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Graphene-Based Nanofluids Effectiveness for Thermal Applications

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Abstract. The surge in global energy demand necessitates efficiency improvements in thermal systems. Nanofluids have emerged as promising working fluids because of their improved thermal performance. This investigation assesses the thermal and pumping behavior of graphene–water nanofluids with 0.01–0.10 vol.% graphene nanoplatelets and varied sodium dodecyl sulphate concentrations over 10–70°C. It also explores the benefit of these suspensions for applications operating under laminar and turbulent flow conditions. The thermophysical data were used to assess laminar effectiveness via the thermal conductivity-to-viscosity ratio ($C\lambda/C\mu > 0.25$) and turbulent performance via the Mouromtseff number ($Mo > 1$), alongside heat-transfer ($FoM_{heat\ transfer}$) and pumping (FoM_{pump}) figures of merit. Results show that higher graphene loadings (0.1 vol.%) with lower surfactant levels maximize heat-transfer performance, especially at elevated temperatures, while the lowest pumping performance occurs at 10 °C with 0.10 vol.% graphene and higher surfactant. These findings reveal that both graphene concentration and temperature critically influence nanofluid effectiveness for enhanced thermal applications.

Introduction

The continued rise in energy needs, including both water and electricity, possess a growing global challenge that is driven primarily by the expansion in population, progress in technology, and ongoing industrialization [1, 2]. Consequently, policymakers have been actively pursuing new strategies to mitigate for such pressure in energy demands. One of the common tactics that can be adopted to overcome such obstacle is to build additional power-generation facilities to increase the energy supply over the demand. However, this approach is not feasible, construed by land availability, time consuming, and would increase the greenhouse emissions. A more convenient option is to improve the efficiency of existing power plants by integrating advanced technologies into their operational cycles.

In the past years, nanotechnology has emerged as a transformative force in the energy sector, as it offers novel avenues to improving thermal systems performance, and thus can help in addressing the increasing demands for sustainable energy [3-5]. For instance, within thermal energy systems, such as solar-driven desalination setups, replacing the conventional working fluid with nanofluids can significantly improve the process overall heat transfer efficiency [6, 7]. The concept of forming suspensions by itself is well known; however, dispersing nano-scaled materials in a basefluid was first introduced by Masuda et al. [8], in 1993, after which it was formally termed

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'nanofluid' by Choi and Eastman [9] two years later. In principle, nanofluids are suspensions made of nanoparticles of size less than 100 nm. These particles need to be uniformly distributed within a non-dissolving hosting liquid.

To fabricate these types of suspensions, scholars have established three principal routes: the single-step (or one-step), two-step, and the effervescent-tablet approach [10]. The one-step method relies on synthesizing and dispersing the nanoparticles the directly within the base liquid, and therefore minimizing the variety of achievable suspensions [11]. On the other hand, the two-step approach allows for a broader array of nanofluid compositions, as dry nanopowders is added to any non-dissolving liquid then dispersed to form the suspension [12]. In contrast, the effervescent tablet route utilizes the bubbles generated from the reaction of the effervescent agents with the liquid as the particles mixing mechanism for producing the nanofluid [13]. Comparing the three production methods, the effervescent tablet approach is the fastest in terms of suspension production duration, user-friendly, and much feasible [14]. However, it can only be applied to aqua liquids.

In solar thermal applications, carbon-based nanomaterials outperform their counterparts due to their relatively low cost, high thermal conductivity, and outstanding solar absorption capability [11]. As such, scientists prefer using them in their nanofluid recipe. For example, Ali [15] has shown that adding graphene to water can increase its thermal conductivity up to 125.72%, thereby demonstrating the significant thermal role of such type of material. Ahmadi et al. [16] showed an 18.87% enhancement in the efficiency of their solar collector test-rig over the basefluid due to the solar absorption characteristics of the dispersed graphene. Li et al. [17] demonstrated an increase in the photothermal conversion efficiency by 172% in their graphene-based suspension. Sainz-Manas et al. [18] has shown that dispersing 0.2 g/L and 0.3 g/L of graphene in a direct absorption solar collector (DASC) can increase the overall system photo-thermal conversion efficiency by 62.3% and 74.3%, respectively. Sathish et al. [19] investigated the thermal performance of heat pipe-based solar tube collectors using 0.1-0.3 vol.% of graphene-based suspensions, where a maximum increase of 41.3% was achieved. In the literature review conducted by Pradeep et al. [20] on cooling towers, the authors have mentioned high cooling rate enhancement from using graphene-based nanofluids, such as 67% (0.1 wt.%) and 36.2% (0.02 wt.%). The previous studies pinpoint the effectiveness of carbon-based nanomaterials in improving the suspensions performance.

In an economic point of view, the use of theoretical means to determine the effectiveness of a suspension before experimentally testing it is more feasible for real-life applications. One way of doing so is via calculating the different figure of merits (FoM) of the fabricated nanofluid that are related to the thermal behavior of the working fluid, its effect on the pumping power, and its effectiveness under laminar and turbulent conditions [21-23].

Due to the previous, this research investigates the thermal and pumping performance of graphene nanoplatelets (GN)-based nanofluids under turbulent and laminar conditions. According to the authors awareness, such research work has not been explored previously in the literature, and hence demonstrates the novelty of this work. The thermophysical properties of GN-water suspensions, of 0.01-0.10 vol.%, were obtained at 10°C-70°C from the study of Ali [15]. Afterwards, the effectiveness of the nanofluids under both turbulent and laminar situations was determined. Next, the effectiveness of the suspensions in terms of their heat transfer capability and influence on the pumping power were determined. Lastly, the performance of the nanofluids was compared to reveal the optimum production recipe.

Materials and Methods

Nanofluid Thermophysical Properties. Thermophysical properties of GN-water suspensions were gathered from the previous work of Ali [15]. Furthermore, the water-based nanofluids fabricated by the scholar used GN of > 99.5 wt. %, 2 to 8 nm (thickness), and 4 to 12 μm (diameter), along

with an average of 3 to 6 graphene layers. The production process consisted of initially mixing 1.0:0.5 to 1.5 weight ratio of GN (0.01-0.10 vol.%) and sodium dodecyl sulphate (SDS) within deionized water (DIW), for 10 min, through a magnetic stirrer. Then, the mixture was intensively segregated for 90 min, at 10°C-70°C, via an ultrasonic microprocessor to reach the suspensions final phase. Afterwards, the density, specific heat capacity, thermal conductivity, and viscosity were measured, and their values were reported. Table 1 tabulates each suspension content. The thermophysical properties of the basefluid and different nanofluids (i.e., NF 1 to NF 9) can be found at Ali's work [15].

Table 1. Suspensions mixed content in 75 mL of basefluid.

Denotation	vol.%	GN:SDS weight ratio
NF 1	0.01	1.0:0.5
NF 2	0.01	1.0:1.0
NF 3	0.01	1.0:1.5
NF 4	0.05	1.0:0.5
NF 5	0.05	1.0:1.0
NF 6	0.05	1.0:1.5
NF 7	0.10	1.0:0.5
NF 8	0.10	1.0:1.0
NF 9	0.10	1.0:1.5

Suspension Performance. Thermophysical properties data were utilized to determine the effectiveness of the nanofluid under both laminar and turbulent flow status. In general, a suspension can be considered beneficial under laminar condition if the ratio between the viscosity enhancement coefficient and the thermal conductivity improvement coefficient (Cλ/Cμ) is > 0.25. However, for a nanofluid to be beneficial under a turbulent flow status, its Mouromtseff number (Mo) should be > 1. The following equations were used to obtain Cλ/Cμ and Mo [24]:

$$\frac{C_\lambda}{C_\mu} = \frac{(\lambda_{NF}-\lambda_{BF})/\lambda_{BF}}{(\mu_{NF}-\mu_{BF})/\mu_{BF}} \quad (1)$$

$$Mo = \left(\frac{\lambda_{NF}}{\lambda_{BF}}\right)^{0.67} \times \left(\frac{\rho_{NF}}{\rho_{BF}}\right)^{0.8} \times \left(\frac{C_{NF}}{C_{BF}}\right)^{0.33} \times \left(\frac{\mu_{NF}}{\mu_{BF}}\right)^{-0.47} \quad (2)$$

where λ, μ, ρ, and C are the thermal conductivity, viscosity, density, and specific heat capacity respectively. The subscript BF and NF in Eqs. (1) and (2) refer to basefluid and nanofluid, respectively.

Furthermore, the performance of both pumping power and heat transfer of the nanofluids were determined through their pumping power figure of merit (FoM_{Pump}) and heat transfer figure of merit ($FoM_{Heat\ transfer}$), consecutively. The equations used in determining both figure of merits are shown below [21]:

$$FoM_{\text{Pump}} = \left(\frac{\rho_{NF}}{\rho_{BF}}\right)^{-2} \times \left(\frac{C_{NF}}{C_{BF}}\right)^{-2.8} \times \left(\frac{\mu_{NF}}{\mu_{BF}}\right)^{0.2} \quad (3)$$

$$FoM_{\text{Heat } transfer} = \left(\frac{\lambda_{NF}}{\lambda_{BF}}\right)^{0.6} \times \left(\frac{\rho_{NF}}{\rho_{BF}}\right)^{0.34} \times \left(\frac{C_{NF}}{C_{BF}}\right)^{0.06} \times \left(\frac{\mu_{NF}}{\mu_{BF}}\right)^{-0.44} \quad (4)$$

Results and Discussion

Suspension Effectiveness Under Different Flow Condition. The effectiveness of the nanofluids denoted as NF 1 to NF 9 under laminar condition is shown in Fig. 1. It can be seen from the plotted data that all of the different nanofluids are beneficial for usage under such flow condition; apart

from the NF 2 type of suspension at 10°C, which had a Cλ/Cμ value of 0.08. This is mainly because the Cλ/Cμ for the different dispersions at various temperatures had a value higher than 0.25, which is the threshold that distinguish between the effectiveness and non-effectiveness of the working fluid. Nevertheless, at a low temperature range (i.e., 10°C to 30°C), the higher vol.% suspensions (NF 7 – NF 9) showed to outperform their counterpart. The previous can be linked to the effectiveness of the SDS surfactant on the dispersion stability at such temperature range and the higher thermal conductivity gains caused by increasing the nanoparticles concentration. On the other hand, raising the temperature reduces the influence of the SDS surfactant on the physical stability of the dispersed particles. This causes higher particles concentrations to cluster faster into forming sedimentation. Hence, the suspension becomes less physical stable, and therefore its thermal conductivity reduces. The previous can be noted from the 70°C scenario, where the NF 1 – NF 3 (i.e., 0.01 vol.% suspensions) showed to be more beneficial under laminar condition compared to the other variants. In general, increasing the temperature was found to increase the effectiveness of the working fluid under laminar condition, simply because the thermal conductivity of the basefluid itself (i.e., water) increases with the rise of its temperature. The highest obtained Cλ/Cμ was 132.8, which corresponds to the NF 1 suspension at 70°C. This Cλ/Cμ value is 72.8% higher than lowest Cλ/Cμ case (i.e., NF 9) at the same temperature.

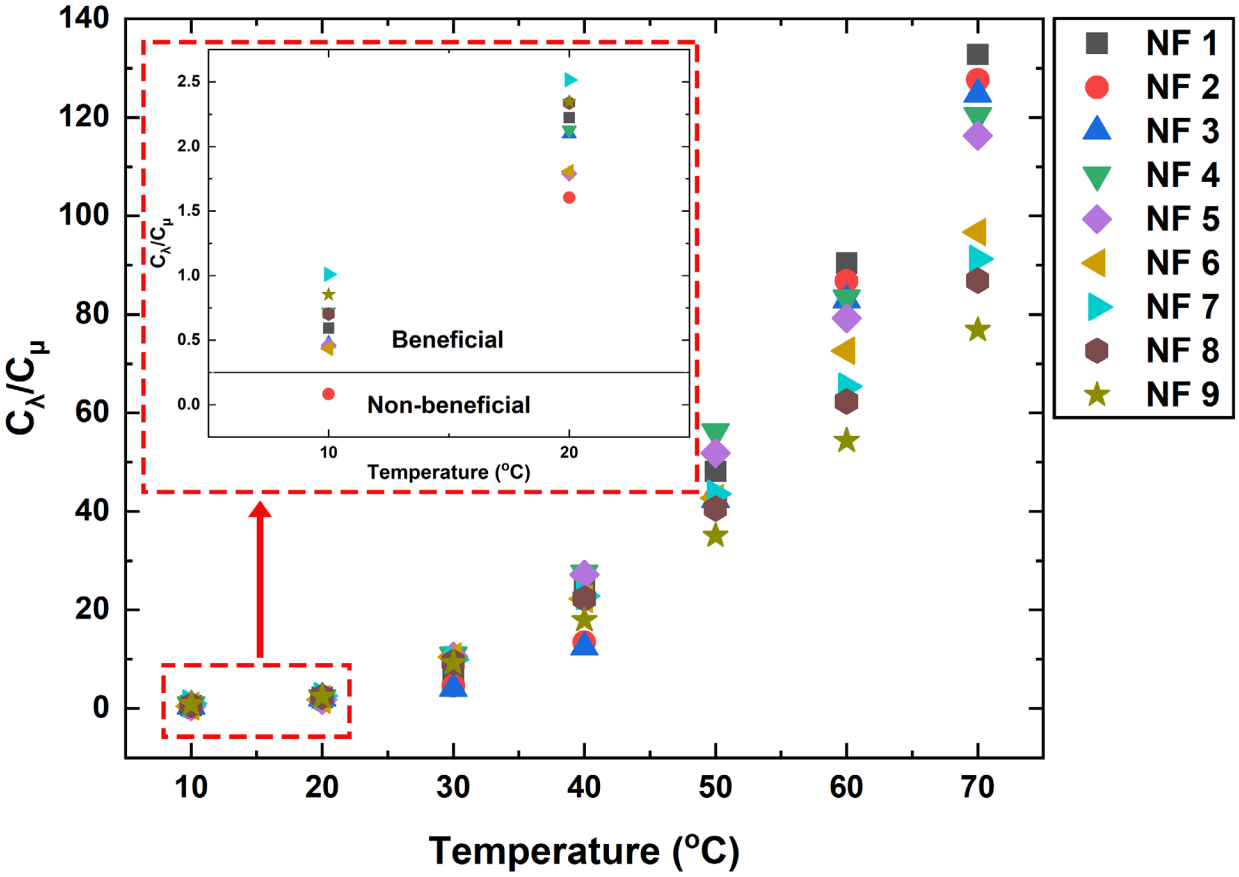

Fig. 1. Ratio between the viscosity enhancement coefficient and the thermal conductivity improvement coefficient of different nanofluids at various temperatures.

As for the effectiveness of the suspensions under turbulent condition (Fig. 2), it was found that all of the different nanofluids were not beneficial for usage in applications operating at 10°C because they had a Mo value less than 1. Also, at 20°C, only NF 1 – NF 4 were able to overcome the Mo > 1 threshold, thus demonstrating their effectiveness under turbulent flow condition. Beyond the 20°C point, all types of nanofluids were found to be effective under turbulent status,

with the highest being NF 7 at 70°C with a Mo of 1.61. It is to be noted that, unlike the laminar from cause, increasing the concentration of GN causes an improvement in the Mo value, and therefore enhancing its effectiveness as a working fluid under turbulent flow condition. The previous is reasonable when considering that turbulent flow improves the mixing of the suspended particles. Hence, the nanofluid can be seen as physically stable and relies considerably on the vol.% of the suspension and the effect of basefluid temperature, which corresponds both to the overall thermal conductivity of the suspension.

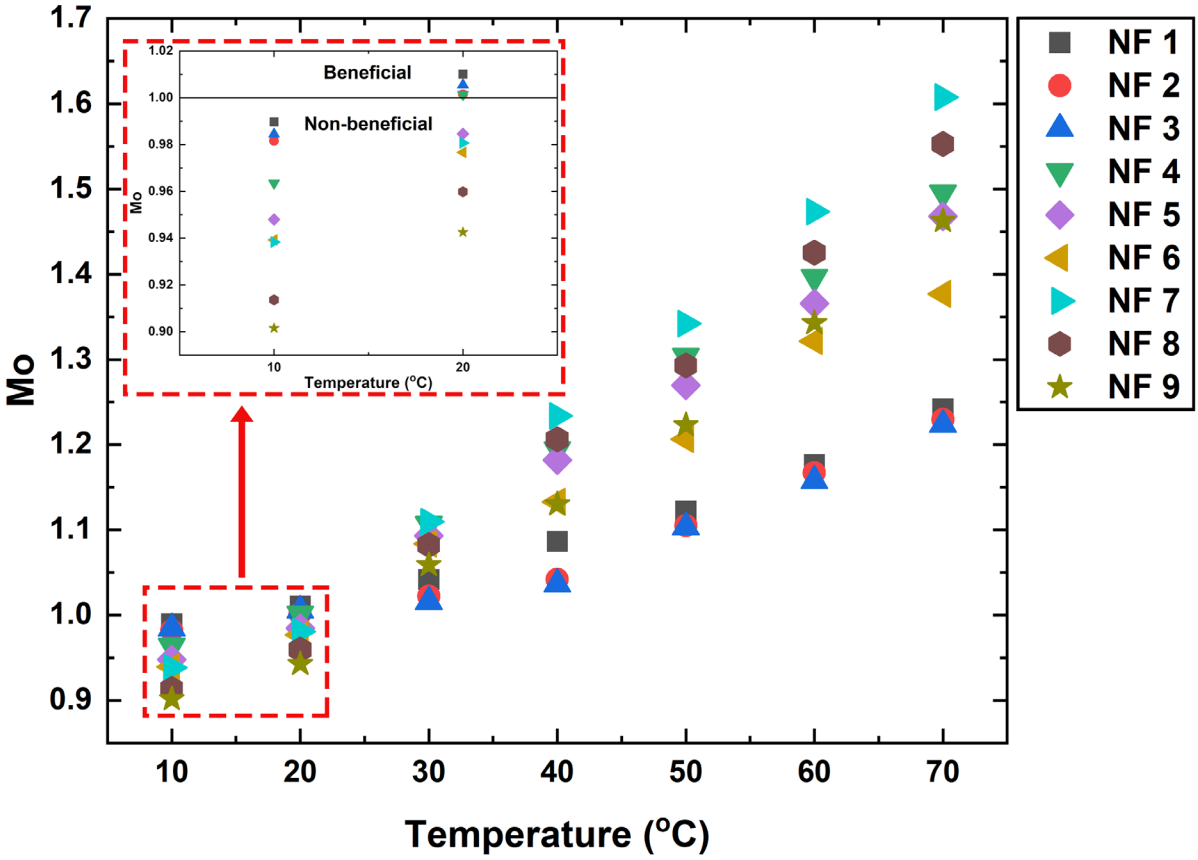

Fig. 2. Mouromtseff number of different nanofluids at various temperatures.

Nanofluid Performance. FoM_{Pump} and $FoM_{Heat\ transfer}$ results are shown in Fig. 3 and Fig. 4, respectively. From Fig. 3, it can be seen that NF 1 – NF 3 had the highest FoM_{Pump}, which is due to these nanofluids having the lowest dispersed GN concentration (i.e., 0.01 vol.%). Increasing the vol.% showed to decrease the FoM_{Pump}, as in the causes of NF 4 – NF 9. Notably, increasing the SDS surfactant concentration was also shown to cause a decrease in the FoM_{Pump}. For example, the level of reduction in the FoM_{Pump} between the NF 7 (GN:SDS weight ratio of 1.0:0.5) and NF 9 (GN:SDS weight ratio of 1.0:1.5) was found to be ~25%. The previous is likely due to the increase in suspension density, which plays a crucial role in calculating the FoM_{Pump}. Furthermore, the temperature of the suspension, as a parameter, had a negligible influence on the previous figure of merit.

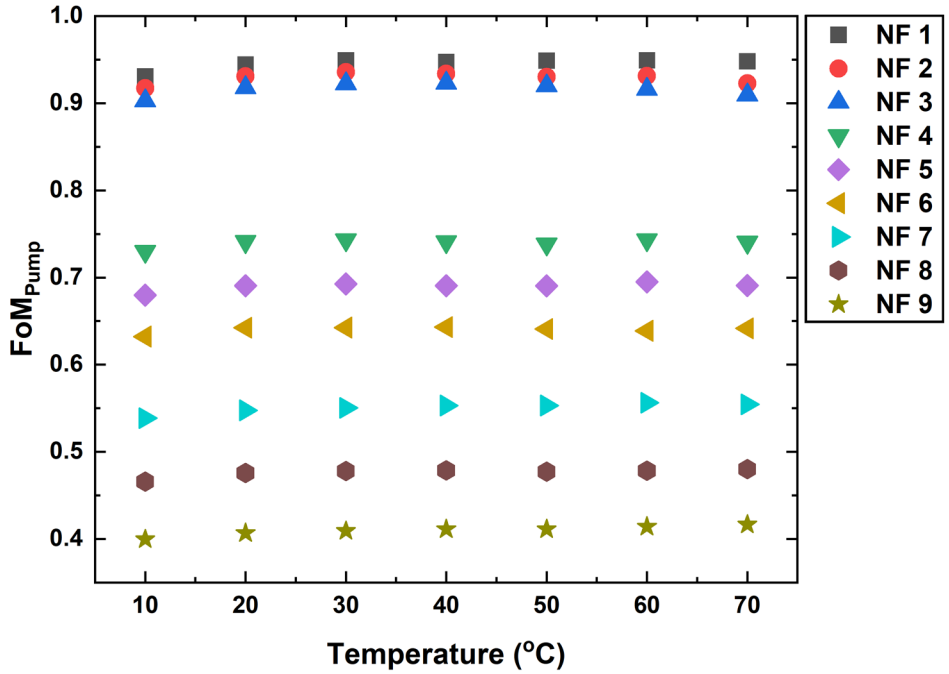

Fig. 3. Pumping power figure of merit of different nanofluids at various temperatures.

In contrast, analysis of the outcomes in Fig. 4 demonstrates that the liquid temperature and GN concentration are both crucial parameters for obtaining a higher $FoM_{Heat\ transfer}$ in the working fluid. In addition, surfactants are well-known to reduce the effective thermal conductivity of the suspension [11]. This is why the nanofluids of high nanoparticles vol.% with lower SDS concentration is seen to overperform thus with similar vol.% but higher SDS concentrations (e.g., NF 7 and NF 9). The highest $FoM_{Heat\ transfer}$ was achieved with the NF 7 suspension at 70°C (i.e., 1.62), whereas the lowest was found to be 1.01 with the NF 2 dispersed at 10°C.

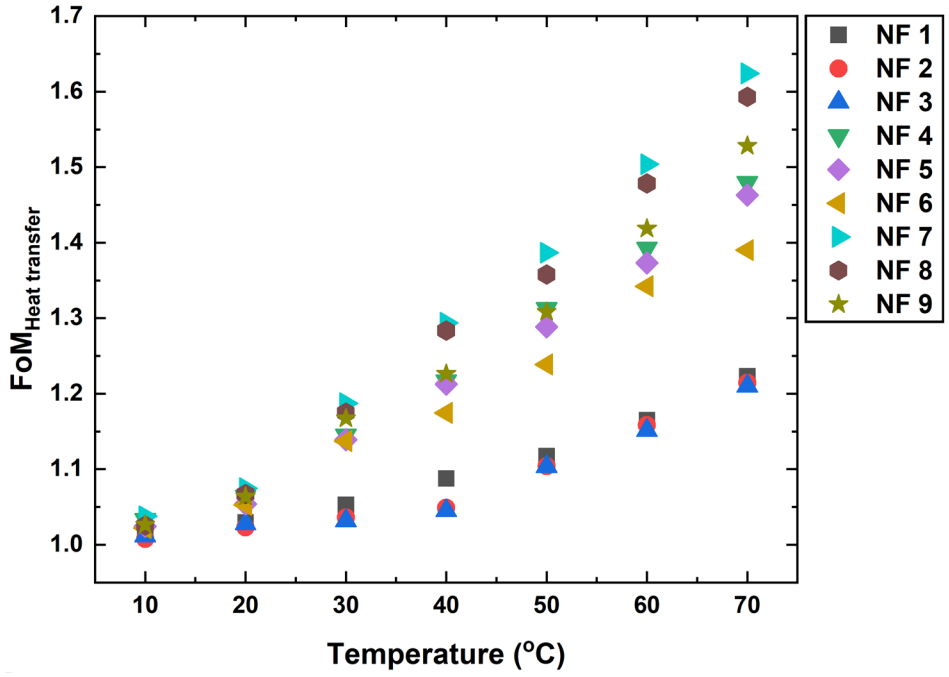

Fig. 4. Heat transfer figure of merit of different nanofluids at various temperatures.

Conclusions

An evaluation of the thermal-hydraulic performance of dispersed graphene in water nanofluids. The explored concentrations of GN were 0.01 vol.% to 0.10 vol.%, across a temperature range of 10°C to 70°C. Sodium dodecyl sulphate surfactant of 0.5 to 1.5:1 (SDS to GN weight ratio) was also encountered in the study due to its importance in maintaining the suspension physical stability. Afterwards, the effectiveness of the suspensions under laminar and turbulent flow conditions were encountered along with the pumping power figure of merit and the heat transfer figure of merit.

The results have shown that all types of nanofluids were effective under laminar flow condition except for the NF 2 case at 10°C, which had a $C\lambda/C\mu < 0.25$. Furthermore, the highest $C\lambda/C\mu$ was found to be 132.8, corresponding to the NF 1 case at 70°C. As for turbulent flow conditions, all of the suspensions at 10°C and most of them at 20°C demonstrated to be non-beneficial due to their Mo value being lower than 1. Beyond these temperature points, all types of nanofluids showed > 1 Mo values, with the highest achieved with the NF 7 dispersion at 70°C (Mo = 1.61). Thus, reflecting the crucial role of dispersed particles concentration and liquid temperature on the effectiveness of the fluid. A clear trade-off was found between the FoM_{Pump} and $FoM_{Heat\ transfer}$, where the first favored the lower particles loading as a pose to the second. Accordingly, the highest FoM_{Pump} was achieved with the 0.01 vol.% suspensions, whereas the 0.10 vol.% nanofluids were more effective in terms of the $FoM_{Heat\ transfer}$.

The results herein can be used by researchers and decision makers as guidelines to examine the effectiveness of similar (or other) suspensions before employing them in their thermal systems. However, other factors should also be considered, such as the techno- and thermo-economic of the dispersion, to fully ensure the success of the operation.

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