JOURNAL OF ADVANCED MECHANICAL ENGINEERING APPLICATIONS
e-ISSN: 2716-6201

Vol. 6 No. 2 (2025) 8-31
https://publisher.uthm.edu.my/ojs/index.php/jamea

JAMEA

Cu and CuO Nanoparticles in Heat Transfer Applications: A Comprehensive Review

Hani Chotai[1], Rupeshkumar V. Ramani[2*], J H Markna[3], Bharat Kataria[3]

[1] *Research Scholar, Mechanical Engineering Department, Gujarat Technological University, Ahmedabad, 382424, INDIA*

[2] *Mechanical Engineering Department, V.V.P Engineering College, Rajkot, 360005, INDIA*

[3] *Department of Nanoscience and Advanced Materials, Saurashtra University, Rajkot, 360005, INDIA*

*Corresponding Author: rupesh.ramani.me@vvpedulink.ac.in
DOI: https://doi.org/10.30880/jamea.2025.06.02.002

Article Info

Received: 27 May 2025
Accepted: 5 November 2025
Available online: 31 December 2025

Keywords

Mono/binary/ternary nanofluids, Cu, CuO, thermal conductivity

Abstract

This review highlights the role of Copper (Cu) and Copper Oxide (CuO) nanoparticles in enhancing heat transfer through mono, binary, and ternary nanofluids. Mono nanofluids consistently improved thermal conductivity, viscosity, pressure drop, and heat transfer coefficient, with higher gains at higher concentrations. Binary systems showed synergistic effects, with CuO–MWCNT yielding maximum conductivity, CuO–TiO_2 showing Newtonian behavior, and Cu with Al_2O_3 and TiO_2 achieving peak conductivity at a 40:40:20 ratio. Ternary mixtures of Cu, CuO, and Al_2O_3 offered further conductivity enhancement but with larger pressure drops, notably at 60:20:20. Overall, nanoparticle selection, base fluid, and mixing proportion are key to balancing thermal performance with hydrodynamic penalties.

1. Introduction

Transfer of heat using a fluid medium is of critical importance in various applications like Refrigeration, Power Plants, Automobile and Heat Exchangers. When heat transfer takes place through fluid medium, convection mode is dominant, and accordingly rigorous research has been done to improve convective heat transfer co-efficient. Heat transfer co-efficient is strongly dependent on thermal conductivity of circulating fluid medium. Of various techniques used to improve thermal conductivity and hence convective heat transfer co-efficient, Nanofluids have emerged as one of the promising alternatives. Nanofluids are fluids containing stable suspensions of solid particles with size less than 100 nm in various base fluids.

Nomenclature	
EG	Ethylene Glycol
MEG	Mono Ethlene Glycol
CNT	Carbon Nanotubes
MWCNT	Multiwalled Carbon Nano Tubes
CNF	Carbon Nanofibre
CMC	Carboxy Methyl Cellulose

The topic has been of importance to many researchers since many years. Pure Metals, Metal Oxides, Metal Carbides, Metal Nitrides as well as different forms of carbon are used as nanoparticles with base fluids like water, ethylene glycol and oil. Variations in parameters like weight concentration, volume concentration, flow temperature, flow velocity, particle size etc have been incorporated to study their effects on various properties like thermal conductivity, viscosity, pressure drop, heat transfer co-efficient etc. Extensive research has been conducted in the field of mono, hybrid, and ternary nanofluids, leading to numerous experimental and theoretical studies. A significant number of review papers have also been published, highlighting the advancements and challenges associated with each category. A concise summary of the key findings and developments from the existing literature is presented in Tables 1, 2, 3, and 4.

Table 1 *List of topics covered by review papers on nanofluids*

Topics
Synthesis methods, characterizations, stability tests, thermophysical properties (thermal conductivity, specific heat capacity, and viscosity) [1].
Effects on Prandtl Number, Reynold Number and Heat Transfer Co-efficient due to variation in Density, Specific Heat, Thermal Conductivity and Viscosity [2].
Applications of nanofluids in various segments like solar water heating, cooling: engine; electronics; transformer oil, improving efficiency of diesel generator, increasing efficiency of chillers & domestic refrigerator, cooling in nuclear reactors, defense and space [3].
Nanofluid preparation methods to find suitable method. (Includes review of Preparation method for 11 non-metallic nanofluids viz. SiO_2, TiO_2, Al_2O_3, ZnO, CuO, Fe_2O_3, AlN, and CNT along with preparation methods for gold, silver and copper nanofluids [4].
Investigation on mechanism of heat transfer enhancement wherein two models used to derive relations for heat transfer co-efficient. One is conventional where nanofluids are treated as the single-phase fluids and another approach is considering multiphase feature of the nanofluid with dispersed nanoparticles [5].
Preparation Methods, Thermophysical Properties, Stability, Friction Factor, Various Correlations and Challenges [6]
Summary of various experimental and numerical studies and an overview of heat transfer mechanisms responsible for the change in thermal performance of heat pipes [7]
Summary of experimental studies that analyze both mono and hybrid nanofluids for single phase convective heat transfer devices viz. tubular heat exchangers, plate heat exchangers and heat sinks as well as for two phase convective heat transfer device viz. heat pipe. [8]
Different factors affecting viscosity of nanofluids including nanofluid preparation methods, particle shape, particle size, temperature, volume fraction effects. [9]
Describes four possible reasons for increase in thermal conductivity on nanofluids viz. (a) Brownian motion (b) Layering of liquid at liquid/particle interface (c) Nature of heat transport in nanoparticles (d) Effects due to clustering of nanoparticles [10]
Effects of concentration, shape, size and flow rate of Nanoparticles on Nusselt number, heat transfer coefficient, thermal conductivity, thermal resistance, friction factor and pressure drop [11]
Nanofluids research for heat transfer application addressing the challenges in formulation, practical application with mechanism understanding [12]
Thermal conductivity of hybrid nanofluids including research done by numerical, experimental, and ANN (artificial neural networking) studies, Parameters affecting thermal conductivity viz. type, concentration & size of nanoparticles; base fluid type, temperature, type of surfactant, variation of pH and sonication time.

Preparation of hybrid nanofluids, methods to measure and enhance stability, methods to measure thermal conductivity and reasons for enhancement of thermal conductivity [13]
Forced convective heat transfer coefficient of the nanofluids: Experimental and numerical investigation [14]
Improvement of heat transfer using nanofluids, research done on preparation of nanofluids and enhancement of stability, Thermo-physical & heat transfer characteristics of nanofluids, Effect of factors viz. particle shape &size, temperature, surfactant on thermal conductivity [15]
Theoretical and Experimental studies on the thermal conductivity of nanofluids, Analysis of effect of various factors like shape, temperature & concentration on thermal conductivity of nanofluids [16]

Table 2 *Summary of research: mono nanofluids*

Nanofluid	Parameters studied
CuO-water	Density and viscosity [17]
	Convective heat transfer coefficient thermal conductivity, viscosity, and pressure loss [18]
	Turbulent convective heat transfer performance and pressure drop [19]
	Viscosity and thermal conductivity [20]
	Nusselt Number [21]
	Nusselt number and Friction Factor [22]
Al2O3/Water	Thermal resistance of heat pipe [23]
	Thermal conductivity and specific heat [24]
	Viscosity and Thermal Conductivity [25]
	Heat Transfer Coefficient [26]
	Heat Transfer Rate [27]
CuO/Oil	Density, thermal conductivities, viscosities and specific heat capacity [28]
	Heat transfer and pressure drop characteristics [29]
CuO/EG	Zeta Potential, Absorbance and Thermal Conductivity [30]
Cu/Water	Convective and overall heat transfer coefficient, thermal resistance [31]
TiO2/Water	Convective Heat Transfer Coefficient [32]
	Stability, viscosity, thermal conductivity [33]
SiC/Water	Viscosity, Thermal Conductivity [34]
AlN/EG	Friction factor, Nusselt number [35]
	Viscosity, thermal and electrical conductivity [36]
AlN/Polypropylene glycol	Rheological Behavior [37]
Ag/Water	LMTD, Effectiveness (of heat exchanger), convective heat transfer coefficient and pressure drop [38]
Mg (OH)2/water	Thermal conductivity and stability [39]
Graphene/Water	Pressure Drop, Convective Heat Transfer Coefficient, Nusselt Number [40]
Graphene oxide/water	Average Nusselt Number and Friction factor [41]
Graphene nanoplatelet (GNP)/water	Convective heat transfer coefficient and pressure drop [42]

ZnO/Water	Viscosity and thermal conductivity [43]
SiO2/Water	Heat transfer co-efficient and friction factor [44]
Fe/EG	Thermal conductivity, Dynamic Viscosity [45]
ZrO2/water	Solid-liquid (S-L) interfacial thermal resistance [46]
AlN/Ethanol	Thermal Conductivity [47]
Cordierite-based Glass-Ceramic/AlN	Thermal Conductivity, Flexural strength, Fracture Toughness [48]
Fe3O4 (magnetic nanoparticles)/water	Viscosity, Thermal Conductivity [49]
ZnO/Oil, MgO/Oil	Viscosity, Thermal conductivity [50]
Al2O3/water, Al2O3/EG	Heat transfer coefficient [51]
	Heat Transfer Enhancement, Wall Shear Stress [52]
Al2O3/water, TiO2/water	Heat transfer characteristics [53]
AlN/EG, AlN/Proylene glycol	Thermal conductivity and viscosity [54]
Au/toluene, Al2O3/water, and CNF/water	Thermal conductivity and thermal diffusivity [55]
CuO, TiO2, MgO, MWCNT, Al2O3 and ZnO water based	Electrical Conductivity, Viscosity, and Density [56]
(MWCNT), Fullerene, CuO, SiO2 with base fluids water, EG and oil	Thermal conductivity and stability [57]
CuO/water, MgO/water, TiO2/water, ZrO2/water, Al2O3/water	Thermal conductivity [58]
Al2O3/water, CuO/water, SiO2/water, ZnO/Water	Thermal conductivity and viscosity [59]
CuO/water, TiO2/water, CuO/EG, TiO2/EG	Thermal conductivity and Convective heat transfer coefficient [60]

Table 3 *Summary of research: hybrid nanofluids, mono nanofluids with binary base fluids & hybrid nanofluids with binary base fluids*

Nanofluid	Parameter Studied
Cu–TiO2/Water	Convective heat transfer coefficient, Nusselt number, Overall heat transfer coefficient [61]
CuO-Ag/Water	Heat Transfer in presence of Radiation, Heat Generation & Chemical Reaction [62]
Al2O3-MWCNT/Water	Heat transfer rate, Collector efficiency, Pressure drop, Environmental effect (CO2 emission and water consumption) [63]
Al2O3-Ag/Water	Thermal Conductivity [64]
Cu–Al2O3/Water	Viscosity, absorbency and extinction coefficient [65]
Cu–Al2O3/EG	Thermal Conductivity [66]
Cu - ZnO/Water	Convective heat transfer coefficient, pressure drop, Nusselt number [67]
Al2O3-AlN/Water	Nusselt Number, Pumping Power [68]
Cu–Al2O3/Kerosene	Thermal conductivity, Dynamic viscosity, Rheological characteristics [69]
SiO2–CuO/C	Specific heat, Thermal conductivity, Viscosity [70]
Al2O3–MWCNT/Water	Natural convection heat transfer coefficient, Nusselt number [71]
	Pressure drop, Heat transfer coefficient [72]
Al2O3–ZnO/Water	Specific Heat Capacity, Viscosity [73]
Al2O3–Fe/Water	Specific Heat Capacity, Thermal Conductivity, Viscosity [74]
MgO-MWCNT/ EG	Thermal conductivity ratio [75]
MWCNT–SiO2/AE40	Relative Viscosity [76]
Fe3O4–Ag/EG	Viscosity measurement at different shear rate [77]
CuO/EG–Water	Thermal Conductivity [78]
	Rheological Behavior [79]
MgO / EG–Water	Thermal Conductivity [80]
CuO/EG–Water, Al2O3 / EG-Water	Heat transfer coefficient, Skin friction coefficient [81]
MgO/Water–EG	Thermal Conductivity [82]
CNT /Water-EG	Average Nusselt Number [83]
Al2O3–CuO/Water–EG	Thermal conductivity, Viscosity, Stability [84]
MWCNT–SiO2/EG–Water	Viscosity with respect to Shear rate [85]
Cu-TiO2/Water-EG	Thermal conductivity [86]

Table 4 *Summary of research: ternary nanofluids*

Nanofluid	Parameter Studied
Cu-MgO– TiO2/Water	Dynamic Viscosity, Thermal Conductivity, Specific Heat Capacity, Density [87]
MWCNT-TiO2-ZnO/Water -EG	Thermal Conductivity [88]

Despite extensive work on nanofluids, limited attention has been given to the comparative and combined use of metals and their corresponding oxides, such as Cu and CuO. Since metals provide superior thermal conductivity and oxides offer better stability, understanding their individual and synergistic effects is essential for optimizing nanofluid design. This gap highlights the need for systematic studies that evaluate both Cu- and CuO-based mono, binary, and ternary nanofluids across different operating conditions. Both nanoparticles can be effectively suspended in water, ethylene glycol, oils, and other fluids, making them versatile for engineering applications. Together, they enable the design of nanofluids that balance thermal performance with long-term stability, which is critical for practical systems such as heat exchangers, solar collectors, and electronic cooling. The present paper provides a critical and comprehensive review focused on Copper (Cu) and Copper Oxide (CuO) nanoparticles. The use of Cu and CuO nanoparticles in mono, binary, and ternary nanofluids is systematically analyzed. To account for the influence of the base fluid, studies involving water, ethylene glycol, various oils, and carboxymethyl cellulose have been included. The review considers the effects of several key parameters, including weight and volume concentration, temperature, fluid velocity, sonication time, and particle size. The resulting variations in thermophysical properties—such as thermal conductivity, viscosity, density, and heat transfer coefficient—are thoroughly discussed.

2. CuO as Nanoparticle

Khedkar, R. S et al. [89] investigated the effect of incorporating CuO nanoparticles with two different base fluids: water and mono-ethylene glycol. The study utilized CuO nanoparticles with an average size of 25 nm. Thermal conductivity enhancement was examined by varying both the nanoparticle volume concentration and sonication time. The results demonstrated that the thermal conductivity of water increased from 0.586 W/m·K to 0.775 W/m·K, while for mono-ethylene glycol, the enhancement ranged from 0.268 W/m·K to 0.346 W/m·K. Notably, a maximum increase of 32% in effective thermal conductivity was observed at the highest volume concentration when water was used as the base fluid. The influence of sonication time on thermal conductivity was also explored. It was found that a sonication time of 1 hour yielded optimal results, beyond which thermal conductivity began to decline. This reduction was attributed to nanoparticle agglomeration or clustering, which negatively impacts thermal performance. The variation in thermal conductivity with respect to both volume concentration and sonication time is illustrated graphically in Fig. 1.

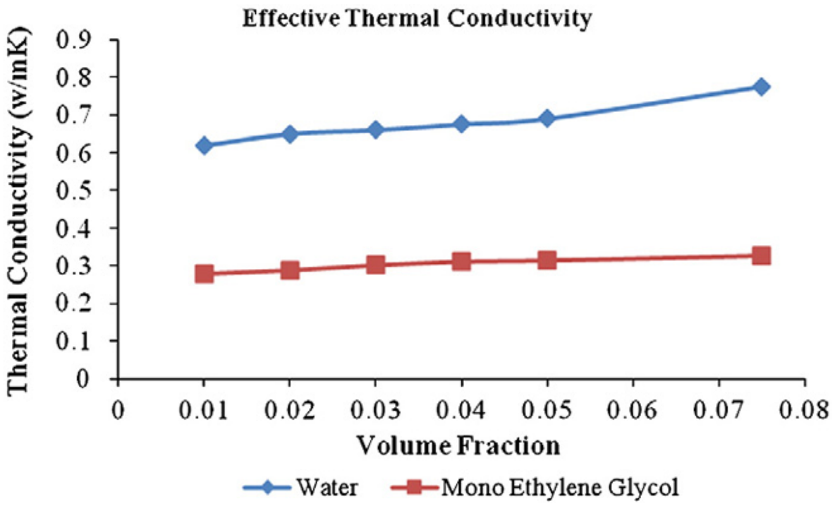

Fig. 1 (a) *Variation in thermal conductivity with variation in volume fraction of CuO in water and MonoEthylene Glycol*

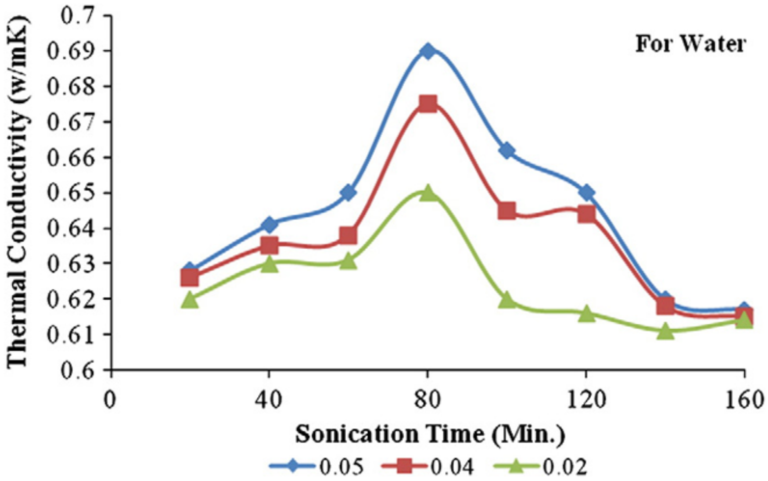

Fig. 1 (b) *Variation in thermal conductivity with variation in Sonification time for CuO - water*

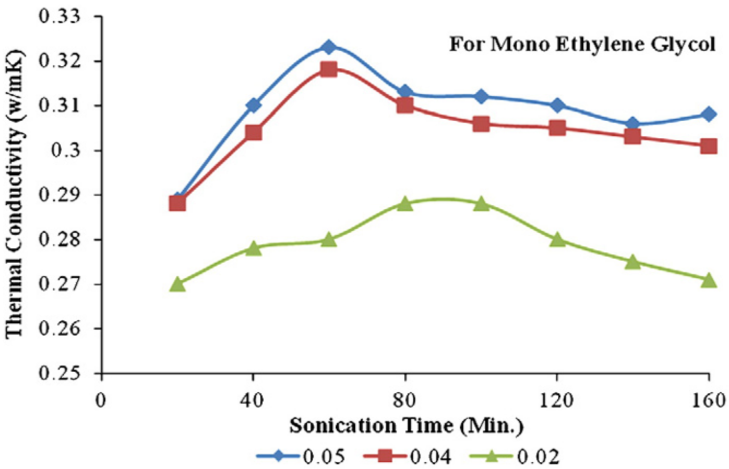

Fig. 1 (c) *Variation in thermal conductivity with variation in sonification time for CuO – MonoEthylene Glycol*

The effect of using carboxymethyl cellulose (CMC) as a base fluid on heat transfer performance was investigated by [90]. Three metal oxide nanoparticles—Fe_2O_3 (30–60 nm), Al_2O_3 (20–30 nm), and CuO (40 nm)—were employed in the study. A shell-and-coil heat exchanger configuration was used, with the nanofluid circulating on the shell side and water on the tube side. Key variables included the weight concentration of nanoparticles (ranging from 0.2% to 1%), the flow rate of the cold fluid (0.5 to 5 LPM), and nanofluid temperature (varied between 40°C and 60°C). The study presented results for both thermal conductivity and wettability of the nanofluids. Among the three metal oxides tested, CuO nanoparticles demonstrated the highest wettability. In terms of thermal conductivity, the nanofluids exhibited enhancements of 13%, 26%, and 37% for Fe_2O_3, Al_2O_3, and CuO respectively at 1% weight concentration and a temperature of 50°C. The comparative thermal conductivity results for the three metal oxides are illustrated in Fig. 2.

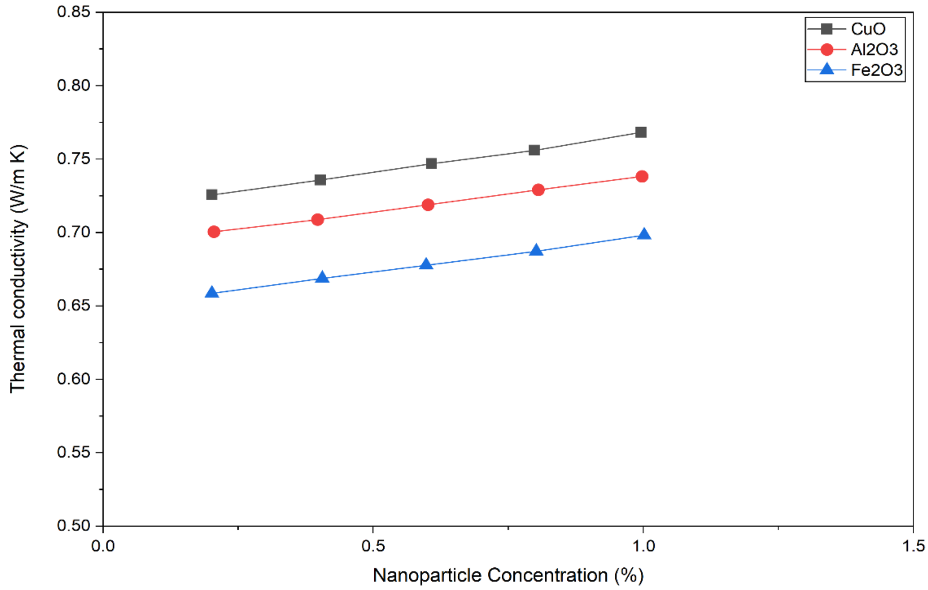

Fig. 2 *Variation in thermal conductivity with variation in volume fraction in CuO, Al_2O_3, Fe_2O_3 [90]*

Investigation of heat transfer and fluid flow characteristics was done by [91] on corrugated plate heat exchanger using 4 different nanoparticles - (Al_2O_3 -30 nm, SiC-40 nm, CuO-30 nm and Fe_3O_4 -25 nm) with water as basefluid. Results were collected for variations in weight concentration (0.05% - 1%) and flow rate (3 – 9 L/m). Increase in overall heat transfer co-efficient was least (4.8%) for CuO while it was highest (6%) for Fe_3O_4. It was also observed that for weight concentration of 0.05%, CuO showed highest heat transfer co-efficient. Collecting and comparing further results, optimum weight concentration for SiC and CuO was concluded to be 0.5% while for Al_2O_3 and Fe_3O_4, it was 1%. At optimum weight concentration, the pressure drop was found to increase by 9.5% for CuO. (Second highest of the four nanoparticles)

Similar experimentation was done by [92] on solar flat plate collector using six different nanoparticles viz. MWCNT, Graphene, CuO, Al_2O_3, TiO_2 and SiO_2. In addition to results for thermophysical properties viz. thermal conductivity, viscosity, specific heat and density, the results for exergy efficiency, entropy generation as well as collector efficiency are presented. The measurement of thermophysical properties are reported for variation in volume concentration as fixed temperature. It was concluded that thermal conductivity, viscosity and density increases with increase in particle volume concentration while specific heat decreases. Of all the nanoparticles, CuO reported highest rise in density and viscosity. The results for the same are shown in Fig. 3.

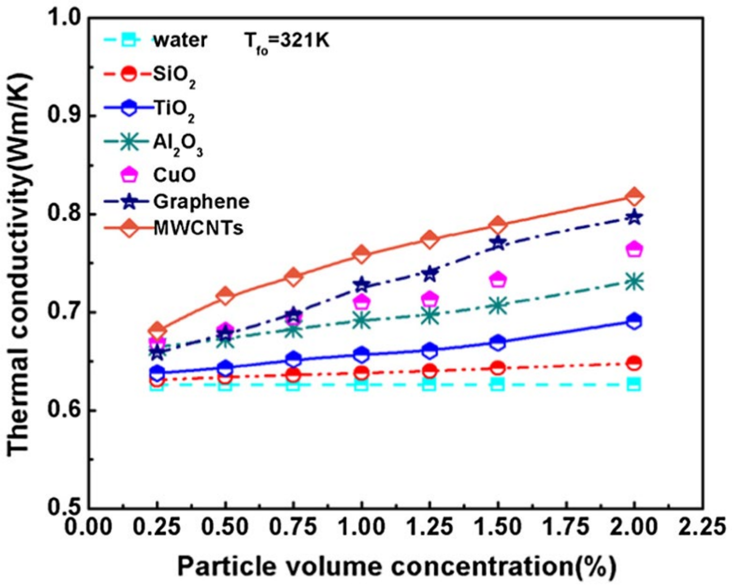

Fig. 3 (a) *Variation in thermal conductivity with variation in volume concentration for SiO_2, TiO_2, Al_2O_3, CuO, Graphene, MWCNT [92]*

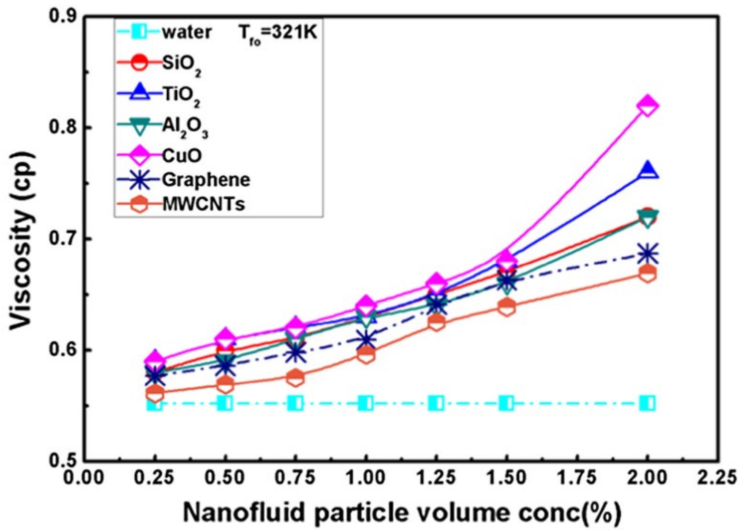

Fig. 3 (b) *Variation in viscosity with variation in volume concentration for SiO_2, TiO_2, Al_2O_3, CuO, Graphene, MWCNT [92]*

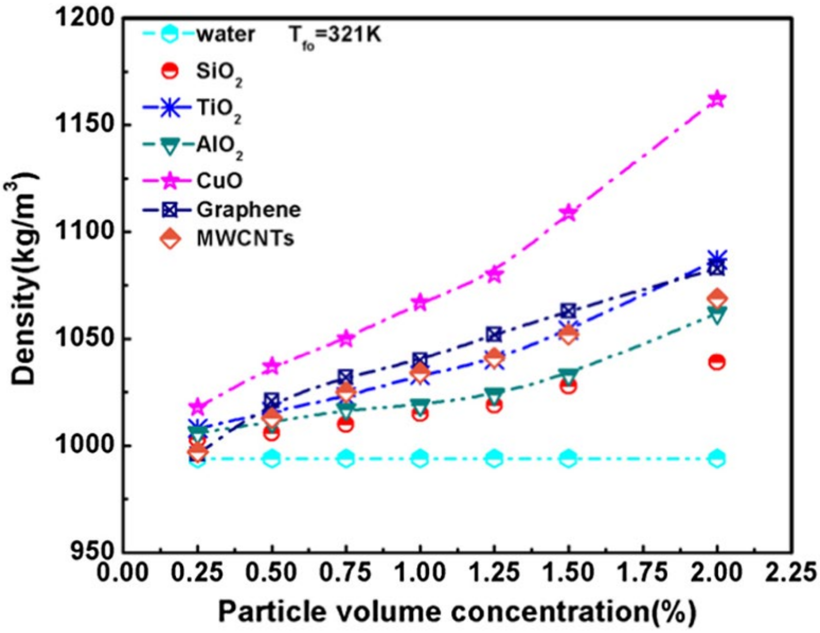

Fig. 3 (c) *Variation in density with variation in volume concentration for SiO_2, TiO_2, Al_2O_3, CuO, Graphene, MWCNT [92]*

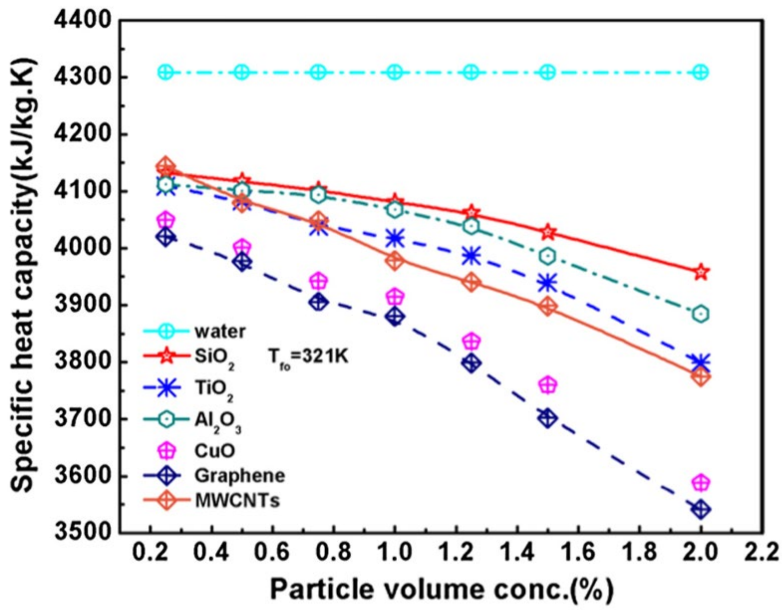

Fig. 3 (d) *Variation in thermal conductivity with variation in volume concentration for SiO_2, TiO_2, Al_2O_3, CuO, Graphene, MWCNT [92]*

CuO has also been investigated in combination with aluminum oxide, titanium oxide, silicon oxide, MWCNT and various other oxides as a *hybrid nanofluid* also to improve heat transfer. Results of few of them are described.

Bahrami, M. et al. [93] investigated results for viscosity variation and decided on the behavior of fluid [Newtonian/non-Newtonian] by preparing hybrid nanofluid with equal volumes of Fe and CuO. Binary mixture of water and ethylene glycol was used as base fluid and volume concentration of hybrid nanofluid was varied. It was concluded that the fluid exhibited Newtonian behavior with low concentration and non-Newtonian (shear thinning behavior) at high concentration. Effect on convective heat transfer and Nusselt number with CuO/MWCNT-oil nanofluid was reported by [94]. The aim was to assess the effect of different nanoparticle volume concentration in the ratio 1:1 and 1:2 [CuO:MWCNT]. Results for density, specific heat and thermal conductivity for mono as well as hybrid nanofluids are also presented. It was observed that for CuO-oil, the density-increase and specific heat-decrease were highest. Local Nusselt number showed an increase with increase in volume concentration. Addition of 3% CuO increase Nusselt number by 78%. However, it was quite lower than 1:2 proportion of CuO:MWCNT. Prandtl number and hence thermal boundary layer were observed to be less for hybrid fluid than mono nanofluid and higher than base fluid.

Asadi, A. et al. [95] studied rheological behavior and dynamic viscosity of CuO-TiO_2/water hybrid nanofluid. X-ray diffraction, Fourier-Transform Infrared Spectroscopy and Field Emission Microscopy tests were conducted to examine chemical, atomic and surface structures of nanoparticles. Dynamic viscosity measurement was done with variation in temperature and volume concentration with fixed proportion (1:1) of both nanoparticles. In order to decide the behavior of fluid, effect of shear rate was also reported. With the shear rate of 30 m/s and temperature range of 25 – 50^0 C, the hybrid nanofluid exhibited Newtonian behavior. Results for dynamic viscosity variations indicated decrease in viscosity with rise in temperature at given volume concentration. Also at any given temperature, viscosity is reported to increase with increase in volume concentration. The highest viscosity was reported at 1% volume and 25^0C.

Xuan, Y. et al. [96] investigated convective heat transfer coefficient and friction factor for turbulent flow using Cu-water nanofluid. The effect of variation in volume concentration (0.3 – 2%) and Reynold number (10,000-25,000) is reported. The heat transfer co-efficient improved with increase in both – volume concentration and Reynold number. However, it was pointed out that one of the studies with Al_2O_3 (13nm) and TiO_2 (27nm) reported heat transfer coefficient to be 12% less at 3% volume concentration. Hence selection of volume fraction, dimensions and material properties of the nanoparticles are critical. Similar to heat transfer coefficient, Nusselt Number also showed similar trend i.e., increase with increase in volume concentration and Reynold number. At 2% volume concentration, increase of 39% was reported. Two reasons are attributed for increased heat transfer: One is the higher value of thermal conductivity of suspended particles and second is the chaotic movement of particles which accelerates energy exchange.

Convective heat transfer and pressure drop characteristics for laminar flow inside uniformly heated circular pipe were investigated [97]. Al_2O_3-Cu/water hybrid nanofluid is tested with fixed 0.1% volume concentration. Results for changes in Nusselt number and friction factor are presented. Nusselt number, which is directly proportional to heat transfer coefficient is reported to increase by 13.56% for small volume concentration of 0.1%. The increase was 6.09% with use of alumina alone, which indicates the role of Cu nanoparticles. Also, it was concluded that even with less improvement in thermal conductivity, rise in Nusselt number was high due to flattened velocity profile. Friction factor was recorded to be higher for hybrid nanofluid than mono fluid as well as bas fluid. The reason attributed to the same is increased viscosity due to clustering, surface adsorption and migration of particles towards centre due to Brownian motion. The increase in friction factor for hybrid nanofluid was reported to be 16.97% when compared to water, while for mono nanofluids, it is reported to be 6%. Fig. 4 shows the results described.

Amiri, M. et al. [98] investigated effect on thermal conductivity of water and ethylene glycol using SiO_2-Cu nanoparticles. SiO_2 nanoparticles with copper modified surface is synthesized and dispersed in water and ethylene glycol base fluids. It is reported that the new synthesized particle had density similar to SiO_2 and thermal conductivity similar to Cu. Also, it did not possess the limitation of quick oxidation when exposed to air, which is usually found in metallic nanoparticles. Results for thermal conductivity are collected for 0.5% and 0.1% of SiO_2/water and 0.25%, 0.5% and 1% of hybrid nanofluid. Addition of SiO_2 increased thermal conductivity in both – water and EG. However, the effect was more pronounced in EG than water due to less thermal conductivity of EG. Changing percentage from 0.5 to 1 did not highlight much change in conductivity due to less value of thermal conductivity of SiO_2. Results for hybrid nanofluid was higher than mono nanofluid. Fig. 5 shows variation in thermal conductivity for mono and hybrid nanofluids.

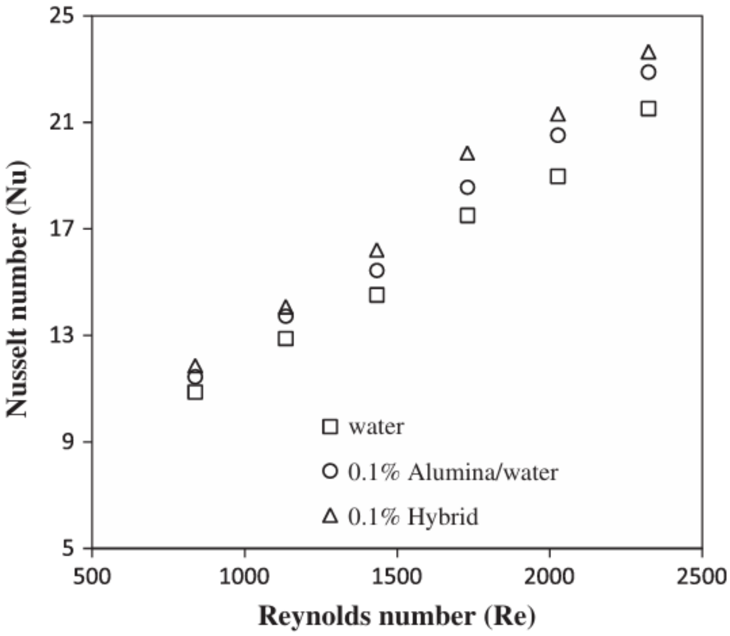

Fig. 4 (a) *Variation in Nusselt number with variation in Reynolds number for Al_2O_3-Water and Al_2O_3-Cu-Water [97]*

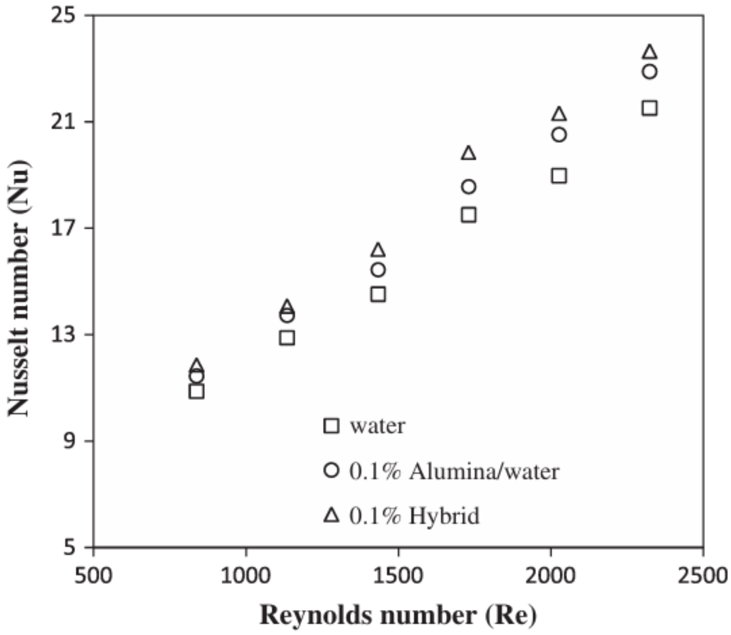

Fig. 4 (b) *Variation in friction factor with variation in Reynolds number for Al_2O_3-Water and Al_2O_3-Cu-Water [97]*

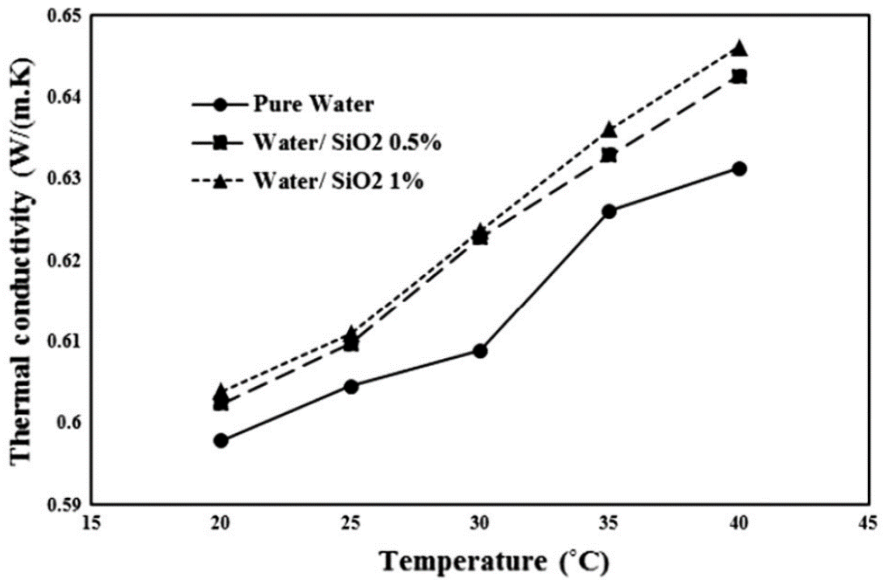

Fig. 5 (a) *Variation in thermal conductivity with variation in Temperature for SiO_2-water [98]*

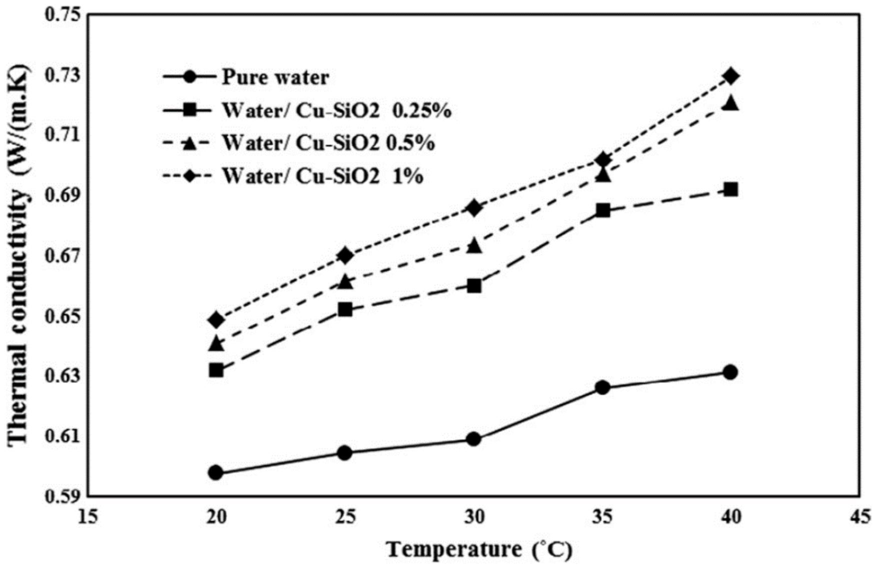

Fig. 5 (b) *Variation in thermal conductivity with variation in Temperature for Cu-SiO_2/water [98]*

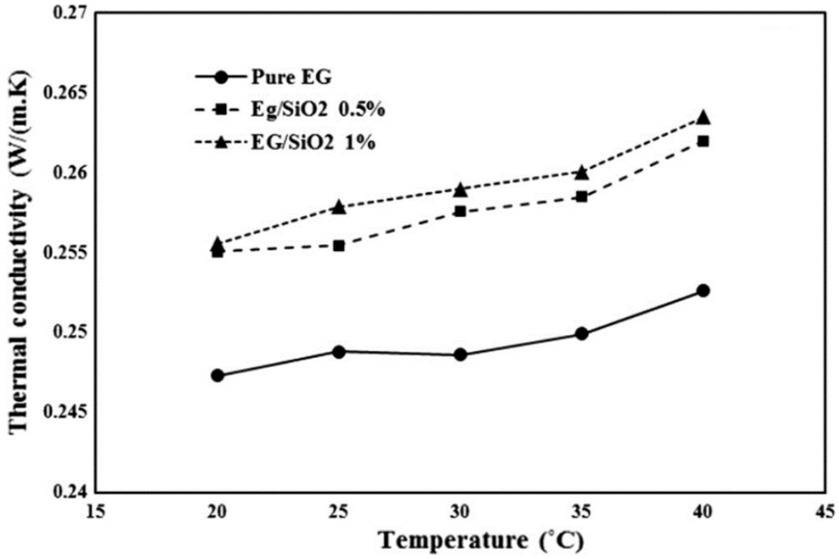

Fig. 5 (c) *Variation in thermal conductivity with variation in temperature for SiO_2-EG [98]*

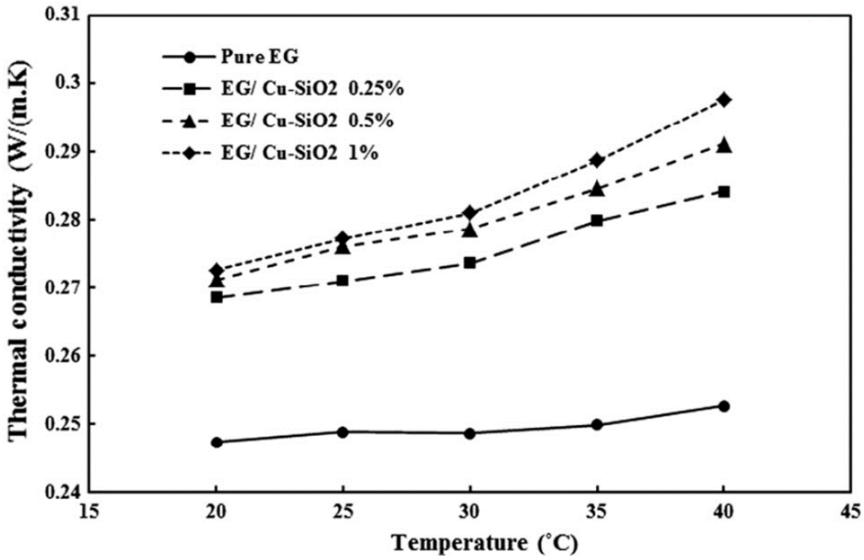

Fig. 5 (d) *Variation in thermal conductivity with variation in temperature for Cu- SiO_2/EG [98]*

Investigation on variation in dynamic viscosity and thermal conductivity was carried out by Dezfulizadeh, A et al. [99] using ternary nanofluid – Cu-SiO_2-MWCNT/water (as shown in Fig. 6). Variation in temperature [15^0C – 65^0C] and volume concentration are incorporated. Viscosity decreased with increase in temperature at given volume concentration, similar to the previous case studies. The decrease was much smoother and uniform at low concentrations than at high concentration. At any given temperature, viscosity increased with increase in volume concentration. Results for thermal conductivity indicated increase with increase in temperature at given volume concentration. The rise was steep until concentration of 1% and became gentle till 2.5%. The reason attributed to the increase in conductivity is Brownian motion of nanoparticles.

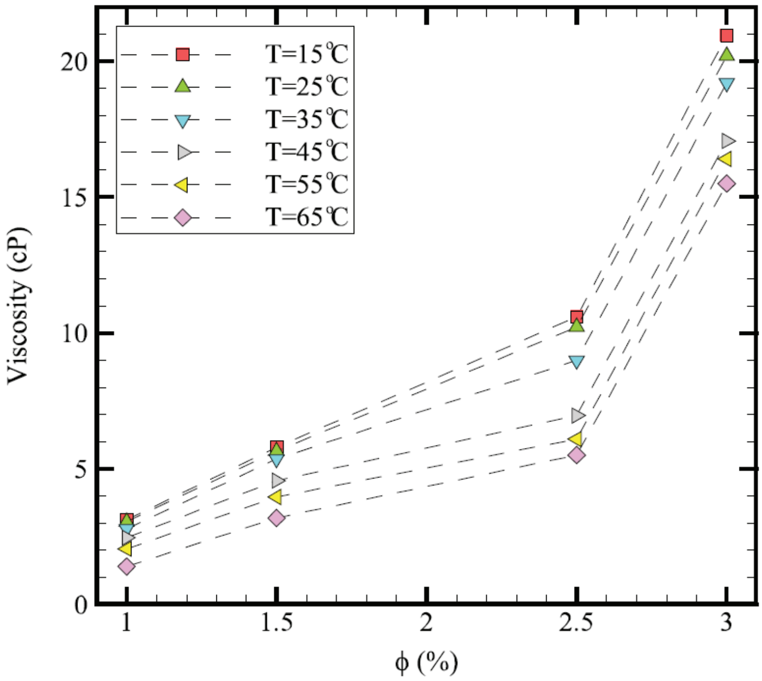

Fig. 6 (a) *Variation in viscosity with variation in volume concentration at different temperatures for Cu-SiO_2-MWCNT/water [99]*

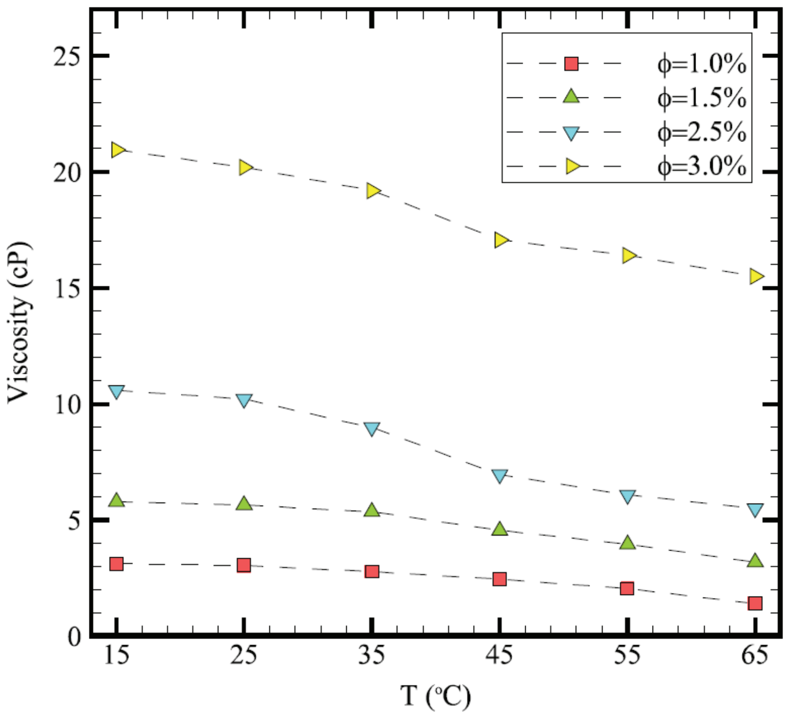

Fig. 6 (b) *Variation in viscosity with variation in temperature at different volume concentration for Cu-SiO_2-MWCNT/water [99]*

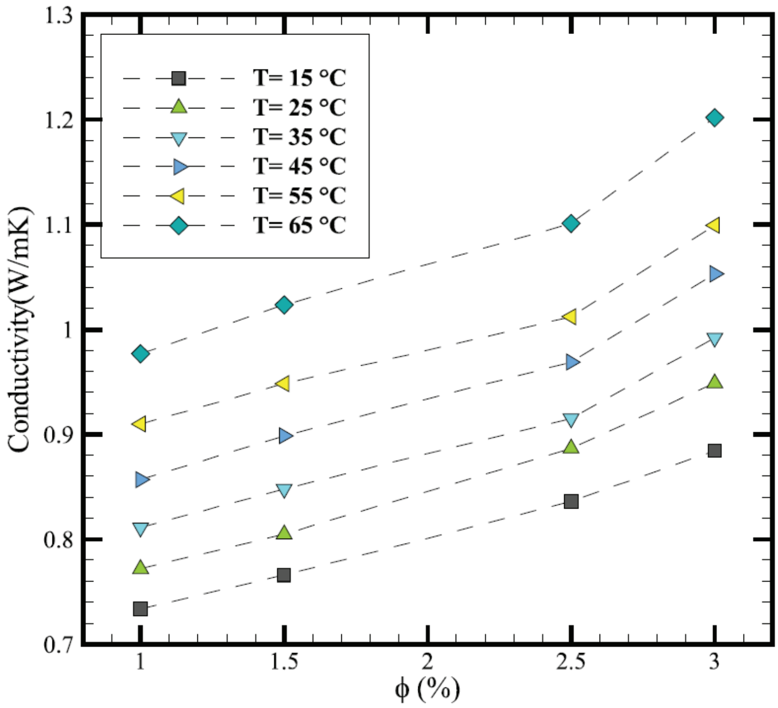

Fig. 6 (c) *Variation in thermal conductivity with variation in volume concentration at different temperatures for Cu-SiO_2-MWCNT/water [99]*

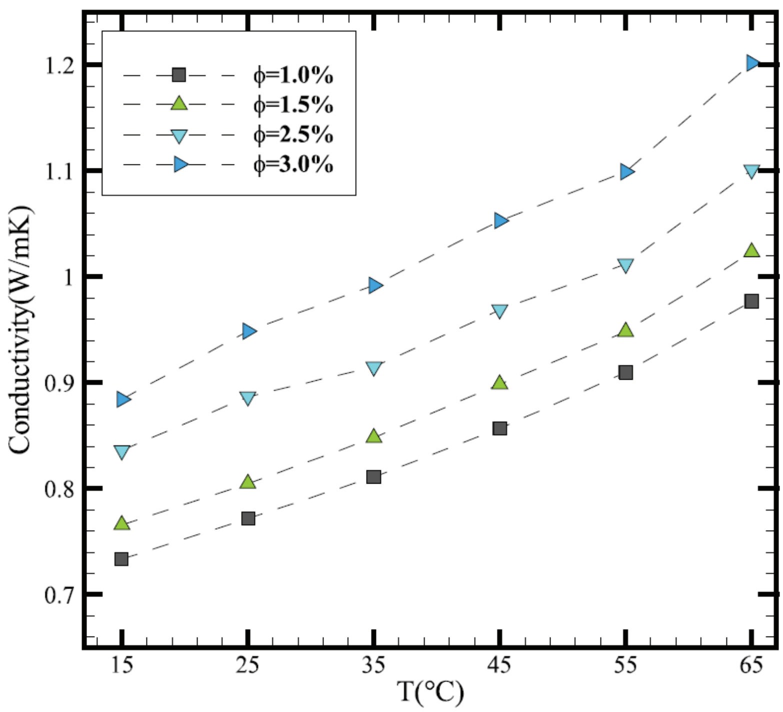

Fig. 6 (d) *Variation in thermal conductivity with variation in temperature at different volume concentration for Cu-SiO_2-MWCNT/water [99]*

Xuan, Z et al. [100] investigated the performance of ternary nanofluid combining Al_2O_3-TiO_2-Cu/Water. Measurements for shear stress, thermal conductivity and viscosity are reported for temperature variation (20 – 60^{0}C) and volume concentration variation (0.005 – 1%). Sensitivity analysis for viscosity and thermal conductivity, at 1% volume concentration, were done to find optimum mixing ratio. Also, economic analysis is conducted to decide optimum volume concentration for laminar and turbulent flow regimes. Average particle size for Al_2O_3, TiO_2 and Cu nanoparticles were 20nm, 40nm and 50nm respectively. Due to large size of Cu particles, the interparticle space is filled by remaining nanoparticles, thereby increasing thermal conductivity of fluid. Based on sensitivity analysis, 40:40:20 (Al_2O_3: TiO_2: Cu) was concluded optimum for high thermal conductivity and low viscosity. Viscosity results indicated decrease in viscosity with increase in temperature and decrease in volume proportion. Thermal conductivity increased with increase in temperature and volume proportion. When compared with base mono nanofluids, thermal conductivity of ternary nanofluids was highest while TiO_2/Water exhibited highest viscosity. Economic analysis suggested use to 0.7% volume proportion of nanofluid for laminar flow and 1% volume proportion of nanofluid for turbulent flow.

Investigation with ternary nanofluid combining Al_2O_3, Cu and CuO was carried out by [101]. The results are presented for full flow regime i.e laminar – transition – turbulent regime with volume proportion of 0.02%. Differences in Nusselt number, pressure drop and friction factor when compared with mono nanofluids are reported. Mixture ratios with 20:50:30, 20:60:20, 30:30:40, 30:50:20 and 60:20:20 [Al_2O_3:Cu:CuO] are used for fixed volume proportion of 0.02%. Results for viscosity indicated an increase due to particle addition. Mixture ratio had very less effect on viscosity. However, results for thermal conductivity exhibited variation with mixture ratio with highest shown by 60:20:20. In order to measure heat transfer parameters, variation in flow rate [10-90 L/h] and temperature [30-35^{0}C] were incorporated. Pressure drop increased with increase in Reynold Number and did not change much with varying mixture ratio. Also, it increased with addition of nanoparticles with ternary nanofluid showing less pressure drop than mono nanofluids. Friction factor showed decrease with increase in Reynold number and addition of nanoparticles. Start of transition from laminar to turbulent shifted to lower Reynold number due to nanoparticles. Nusselt number of ternary nanofluids increased by 45.6% compared to water while for Al_2O_3/water, the increase was 20.1%. This indicates that use of ternary nanofluid exhibited better heat transfer. Mixture ratio 30:30:40 exhibited 1.73 times higher Nusselt number compared to CuO (1.36 times). A tabulated form of parameters studied for various nanofluids is given in Table 5.

Table 5 *Summary of studied parameters for various mono and hybrid nanofluids, highlighting thermal, flow, and heat transfer characteristics*

Nanoparticle	Parmeter Studied
CuO-water & CuO-MEG	Thermal Conductivity
CuO/CMC, Fe2O3/CMC, Al2O3/CMC	Thermal Conductivity, Wettability
Al2O3/water, SiC/water, CuO/water, Fe3O4/water	Heat transfer co-efficient, Pressure drop
MWCNT/water, Graphene/water, CuO/water, Al2O3/water, TiO2/water, SiO2/water	Thermal conductivity, Viscosity, Density, Specific heat
CuO-Fe/Water-EG	Viscosity
CuO-MWCNT/oil	Density, specific heat, Nusselt number
CuO-TiO2/water	Viscosity
Cu-Water	Nusselt number, heat transfer co-efficient
Al2O3-Cu/Water	Friction factor, Nusselt number
SiO2-Cu/Water, SiO2-Cu/EG	Thermal conductivity, Viscosity
Cu-SiO2-MWCNT/water	Thermal conductivity, Viscosity
Al2O3-TiO2-Cu/water	Viscosity, Thermal conductivity, Sensitivity & Economic Analysis.
Al2O3-Cu-CuO/water	Viscosity, Thermal conductivity, Pressure drop, Friction factor, Nusselt number

3. Conclusion

This paper compares Copper (Cu) and Copper Oxide (CuO) nanoparticles in nanofluids across various base fluids. Cu generally provides higher thermal conductivity gains, while CuO offers better chemical stability and dispersion but with higher viscosity and density penalties. Hybrid and ternary mixtures (e.g., Cu–Al_2O_3, CuO–MWCNT, Cu–Al_2O_3–TiO_2) show improvements in conductivity, Nusselt number, and heat transfer coefficient compared to their mono parts. The enhancement in thermophysical properties exhibited by both nanoparticles is not consistent across all nanofluids, as the variations can be attributed to factors such as particle size and shape, concentration, dispersion stability, interfacial interactions with the base fluid, temperature dependence, and the possible formation of aggregates or clusters. However, key challenges persist viz. nanoparticle agglomeration and clustering reduce long-term stability; viscosity rise and pressure drop increase pumping power requirements; and optimal concentration and mixing ratios vary widely between systems. Future research should focus on surfactants and surface modification for stability, predictive modeling of thermophysical behavior, and techno-economic studies to establish industrial feasibility.

Acknowledgement

Authors of the paper sincerely acknowledge all our colleague members for their critical evaluation of the draft manuscript and fruitful feedback.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Selection of research papers for review:*** *Hani Chotai, Rupeshkumar V. Ramani, J H Markna*; ***study of research papers and draft preparation of manuscript:*** *Hani Chotai*; ***suggestions of required modifications and best suitable approach for publication:*** *J H Markna, Bharat Kataria. All authors reviewed the draft and approved the final version of the manuscript.*

References

[1] Adun, H., Kavaz, D., & Dagbasi, M. (2021). Review of ternary hybrid nanofluid: Synthesis, stability, thermophysical properties, heat transfer applications, and environmental effects. Journal of Cleaner Production, 328, 129525.https://doi.org/10.1016/j.jclepro.2021.129525

[2] Vajjha, R. S., & Das, D. K. (2012). A review and analysis on influence of temperature and concentration of nanofluids on thermophysical properties, heat transfer and pumping power. International Journal of Heat and Mass Transfer, 55, 4063-4078, https://doi.org/10.1016/j.ijheatmasstransfer.2012.03.048

[3] Saidur, R., Leong, K. Y., & Mohammed, H. A. (2011). A review on applications and challenges of nanofluids. Renewable and Sustainable Energy Reviews, 15, 1646-1668. https://doi.org/10.1016/j.rser.2010.11.035

[4] Sidik, N. A., Mohammed, H. A., Alawi, O. A., & Samion, S. (2014). A review on preparation methods and challenges of nanofluids. International Communications in Heat and Mass Transfer, 54, 115-125. https://doi.org/10.1016/j.icheatmasstransfer.2014.03.002

[5] Xuan, Y., & Roetzel, W. (2000). Conceptions for heat transfer correlation of nanofluids. International Journal of Heat and Mass Transfer, 43, 3701-3707. https://doi.org/10.1016/S0017-9310(99)00369-

[6] Hamzah, M. H., Sidik, N. A., Ken, T. L., Mamat, R., & Najafi, G. (2017). Factors affecting the performance of hybrid nanofluids: A comprehensive review. International Journal of Heat and Mass Transfer, 115, 630-646, https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.021

[7] Gupta, N. K., Tiwari, A. K., & Ghosh, S. K. (2018). Heat transfer mechanisms in heat pipes using nanofluids – A review. Experimental Thermal and Fluid Science, 90, 84-100. https://doi.org/10.1016/j.expthermflusci.2017.08.013

[8] Vallejo, J. P., Prado, J. I., & Lugo, L. (2022). Hybrid or mono nanofluids for convective heat transfer applications. A critical review of experimental research. Applied Thermal Engineering, 203, 117926. https://doi.org/10.1016/j.applthermaleng.2021.117926

[9] Mahbubul, I. M., Saidur, R., & Amalina, M. A. (2012). Latest developments on the viscosity of nanofluids. International Journal of Heat and Mass Transfer, 55, 874-885. https://doi.org/10.1016/j.ijheatmasstransfer.2011.10.021

[10] Keblinski, P., Phillpot, S. R., Choi, S. U., & Eastman, J. A. (2002). Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids). International Journal of Heat and Mass Transfer, 45, 855-863, https://doi.org/10.1016/S0017-9310(01)00175-2

[11] Sajid, M. U., & Ali, H. M. (2019). Recent advances in application of nanofluids in heat transfer devices: A critical review. Renewable and Sustainable Energy Reviews, 103, 556-592. https://doi.org/10.1016/j.rser.2018.12.057

[12] Wen, D., Lin, G., Vafaei, S., & Zhang, K. (2009). Review of nanofluids for heat transfer applications. Particuology, 7, 141-150,https://doi.org/10.1016/j.partic.2009.01.007

[13] Sajid, M. U., & Ali, H. M. (2018). Thermal conductivity of hybrid nanofluids: A critical review. International Journal of Heat and Mass Transfer, 126, 211-234, https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.021

[14] Daungthongsuk, W., & Wongwises, S. (2007). A critical review of convective heat transfer of nanofluids. Renewable and Sustainable Energy Reviews, 11, 797-817, https://doi.org/10.1016/j.rser.2005.06.005

[15] Ali, A. R., & Salam, B. (2020). A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application. SN Applied Sciences, 2, 1636, https://doi.org/10.1007/s42452-020-03427-1

[16] Ahmadi, M. H., Mirlohi, A., Nazari, M. A., & Ghasempour, R. (2018). A review of thermal conductivity of various nanofluids. Journal of Molecular Liquids, 265, 181-188, https://doi.org/10.1016/j.molliq.2018.05.124

[17] Pastoriza-Gallego, M. J., Casanova, C., Legido, J. L., & Piñeiro, M. M. (2011). CuO in water nanofluid: Influence of particle size and polydispersity on volumetric behaviour and viscosity. Fluid Phase Equilibria, 300, 188-196, https://doi.org/10.1016/j.fluid.2010.10.015

[18] Suresh, S., Chandrasekar, M., & Sekhar, S. C. (2011). Experimental studies on heat transfer and friction factor characteristics of CuO/water nanofluid under turbulent flow in a helically dimpled tube. Experimental Thermal and Fluid Science, 35, 542-549. https://doi.org/10.1016/j.expthermflusci.2010.12.008

[19] Fotukian, S. M., & Esfahany, M. N. (2010). Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube. International Communications in Heat and Mass Transfer, 37, 214-219, https://doi.org/10.1016/j.icheatmasstransfer.2009.10.003

[20] Priya, K. R., Suganthi, K. S., & Rajan, K. S. (2012). Transport properties of ultra-low concentration CuO–water nanofluids containing non-spherical nanoparticles. International Journal of Heat and Mass Transfer, 55, 4734-4743, https://doi.org/10.1016/j.ijheatmasstransfer.2012.04.035

[21] Dogonchi, A. S., Waqas, M., & Ganji, D. D. (2019). Shape effects of Copper-Oxide (CuO) nanoparticles to determine the heat transfer filled in a partially heated rhombus enclosure: CVFEM approach. International Communications in Heat and Mass Transfer, 107, 14-23, https://doi.org/10.1016/j.icheatmasstransfer.2019.05.014

[22] Sheikholeslami, M., Jafaryar, M., & Li, Z. (2018). Nanofluid turbulent convective flow in a circular duct with helical turbulators considering CuO nanoparticles. International Journal of Heat and Mass Transfer, 124, 980-989, https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.022

[23] Mousa, M. G. (2011). Effect of nanofluid concentration on the performance of circular heat pipe. Ain Shams Engineering Journal, 2, 63-69, https://doi.org/10.1016/j.asej.2011.03.003

[24] Bergman, T. L. (2009). Effect of reduced specific heats of nanofluids on single phase, laminar internal forced convection. International Journal of Heat and Mass Transfer, 52, 1240-1244, https://doi.org/10.1016/j.ijheatmasstransfer.2008.08.019

[25] Lee, J.-H., Hwang, K. S., Jang, S. P., Lee, B. H., Kim, J. H., Choi, S. U., & Choi, C. J. (2008). Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al2O3 nanoparticles. International Journal of Heat and Mass Transfer, 51, 2651-2656. https://doi.org/10.1016/j.ijheatmasstransfer.2007.10.026

[26] Wen, D., & Ding, Y. (2004). Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions. International Journal of Heat and Mass Transfer, 47, 5181-5188, https://doi.org/10.1016/j.ijheatmasstransfer.2004.07.012

[27] Peyghambarzadeh, S. M., Hashemabadi, S. H., Jamnani, M. S., & Hoseini, S. M. (2011). Improving the cooling performance of automobile radiator with Al2O3/water nanofluid. Applied Thermal Engineering, 31, 1833-1838, https://doi.org/10.1016/j.applthermaleng.2011.02.029

[28] Saeedinia, M., Akhavan-Behabadi, M. A., & Razi, P. (2012). Thermal and rheological characteristics of CuO–Base oil nanofluid flow inside a circular tube. International Communications in Heat and Mass Transfer, 39, 152-159, https://doi.org/10.1016/j.icheatmasstransfer.2011.08.001

[29] Razi, P., Akhavan-Behabadi, M. A., & Saeedinia, M. (2011). Pressure drop and thermal characteristics of CuO–base oil nanofluid laminar flow in flattened tubes under constant heat flux. International Communications in Heat and Mass Transfer, 38, 964-971. https://doi.org/10.1016/j.icheatmasstransfer.2011.04.010

[30] Sahooli, M., & Sabbaghi, S. (2013). Investigation of thermal properties of CuO nanoparticles on the ethylene glycol–water mixture. Materials Letters, 93, 254-257, https://doi.org/10.1016/j.matlet.2012.11.097

[31] AbdElhafez, S. E., El-Shazly, A. H., & El-Maghraby, A. (2016). Improving the rate of solar heat recovery from nanofluids by using micro heat exchanger. Desalination and Water Treatment, 57, 23066-23073. https://doi.org/10.1080/19443994.2016.1157987

[32] Bahiraei, M., & Hosseinalipour, S. M. (2013). Particle migration in nanofluids considering thermophoresis and its effect on convective heat transfer. Thermochimica Acta, 574, 47-54. https://doi.org/10.1016/j.tca.2013.09.010

[33] Zhang, H., Qing, S., Zhai, Y., Zhang, X., & Zhang, A. (2021). The changes induced by pH in TiO2/water nanofluids: Stability, thermophysical properties and thermal performance. Powder Technology, 377, 748-759, https://doi.org/10.1016/j.powtec.2020.09.004

[34] Lee, S. W., Park, S. D., Kang, S., Bang, I. C., & Kim, J. H. (2011). Investigation of viscosity and thermal conductivity of SiC nanofluids for heat transfer applications. International Journal of Heat and Mass Transfer, 54, 433-438, https://doi.org/10.1016/j.ijheatmasstransfer.2010.09.026

[35] Hussein, A. M. (2017). Thermal performance and thermal properties of hybrid nanofluid laminar flow in a double pipe heat exchanger. Experimental Thermal and Fluid Science, 88, 37-45, https://doi.org/10.1016/j.expthermflusci.2017.05.015

[36] Żyła, G., & Fal, J. (2016). Experimental studies on viscosity, thermal and electrical conductivity of aluminum nitride–ethylene glycol (AlN–EG) nanofluids. Thermochimica Acta, 637, 11-16, https://doi.org/10.1016/j.tca.2016.05.006

[37] Wozniak, M., Danelska, A., Kata, D., & Szafran, M. (2013). New anhydrous aluminum nitride dispersions as potential heat-transferring media. Powder Technology, 235, 717-722, https://doi.org/10.1016/j.powtec.2012.11.023

[38] Godson, L., Deepak, K., Enoch, C., Jefferson, B., & Raja, B. (2014). Heat transfer characteristics of silver/water nanofluids in a shell and tube heat exchanger. Archives of Civil and Mechanical Engineering, 14, 489-496, https://doi.org/10.1016/j.acme.2013.08.002

[39] Asadi, A., Asadi, M., Siahmargoi, M., Asadi, T., & Andarati, M. G. (2017). The effect of surfactant and sonication time on the stability and thermal conductivity of water-based nanofluid containing Mg(OH)2 nanoparticles: An experimental investigation. International Journal of Heat and Mass Transfer, 108, 191-198, https://doi.org/10.1016/j.ijheatmasstransfer.2016.12.022

[40] Demirkır, Ç., & Ertürk, H. (2021). Convective heat transfer and pressure drop characteristics of graphene-water nanofluids in transitional flow. International Communications in Heat and Mass Transfer, 121, 105092, https://doi.org/10.1016/j.icheatmasstransfer.2020.105092

[41] Ranjbarzadeh, R., Isfahani, A. H., Afrand, M., Karimipour, A., & Hojaji, M. (2017). An experimental study on heat transfer and pressure drop of water/graphene oxide nanofluid in a copper tube under air cross-flow: Applicable as a heat exchanger. Applied Thermal Engineering, 125, 69-79. https://doi.org/10.1016/j.applthermaleng.2017.06.110

[42] Sadeghinezhad, E., Mehrali, M., Tahan Latibari, S., Mehrali, M., Kazi, S. N., Oon, C. S., & Metselaar, H. S. (2014). Experimental Investigation of Convective Heat Transfer Using Graphene Nanoplatelet Based Nanofluids under Turbulent Flow Conditions. Industrial & Engineering Chemistry Research, 53, 12455-12465. https://doi.org/10.1021/ie501947u

[43] Jeong, J., Li, C., Kwon, Y., Lee, J., Kim, S. H., & Yun, R. (2013). Particle shape effect on the viscosity and thermal conductivity of ZnO nanofluids. International Journal of Refrigeration, 36, 2233-2241. https://doi.org/10.1016/j.ijrefrig.2013.07.024

[44] Azmi, W. H., Sharma, K. V., Sarma, P. K., Mamat, R., Anuar, S., & Rao, V. D. (2013). Experimental determination of turbulent forced convection heat transfer and friction factor with SiO2 nanofluid. Experimental Thermal and Fluid Science, 51, 103-111. https://doi.org/10.1016/j.expthermflusci.2013.07.006

[45] Esfe, M. H., Saedodin, S., Sina, N., Afrand, M., & Rostami, S. (2015). Designing an artificial neural network to predict thermal conductivity and dynamic viscosity of ferromagnetic nanofluid. International Communications in Heat and Mass Transfer, 68, 50-57. https://doi.org/10.1016/j.icheatmasstransfer.2015.06.013

[46] Ueki, Y., Oyabu, T., & Shibahara, M. (2020). Experimental study of influence of nanoparticles adhesion and sedimentation layer on solid-liquid interfacial thermal resistance. International Communications in Heat and Mass Transfer, 117, 104807, https://doi.org/10.1016/j.icheatmasstransfer.2020.104807

[47] Hu, P., Shan, W.-L., Yu, F., & Chen, Z.-S. (2008, December). Thermal Conductivity of AlN–Ethanol Nanofluids. International Journal of Thermophysics, 29, 1968–1973, https://doi.org/10.1007/s10765-008-0529-3.

[48] Chen, G.-h., & Liu, X.-y. (2007). Influence of AlN addition on thermal and mechanical properties of cordierite-based glass/ceramic composites. Journal of Materials Processing Technology, 190, 77-80. https://doi.org/10.1016/j.jmatprotec.2007.03.106

[49] Afrand, M., Toghraie, D., & Sina, N. (2016). Experimental study on thermal conductivity of water-based Fe3O4 nanofluid: Development of a new correlation and modeled by artificial neural network. International Communications in Heat and Mass Transfer, 75, 262-269. https://doi.org/10.1016/j.icheatmasstransfer.2016.04.023

[50] Asadi, A., & Pourfattah, F. (2019). Heat transfer performance of two oil-based nanofluids containing ZnO and MgO nanoparticles; a comparative experimental investigation. Powder Technology, 343, 296-308, https://doi.org/10.1016/j.powtec.2018.11.023

[51] Maïga, S. E., Palm, S. J., Nguyen, C. T., Roy, G., & Galanis, N. (2005). Heat transfer enhancement by using nanofluids in forced convection flows. International Journal of Heat and Fluid Flow, 26, 530-546. https://doi.org/10.1016/j.ijheatfluidflow.2005.02.004

[52] Maïga, S. E., Nguyen, C. T., Galanis, N., & Roy, G. (2004). Heat transfer behaviours of nanofluids in a uniformly heated tube. Superlattices and Microstructures, 35, 543-557. https://doi.org/10.1016/j.spmi.2003.09.012

[53] Farajollahi, B., Etemad, S. G., & Hojjat, M. (2010). Heat transfer of nanofluids in a shell and tube heat exchanger. International Journal of Heat and Mass Transfer, 53, 12-17. https://doi.org/10.1016/j.ijheatmasstransfer.2009.10.019

[54] Yu, W., Xie, H., Li, Y., & Chen, L. (2011). Experimental investigation on thermal conductivity and viscosity of aluminum nitride nanofluid. Particuology, 9, 187-191. https://doi.org/10.1016/j.partic.2010.05.014

[55] Zhang, X., Gu, H., & Fujii, M. (2007). Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles. Experimental Thermal and Fluid Science, 31, 593-599, https://doi.org/10.1016/j.expthermflusci.2006.06.009

[56] Shoghl, S. N., Jamali, J., & Moraveji, M. K. (2016). Electrical conductivity, viscosity, and density of different nanofluids: An experimental study. Experimental Thermal and Fluid Science, 74, 339-346. https://doi.org/10.1016/j.expthermflusci.2016.01.004

[57] Hwang, Y., Lee, J. K., Lee, C. H., Jung, Y. M., Cheong, S. I., Lee, C. G., . . . Jang, S. P. (2007). Stability and thermal conductivity characteristics of nanofluids. Thermochimica Acta, 455, 70-74. https://doi.org/10.1016/j.tca.2006.11.036

[58] Maheshwary, P. B., Handa, C. C., Nemade, K. R., & Chaudhary, S. R. (2020). Role of nanoparticle shape in enhancing the thermal conductivity of nanofluids. Materials Today: Proceedings, 28, 873-878. https://doi.org/10.1016/j.matpr.2019.12.315

[59] Alawi, O. A., Sidik, N. A., Xian, H. W., Kean, T. H., & Kazi, S. N. (2018). Thermal conductivity and viscosity models of metallic oxides nanofluids. International Journal of Heat and Mass Transfer, 116, 1314-1325, https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.133

[60] Kumar, N., & Sonawane, S. S. (2016). Experimental study of thermal conductivity and convective heat transfer enhancement using CuO and TiO2 nanoparticles. International Communications in Heat and Mass Transfer, 76, 98-107, https://doi.org/10.1016/j.icheatmasstransfer.2016.04.028

[61] Madhesh, D., Parameshwaran, R., & Kalaiselvam, S. (2014). Experimental investigation on convective heat transfer and rheological characteristics of Cu–TiO2 hybrid nanofluids. Experimental Thermal and Fluid Science, 52, 104-115, https://doi.org/10.1016/j.expthermflusci.2013.08.026

[62] Hayat, T., & Nadeem, S. (2017). Heat transfer enhancement with Ag–CuO/water hybrid nanofluid. Results in Physics, 7, 2317-2324, https://doi.org/10.1016/j.rinp.2017.06.034

[63] Mashhadian, A., Heyhat, M. M., & Mahian, O. (2021). Improving environmental performance of a direct absorption parabolic trough collector by using hybrid nanofluids. Energy Conversion and Management, 244, 114450, https://doi.org/10.1016/j.enconman.2021.114450

[64] Aparna, Z., Michael, M., Pabi, S. K., & Ghosh, S. (2019). Thermal conductivity of aqueous Al2O3/Ag hybrid nanofluid at different temperatures and volume concentrations: An experimental investigation and development of new correlation function. Powder Technology, 343, 714-722. https://doi.org/10.1016/j.powtec.2018.11.096

[65] Menbari, A., Alemrajabi, A. A., & Ghayeb, Y. (2016). Investigation on the stability, viscosity and extinction coefficient of CuO–Al2O3/Water binary mixture nanofluid. Experimental Thermal and Fluid Science, 74, 122-129, https://doi.org/10.1016/j.expthermflusci.2015.11.025

[66] Parsian, A., & Akbari, M. (2018). New Experimental Correlation for the Thermal Conductivity of Ethylene Glycol Containing Al2O3–Cu Hybrid Nanoparticles. Journal of Thermal Analysis and Calorimetry, 131, 1605-1613, https://doi.org/10.1007/s10973-017-6694-5

[67] Behera, M., Nayak, J., & Bal, S. (2024). Heat transfer analysis of CuO-ZnO/water hybrid nanofluid in a Shell and tube heat exchanger with various tube shapes. International Journal of Thermofluids, 24, 100972, https://doi.org/10.1016/j.ijft.2024.100972

[68] Rabby, M. I., Sharif, M. A., & Hossain, F. (2022). Numerical study of laminar convective heat transfer from a corrugated pipe into an Al2O3–AlN/H2O hybrid nanofluid. Case Studies in Thermal Engineering, 39, 102454, https://doi.org/10.1016/j.csite.2022.102454

[69] Hafeez, A., Aldosari, F. M., Helmi, M. M., Ghazwani, H. A., Hussien, M., & Hassan, A. M. (2023). Heat transfer performance in a Hybrid nanofluid (Cu-Al2O3 /kerosene oil) flow over a shrinking cylinder. Case Studies in Thermal Engineering, 52, 103539, https://doi.org/10.1016/j.csite.2023.103539

[70] Akilu, S., Baheta, A. T., M.Said, M. A., Minea, A. A., & Sharma, K. V. (2018). Properties of glycerol and ethylene glycol mixture based SiO2-CuO/C hybrid nanofluid for enhanced solar energy transport. Solar Energy Materials and Solar Cells, 179, 118-128, https://doi.org/10.1016/j.solmat.2017.10.027

[71] Scott, T. O., Ewim, D. R., & Eloka-Eboka, A. C. (2023). Experimental study on the influence of volume concentration on natural convection heat transfer with Al2O3-MWCNT/water hybrid nanofluids. Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2023.07.290

[72] Huang, D., Wu, Z., & Sunden, B. (2016). Effects of hybrid nanofluid mixture in plate heat exchangers. Experimental Thermal and Fluid Science, 72, 190-196. https://doi.org/10.1016/j.expthermflusci.2015.11.009

[73] Wole-Osho, I., Okonkwo, E. C., Kavaz, D., & Abbasoglu, S. (2020). An experimental investigation into the effect of particle mixture ratio on specific heat capacity and dynamic viscosity of Al2O3-ZnO hybrid nanofluids. Powder Technology, 363, 699-716, https://doi.org/10.1016/j.powtec.2020.01.015

[74] Okonkwo, E. C., Wole-Osho, I., Kavaz, D., & Abid, M. (2019). Comparison of experimental and theoretical methods of obtaining the thermal properties of alumina/iron mono and hybrid nanofluids. Journal of Molecular Liquids, 292, 111377, https://doi.org/10.1016/j.molliq.2019.111377

[75] Vafaei, M., Afrand, M., Sina, N., Kalbasi, R., Sourani, F., & Teimouri, H. (2017). Evaluation of thermal conductivity of MgO-MWCNTs/EG hybrid nanofluids based on experimental data by selecting optimal artificial neural networks. Physica E: Low-dimensional Systems and Nanostructures, 85, 90-96. https://doi.org/10.1016/j.physe.2016.08.020

[76] Afrand, M., Najafabadi, K. N., Sina, N., Safaei, M. R., Kherbeet, A. S., Wongwises, S., & Dahari, M. (2016). Prediction of dynamic viscosity of a hybrid nano-lubricant by an optimal artificial neural network. International Communications in Heat and Mass Transfer, 76, 209-214. https://doi.org/10.1016/j.icheatmasstransfer.2016.05.023

[77] Afrand, M., Toghraie, D., & Ruhani, B. (2016). Effects of temperature and nanoparticles concentration on rheological behavior of Fe3O4–Ag/EG hybrid nanofluid: An experimental study. Experimental Thermal and Fluid Science, 77, 38-44, https://doi.org/10.1016/j.expthermflusci.2016.04.007

[78] Esfe, M. H., Saedodin, S., Akbari, M., Karimipour, A., Afrand, M., Wongwises, S. Dahari, M. (2015). Experimental investigation and development of new correlations for thermal conductivity of CuO/EG–water nanofluid. International Communications in Heat and Mass Transfer, 65, 47-51. https://doi.org/10.1016/j.icheatmasstransfer.2015.04.006

[79] Namburu, P. K., Kulkarni, D. P., Misra, D., & Das, D. K. (2007). Viscosity of copper oxide nanoparticles dispersed in ethylene glycol and water mixture. Experimental Thermal and Fluid Science, 32, 397-402. https://doi.org/10.1016/j.expthermflusci.2007.05.001

[80] Esfe, M. H., Rostamian, H., Afrand, M., Karimipour, A., & Hassani, M. (2015). Modeling and estimation of thermal conductivity of MgO–water/EG (60:40) by artificial neural network and correlation. International Communications in Heat and Mass Transfer, 68, 98-103. https://doi.org/10.1016/j.icheatmasstransfer.2015.08.015

[81] Vajjha, R. S., Das, D. K., & Namburu, P. K. (2010). Numerical study of fluid dynamic and heat transfer performance of Al2O3 and CuO nanofluids in the flat tubes of a radiator. International Journal of Heat and Fluid Flow, 31, 613-621, https://doi.org/10.1016/j.ijheatfluidflow.2010.02.016

[82] Esfe, M. H., Afrand, M., Karimipour, A., Yan, W.-M., & Sina, N. (2015). An experimental study on thermal conductivity of MgO nanoparticles suspended in a binary mixture of water and ethylene glycol. International Communications in Heat and Mass Transfer, 67, 173-175. https://doi.org/10.1016/j.icheatmasstransfer.2015.07.009

[83] Esfe, M. H., Arani, A. A., Yan, W.-M., Ehteram, H., Aghaie, A., & Afrand, M. (2016). Natural convection in a trapezoidal enclosure filled with carbon nanotube–EG–water nanofluid. International Journal of Heat and Mass Transfer, 92, 76-82, https://doi.org/10.1016/j.ijheatmasstransfer.2015.08.036

[84] Wanatasanappan, V. V., Abdullah, M. Z., & Gunnasegaran, P. (2020). Thermophysical properties of Al2O3-CuO hybrid nanofluid at different nanoparticle mixture ratio: An experimental approach. Journal of Molecular Liquids, 313, 113458, https://doi.org/10.1016/j.molliq.2020.113458

[85] Eshgarf, H., & Afrand, M. (2016). An experimental study on rheological behavior of non-Newtonian hybrid nano-coolant for application in cooling and heating systems. Experimental Thermal and Fluid Science, 76, 221-227, https://doi.org/10.1016/j.expthermflusci.2016.03.015

[86] Esfe, M. H., Wongwises, S., Naderi, A., Asadi, A., Safaei, M. R., Rostamian, H. Karimipour, A. (2015). Thermal conductivity of Cu/TiO2–water/EG hybrid nanofluid: Experimental data and modeling using artificial neural network and correlation. International Communications in Heat and Mass Transfer, 66, 100-104, https://doi.org/10.1016/j.icheatmasstransfer.2015.05.014

[87] Mousavi, S. M., Esmaeilzadeh, F., & Wang, X. P. (2019). Effects of Temperature and Particles Volume Concentration on the Thermophysical Properties and the Rheological Behavior of CuO/MgO/TiO2 Aqueous Ternary Hybrid Nanofluid. Journal of Thermal Analysis and Calorimetry, 137, 879-901, https://doi.org/10.1007/s10973-019-08006-0

[88] Boroomandpour, A., Toghraie, D., & Hashemian, M. (2020). A comprehensive experimental investigation of thermal conductivity of a ternary hybrid nanofluid containing MWCNTs- titania-zinc oxide/water-ethylene glycol (80:20) as well as binary and mono nanofluids. Synthetic Metals, 268, 116501, https://doi.org/10.1016/j.synthmet.2020.116501

[89] Khedkar, R. S., Sonawane, S. S., & Wasewar, K. L. (2012). Influence of CuO nanoparticles in enhancing the thermal conductivity of water and monoethylene glycol based nanofluids. International Communications in Heat and Mass Transfer, 39, 665-669, https://doi.org/10.1016/j.icheatmasstransfer.2012.03.012

[90] Naik, B. A., & Vinod, A. V. (2018). Heat transfer enhancement using non-Newtonian nanofluids in a shell and helical coil heat exchanger. Experimental Thermal and Fluid Science, 90, 132-142. https://doi.org/10.1016/j.expthermflusci.2017.09.013

[91] Zheng, D., Wang, J., Chen, Z., Baleta, J., & Sundén, B. (2020). Performance analysis of a plate heat exchanger using various nanofluids. International Journal of Heat and Mass Transfer, 158, 119993. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119993

[92] Verma, S. K., Tiwari, A. K., & Chauhan, D. S. (2017). Experimental evaluation of flat plate solar collector using nanofluids. Energy Conversion and Management, 134, 103-115. https://doi.org/10.1016/j.enconman.2016.12.037

[93] Bahrami, M., Akbari, M., Karimipour, A., & Afrand, M. (2016). An experimental study on rheological behavior of hybrid nanofluids made of iron and copper oxide in a binary mixture of water and ethylene glycol: Non-Newtonian behavior. Experimental Thermal and Fluid Science, 79, 231-237. https://doi.org/10.1016/j.expthermflusci.2016.07.015

[94] Najafabadi, M. K., Hriczó, K., & Bognár, G. (2024). Enhancing the heat transfer in CuO-MWCNT oil hybrid nanofluid flow in a pipe. Results in Physics, 64, 107934. https://doi.org/10.1016/j.rinp.2024.107934

[95] Asadi, A., Alarifi, I. M., & Foong, L. K. (2020). An experimental study on characterization, stability and dynamic viscosity of CuO-TiO2/water hybrid nanofluid. Journal of Molecular Liquids, 307, 112987. https://doi.org/10.1016/j.molliq.2020.112987

[96] Xuan, Y., & Li, Q. (2003, January). Investigation on Convective Heat Transfer and Flow Features of Nanofluids. Journal of Heat Transfer, 125, 151–155, https://doi.org/10.1115/1.1532008

[97] Suresh, S., Venkitaraj, K. P., Selvakumar, P., & Chandrasekar, M. (2012). Effect of Al2O3–Cu/water hybrid nanofluid in heat transfer. Experimental Thermal and Fluid Science, 38, 54-60. https://doi.org/10.1016/j.expthermflusci.2011.11.007

[98] Amiri, M., Movahedirad, S., & Manteghi, F. (2016). Thermal conductivity of water and ethylene glycol nanofluids containing new modified surface SiO2-Cu nanoparticles: Experimental and modeling. Applied Thermal Engineering, 108, 48-53, https://doi.org/10.1016/j.applthermaleng.2016.07.091

[99] Dezfulizadeh, A., Aghaei, A., Joshaghani, A. H., & Najafizadeh, M. M. (2021). An experimental study on dynamic viscosity and thermal conductivity of water-Cu-SiO2-MWCNT ternary hybrid nanofluid and the development of practical correlations. Powder Technology, 389, 215-234. https://doi.org/10.1016/j.powtec.2021.05.029

[100] Xuan, Z., Zhai, Y., Ma, M., Li, Y., & Wang, H. (2021). Thermo-economic performance and sensitivity analysis of ternary hybrid nanofluids. Journal of Molecular Liquids, 323, 114889. https://doi.org/10.1016/j.molliq.2020.114889

[101] Xuan, Z., Wang, S., Zhai, Y., & Wang, H. (2023). Thermodynamic performance of Al2O3-Cu-CuO/water (W) ternary nanofluids in the full-flow regime of convective heat transfer. Experimental Thermal and Fluid Science, 147, 110959, https://doi.org/10.1016/j.expthermflusci.2023.110959