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Ethylene- and Propylene-Glycol Based Nanofluids: A Literature Review on Their Thermophysical Properties and Thermal Performances

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Abstract: Nanofluids are considered a promising way to improve the heat transfer capability of base fluids. Water is the most commonly-used heat transfer fluid. However, in refrigeration systems, it may be necessary to mix water with either ethylene- or propylene-glycol to lower its freezing point and prevent from ice formation. In the same way, for car radiators or industrial heat exchangers, the boiling point of water can be pushed up by mixing it with glycol-based fluids. The increasing awareness of energy saving and industrial energy efficiency improvement results in the growing interest in ethylene- or propylene-glycol-based nanofluids for applications in various thermal systems. The present paper proposes an extensive review of the most recent and relevant experimental and numerical works on the thermophysical properties and performances of ethylene- or propylene-glycol-based nanofluids. Research perspectives are also provided with the long-term objective that these nanofluids be more widely considered in real industrial applications.

Keywords: nanofluid; ethylene-glycol; propylene-glycol; thermophysical properties; heat transfer enhancement

1. Introduction

Heat transfer fluids (HTF) play a crucial role to remove the excess of heat from a system with various applications ranging from building heating, ventilation and air-conditioning (HVAC) systems, electronics, automotive, or biomedicine [1]. In cold regions, such as Canada, Alaska, the Arctic, or subarctic regions, a huge amount of energy is expended for heating industrial and residential buildings since during winter, the ambient temperature may reach regularly $-40\text{ }^{\circ}\text{C}$. Therefore, it is a common practice to use ethylene-glycol or propylene-glycol mixed with water in different proportions as an HTF to lower the freezing point of liquid water. For high temperature applications like in car radiators or industrial heat exchangers, mixtures of ethylene-glycol and water (EG-W), or propylene-glycol and water (PG-W), are used to elevate the aqueous boiling points. Tables 1 and 2 summarize the given freezing and boiling points of both EG-W and PG-W mixtures.

Table 1. Freezing points of ethylene-glycol- and propylene-glycol-based water solutions at various temperatures [2].

Ethylene Glycol Solution (% by Volume)	0	10	20	30	40	50	60
Temperature ($^{\circ}\text{C}$)	0	−3.4	−7.9	−13.7	−23.5	−36.8	−52.8
Propylene-glycol solution (% by volume)	0	10	20	30	40	50	60
Temperature ($^{\circ}\text{C}$)	0	−3	−8	−14	−22	−34	−48

Table 2. Boiling points of ethylene-glycol- and propylene-glycol-based water solutions at various temperatures [2].

Ethylene Glycol Solution (% by Volume)	0	10	20	30	40	50	60
Temperature (°C)	100	101.1	102.2	104.4	104.4	107.2	111.1
Propylene-glycol solution (% by volume)	0	10	20	30	40	50	60
Temperature (°C)	100	100	100.5	102.2	103.8	105.5	107.2

As shown in Tables 1 and 2, EG-W solutions exhibit lower freezing points and higher boiling points compared to PG-W solutions. However, it is strongly recommended to use PG-W mixtures especially in human interaction applications such as heating residential buildings because propylene-glycol is non-toxic and easily decomposes in the environment, contrary to ethylene-glycol, which is toxic and takes a longer time to degrade [3–7].

Ethylene- and propylene-glycol mixtures are also characterized by a thermal conductivity about three-times lower than that of water at 20 °C (Table 3). This constitutes the primary limitation in the development of thermally-efficient systems. The other limitations are due to their lower heat capacities and higher dynamic viscosities, which are severe limiting factors regarding their capacity of thermal energy storage and the pumping power required to transport them, respectively. During the last few decades, engineers and researchers made substantial efforts to improve the heat transfer efficiency of these HTFs by means of passive or active methods: chaotic advection, enhanced turbulence (turbulators), HTFs with higher thermal properties, or any combination [8]. Among these methods, nanofluids have proven to be an effective way to achieve that objective without increasing the size, cost, and complexity of thermal equipments too much. Ethylene- and propylene-glycol-based nanofluids have been then widely considered for their applications, mainly to remove heat in car radiators [9–21], diesel electric generators [22], industrial heat exchangers [23], and electronic devices [24,25].

Table 3. Thermophysical properties of ethylene- and propylene-glycol compared to those of water at 20 °C.

Properties	ρ (kg·m ⁻³)	C_p (J·kg ⁻¹ ·K ⁻¹)	k (W·m ⁻¹ ·K ⁻¹)	μ (Pa·s)
Ethylene-glycol	1126	2354	0.256	21×10^{-3}
Propylene-glycol	1035.3	2479	0.1962	57.571×10^{-3}
Water	999	4185	0.6	1.002×10^{-3}

General reviews on nanofluids have been published so far in the literature focusing on the preparation and stability of nanofluids [26,27], on the synthesis, thermo-physical properties, and heat transfer mechanisms of nanofluids [28], or on their applications in heat exchangers [29]. Wang and Mujumdar [30] and then Kleinstreuer and Xu [25] proposed also detailed reviews on the theoretical and/or numerical methods dedicated to the simulation of nanofluids and nano-lubricants, respectively. Patel et al. [31] summarized the thermophysical properties and performance of nano-refrigerants in a refrigeration system. All these aspects are also discussed in detail in the monograph of Bianco et al. [32]. To the best of our knowledge, there is then no updated review up to 2018 specific to ethylene- and propylene-glycol-based nanofluids. The purpose of the present work is then to fill this gap by summarizing the important published findings on their thermophysical properties and heat transfer enhancement.

The present paper is organized as follows: Section 2 focuses on the thermophysical properties of ethylene- and propylene-glycol-based nanofluids, while Section 3 reports on the heat transfer enhancement due to these nanofluids in some current applications. Finally, Section 4 proposes some research perspectives for nanofluids to penetrate the industrial sector more broadly.

2. Thermophysical Properties

In order to have more insights into the influence of using nanofluids as coolants, accurate measurements of their thermophysical properties are becoming increasingly important. The most needed thermophysical properties of nanofluids are their thermal conductivity, viscosity, density, and specific heat. Numerous papers have been published on the thermal conductivity and dynamic viscosity of different EG- and PG-based nanofluids. However, the literature is very limited on their specific heat and density. The present review will only address the experimental studies on the nanofluid thermophysical properties since until now, there are no universal theoretical or empirical models available in the literature for predicting exactly the nanofluid properties despite the substantial attempts made by researchers. This can be due to different mechanisms, playing a role in the performance of nanofluids, not taken into account in the models (see the reviews by [30,33–35]).

2.1. Density

In order to evaluate the fluid dynamics and heat transfer performances of nanofluids, the density must be known. However, limited data are available for nanofluids, specifically related to EG-W and PG-W solutions. Most authors prefer to use the classical mixture law:

$$\rho_{nf} = \rho_{np}\varphi + (1 - \varphi)\rho_{bf} \quad (1)$$

Vajjha et al. [36] conducted density measurements for Al_2O_3 , ZnO and $Sb_2O_5 : SnO_2$ nanoparticles dispersed separately into a 60:40 EG-water mixture with different volumetric concentrations up to $\varphi = 10\%$ and temperatures ranging between 0 °C and 50 °C. The results revealed that for all the studied nanofluids, the density augments by increasing the nanoparticle concentration φ . For example, at $T = 10\text{ °C}$, the nanofluid density increases by nearly 22% when the loading of Al_2O_3 nanoparticles in the base fluid increases from $\varphi = 1$ to 10 vol.% (Figure 1a). Density slightly decreases linearly with temperature for these sets of parameters (Figure 1b). They compared their results to the Pak and Cho [37] Equation (1) and stated that their data agreed particularly with it within $\pm 1\%$, except for ZnO nanofluids, which exhibited deviations from 2–8%, for increasing values of φ . To compensate this discrepancy, they proposed a correction factor, which is a function of φ .

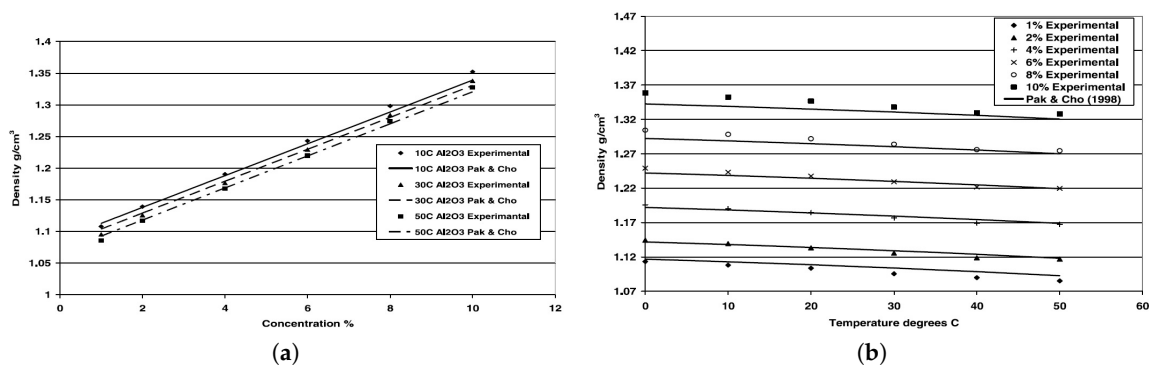


Figure 1. Comparisons between the density measurements of Vajjha et al. [36] and the Pak and Cho [37] equation for Al_2O_3 nanofluids: (a) influence of concentration at three temperatures and (b) influence of temperature for six nanoparticle concentrations. The base fluid is a mixture of 60:40 ethylene-glycol/water by mass. After [36], with permission from Taylor and Francis.

Density measurements were performed also by Satti et al. [38] on several nanofluids containing nanoparticles of aluminium oxide, zinc oxide, copper oxide, titanium oxide, silicon dioxide, and carbon nanotubes individually dispersed in a base fluid of 60:40 propylene-glycol and water over a temperature range between 0 and 90 °C. The results indicated that the nanofluid densities were independent of the nanoparticle size, but they increased with an increase in the nanoparticle

concentration and decreased as the temperature increased. They compared their experimental data with the values predicted by the theoretical Equation (1) of Pak and Cho [37] for nanoparticle concentrations up to 6 vol.% and nanoparticle sizes ranging from 10–76 nm. They found that the experimental results were in a good agreement with the available theory with a maximum deviation of −3.8% for CuO nanofluid and an average deviation of −0.1% for all the nanofluids tested.

As shown in Table 3, the densities of EG and PG are only 12.7% and 3.6% higher than that of liquid water at 20 °C. From that point of view, none of these base fluids may be recommended preferably in regards to the sedimentation phenomenon.

2.2. Specific Heat

To the best of the authors' knowledge, there are no available experimental studies on the specific heat of EG-W- and PG-W-based nanofluids in the literature. However, two major correlations exist to determine the nanofluid specific heat suggested by Pak and Cho (Equation (2)) [37] and Xuan and Roetzel (Equation (3)) [39]:

$$Cp_{nf} = Cp_{np}\varphi + (1 - \varphi)Cp_{bf} \quad (2)$$

$$Cp_{nf} = \frac{\varphi(\rho Cp)_{np} + (1 - \varphi)(\rho Cp)_{bf}}{\rho_{nf}} \quad (3)$$

The first correlation (Equation (2)) is based on the mixture rule, which assumes that the equivalent specific heat is obtained by a simple volumetric combination of the specific heat of each component. Only a few researchers have opted for this correlation in their studies [37,40,41]. The second correlation (Equation (3)) is based on the assumption that there is a thermal equilibrium that exists between the nanoparticles and the base fluid. Thus, the nanofluid specific heat can be defined from a thermal balance including the mixture rule. This equation has been widely used by [42–44] among other references.

Contrary to the density and the specific heat, there are far more experimental studies existing in the literature for the evaluation of the thermal conductivity and the dynamic viscosity of nanofluids, as will be shown in the following sections.

2.3. Thermal Conductivity

The thermal conductivities k of pure ethylene- and propylene-glycol are 2.3 and 3.1 lower than that of liquid water at 20 °C, respectively (Table 3). The addition of nanoparticles in these base fluids is necessary to compensate this limitation and reaches higher heat transfer rates by conduction. Plenty of correlations have been developed to predict the thermal conductivity of nanofluids k_{nf} as a function of the nanoparticle k_{np} and base fluid k_{bf} thermal conductivities and the nanoparticle volume fraction φ . They have been already extensively reviewed in the literature [25,32,45,46]. Only the main correlations are briefly recalled here. The Hamilton–Crosser model is a generalization of the Maxwell model:

$$k_{nf} = k_{bf} \frac{k_{np} + (n - 1)k_{bf} - (n - 1)(k_{np} - k_{bf})\varphi}{k_{np} + (n - 1)k_{bf} + (k_{np} - k_{bf})\varphi} \quad (4)$$

where n is an empirical shape factor $n = 3/S$ and S the nanoparticle sphericity. For spherical particles $S = 1$, one recovers the Maxwell model developed for low microparticle concentrations.

More interestingly, we will focus in the following subsections on the results and correlations given the thermal conductivity of EG-W- and PG-W-based nanofluids.

2.3.1. Ethylene-Glycol-Based Nanofluids

Among the first studies on the thermal enhancement due to EG-based nanofluids are those done at the Argonne National Laboratory. Lee et al. [47] investigated experimentally the effect of nanoparticles and base fluid type on the thermal conductivity of the solution. Two oxide nanoparticles, Al_2O_3 and

CuO, were dispersed separately in water or in EG, resulting in four different nanofluids. The results showed that the mixture thermal conductivity increased linearly with the nanoparticle concentration. The authors stated that the *CuO*-ethylene-glycol nanofluid exhibited a better thermal conductivity enhancement compared to *CuO*-water, Al_2O_3 -EG, and Al_2O_3 -water nanofluids. For instance, for the same nanoparticle volume fraction $\varphi = 4\%$, the EG thermal conductivity increased by about 20% and 14% by adding *CuO* and Al_2O_3 nanoparticles, respectively. Wang and Choi [48] considered nanofluids composed of Al_2O_3 and *CuO* nanoparticles dispersed in water, a vacuum pump fluid, engine oil, or ethylene-glycol. They noted that adding a small nanoparticle volume fraction to one of these base fluids increased noticeably the mixture thermal conductivity. The latter increased as φ increased. For instance, the effective EG thermal conductivity was enhanced by 26% and 40% for $\varphi = 5\%$ and 8% of Al_2O_3 nanoparticles, respectively. The enhancement rates for EG and engine oil were the highest, whereas that of the pump fluid was the lowest. Dispersing $\varphi = 5\%$ of Al_2O_3 and *CuO* powders into EG increased the effective thermal conductivity by about 20% and 26% compared to pure EG, respectively. They stated that the nanofluid-based EG was very stable up to a volume fraction of 16%. However, the water-, engine oil- and pump fluid-based nanofluids started flocculating from $\varphi = 10\%$. Reddy and Rao [49] performed experimental measurements of the effective thermal conductivity of nanofluids containing TiO_2 nanoparticles ($d_{np} = 21$ nm) dispersed separately in water, 40:60 and 50:50 EG-water mixtures for $30 < T < 70$ °C and $0.2 < \varphi < 1\%$. They noted that as the titanium oxide concentration increased, the nanofluid thermal conductivity was enhanced. The 50:50 EG-water-based nanofluid showed a higher k enhancement compared to pure water and 40:60 EG-water-based fluids. For example, at $T = 30$ °C, the thermal conductivity enhancements were measured to be 10.64% and 14.2% by adding 0.2 vol.% and 1 vol.% of TiO_2 nanoparticles to a 50:50 EG-water mixture, respectively. However, under the same conditions, the enhancement in the thermal conductivity was much lower, namely between 0.649% and 5.01% and between 1.94% and 4.38% for water and 40:60 EG-water-based nanofluids, respectively. Their results can be correlated by:

$$k_{nf} = k_{bf}[a + b\varphi] \quad (5)$$

with a and b adjusting parameters, which depend on φ .

Experimental thermal conductivity measurements of Al_2O_3 and *CuO* nanoparticles dispersed in a 50:50 ethylene-glycol-water mixture were conducted by Sundar et al. [50]. They reported that the thermal conductivities of both nanofluids increased by increasing both the nanoparticle volume fraction and temperature. The *CuO*-based nanofluid exhibited a better thermal conductivity enhancement compared to the Al_2O_3 -based nanofluid under the same operating conditions. They noted that the thermal conductivity enhancement of the Al_2O_3 nanofluid varied from 9.8–17.89%, and for *CuO* nanofluid, it varied from 15.6–24.56% within the temperature range [15 °C; 50 °C] at $\varphi = 0.8$ vol.% compared to the base fluid. Usri et al. [51] investigated the thermal conductivity of Al_2O_3 /EG-W nanofluids in different water:EG proportions: 40:60, 50:50, and 60:40. The measurements by the KD2pro for the thermal conductivity were performed for $d_{np} = 13$ nm, $T = [30\text{--}70$ °C] and $0.5 \leq \varphi \leq 2\%$. All their results can be correlated within a 5% confidence interval by:

$$k_{nf} = 0.634(1 + \varphi)^{0.1045} \left(\frac{T}{70} \right)^{0.1094} (1 + BR)^{-1.159} \quad (6)$$

where BR is the base ratio, equal to $BR = 0.4$ for a 40:60 W:EG mixture.

Figure 2 summarizes the experimental data obtained by Chen et al. [52] for TiO_2 nanoparticles dispersed in pure ethylene-glycol at two temperatures, 20 and 40 °C. The addition of these nanoparticles enhanced the thermal conductivity of the mixture, and this enhancement was slightly higher if T increased from 20–40 °C. However, the differences remained within the error bars. More interestingly, their results showed firstly that a better thermal enhancement could be achieved by choosing nanoparticles (here, 25 nm) if one compared their data to the Maxwell theory obtained

for micro-sized particles. Secondly, these authors proposed an interesting correlation for the thermal conductivity, which is a modified version of the Maxwell correlation accounting for the thermal conductivity of aggregates. This rather complex correlation works particularly well in their case for $\varphi \geq 0.4$ vol.%.

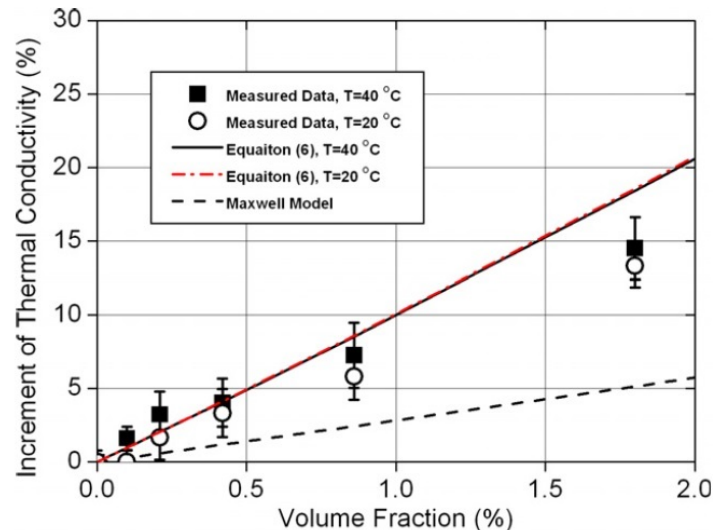


Figure 2. Thermal conductivity enhancement for TiO_2 nanoparticles dispersed in pure ethylene-glycol at two temperatures 20 and 40 °C. After [52], with permission from Elsevier.

The thermal performance enhancement of nanofluid containing diamond nanoparticles dispersed into a mixture of EG and water (45:55) was carried out by Xie et al. [53]. They observed that the fluid thermal conductivity increased linearly with the nanoparticle volume fraction. They noted that loading 2 vol.% diamond nanoparticles enhanced the EG-water thermal conductivity by more than 18%. The authors claimed that the optimal nanofluid thermal performance was found to be at $\varphi = 0.5$ vol.%.

Significantly larger improvements in terms of thermal conductivity were reported by Eastman et al. [54] by adding copper nanoparticles to EG. Only 0.3 vol.% of Cu nanoparticles increased the EG thermal conductivity by 40%. Hong and Yang [55] reported an 18% enhancement by dispersing 0.55 vol.% Fe nanocrystalline powder. Loading 0.1 vol.% of Cu nanoparticles in EG led to enhancement of its thermal conductivity by almost 9%, after [56]. Xie et al. [57] studied the thermal conductivity of EG-based nanofluids containing oxides including MgO , TiO_2 , ZnO , Al_2O_3 , and SiO_2 nanoparticles. The results demonstrated that, at the same volume fraction, the MgO -EG nanofluid exhibited the highest improvement in terms of thermal conductivity compared to the other nanofluids. They noted that the maximum enhancement was up to 40.6% at $\varphi = 4$ vol.% of MgO nanoparticles. Vajjha and Das [45] provided a comprehensive set of measured thermal conductivity data for three nanofluids: Al_2O_3 , CuO , and ZnO dispersed in a 60:40 ethylene-glycol-water mixture. The results revealed that the thermal conductivity was a linear function of φ for all the studied nanofluids. For instance, at a given temperature, the thermal conductivity increased over the base fluid one by 42%, 46%, and 60% by suspending 6 vol.% of ZnO , Al_2O_3 , and CuO nanoparticles, respectively. The authors also examined the influence of the nanoparticle size on EG-W thermal conductivity. Two sets of measurements were conducted for the ZnO -based nanofluid with particle sizes 29 and 77 nm. They found that the thermal conductivity was higher for the smaller nanoparticle diameter since the former provided more surface area for the transfer of thermal energy. As an example, at $\varphi = 4$ vol.%, the thermal conductivity was 3.3% higher for 29-nm particles compared to that of 77-nm particles. Their experimental measurements can be correlated by a modified version of the Maxwell correlation:

$$k_{nf} = k_{bf} \frac{k_{np} + 2k_{bf} - 2(k_{bf} - k_{np})\varphi}{k_{np} + 2k_{bf} + (k_{bf} - k_{np})\varphi} + 5 \times 10^4 \beta \varphi \rho_{bf} C p_{bf} f(T, \varphi) \sqrt{\frac{\kappa T}{\rho_{np} d_{np}}} \quad (7)$$

$$f(T, \varphi) = (2.8217 \times 10^{-2} \varphi + 3.917 \times 10^{-3}) \left(\frac{T}{T_0} \right) + (-3.0669 \times 10^{-2} \varphi - 3.91123 \times 10^{-3}) \quad (8)$$

where β is a function of φ , which depends on the nanoparticle type, κ the Boltzmann constant and $T_0 = 273$ K. This correlation is valid for three nanoparticle diameters (29, 53, and 77 nm) over a wide range of temperature $298 < T < 363$ K. In terms of volume fraction, it varies between 1% and φ_{max} , where $\varphi_{max} = 10, 7$, and 6% for Al_2O_3 , ZnO , and CuO nanoparticles, respectively.

Xie et al. [58] investigated the thermal conductivity behaviour of SiC nanoparticle suspensions. Spherical SiC particles with an average diameter of $d_{np} = 26$ nm and cylindrical SiC particles with an average diameter of 600 nm were dispersed in water and ethylene-glycol separately. The measured data clearly indicated that the ratio of thermal conductivity (ratio of thermal conductivity of the mixture to that of the base liquid) depended on the nanoparticle concentration, size, and shape. They noticed that for the same nanoparticle morphology, the thermal conductivity ratios were independent of the base liquid, but the absolute value of the nanofluid thermal conductivity was proportional to that of the base liquid. A comparative study on the thermal performance of 4 vol.% SiC nanoparticles in water and 50:50 ethylene-glycol-water mixture was performed by Timofeeva et al. [59]. They noted that the thermal conductivity of SiC /EG-W nanofluids increased by increasing the particle size, which was similar to the behaviours reported for SiC -water nanofluids, but with different increment values. For example, at the same nanoparticle concentration, the thermal conductivity enhancement of SiC /EG-W increased from 11.5–17% by increasing the particle size from 16–90 nm, respectively, as displayed in Figure 3. The results indicated that the addition of SiC nanoparticles in EG-W resulted in a 4–5% higher enhancement than in pure water at the same operating conditions. The authors referred their findings to the lower values of the interfacial thermal resistance (better wettability) in EG-W than in water-based nanofluids. They mentioned also that such an effect could not be explained simply by the lower thermal conductivity of the EG-W base fluid since the difference in terms of the enhancement values expected from the effective medium theory was less than 0.1%.

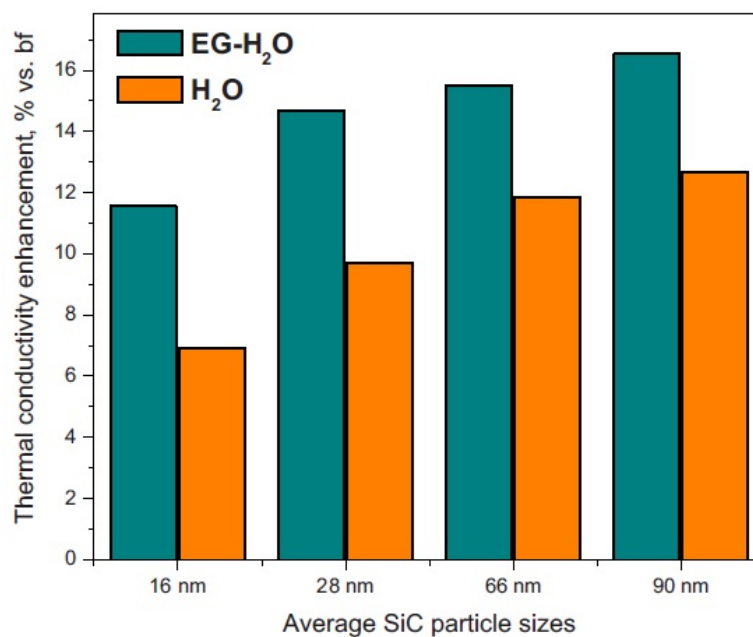


Figure 3. Comparison of the thermal conductivity enhancement in 4 vol.% SiC nanofluids with ethylene-glycol (EG)/ H_2O and H_2O as base fluids at various particle sizes. After [59], with permission from AIP.

For a suspension consisting of ethylene-glycol and carbon nanotubes (CNTs) at $\varphi = 1$ vol.%, 12.6%, and 12.4% thermal conductivity enhancements were reported by Xie et al. [60] and Liu et al. [61], respectively. They noted that the mixture thermal conductivity increased monotonously with the CNT volume fraction. For example, the EG thermal conductivity was enhanced by 1.6% and 12.4% compared to that of pure EG by adding 0.2 vol.% and 1 vol.% CNTs, respectively [61]. Harish et al. [62] conducted measurements of the effective thermal conductivity of single-walled carbon nanotubes (SWCNTs) dispersed in ethylene-glycol. They reported that the thermal conductivity of the medium enhanced with respect to the nanotube loading. The maximum enhancement in thermal conductivity was found to be 14.8% at $\varphi = 0.2$ vol.% compared to that of pure ethylene-glycol.

For the interested reader, the review of Puliti et al. [63] compiled some of the previous studies up to 2012 on the thermal conductivity of ethylene-glycol-based nanofluids and provided a useful comparison on the thermal conductivity enhancement obtained from different references. The main correlations used to predict their thermal conductivity were also listed. One could cite also the work of Prasher et al. [64], who displayed the validation of the multi-sphere Brownian model by experimental data on the thermal conductivity of ethylene-glycol-based nanofluids.

2.3.2. Propylene-Glycol-Based Nanofluids

Table 4 summarizes the main results regarding the thermal conductivity of EG- or PG-based nanofluids. It clearly shows, among other things, that the thermal conductivity of PG-based nanofluids has not been considered so far in the literature. Palabiyik et al. [5] studied experimentally the dispersion stability and the thermal conductivity of PG-based nanofluids containing Al_2O_3 and TiO_2 nanoparticles for different concentrations (1, 6, and 9 wt.%) within the temperature range [20 °C ; 80 °C]. They interestingly found that the average size of the nanoparticle suspensions was observed to decrease with increasing temperature in contrast to the common belief [65]. For example, at a 1 wt.% alumina concentration, the nanoparticle size decreased from 90–70 nm over the temperature range of interest. They found also that the thermal conductivity enhancement for both nanofluids was a nonlinear function of concentration and was temperature independent.

Satti et al. [6] carried out an experimental study to determine the thermal conductivity of five different nanofluids containing Al_2O_3 , CuO , ZnO , SiO_2 , and TiO_2 nanoparticles dispersed in a base fluid composed of a 60:40 propylene-glycol and water mixture within the temperature range [−30; 90 °C]. Contrary to [5], they found that the thermal conductivity of nanofluids was strongly dependent on temperature, nanoparticle concentration, nanoparticle size, type of nanoparticles, and base fluid. The results showed an increase in the thermal conductivity of nanofluids by increasing either concentration or temperature. As the nanoparticle diameter increased, the thermal conductivity increased as well.

Leena and Srinivasan [66] considered the dispersion of TiO_2 nanoparticles in a 70:30 (% by weight) water-propylene-glycol mixture for φ within the range [0.1–0.8%]. The results demonstrated that the thermal conductivity of the nanofluids increased with the volume concentration and temperature and could be correlated. Interestingly, these authors discussed also the potential heat transfer benefits of using these nanofluids under laminar and turbulent flow conditions.

Table 4. Summary of the experimental data for the determination of the thermal conductivity of EG- and propylene-glycol (PG)-based nanofluids.

Authors	Nanofluid	Nanoparticle Concentration φ	Particle Size (nm)	Increase in k (%)	Temperature Range (°C)
Eastman et al. [54]	Cu/EG	0.3 vol.%	10	40	17–37
Lee et al. [47]	CuO/EG	1–4 vol.%	24	4–20	17–37
	Al_2O_3 /EG	1–4 vol.%	38	2–14	17–37
Wang and Choi [48]	Al_2O_3 /EG	6–10 vol.%	28	26–40	20
	CuO/EG	5–15 vol.%	23	20–55	20

Table 4. Cont.

Authors	Nanofluid	Nanoparticle Concentration ϕ	Particle Size (nm)	Increase in k (%)	Temperature Range (°C)
Hong and Yang [55]	Fe/EG	10 vol.%	0.55	18	20
Xie et al. [60]	CNTs/EG	1 vol.%	15×310^{-4}	12.6	20
Xie et al. [58]	SiC/EG	4.2 vol.%	26	15.8	4
			(spherical shape)		
	SiC/EG	4 vol.%	600	22.9	4
			(cylindrical shape)		
Chen et al. [52]	TiO ₂ /EG	≤ 1.8 vol.%	25	≤ 14.5	20, 40
Garg et al. [67]	Cu/EG	0.04–2 vol.%	200	2–12.6	25
Xie et al. [57]	MgO/EG	5 vol.%	20	40.6	10–60
	Al ₂ O ₃ /EG	5 vol.%	20	28.2	10–60
	TiO ₂ /EG	5 vol.%	20	27.2	10–60
	ZnO/EG	5 vol.%	20	26.8	10–60
	SiO ₂ /EG	5 vol.%	20	25.3	10–60
Chopkar et al. [68]	Al ₂ Cu/EG	0.2–2.5 vol.%	15	6–220	20
	Ag ₂ Al/EG	0.2–2.5 vol.%	18	8–250	20
Palabiyik et al. [5]	Al ₂ O ₃ /PG	1–9 wt.%	70–100	3.6–11	20–80
	TiO ₂ /PG	1–9 wt.%	100–140	1.4–9	20–80
Harish et al. [62]	SWCNT/EG	0.2 vol.%	1.6×150	14.8	27–57
Xie et al. [53]	Diamond/EG-W(45:55)	0.5–2 vol.%	10	6–18	10–60
Timofeeva et al. [59]	SiC/EG-W(50:50)	4 vol.%	16, 29, 66 and 90	11.5–17	15–85
Vajjha and Das [45]	Al ₂ O ₃ /EG-W(60:40)	1–10 vol.%	53	8–69	25–90
	CuO/EG-W(60:40)	1–6 vol.%	29	14–60	25–90
	ZnO/EG-W(60:40)	1–7 vol.%	29 and 77	9.8–48.5	25–90
Sundar et al. [50]	Al ₂ O ₃ /EG-W(50:50)	0.2–0.8 vol.%	36.5	9.8–17.89	15–50
	CuO/EG-W(50:50)	0.2–0.8 vol.%	27	15.6–24.56	15–50
Reddy and Rao [49]	TiO ₂ /EG-W(40:60)	0.2–1 vol.%	21	1.94–4.3	30–70
	TiO ₂ /EG-W(50:50)	0.2–1 vol.%	21	10.64–14.2	30–70
Satti et al. [6]	Al ₂ O ₃ /PG-W(60:40)	0.5–6 vol.%	15–45	2–12.2	–30–90
	ZnO/PG-W(60:40)	0.5–6 vol.%	36–76	1.6–21.36	–30–90
	CuO/PG-W(60:40)	0.5–6 vol.%	30	2.3–15.6	–30–90
	SiO ₂ /PG-W(60:40)	6 vol.%	30	4.7–7.2	–30–90
	TiO ₂ /PG-W(60:40)	0.5–1.5 vol.%	15	1–7.3	–30–90

2.4. Rheological Behaviour of Nanofluids

The dynamic viscosities μ of pure ethylene- and propylene-glycol are 21- and 57.6-times higher than that of liquid water at 20 °C, respectively (Table 3). It is now a well-known fact the addition of nanoparticles in these base fluids will accentuate that. For industrial applications where the HTF needs to be transported, it is a primary concern as the dynamic viscosity of the HTF will directly impact the pressure drop, and so the required pumping power to transport it. The dynamic viscosity is then certainly as critical as the thermal conductivity when choosing the appropriate nanofluid for a given engineering system. However, most of the published works to date have mainly focused their effort on the heat transfer part, and as shown in Table 5, fewer provided reliable data on the dynamic viscosity of EG- or PG-based nanofluids. Most authors still use general correlations to predict the rheological behaviour of PG-W- or EG-W-based nanofluids like the Brinkman equation:

$$\mu_{nf} = \mu_{bf} \frac{1}{(1 - \phi)^{2.5}} \quad (9)$$

or the viscosity-volume fraction correlation, which accounts for the Brownian motion:

$$\mu_{nf} = \mu_{bf} \left(1 + \mu_{int} \varphi + k_H \varphi^2 + O(\varphi^3) \right) \quad (10)$$

where μ_{int} is the intrinsic viscosity equal to 2.5 for uncharged spheres (Einstein's correlation) and k_H the coefficient accounting for the interaction between two colliding particles equal to 6.2 (Batchelor's model). This equation is considered as valid for stable suspensions up to $\varphi = 15\%$. Other correlations exist [25,32], but are mainly based on this last model with different values of μ_{int} and k_H . In the following subsections, only the specific correlations developed for EG-W- and PG-W-based nanofluids on an experimental basis will be presented.

Table 5. Summary of the existing studies on the dynamic viscosity of EG- and PG-based nanofluids. f-GnPs, functionalized graphene nanoplatelets.

Authors	Nanofluid	Nanoparticle Concentration φ	Particle Size (nm)	Increase in μ (%)	Temperature Range (°C)
Chen et al. [52]	TiO ₂ /EG	0.5–8 wt.%	70–100	0.55–22.75	20–60
Wang and Choi [48]	Al ₂ O ₃ /EG	1.2–3.5 vol.%	28	8–40	20
Garg et al. [67]	Cu/EG	0.04–2 vol.%	200	4.7–23.8	25
Xie et al. [57]	MgO/EG	5 vol.%	20	17.4	10–60
	Al ₂ O ₃ /EG	5 vol.%	20	28.2	10–60
	TiO ₂ /EG	5 vol.%	20	31.2	10–60
	ZnO/EG	5 vol.%	20	129.2	10–60
	SiO ₂ /EG	5 vol.%	20	31.5	10–60
Akbari et al. [69]	SiO ₂ /EG	0.1–3 vol.%	25	8–116	30–50
Namburu et al. [70]	CuO/EG-W(60:40)	1–6.12 vol.%	29	12.25–45.6	−35–50
Timofeeva et al. [59]	SiC/EG-W(50:50)	4 vol.%	16–90	48–14	15–85
Kulkarni et al. [3]	CuO/PG-W(60:40)	1–5.9 vol.%	29	100	−35–50
Naik et al. [4]	CuO/PG-W(60:40)	0.025–1.2 vol.%	50	0.2–5	−15–60
Kumar et al. [71]	ZnO/PG-W(10:90)	0.02–0.1 wt.%	30	1.69–3.48	30–40
Afrand et al. [72]	MgO/EG-W(50:50)	0.1–1.5 vol.%	40	2.15–52.72	25–50
Vallejo et al. [7]	f-GnPs/PG-W(10:90)	0.25–0.5 wt.%	-	60–110	5–50
	f-GnPs/PG-W(30:70)	0.25–1 wt.%	-	40–222	5–50

2.4.1. Ethylene-Glycol-Based Nanofluids

Namburu et al. [73] proposed viscosity measurements of SiO₂ nanoparticles dispersed in an EG/water (60:40 by mass) mixture under sub-zero temperature operations. Their results showed that μ decreased monotonously from −35 °C to 50 °C whatever the nanoparticle concentration between $\varphi = 2$ and 10 vol.%. At $\varphi = 6$ vol.%, they showed also that the nanoparticle diameter had only a weak influence on the dynamic viscosity of the mixture within the range [20–100] nm. Similar measurements were also performed for Al₂O₃ nanoparticles (mean diameter of 53 nm) dispersed in a 60:40 EG/water mixture for $\varphi = [1–10 \text{ vol.}\%]$. Akbari et al. [69] considered the same type of nanoparticles ($d_{np} = 20–30 \text{ nm}$), but dispersed in pure ethylene-glycol for $\varphi \leq 3 \text{ vol.}\%$ and $T = [30–50 \text{ °C}]$. The measurements showed that the SiO₂/EG nanofluid exhibited a Newtonian behaviour for all considered conditions. They noted that the dynamic viscosity increased by increasing the silica volume fraction and diminished as the temperature increased. This variation with temperature was expected since the dynamic viscosity of all pure liquids decreased with T . In their case, the viscosity increased by about 116% by increasing the SiO₂ nanoparticle concentration from 0.1–3 vol.% at $T = 40 \text{ °C}$ as an example. They finally proposed a new correlation covering the whole range of operational parameters:

$$\frac{\mu_{nf}}{\mu_{bf}} = -24.81 + 3.23T^{0.08014}e^{1.838\varphi^{0.002334}} - 0.0006779T^2 + 0.024\varphi^3 \quad (11)$$

Chen et al. [52] studied the rheological behaviour of TiO_2 nanoparticles ($d_{np} = 25$ nm) in pure ethylene-glycol for φ from 0.5–8 wt.%. After dispersing the nanoparticles into the base fluid, agglomerates were formed, and then, an ultrasonication treatment was done. Finally, they obtained a very stable nanofluid for over two months with nanoparticle diameters between 70 and 100 nm. They found that the TiO_2 -EG nanofluid exhibited a Newtonian behaviour over a shear rate range between 0.5 and 10^4 s $^{-1}$ and temperature varying between 20 °C and 60 °C. They noted that the nanofluid viscosity depended strongly on temperature and nanoparticle concentration, as shown in Figure 4. μ is a decreasing function of T in a logarithmic way and increases with φ following a second-order polynomial. For instance, adding 8 wt.% TiO_2 nanoparticles increases the EG viscosity by 22.75%. They stated that the agglomeration phenomenon could be one of the key parameters responsible for the increase in viscosity. Their results compare fairly well with the following empirical correlation based on the aggregate diameter d_{agg} :

$$\frac{\mu_{nf}}{\mu_{bf}} = \left(1 - \frac{\varphi}{0.605} \left(\frac{d_{agg}}{d_{np}}\right)\right)^{-1.5125} \quad (12)$$

where the value 0.605 represents the maximum packing factor and $d_{agg} = 3.34d_{np}$.

The rheological behaviour of MgO -EG nanofluid has been investigated by Xie et al. [57] at ambient temperature. The experimental measurements showed a linear relation between the shear stress and the shear rate, which indicated a Newtonian behaviour of the nanofluid. They mentioned that the nanofluid viscosity decreased rapidly with temperature. However, it increased, at the same time, considerably with the nanoparticle volume fraction.

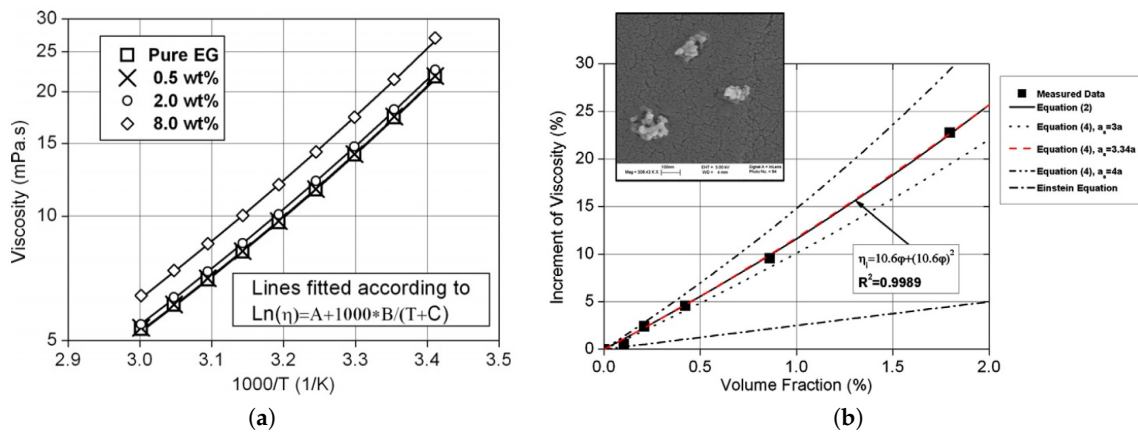


Figure 4. Influence of the (a) temperature and (b) nanofluid volume fraction on the dynamic viscosity of TiO_2 nanoparticles dispersed in pure ethylene-glycol. After [52], with permission from Elsevier.

An experimental investigation of the rheological properties of copper oxide nanoparticles suspended in a 60:40 ethylene-glycol and water mixture has been conducted by Namburu et al. [70] for temperatures ranging from -35 °C– 50 °C and particle volume concentrations up to 6.12%. They noted that the base fluid freezes at -45 °C, and therefore, the last measurement was done at -35 °C. Their results revealed that the CuO -based nanofluids exhibited a Newtonian behaviour under all experimental conditions. They observed that the nanofluid viscosity increased with the increase of the nanoparticle concentration. For instance, at $T = -35$ °C and $\varphi = 6.12$ vol.%, the viscosity of the base fluid increased by a factor of four. They also noted that the nanofluid viscosity decreased exponentially as the temperature increased.

Timofeeva et al. [59] assessed the viscosity variations of water and EG-water mixture when adding 4 vol.% SiC nanoparticles. They showed that the relative viscosity decreased with the increase of the

average particle size in both EG-water and water suspensions. However, at the same SiC nanoparticle volume fraction, the relative viscosity increase was smaller in the EG-water suspension than in pure water-based nanofluids, especially for suspensions containing smaller nanoparticles. For example, for a nanoparticle diameter equal to 16 nm and $\varphi = 4$ vol.%, the viscosities of water and EG-water were increased by 75% and 48%, respectively, compared to that of the base fluids. They affirmed that the observed phenomena could be related to the difference in the structure and thickness of the diffuse fluid layers around the nanoparticles in various base fluids, which affects the effective volume concentration and ultimately the viscosity of the suspensions.

The Newtonian behaviour of diamond nanoparticles dispersed in a 45:55 EG-W solution was reported by Xie et al. [53] for nanoparticle volume fractions varying from 0.5–2 vol.%. They indicated that the inversely proportional relation between the nanofluid viscosity and the temperature was due to a weakening effect of the inner-particle/inter-molecular forces. Interestingly, though not being simultaneous, these viscosity measurements were coupled to thermal conductivity and heat transfer measurements, treating the performance of this nanofluid as a whole.

Afrand et al. [72] measured the dynamic viscosity of magnesium oxide nanoparticles dispersed in a 50:50 EG-W mixture for φ up to 3% and temperatures within the range [25–50 °C]. The results revealed that the nanofluids with volume fractions less than 1.5% exhibited a Newtonian behaviour. The dynamic viscosity increased linearly with φ in that case and decreased with T , as shown in Figure 5a. On the contrary, nanofluids with volume fractions $\varphi \geq 3\%$ showed a shear-thinning behaviour as the dynamic viscosity decreased with the shear rate (Figure 5b). Through a sensitivity analysis, they demonstrated that the viscosity sensitivity of nanofluids to temperature at large φ values was higher than that at low φ values. Based on their experimental data, the authors proposed a new correlation for predicting the viscosity of MgO/EG-W (50:50) nanofluids valid for $d_{np} = 40$ nm, $\varphi \leq 1.5\%$ and $T = [25–50]$ °C:

$$\frac{\mu_{nf}}{\mu_{bf}} = 1.0198 + 11.82\varphi^{0.7465}T^{-1.3841}e^{0.015\varphi^{0.264}T^{1.2203}} \quad (13)$$

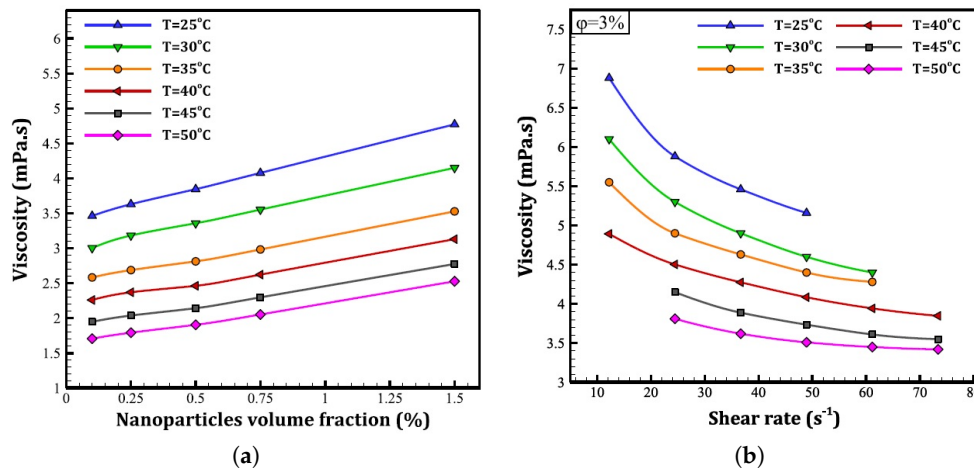


Figure 5. Dynamic viscosity of the (a) Newtonian ($\varphi \leq 1.5\%$) and (b) non-Newtonian ($\varphi = 3\%$) nanofluid samples at different temperatures. Results obtained by Afrand et al. [72] for magnesium oxide nanoparticles dispersed in a mixture composed of water and ethylene-glycol (50:50). After [72], with permission from Elsevier.

2.4.2. Propylene-Glycol-Based Nanofluids

As for the thermal conductivity, the dynamic viscosities of PG-based nanofluids have been less considered compared to the ones of EG-based nanofluids, as reported in Table 5.

The dynamic viscosity of a 60:40 propylene-glycol and water mixture with different volume

fractions of copper oxide nanoparticles ($d_{np} = 29$ nm) had been measured by Kulkarni et al. [3] over a temperature range from -35 °C– 50 °C. They noted that the nanofluid viscosity increased with the increase of CuO nanoparticle concentration, and as expected, it diminished as the temperature increased. As an example, at $T = -35$ °C, the viscosity increased from 0.736 – 3.291 Pa·s by adding 1 vol.% and 5.9 vol.% of CuO nanoparticles to PG-water, respectively. The effective viscosity decreased by about 100-times when the temperature increased from -35 °C– 50 °C at $\varphi = 1$ vol.%. All nanofluids exhibited a Newtonian behaviour for $\varphi = [0$ – 5.9 vol.%] in the whole temperature range considered. They proposed the following correlation covering all of the parameter range they considered:

$$\mu_{nf} = Ae^{B\varphi} \quad \ln A = 736.9e^{-0.0199T} \quad (14)$$

$$B = 44.794 - 0.0765T$$

Naik et al. [4] investigated the rheological behaviour of copper oxide nanoparticles ($\varphi = [0.025$ – 1.2 vol.%]) dispersed in a 60:40 PG-water solution for $T = [-15$; 60 °C]. They reported also a Newtonian behaviour of the nanofluids under all the operating conditions. They obtained similar trends for the variations of the nanofluid viscosity as a function of T and φ as in [3]. It has also been confirmed later by Leena and Srinivasan [66] for TiO_2 nanoparticles dispersed in a 70:30 (% by weight) water–propylene-glycol mixture. These last authors proposed correlations for the dynamic viscosity of these nanofluids over $\varphi = [0.1$; 0.8%] and discussed the potential heat transfer benefits of their use in laminar and turbulent flow conditions. Viscosity measurements of zinc oxide nanoparticles dispersed in a 10:90 propylene-glycol and water mixture were recently conducted by Kumar et al. [71] for different temperatures ($T = 30, 35$, and 40 °C). They stated that the nanofluid viscosity increased by increasing the ZnO nanoparticle concentration up to 0.04 wt.% because of the increasing molecular interactions between ZnO , water, and PG. After that, the viscosity decreased by increasing the nanoparticle concentration up to 0.08 wt.%, which may be attributed to stronger molecular interactions between ZnO with water and propylene-glycol and to lower molecular interactions between water and propylene-glycol. With further loading of ZnO nanoparticles (0.1 wt.%), the nanofluid viscosity started increasing again because of the nanoparticle agglomeration.

Vallejo et al. [7] studied experimentally the rheological behaviour of different dispersions of functionalized graphene nanoplatelets, f-GNPs (from 0.25 – 1 wt.%) in two propylene-glycol-water mixtures (10:90 and 30:70) within the temperature range $[5$ – 50 °C]. They reported also a Newtonian behaviour over all the concentrations, temperatures and shear rate ranges they considered. They found that a less viscous base fluid implied higher viscosity increments of the constituted nanofluids, especially at lower temperatures. The dynamic viscosity was found to increase with the loading of nanoplatelets by 222% for the dispersion of 1 wt.% f-GNPs in the 30:70 PG-W mixture compared to the base fluid at 5 °C. They proposed a new correlation to describe the viscosity dependence on both the temperature and the nanoparticle volume concentration of graphene nanoplatelet-based nanofluids:

$$\mu_{nf} = \mu_0 e^{AT_0/(T-T_0)} + Be^{C/T} \varphi - D\varphi^2 \quad (15)$$

where φ is the nanoparticle volume fraction, T the temperature in K, B , C , and D are fitting parameters and μ_0 , A , and T_0 are adjustable parameters taken from the Vogel–Fulcher–Tammann equation for the base fluid. This correlation is valid for mixtures of PG-W solution at 10:90 wt.% and 30:70 wt.% with particle mass fractions up to 0.5 wt.%.

3. Heat Transfer Enhancement

Due to the observed improvement in the thermal conductivity, nanofluids are expected to provide enhanced heat transfer potential of base fluids, which can offer the possibility to develop highly compact and effective heat transfer equipment for many industrial applications including electronics, transportation, food, and biomedicine. The present review focuses only on the applications including ethylene-glycol- and propylene-glycol-based nanofluids. The existing experimental and

numerical studies in the literature have mainly investigated the effect of nanoparticle suspensions on the performance of cooling systems, especially car radiators.

3.1. Experimental Results

Experimental investigations of forced convective heat transfer of Al_2O_3 /EG and CuO /EG nanofluids flowing through double pipe and plate heat exchangers under turbulent flow conditions were conducted by Zamzamian et al. [23]. The results indicated a considerable enhancement in the heat transfer performance with nanofluids compared to pure EG for both heat exchangers and all the operating conditions. For example, in the double pipe heat exchanger, adding 1 vol.% of Al_2O_3 and CuO nanoparticles to EG increased the effective heat transfer by about 26% and 37% compared to the base fluid, respectively. They attributed this enhancement to the fact that the chaotic motion of the nanoparticles could accelerate the energy exchange process between the fluid and the wall.

Kulkarni et al. [22] studied experimentally the evaluation of the cogeneration and heat exchanger efficiency of a diesel electric generation (DEG) device involving nanofluids. The thermal properties of nanofluids consisting of aluminium oxide nanoparticles dispersed in a 50:50 EG/W mixture were studied for temperatures within the range [25–70 °C]. They reported that the nanofluid specific heat decreased by increasing the nanoparticle volume fraction, which means that for higher concentrations of alumina nanoparticles, less heat input was required to increase the temperature of the nanofluid or at the same heat input. They affirmed that by reducing the time required to heat, employing the nanofluid as a jacket water would be very beneficial in the automobile industry especially in Arctic or subarctic regions. They assessed the effect of nanofluids on the cogeneration efficiency, which is defined by the sum of the electrical power reduced and the rate of heat-recovered divided by the energy rate associated with the fuel input to the generator. The results showed that the diesel engine cogeneration efficiency decreased by increasing the Al_2O_3 nanoparticle concentration. For example, the cogeneration efficiency of the pure EG/W mixture slightly dropped from 79.1% to 76.11% by adding 6 vol.% of Al_2O_3 nanoparticles. They also examined the effect of the nanoparticles on the efficiency of the heat exchanger connected to the diesel engine. They observed that as the nanoparticle concentration increased, the heat exchanger efficiency was enhanced because of the higher heat transfer coefficient with the nanofluid compared to the base fluid case. For instance, dispersing 6 vol.% of Al_2O_3 nanoparticles into the EG/W mixture improved the heat exchanger efficiency by up to 81.11% compared to an enhancement of 78.1% for EG/W only.

Heris et al. [15] investigated experimentally the influence of using CuO in a 50:50 EG/W mixture as a coolant on the heat transfer performance of a car radiator over a temperature range between 35 and 54 °C. The results showed a significant enhancement in the heat transfer rate by adding CuO nanoparticles to the base fluid. They noted that the overall heat transfer increased when the Reynolds number was increased, as well as the nanoparticle volume concentration. The highest Nusselt number enhancement was found to be about 55% at $\phi = 0.8\%$ compared to EG/W. An experimental test rig has been recently designed by Beriache et al. [17] to evaluate the heat transfer performance of a Perodua Kelisa 1000cc radiator system (Figure 6a) operating with nanofluids containing multi-walled carbon nanotubes dispersed into a 50:50 EG/W in the laminar flow regime. The results revealed that the thermal performance of the car radiator was improved by adding MWCNTs to the EG/W solution (Figure 6b). As expected, h is an increasing function of the Reynolds number. The heat transfer coefficient enhancement was found to be 26.8%, 135.3%, and 196.3% for $\phi = 0.1, 0.25$, and 0.5 vol.% compared to the base fluid, respectively.

Peyghambarzadeh et al. [11] conducted heat transfer experiments for nanofluids flowing inside flat aluminium tubes of a car radiator under turbulent flow conditions. They compared the heat transfer performances of three different alumina-based nanofluids: Al_2O_3 in water, in EG, or in an EG/W mixture. They noted that the heat transfer behaviours of these nanofluids were highly dependent on the particle concentration and the flow conditions and weakly dependent on the temperature. The highest Nusselt number enhancement up to 40% was obtained by suspending only

1 vol.% of Al_2O_3 nanoparticles into both water and ethylene-glycol. They assessed the effect of three concentrations of EG/W-based nanofluids including 5, 10, and 20 vol.% of ethylene-glycol on the heat transfer characteristics. They found that as the EG concentration in water increased, the Nusselt number decreased. For instance, at $\phi = 0.3$ vol.% and an inlet temperature equal to 45°C , the Nusselt number slightly reduced from 114.56–110.55 by increasing the EG concentration from 5–20 vol.%, respectively. However, for any given EG/W mixture concentration, the heat transfer rate was enhanced by adding alumina nanoparticles. As an example, suspending 0.3 vol.% of Al_2O_3 nanoparticles into a 20:80 EG/W mixture increased the Nusselt number up to 22% compared to the pure base fluid.

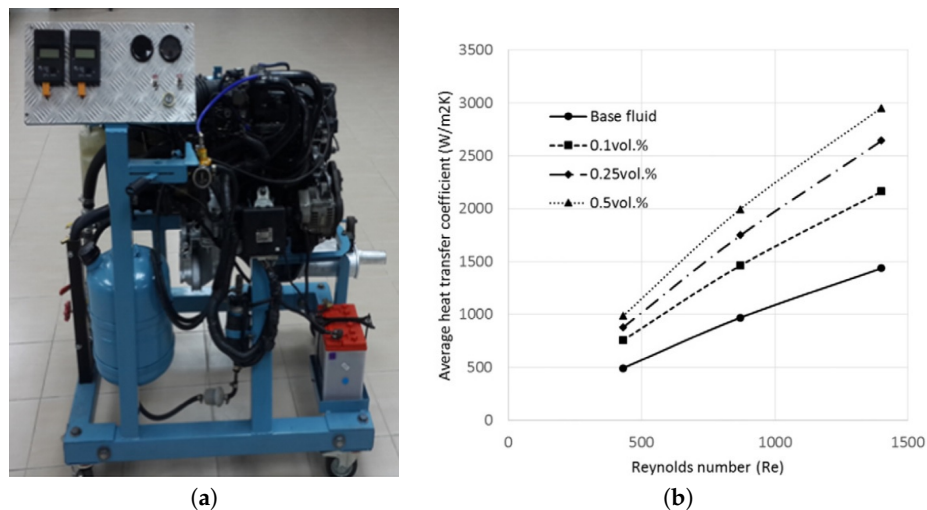


Figure 6. (a) Photograph of a real car radiator setup; (b) heat transfer coefficient at different Reynolds numbers and volume fractions of MWCNT in a water-ethylene-glycol mixture (50:50). After [17], with permission from Elsevier.

The heat dissipation performance of a motorcycle radiator filled with multi-walled carbon nanotubes (MWCNTs) dispersed into a 50:50 EG/W mixture has been investigated experimentally by Teng and Yu [13]. The experiments were carried under the temperature range $[80\text{--}95^\circ\text{C}]$ and volumetric flow rates varying from 4.5–8.5 L/min. They prepared three nano-coolants with different concentrations of MWCNTs, namely 0.1, 0.2, and 0.4 wt.%. They found that the Nusselt number with any of these nano-coolants was lower than EG/W because of the larger enhancement of the thermal conductivity compared to that of the heat transfer coefficient. They evaluated the overall efficiency of the heat exchanger by calculating the ratio of heat exchange capacity and the pumping power defined as the efficiency factor. They reported that the nano-coolant with $\phi = 0.1$ wt.% exhibited the highest heat exchange capacity and efficiency factor compared to the two other nano-coolants and base fluid. They affirmed that a high concentration of MWCNTs could not guarantee a better heat exchange capacity because the uneven density of nano-coolant in the flow state increased the thermal resistance of the solid–liquid interface, which effectively decreased the contact area between the MWCNTs and the EG/W mixture. For all the experimental conditions, the maximum enhancement ratios of heat exchange, pumping power and efficiency factor were approximately 12.8%, 4.9%, and 14.1%, respectively, in comparison with the base fluid.

The performances of ethylene-glycol- and water-based TiO_2 nanofluids as an automobile radiator coolant have been studied by Devireddy et al. [18]. The nanofluids were prepared by dispersing different TiO_2 nanoparticle concentrations (0.1, 0.3, and 0.5 vol.%) into a 40:60 EG/W mixture. The nanofluids flowed through the radiator tubes with an elliptical cross-section under turbulent flow conditions. The results demonstrated that the presence of titanium oxide nanoparticles enhanced considerably the heat transfer rate in the automobile radiator by up to 37% compared to the base fluid. They observed that increasing the fluid circulation rate could improve the heat transfer performance while the fluid inlet temperature had a small effect for both the pure base fluid and the nanofluids for

this set of parameters. The effective thermal conductivity was found to increase as the nanoparticle concentration increased. However, they noted that this enhancement was not solely responsible for the overall heat transfer performance of the car radiator.

The benefits of dispersing Al_2O_3 nanoparticles into a 50:50 EG/W mixture as a car radiator coolant was experimentally investigated by Subhedar et al. [20] under laminar flow conditions for different nanoparticle volume fractions up to 0.8% and temperatures between 65 and 85 °C. The results revealed that the heat transfer performance of the radiator was enhanced by using nanofluids compared to the base HTF. They noted that the heat transfer rate increased by increasing the nanoparticle concentration. For example, at a given flow rate, the Nusselt number was enhanced from 3.89%–28.47% when the Al_2O_3 volume fraction increased from 0.2–0.8 vol.%. They stated that the use of nanofluid makes possible the design of compact car radiators, which could reduce the system weight, diminish the drag, and so, save fuel consumption.

Salamon et al. [19] analyzed experimentally the heat transfer characteristics of a car radiator using PG/W-based TiO_2 nanofluid as a coolant. The nanofluids were prepared by dispersing 0.1 and 0.3 vol.% of TiO_2 nanoparticles into a 30:70 PG/W under different operating temperatures within the range [50–80 °C]. They observed that the Nusselt number increased by increasing both the inlet temperature and the flow rate. They reported that at low inlet coolant temperatures, the PG/W mixture exhibited higher heat transfer rates compared to those obtained with the nanofluids. However, at higher flow rates and higher operating temperatures, the latter showed better heat transfer performances. For example, adding 0.3 vol.% of TiO_2 nanoparticles to EG/W increased the Nusselt number by up to 8.5% compared to the base fluid at $T = 80$ °C. Finally, they concluded from their results that the nanofluid coolants were suitable for heavy-duty engines. This experimental study was unfortunately one of the few using propylene-glycol in a realistic application.

3.2. Numerical Simulations

The purpose of the present section is to report on the most important numerical results regarding the thermal and hydraulic performances of EG- and PG-based nanofluids in realistic configurations. The interested reader can refer to the review of Bahiraei [74] for a detailed description of the numerical methods currently used to model the multiphase nature of nanofluids.

Turbulent flow and heat transfer of three different nanofluids, Al_2O_3 , CuO , and SiO_2 , based on a 60:40 (by mass) EG/W mixture flowing through a circular tube under constant heat flux conditions have been numerically studied by Namburu et al. [73]. The heat transfer coefficient h increased by increasing both the nanoparticle concentration and the Reynolds number. As an example, at $Re = 20,000$, the Nusselt number was enhanced by about 1.35-times by adding 6. vol.% of CuO nanoparticles compared to the base fluid. For the same operating conditions, the CuO nanofluid exhibited higher heat transfer performances followed successively by the Al_2O_3 - and SiO_2 -based nanofluids.

The performances of finned tube heating units with nanofluids have been compared to that of a conventional HTF composed of 60% ethylene-glycol and 40% water by Strandberg and Das [75]. Al_2O_3 and CuO nanoparticles were suspended in the 60:40 EG/W mixture at different concentrations ranging from 1–4 vol.%. The incoming fluid conditions were typical of heating systems in subarctic and Arctic regions. The results indicated that finned tube heating performance was enhanced by employing nanofluids as a heat transfer medium. For instance, their model predicted enhancements by 11.6% and 8.7% in terms of the finned tube heating output by adding 4 vol.% of Al_2O_3 and CuO nanoparticles to EG-water, respectively. They noted also that the pumping power required for a given heating output and a given finned tube geometry was reduced with both the Al_2O_3 /EG-water and the CuO /EG-water nanofluids compared to the base fluid. For all these fluids, the finned tube with $\phi = 4$ vol.% of Al_2O_3 nanoparticles in the EG-water mixture offered the lowest liquid pumping power.

Leong et al. [10] investigated the heat transfer enhancement in an automotive car radiator operating with copper/EG-based nanofluids. Their analysis showed that such nanofluids enhanced the overall heat transfer rate in an engine cooling system. They noted that the heat transfer coefficient

h increased by increasing the nanoparticle volume fraction. At a Reynolds number $Re = 5000$, adding 2 vol.% of copper nanoparticles to EG was found to enhance the heat transfer rate by roughly 4% and reduce the air frontal areas by nearly 19%. However, for the same flow rate, a 12.13% increase in the pumping power was reported. A three-dimensional laminar flow and the associated heat transfer were investigated numerically by Vajjha et al. [9] for two different nanofluids, composed either of Al_2O_3 or CuO nanoparticles dispersed into a 60:40 EG/W mixture. The geometry corresponds to flat tubes within a car radiator. The results showed that at various Reynolds numbers, the heat transfer coefficient, the friction factor and the pressure drop increased by increasing the nanoparticle volume concentration. However, they mentioned that due to the reduced volumetric flow needed for the same amount of heat transfer, the required pumping power diminished. As an example, for the same amount of heat transfer, the pumping power requirement was 82% lower for Al_2O_3 nanofluid at $\phi = 10$ vol.% and 77% lower for CuO nanofluid with $\phi = 6$ vol.% with respect to the base fluid. They proposed new Nusselt number correlations for both the entrance and fully-developed flow regions. Tijani and bin Sudirman [21] studied numerically the thermal performance of a car radiator filled with alumina and copper oxide nanoparticles suspended separately in a 50:50 EG-water mixture. Figure 7 displays the temperature maps at 6 L/min for three nanofluids. The results showed that the heat transfer performance was highly enhanced by the use of nanofluid as coolant compared to the conventional coolant. Adding 0.3 vol.% of Al_2O_3 and CuO nanoparticles to the EG/W solution increased the latter thermal conductivity by about two times. They found that the CuO -based nanofluid exhibited a higher heat transfer performance compared to that of the Al_2O_3 -based nanofluid. For example, at $\phi = 0.3$ vol.% and a volumetric flow rate of 6 L/min, the Nusselt number was enhanced by 5.4% and 27% for Al_2O_3 - and CuO -based nanofluids compared to the base EG/W solution, respectively.

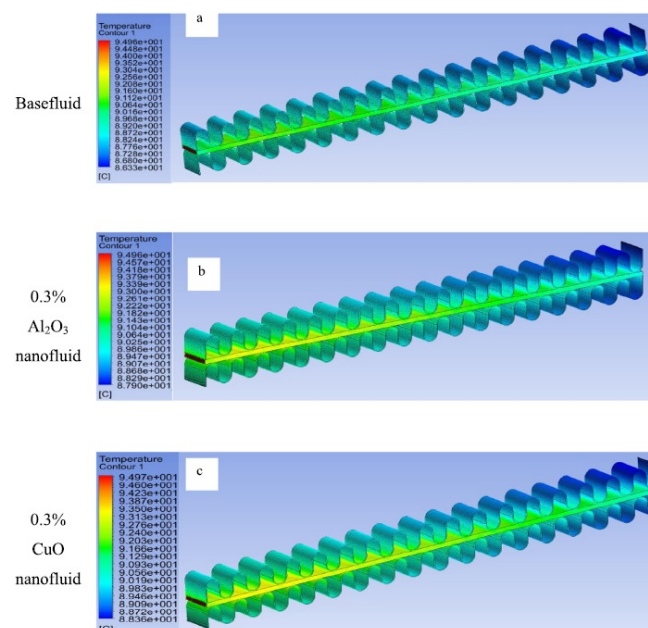


Figure 7. Temperature and streamline profiles of a coolant at 6 L/min in a car radiator: (a) base fluid; (b) Al_2O_3 nanofluid ($\phi = 0.3$ vol.%); (c) CuO nanofluid ($\phi = 0.3$ vol.%). Results obtained by Tijani and bin Sudirman [21] for a 50:50 EG-water mixture and reproduced with permission from Elsevier.

The literature review reveals that numerical studies in realistic configurations using propylene-glycol-based nanofluids do not exist yet.

4. Research Perspectives

According to the above discussion, nanofluids can be regarded as functionalized colloids with special requirements of low-particle loading to prevent from agglomeration, sedimentation and

clogging of the transport lines, favourable rheological behaviour to limit the pumping power required to transport them, and of course, high thermal performances for thermal energy storage and/or heat transfer. However, the characterization of the thermophysical properties and performances of nanofluid coolants, especially in the sub-zero temperature regime, still remain very limited, and only very few works have been devoted to this research topic for refrigeration applications. On the contrary, more research has been published for high temperatures, especially to increase the heat transfer rate in car radiators.

More research has still to be done on the nanofluid synthesis, stability and compatibility with other materials of the thermal systems. For commercial or industrial applications, the preparation and stability of ethylene- or propylene-glycol-based nanofluids should be more carefully considered. To go towards their potential commercialization, their preparation should be as simple as possible by limiting the control of pH, the use of surfactants and the sonification step. A similar study to that of Bouguerra et al. [76] done for Al_2O_3 water-based nanofluids should be performed for these other nano-coolants to see, among other things, if surfactants are necessary to guarantee their long-term stability.

Further experimental research investigations on the effective thermal conductivity, heat capacity, density, and dynamic viscosity are also needed to better understand the heat transfer and transport characteristics of nanofluids over a wider range of low temperatures $[-50; 0\text{ }^{\circ}\text{C}]$. Appropriate measurement techniques, especially the thermal hot wire technique for the thermal conductivity and the stress-controlled rheometer for the dynamic viscosity, should be preferred over the KD2pro device and pressure drop/flow rate measurements to get more reliable experimental data. They could serve hereafter as reference data to develop accurate and more specific correlations for these properties, which could be implemented in future numerical models. Particular attention should also be paid to the hysteresis phenomenon when temperature varies. This has been observed experimentally by Bouguerra [77] through simultaneous measurements of dynamic viscosity and thermal conductivity for Al_2O_3 water-based nanofluids, even at low concentrations. It may have a large impact on the pumping capacity of a given system, while providing, at the same time, useful information regarding the dispersion regime and stability of the suspensions.

To validate numerical models, more measurements are also required in canonical than complex geometries, including pipes or channels with or without turbulence promoters. Local temperature, velocity, and concentration measurements are specifically required for detailed comparisons. Each system should be characterized also over a whole life cycle by quantifying the degradation of the nanofluid performances over hundreds of heating/cooling cycles. It would give better insight into the long-term stability of nano-coolants in real systems.

The performances of nanofluid flows are difficult to assess, and comparisons between two nanofluids are rarely discussed regarding objective criteria, as their characteristics depend on so many parameters like the nanoparticle size, type and concentration, the geometry of the considered system, and the operating parameters (flow rate, temperature, pressure). Merit criteria should be more systematically used, as was done by Sekrani et al. for Al_2O_3 water-based nanofluids in turbulent pipe flows [44] and laminar channel flows [78]. The most common criteria include:

- the C_{μ}/C_k ratio introduced by Prasher et al. [79], which gathers the thermal conductivity and dynamic viscosity of the nanofluid.
- the Mouromtseff number $Mo = \rho^a k^b C_p^c / \mu^d$, which gathers the four main thermophysical properties and where the exponents a , b , c , and d take on values appropriate for the heat transfer mode of interest and the corresponding heat transfer correlation, as proposed by Simons [80].
- the performance evaluation criterion $PEC = \dot{m} c_{p_{nf}} \delta T / (\dot{V} \delta P)$ introduced by Ferrouillat et al. [81], which is based on the ratio of heat transferred to the requiring pumping. $\dot{m}$, δT , $\dot{V}$, and δP are the mass flow rate, temperature difference, volumetric flow rate, and pressure drop, respectively.
- the overall efficiency $\eta = Nu_{nf} \delta P_{bf} / (Nu_{bf} \delta P_{nf})$, where Nu represents the Nusselt number.

- the efficiency of nanofluids based on the first and the second laws of thermodynamics can be tackled by considering the performance parameter PE proposed by Siavashi and Jamali [82]: $PE = Nu_{nf}Ns_{bf}/(Nu_{bf}Ns_{nf})$, where Ns is the dimensionless entropy generation.

Artificial neural networks (ANNs) are a valuable tool for the predictions of both the thermophysical properties of nanofluids and their thermal performances in industrial applications. Moreover, they can serve to compare experimental and/or numerical results obtained through different methods and then explain the huge variability of published results. Coupled to multiobjective algorithms like genetic ones, they could also be used to find the optimal design of thermal systems involving nanofluids, whose performances are dependent on a large number of geometrical and operational parameters. ANN models have been widely applied for water-based nanofluids, but less for ethylene- or propylene-glycol-based nanofluids. It can be explained by a lack of reliable experimental data used to train, test, and validate ANNs. For ethylene-glycol-based nanofluids, one can cite only the works of Esfe et al. on the thermal conductivity of suspensions with SWCNT- Al_2O_3 nanoparticles [83] and on the thermal conductivity and dynamic viscosity of suspensions with Al_2O_3 nanoparticles [84]. Similar studies must be generalized to other types of nanofluids to predict their thermal properties, as well as their performances in real applications.

Finally, due to the lack of studies on the nanoparticle agglomeration, settling, and erosion phenomena over several heating/cooling cycles at low temperatures ($\leq 0^\circ\text{C}$), the use of nanofluids in industrial applications still remains questionable and certainly hinders their commercialization. Serious attempts should be carried out to fill this gap and then exploit the results found to develop more efficient and compact thermal systems working with enhanced thermal properties of nano-coolants.

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Abbreviations

The following abbreviations are used in this manuscript:

C_p	specific heat, $\text{J}\cdot\text{K}^{-1}\cdot\text{kg}^{-1}$
C_μ, C_k	coefficients related to the dynamic viscosity and thermal conductivity, respectively, —
d_{np}	average nanoparticle diameter, nm
h	heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
k	thermal conductivity, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
$\dot{m}, \dot{V}$	mass and volumetric flow rates, $\text{kg}\cdot\text{s}^{-1}$ and $\text{m}^3\cdot\text{s}^{-1}$
Mo	Mouromtseff number, —
Ns	dimensionless entropy generation, —
Nu	Nusselt number, —
PE	performance parameter, —
Re	Reynolds number, —
T	temperature, K
$\delta P, \delta T$	pressure drop (Pa) and temperature difference (K)
η	overall efficiency, —
φ	volume fraction, —
μ	dynamic viscosity, $\text{Pa}\cdot\text{s}$
ρ	density, $\text{kg}\cdot\text{m}^{-3}$
bf	base fluid
nf	nanofluid

np	nanoparticles
ANN	artificial neural network
EG	ethylene-glycol
MWCNT, SWCNT	multi-, single-wall carbon nanotube
PEC	performance evaluation criterion, –
PG	propylene-glycol
vol.	refers to proportions in terms of volume
W	water
wt.	refers to proportions in terms of mass

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