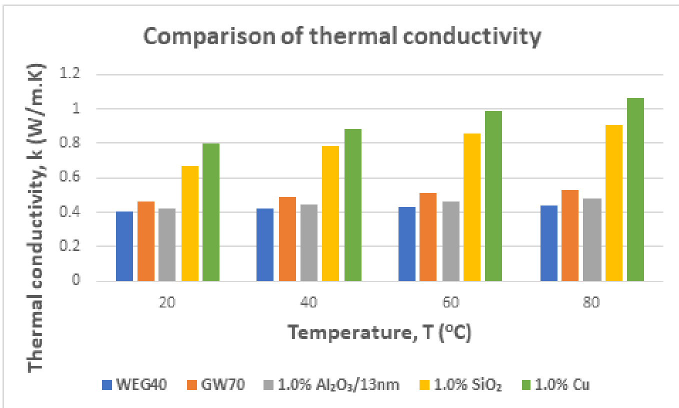

Figure 10: Comparison of thermal conductivity data with Al_2O_3/13nm in WEG40.

The empirical 'k' data for Cu and SiO_2 nanofluids is given in Table 4. 'k' increased as temperature and particle loading increases. Maximum enhancement in 'k' is observed for 1.0% vol. concentration at 80°C for Cu and SiO_2 nanofluids to be 100.38 % and 71.32% respectively. Enhancement can be attributed to increased surface-volume ratio available because of nanoparticles dispersion, improved Brownian movement of many small-size nanoparticles and at elevated temperatures. [43,44].

Table 4: Thermal conductivity enhancement percentage of Cu and SiO_2 nanofluids.

Temperature/ Concentration	20°C	40°C	60°C	80°C
0.2% Cu	27.39	33.61	45.49	46.42
0.6% Cu	48.26	51.75	67.25	73.21
1.0% Cu	73.48	81.86	93.33	100.38
0.2% SiO_2	6.09	22.68	20.78	22.83
0.6% SiO_2	23.48	41.86	42.35	46.04
1.0% SiO_2	46.09	62.06	67.84	71.32

Experimental 'k' data of Cu and SiO_2 nanofluids in GW70 base fluid is not available in the literature for comparison. Experimental results of 'k' of nanofluids in GW70 are compared with water-EG (60:40 ratio by volume) -Al_2O_3/13nm nanofluids, referred to as WEG40, by Azmi et al. [41]. This comparison is made as GW70 viscosity data is very close to the WEG40 data. As seen in Fig.10, the 'k' increases with increasing temperature for all nanofluids.

Specific heat-Cu, SiO_2 nanofluids

The Cp of GW70 based liquid obtained from experiments is compared with the values computed using the model developed by Righetti et al. [45]. They measured the C_p of glycerol at T= 25 to 110°C. They used a Differential Scanning Calorimeter (DSC) along with a modulated scanning calorimeter at 5mHz. The data obtained is fitted into relation as shown in Eq. (16). The specific heat of water obtained from the data book is regressed and given as Eq.(17). A linear mixture relation Eq. (18) is proposed by Righetti to compute the specific heat capacity of GW mixtures.

$$C_{pg}=90.983+0.4335T \quad (16)$$

$$C_pw=4217.629-3.20888T+0.09503T^2-0.00132T^3+0.00000941T^4-0.000000025479T^5 \quad (17)$$

$$C_{pgw}=C_{pg}\,w_g+C_{pw}\,w_w \quad (18)$$

Where w_g and w_w are weight fractions of glycerol and water. In the present work, 30% of the volume of glycerol corresponds to a weight fraction are 0.3511 while the remaining 0.6489 is water.

It can be observed that the empirical data is very closer to computed values using Eq.(18). However, at higher temperatures of 60 and 80°C the predicted values are slightly lower than the empirical Cp values of GW70. A comparison of experimental 'Cp' for GW70 base liquid with computed values from Righetti model is shown in Fig. 11. They are in good agreement and highest deviation is 1%.

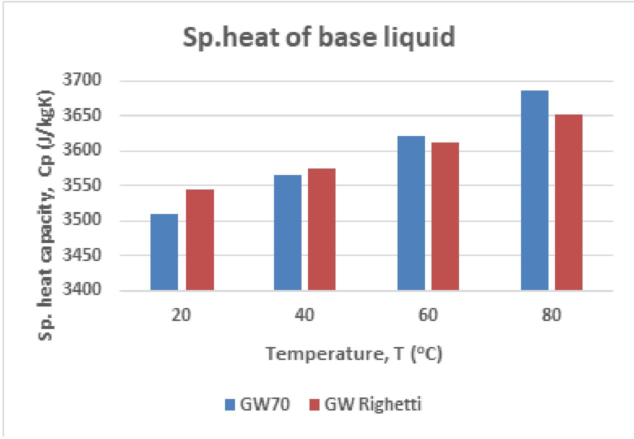

Figure 11: Comparison of GW70 base liquid specific heat of with Righetti model [45].

The experimental 'C_p' of base liquid and nanofluids against temperature in the range of 20-80°C for three concentrations is given in Table 5. 'C_p' is more when T is more, and decreased when 'φ' is more. 'C_p' of base liquid significantly reduced on addition on the nanoparticles. For example, the 'C_p' of the base liquid at 20°C was 3550 J/kg K and with the addition of Cu and SiO_2 nanoparticles, and it dropped to 3499 J/kgK and 3538 J/kg K respectively at 20°C for 0.2% concentration. This reduction is even greater at higher concentrations. However, the 'C_p' increased at elevated temperatures.

Table 5: Specific heat data of Cu and SiO_2 nanofluids.

Specific heat (J/kgK)				
Temperature → Concentration ↓	20°C	40°C	60°C	80°C
GW70	3510	3566	3622	3686
0.2% Cu	3432	3486	3545	3598
0.6% Cu	3342	3394	3448	3498
1.0% Cu	3256	3301	3348	3399
0.2% SiO_2	3468	3524	3586	3652
0.6% SiO_2	3448	3504	3572	3645
1.0% SiO_2	3436	3488	3546	3601

The 'Cp' of 1.0% concentration for Cu and SiO_2 nanofluid at 20°C is respectively 3305 J/kgK and 3488 J/kgK which increases to 3438 J/kgK and 3634 J/kgK at 80°C. Probably, the energy stored in the solid and liquid medium at higher temperatures could be the reason for the increment. Table 5 shows the 'Cp' data at different temperatures for Cu and SiO_2 nanofluids compared to base liquid. The 'C_p' decrement of Cu and SiO_2 nanofluid for 1.0% concentration at 80°C is 7.79 and 2.31. The findings are closure to published works [28-30]

Density of Cu and SiO_2 nanofluids

The experimental data of GW70 base liquid is illustrated in Fig.12 and compared to values from regression Eqs. (19) ,(20) developed by Chrischanto [46] and Delgado [47] respectively. They used the experimental data of GW mixtures in the determination of the constants for the Jouyban-Acree model. The model is preferred over Redlich-Krister equation as it includes the effect of temperatures and for estimating density at other temperatures.

$$\ln \rho_{m,T} = x_1 \ln\rho_{1,T} + x_2 \ln\rho_{2,T} + 93.766\frac{x_1 x_2}{T} - 77.285\,\frac{x_1 x_2 (x_1 - x_2)}{T} + 73.028\frac{x_1 x_2 (x_1 - x_2)^2}{T} \quad (19)$$

$$\ln \rho_{m,T} = x_1 \ln\rho_{1,T} + x_2 \ln\rho_{2,T} + 83.896\frac{x_1 x_2}{T} - 81.181\,\frac{x_1 x_2 (x_1 - x_2)}{T} + 101.858\frac{x_1 x_2 (x_1 - x_2)^2}{T} \quad (20)$$

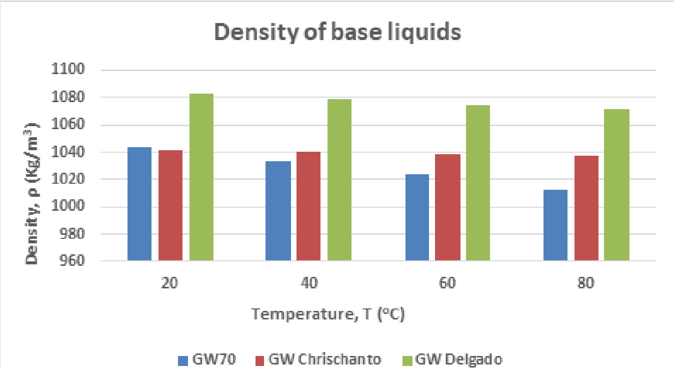

Figure 12: Comparison of density of GW70 base liquid with Chrischanto [46] and Delgado [47] models.

Where, $\rho_{(m,T)}$, $\rho_{(1,T)}$ and $\rho_{(2,T)}$ denotes mixture solvent, co-solvent, water density respectively; T is temperature. x_1,x_2 – cosolvent, water mole fractions.

Maximum deviation between experimental data of GW70 base liquid with Eqs. (19) and (20) are respectively 2.5 and 5.8% and shown in Fig. 12 The density data of Cu and SiO_2 nanofluids at different temperatures are reported in Table. 6. Nanofluids 'ρ' is more as 'φ' is more and is less when temperature is increased. Maximum 'ρ' for Cu nanofluid is 1102 kg/m^3 at 1.0% concentration at 20°C while the lowest density is 1023 kg/m^3 for 0.2 % concentration at 80°C. The corresponding densities estimated for SiO_2 are 1057 kg/m^3 and 1018 kg/m^3 respectively.

Table 6: Density data of Cu and SiO_2 nanofluids.

Density (kg/m^3)				
Temperature→ / **Concentration ↓**	20°C	40°C	60°C	80°C
GW70	1044	1033	1024	1013
0.2% Cu	1052	1041	1032	1023
0.6% Cu	1078	1069	1062	1054
1.0% Cu	1102	1098	1085	1089
0.2% SiO_2	1048	1037	1028	1018
0.6% SiO_2	1054	1043	1034	1026
1.0% SiO_2	1057	1048	1032	1028

Error analysis

Error analysis for each property measured experimentally is computed based on the instrument's reproducibility. For thermal conductivity, the error variation is 2%, for thermal diffusivity of 10%, and specific heat capacity 12% as per the manufacturer's information. Weight percentage is measured with a precise electronic weighing machine of ±0.0001g accuracy. Temperature sensors with an accuracy of ±0.5°C are used. DV2 model viscometer with ±1% accuracy was used to measure dynamic viscosity. Eqs. (21) to (24) are used to compute the cumulative error in the experimental measurement of properties. Maximum error determined from Eqs. (21) to (24) is 2.7, 4.2, 2.5, and 5.5% for 'μ', 'k', 'Cp' and 'ρ' respectively.

$$\text{Dynamic viscosity} = \pm\sqrt{\left(\frac{\Delta\mu}{\mu}\right)^2 + \left(\frac{\Delta w}{w}\right)^2 + \left(\frac{\Delta T}{T}\right)^2} \quad (21)$$

$$\text{Thermal conductivity} = \pm\sqrt{\left(\frac{\Delta k}{k}\right)^2 + \left(\frac{\Delta w}{w}\right)^2 + \left(\frac{\Delta T}{T}\right)^2} \quad (22)$$

$$\text{Specific heat capacity} = \pm\sqrt{\left(\frac{\Delta c_p}{c_p}\right)^2 + \left(\frac{\Delta w}{w}\right)^2 + \left(\frac{\Delta T}{T}\right)^2} \quad (23)$$

$$\text{Density} = \pm\sqrt{\left(\frac{\Delta\mu}{\mu}\right)^2 + \left(\frac{\Delta k}{k}\right)^2 + \left(\frac{\Delta c_p}{c_p}\right)^2} \quad (24)$$

Enhancement Ratio (ER)

Enhancement Ratio (ER) considers the combined influence of 'k' and 'μ' of nanofluids. It is the ratio of enhancement of 'μ' over the enhancement of 'k' both over the base liquid. Garg et al [48] concluded as the ER values are below 5, the nanofluid will aid in heat transfer enhancement. As seen from Table 7, ER of both Cu and SiO_2 nanofluids are well below the threshold value indicating and confirming a good choice for heat transfer enhancement.

Table 7: Enhancement Ratio of Cu and SiO_2 nanofluids.

Enhancement Ratio				
Temperature→ / Concentration ↓	20°C	40°C	60°C	80°C
0.2% Cu	1.68	1.31	1.23	1.14
0.6% Cu	1.58	1.37	1.26	1.23
1.0% Cu	1.57	1.40	1.32	1.28
0.2% SiO_2	2.96	1.21	1.02	0.95
0.6% SiO_2	2.08	1.52	1.35	1.24
1.0% SiO_2	2.00	1.66	1.53	1.43

CONCLUSION

Cu and SiO_2 nanofluids are prepared in the base liquid of glycerol-water mixture in the volume ratio of 30:70, referred to as GW70, and their properties are measured at T= 20°C to 80°C. viscosity, thermal conductivity, specific heat and density enhancement/decrement percentages are computed, and the enhancement ratio (ER) is obtained for Cu and SiO_2 nanofluids.

1. Dynamic viscosity enhanced with particle concentration and declined with an enhancement in temperature. Viscosity increment of Cu and silica nano-fluids is maximum at 1.0% vol. concentration and 80°C and measured as 63.41% and 35.69% respectively.

2. Thermal conductivity enhanced with 'φ' and 'T'.

Enhancement of ‘k’ is determined to be 100.38% and 71.32% at the same concentration and temperature.

3. ‘Cp’ of nanofluids decreases with concentration and enhanced with temperature. Maximum decrement of 7.79% and 2.31% observed for Cu , Silica nanofluids at φ= 1.0% ;T= 80°C.

4. Density enhanced with ‘φ’ and reduced as ‘T’ increases. Maximum increment of 7.50% and 1.48% observed for Cu, Silica nanofluids at φ= 1.0% ;T= 80°C.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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