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ORIGINAL ARTICLE

Hybrid nanofluids for working fluid in a microchannel heat sink; hydrothermal analysis

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Abstract
Hybrid nanofluids with superior thermal characteristics can be a new choice of working fluid in enhancing the heat dissipation rate of microchannels heat sink. Therefore, this paper deals with the hydrothermal characteristics of a microchannel heat sink utilizing MWCNT-Al_2O_3/water hybrid nanofluids. The thermal conductivity and viscosity of mono and hybrid nanofluids were measured and new experiential correlations were derived. The convective tests were carried out in three different composition ratios as well as two volume fractions of hybrid nanofluids at different Reynolds numbers. The results showed that MWCNT-Al_2O_3/water hybrid nanofluid at composition ratio of (80:20) and 0.05% vol. had the highest performance evaluation criteria value.

Abbreviations

Nomenclature

c_p	Specific Heat Coefficient
d	Diameter, m
D	Hydraulic Diameter
DFE	Degrees of Freedom Error
EM	Electron Microscope
FESEM	Field Emission Scanning Electron Microscopy
h	Heat Transfer Coefficient
k	Thermal conductivity,$\frac{W}{mK}$
Q	Heat Dissipated
$\dot{m}$	Flow Rate
MSE	Mean Square Error
Re	Reynolds Number
S	Standard Deviation
SEM	Scanning Electron Microscope
SSE	Sum of the Squared Errors
T	Temperature, K
TEM	Transmission Electron Microscopy
V	Flow Velocity

Greek symbols

ρ	Density, $\frac{kg}{m^3}$
ϕ	Volume fraction
μ	Dynamic viscosity, cP

Subscript

bf	Base fluid
Eff	Effective
hnf	Hybrid nanofluid
in	Inlet
m	Mean
nf	Nanofluid
out	Outlet
p	Paticle
S	Surface

1 Introduction

Thermal management plays an important role in several critical industrial sectors including microelectronics, transportation, thermal power plants, and concentrated solar thermal systems [1–5]. With recent advancement in the microelectronics industry, microchip transistors have shifted towards micro/nano-sized scales generating a significant amount of heat at a small footprint. Therefore, the need for more efficient cooling systems to effectively transfer more heat away from microchips is essential. The new cooling systems need to be proportionate to the dimensions of the microchips.

One of the most efficient methods in the electronics industry to eliminate high heat flux is to use mini / microchannels due to their large size and ability to dissipate heat. [6]. Tuckerman and Pease first proposed the idea of using microchannels in 1981 [7]. They proposed using

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microchannels for very large scale integrated circuits (VLSI) about three decades ago to achieve high-capacity cooling. Choi and Eastman [8] dispersed nanometer-scale particles in the base fluid and creating a new generation of fluids called nanofluids. Heat transfer rate is raised by using nanofluids instead of common fluids such as water, oil and ethylene glycol. Ho et al. [9] studied Al_2O_3/water nanofluids in a microchannel heat sink by 25 channels with a rectangular cross section and a length of 50 mm. They investigated the rate of heat transfer in the range of Reynolds numbers from 276 to 1676. Their results showed that at a volumetric concentration of 1%, the coefficient of heat transfer increases by 70% compared to water. The effect of different cross-sectional areas on microchannel performance was studied by Vinoth and Kumar [10]. They employed Al_2O_3/water nanofluid as thermal fluid in the microchannel. In their experiments, Reynolds number was between 250 and 850 and three cross-sections of semicircular, trapezoidal and square were used. A trapezoidal cross-section microchannel showed better performance than the other two. When water was employed as the operating fluid in the trapezoidal channel, the Nusselt number increased by 8.47% and 18.3% compared to the cross sectional area of the square and semicircle, respectively. They also showed that the use of nanofluids in the trapezoidal microchannel increases the Nusselt number compared to the square and semicircular channels by 7.03 and 17.47%, respectively. The thermal and hydrodynamic performance of CNT/water in microchannels was studied by Ghazali et al. [11]. They also examined the effect of the micro-channel cross-section and showed that a channel with a circular channel performed better in terms of pressure drop.

Prior studies have shown that nanofluids also increase the pressure drop penalty within microchannels. Therefore, to make a better use of nanofluids and reduce the high pressure drop caused by them, a new generation of multiphase fluids, termed as hybrid nanofluids, was introduced. In this case, by suspending several different types of nanoparticles in the base fluid, it is possible to achieve the desired thermal properties of the nanofluid with less pressure drop.

Dynamic viscosity of MEPCM- Al_2O_3/water with mass fraction of 2, 5 and 10 percent was measured by Ho et al. [12]. Viscosity results at 30° C showed that Al_2O_3/ water nanofluid had higher viscosity than to MEPCM- Al_2O_3/ water and MEPCM / water hybrid nanofluid. They also observed that by increasing mass concentration dynamic viscosity increases. Thermal conductivity of MWCNT-COOH – Ag / water was investigated experimentally by Pourrajab et al. [13] at different concentrations of 0.004, 0.008, 0.04, and 0.16, and a temperature range of 20–50 °C. They found that thermal conductivity of MWCNT-COOH (0.16 vol %) – Ag (0.04 vol %) / water was 47.3% higher than the base fluid. Also, they presented a new correlation to estimate MWCNT-COOH–Ag/ water thermal conductivity. By measuring the hybrid nanofluids properties, studies were conducted to investigate thermal and hydrodynamic performances of them in mini-channels and microchannels. Ho et al. [14, 15] used Al_2O_3-MEPCM nanofluid in a copper mini-channel with 10 rectangular channels ($1 \times 1.5 \times 50mm$). The results showed that Al_2O_3 /water nanofluids were more efficient than hybrid nanofluids at high Reynolds. Sundar et al. [16] examined the Fe_3O_4-MWCNT / water stream in a tube. They found that using the hybrid nanofluids improved the Nusselt number by 14.81% and 31.1% in Reynolds of 3000 and 22,000, respectively. The pressure drop and heat transfer of TiO_2- Al_2O_3 in mini-channel was investigated by Kumar and Sarkar [17]. They showed that by increasing Al_2O_3 particle ratio in hybrid nanofluid, the heat transfer coefficient improved. About 12.77% increment was observed experimentally for Al_2O_3 nanofluids. Vinoth and Sachuthananthan [18] studied flow and heat transfer performance of nanofluids in two different microchannels. They used CuO/water, Al_2O_3/water and their hybrid nanofluid. They found that by applying pentagonal channel, heat transfer is increased by 12.34% compared to triangular channel. Kumar and Sarkar [19] experimentally investigated the Al_2O_3-MWCNT/water hybrid nanofluid effect on heat transfer and pressure drop of minichannel heat sink. They experimentally obtained that Al_2O_3-MWCNT/water improved the heat transfer rate by 44.02% than to the water. Moreover, the pressure drop than to the water, was increased by 51.2%. Xu et al. [20] investigated the effect of using GOPs/water in 0.4 wt. % and pulsing flows on the microchannel thermal performance. They investigated the effect of 4 signals on the microchannel thermal performance. They found that using the square frequency always increases the flow rate and heat transfer.

As mentioned, to improve the thermal systems performance, mini-channel and micro-channel heat sinks are employed. The use of microchannels is expected to further improve heat transfer rate than mini-channels. Also, the use of these heat sinks in micrometer dimensions allows us to cool electronic microchips at small-scale. The above literature survey reveals that mono and hybrid nanofluids have better thermal performance than conventional fluids. Moreover, hybrid nanofluids have several advantages due to their combined effects of nanomaterials. Therefore, in the present study, in order to cool small electronics equipment, a microchannel heat sink was studied. Additionally, MWCNT-Al_2O_3/water was considered as operating fluid. Due to the novelty of hybrid nanofluids, sufficient desirable models and correlations have not yet been developed to measure the properties of these thermal fluids. Therefore, the properties of hybrid nanofluids are also measured and empirical correlations are proposed to calculate their properties, in the present study. Furthermore, hybrid nanofluids effect on the microchannel heat sink performance is experimentally investigated.

2 Experimental apparatus and testing procedure

2.1 Preparing hybrid nanofluids

In present study, to prepare nanofluids in large quantities, two-step method was used. By dispersing spherical nanoparticles of Al_2O_3 (Plasma Chem GmbH) with a mean diameter of 40 nm in distilled water, Al_2O_3 nanofluid was prepared. The Al_2O_3 nanoparticles Properties are listed in Table 1. To create a uniform mixture, the solution was sonicated at 400 W and 24 kHz for 4 h with an ultrasonic probe (UP400S, Hielscher GmbH). Then, a homogeneous Al_2O_3/water suspension was obtained in a volume concentration of 0.1%. Solutions with concentrations of 0.05% and 0.01% were also obtained by diluting the 0.1% suspension. In each step, the nanofluid was diluted and then placed in an ultrasonic device for 30 min.

The MWCNT/water nanofluids with a 1% mass concentration were purchased from VCN Materials Company and diluted to 0.1, 0.05 and 0.01% volumetric concentrations. The diluted nanofluid was sonicated for 30 min before being tested. Table 2 lists the properties of the carbon nanotubes used in this study. The nanofluids prepared in the prior steps were used in composition ratios of 80:20, 70:30, 50:50, 30:70, and 20:80 at volumetric concentrations of 0.1, 0.05, and 0.01, to produce the Al_2O_3-MWCNT/water hybrid nanofluids. Samples stability based on our sedimentation examination was acceptable after 30 days.

Electron microscope (EM) images of the nanofluids were taken to evaluate shape, size, and scale of the particles. Figure 1a to c show a transmission electron microscopy (TEM) image of the MWCNT/water at 1% wt., scanning electron microscope (SEM) image of the Al_2O_3/water in 0.1% vol., and a field emission scanning electron microscopy (FESEM) image of the Al_2O_3-MWCNT/water at 0.05% vol. concentration, respectively.

2.2 Microchannel heat sink

As illustrated in Fig. 2, a copper microchannel heat sink employing 40 parallel channels with a rectangular cross-sectional area of $216 \times 40\ \mu m^2$ and a length of 25 mm was fabricated. To simulate the heat flux from the CPU, two cartridge heaters with a diameter of 8 mm and a power density of 250 W/cm^2 were used. Experimental setup was shown in Fig. 3. A 3 kW dimmer was used to control the heater's voltage. The microchannel surface temperature was measured by four K-type thermocouples. The fluid tank was located in a constant temperature bath. The temperature of the inlet and outlet fluid was measured using two digital thermometers. The nanofluid was pump by a gear pump whose voltage and current were adjusted by a power supply (Megatek-MP-3010). The fluid pressure was measured by a pressure transmitter (Wikia10) and data were transferred to a computer using a data logger. The experiment was performed on four different Reynolds numbers of 300, 500, 700, and 900.

Table 1 Properties of Al_2O_3 nanoparticles

Purity	+99.9%
Shape	Spherical
Mean Diameter	nm 40
Color	White
Density (ρ)	3.97 $^{g}/_{cm^3}$

Table 2 Properties of MWCNT nanoparticle

Purity	+95%
Length	µm 10–50
Mean Diameter	nm 20–30
specific surface area	> 200$^{m^2}/_{g}$
Color	Black
Density (ρ)	2.1 $^{g}/_{cm^3}$

2.3 Property measurement

In this research, viscosity, thermal conductivity, and density of MWCNT/water, Al_2O_3/water and their hybrid nanofluids were experimentally measured. The thermal conductivity of nanofluids was investigated by a KD2-Pro analyzer [21]. The kinematic viscosity was measured experimentally via a Fischer reverse tube capillary viscometer. Furthermore, a hydrometer was used to measure the nanofluid density. Figure 4 illustrates a schematic of property measurement setup. The simple and hybrid nanofluids thermophysical properties were measured in the temperature between 25 to 65 °C. In the process of measuring the properties, there was the challenge of keeping the nanofluid temperature constant at high temperatures. For this purpose, a constant temperature water bath was employed.

2.4 Data reduction

The definition of Reynolds number is:

$$Re = \frac{VD}{\nu} \tag{1}$$

Measuring the temperatures of inlet and outlet working fluid, heat dissipated by the microchannel heat sink is calculated as:

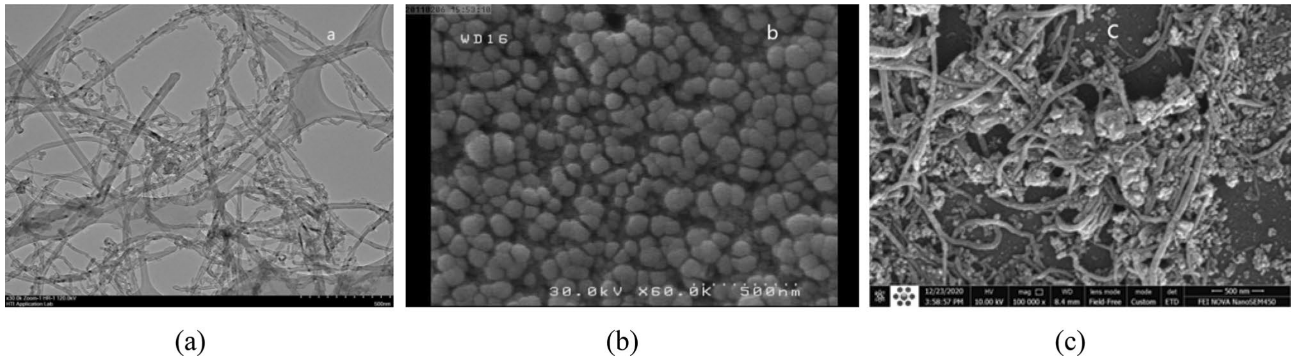


Fig. 1 Electron Microscope (EM) images of constructed nanofluids: **a** MWCNT/water, **b** Al_2O_3/water, and **c** Al_2O_3-MWCNT/water

$$Q = \dot{m}C_p(T_{out} - T_{in}) \tag{2}$$

Equation (3) calculated the base area of heat sink:

$$A = N[L_{CH}(W_{CH} + 2H_{CH})] \tag{3}$$

Equation (4) calculates the heat transfer coefficient:

$$h = \frac{Q}{A(T_s - T_m)} \tag{4}$$

The microchannel surface temperature is also calculated from the averaged measured temperatures by the four thermocouples accounting the distance between the center hole of thermocouples and the solid–liquid interface applying Fourier law.

$$T_s = \frac{\sum_{i=1}^{4} T_{s.i}}{4} \tag{5}$$

The fluid mean temperature is also obtained from the average inlet and outlet fluid temperatures.

$$T_m = \frac{T_{out} + T_{in}}{2} \tag{6}$$

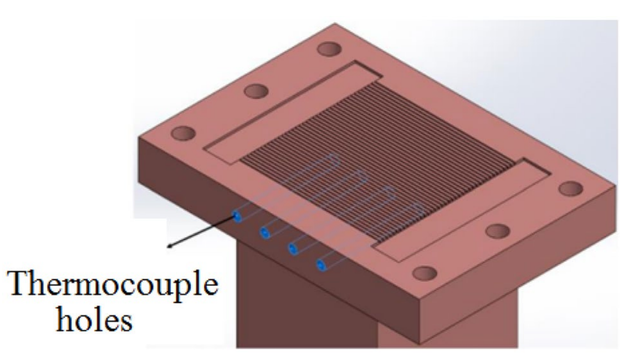


Fig. 2 The studied microchannel heat sink

The Nusselt number is also calculated according to Eq. (7):

$$Nu = \frac{hD}{k} \tag{7}$$

By measuring the flow rate and pressure drop, the friction factor is calculated as follows:

$$\mathrm{f} = \frac{2D\Delta P}{L\rho U^2} \tag{8}$$

2.5 Uncertainty analysis

Uncertainty of an experimental measurement can be estimated by Eq. (9) presented by Kline and McClintock [22]:

$$\omega_R = \left[\left(\frac{\partial R}{\partial x_1}\omega_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\omega_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\omega_n\right)^2\right]^{1/2}$$
$$\therefore \mathrm{R} = \mathrm{f}(x_1, x_2, \cdots, x_n) \tag{9}$$

where ω_i is uncertainty for measurement x_i. Uncertainty of thermal conductivity measurement through KD2-Pro device is ± 0.01 for the range of $0.02 - 0.2\left(\frac{W}{m.K}\right)$ and $\pm 5\%$ for the range of $0.2 - 2\left(\frac{W}{m.K}\right)$. Uncertainty of capillary viscometer is a function of viscometer precision (0.3%) and uncertainty of timing.

Since each test was repeated six times, uncertainty of the measurement is equal to the standard deviation of the experimental point. The standard deviation is calculated from Eq. (10).

$$\sigma = \left[\frac{\sum_{i=1}^{n}(x_i - x_m)^2}{n-1}\right]^{1/2} \tag{10}$$

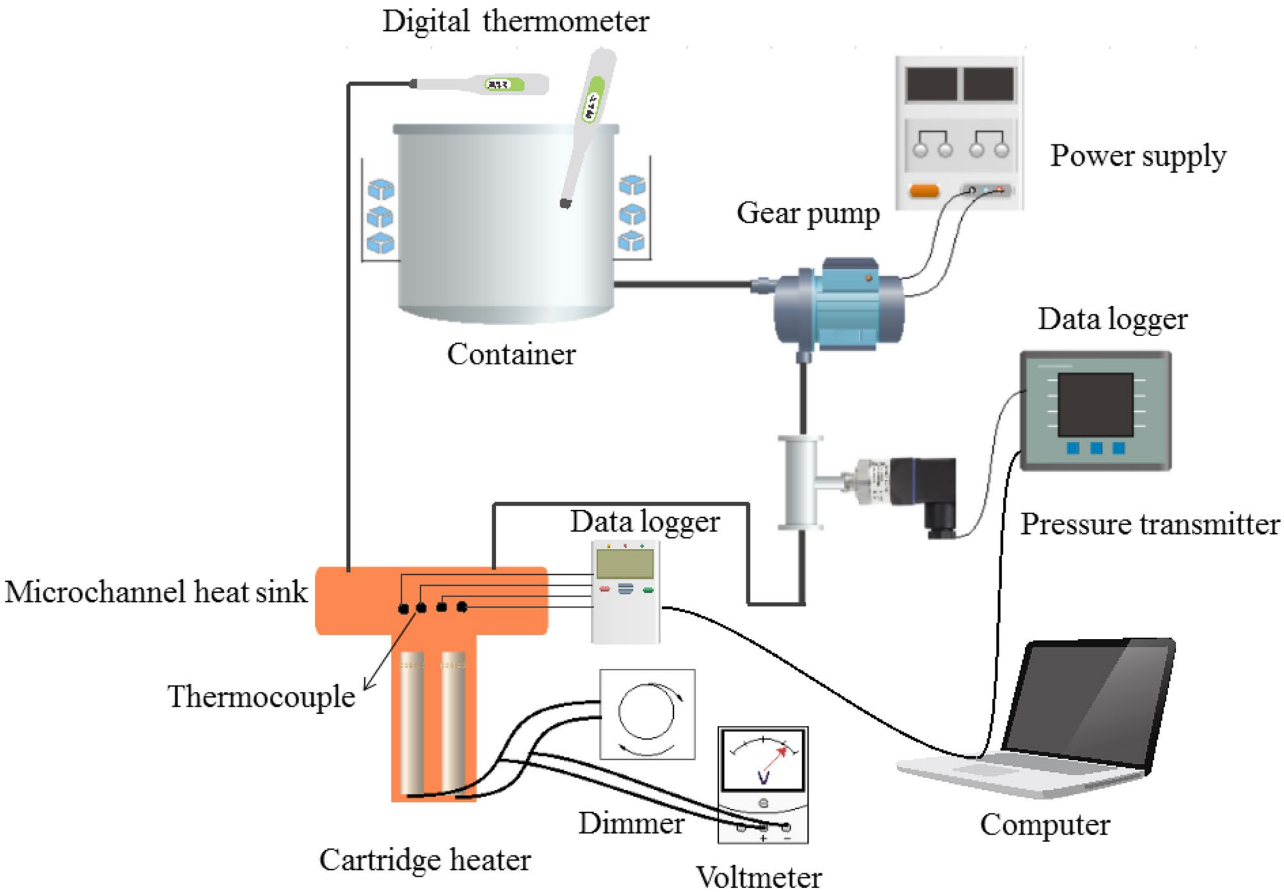


Fig. 3 Experimental setup of the microchannel heat sink

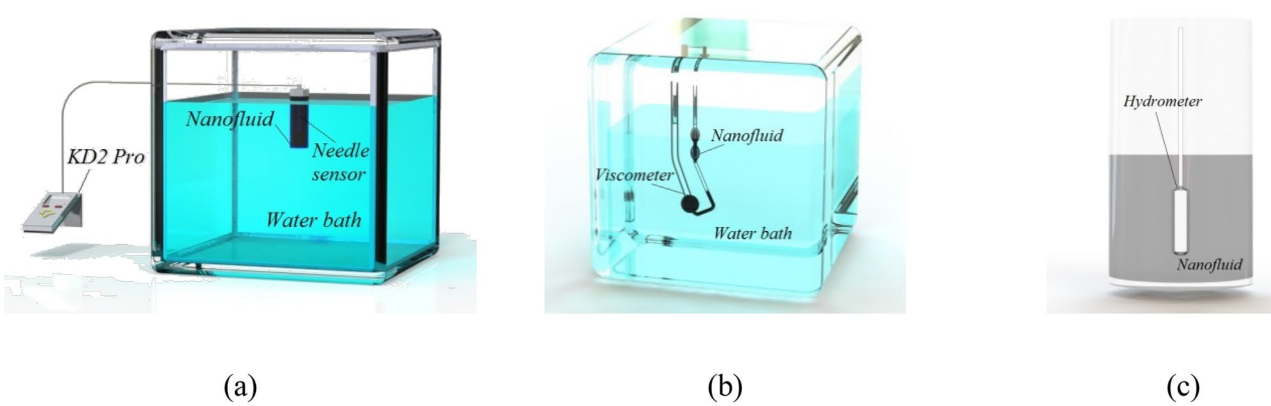


Fig. 4 A schematic of **a** the thermal conductivity analyzer, **b** capillary viscometer, and **c** hydrometer

3 Results

3.1 Properties measurement results

The effects of nanoparticles composition ratio, temperature, and volumetric concentration on hybrid and mono nanofluids thermophysical properties were first studied. To estimate the hybrid nanofluids viscosity and thermal conductivity, new empirical correlations were proposed. To evaluate equipment and method accuracies, properties of pure water was measured and compared with reference data [23]. Results showed a proper conformity of the present work and the reference data as Fig. 5 demonstrates.

Properties of MWCNT/water, Al_2O_3/water, and hybrid nanofluids were measured at different composition ratios and temperatures. The effects of temperature and composition ratio

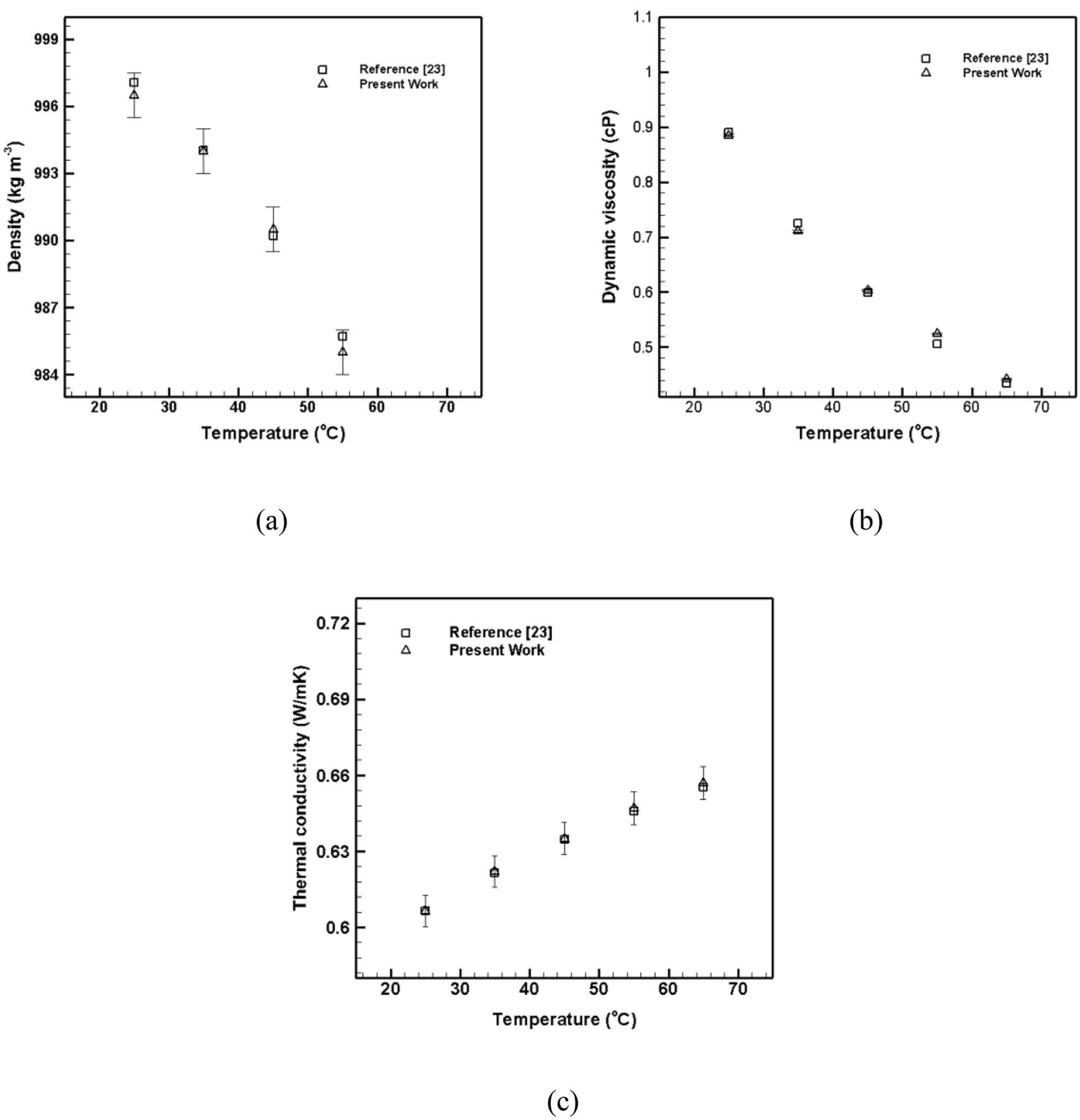


Fig. 5 A comparison of measured water **a** density, **b** dynamic viscosity and **c** thermal conductivity against reference data at different temperatures

are shown in Fig. 6. As evident, by raising the temperature, density and viscosity of the hybrid nanofluid decrease. As illustrated in Fig. 6a, the changes in density at higher temperatures are more sensitive to the addition of nanoparticles. While on the contrary, the viscosity of fluid is more sensitive to the addition of nanoparticles in lower temperatures as found from Fig. 6b. Also, the nanofluids with higher MWCNT content are often more viscous. Figure 6c shows the change in nanofluids thermal conductivity is greater at high temperatures. Moreover, nanofluids with more MWCNTs have greater thermal conductivity than others. For instance, the measured thermal conductivities of hybrid nanofluids with composition ratios of (30:70), (50:50), and (70:30) are 0.736, 0.712, and 0.697 $Wm^{-1} K^{-1}$, respectively.

Two experimental correlations are proposed to predict the thermal conductivity and viscosity of studied nanofluids, i.e. Equations (11, 12). By using a curve fitting method, the obtained correlations reproduce the hybrid nanofluids

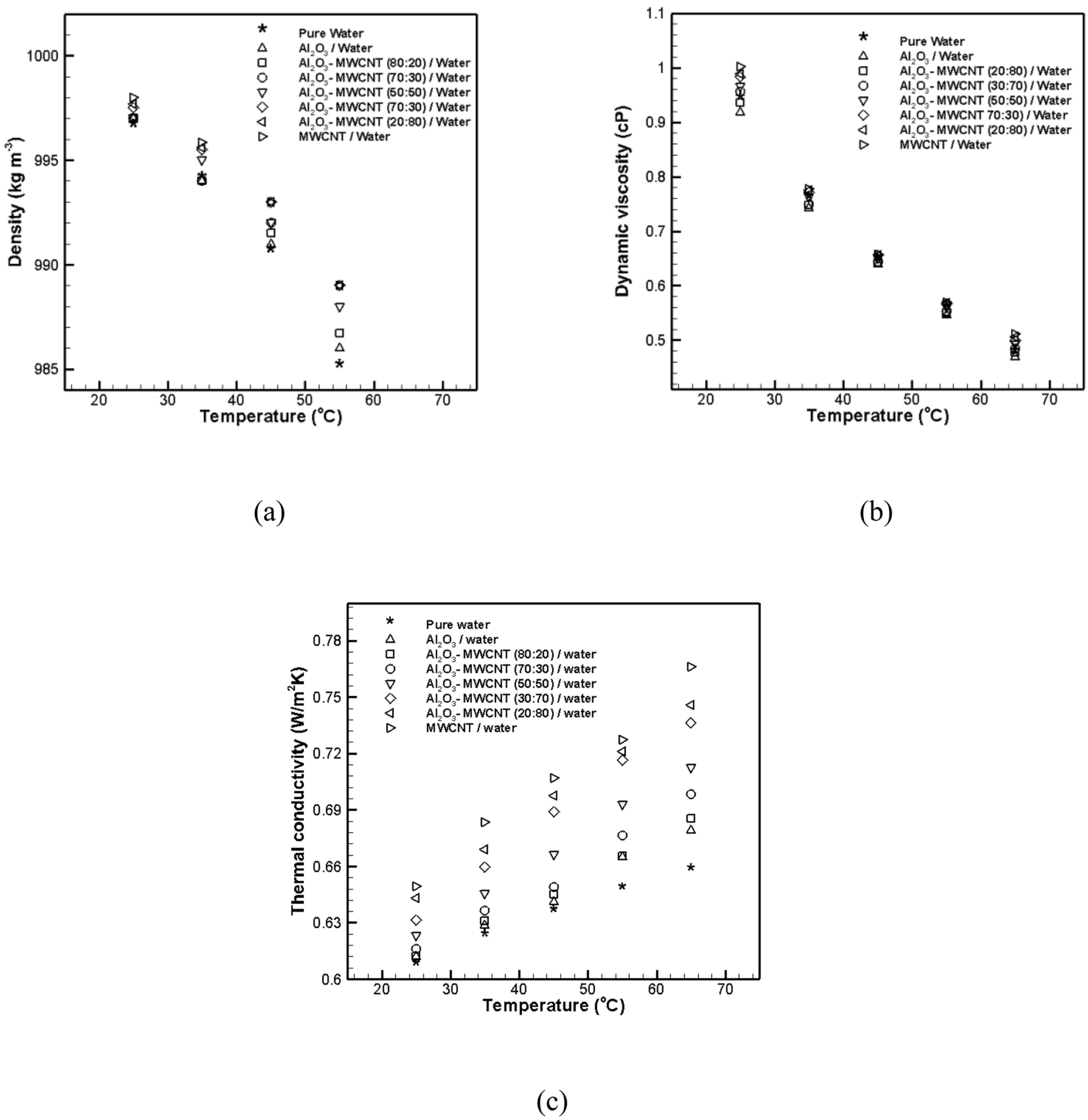


Fig. 6 **a** Density, **b** dynamic viscosity, and **c** thermal conductivity of nanofluids against temperature at a volume concentration of 0.1%

thermal conductivity and viscosity values with a maximum error of 4% and 2%, respectively. The outcomes of the proposed correlations versus the measured data of the present study are compared in Fig. 7.

$$\mu = -1.00234e^{0.00014T}\left\{\phi\left[-1.73507n_{Al}\rho_{Al} -26.92520n_{CNT}\rho_{CNT}\right] + (\phi - 1)\mu_b\right\} \tag{11}$$

$$k = 0.6480e^{(0.0014T)}\left\{\phi\left[-0.2615n_{Al}k_{Al} +0.0159(n_{CNT})k_{CNT}\right] + (1-\phi)k_b\right\} \tag{12}$$

3.2 Nusselt number

The Nusselt number can be a criterion for evaluating the microchannel heat sink thermal performance. Figure 8 shows the Nusselt number in terms of Reynolds variable in volumetric fraction of 0.05% and 0.1%. As illustrated in Fig. 8a, with raising the Reynolds number, the Nusselt number raises due to the thinning of the thermal boundary layer as well as reinforcement of convection. As shown in Fig. 8b, the results indicate that the heat transfer is further improved by raising the ratio of MWCNTs to Al_2O_3 in the hybrid nanofluid. This can be attributed to the higher thermal conductivity in addition to higher surface area of MWCNTs than Al_2O_3 nanoparticles. For example, the heat transfer rate for 0.1% vol. concentration of MWCNT/water than to the base fluid is augmented by 27.41% at Reynolds number of 900. Also, the heat transfer rate is increased by 9.35% and 4.95% for 0.1 and 0.05% Al_2O_3/water nanofluid, respectively. Adding a small amount of MWCNT particles to the Al_2O_3/water nanofluids can improves the heat transfer capability significantly. The heat transfer rate of Al_2O_3–MWCNT (80:20)/water hybrid nanofluid at 0.05% and 0.1% volume concentrations, increases by about 5.7% and 6.7% compared to the Al_2O_3/water nanofluids, respectively, which shows the importance of using hybrid nanofluids. The results also show that the Al_2O_3–MWCNT (20:80)/water increases the heat transfer by 21.87% more than the base fluid.

3.3 Pressure drop characteristics

The nanofluids pressure drop in the microchannel is shown in Fig. 9. As shown, with raising the nanofluid concentration, the pressure drop raises. In addition, with increasing the ratio of MWCNTs to Al_2O_3 due to increasing the viscosity of nanofluids, the pressure drop penalty increases. At a volume fraction of 0.1%, MWCNT/water than to the base fluid increases the pressure drop by about 89%. However, replacing 20% of MWCNT with Al_2O_3 nanoparticles can reduce the pressure drop increment to 64% relative to the base fluid.

3.4 Friction factor

The friction factor of nanofluids is shown in Fig. 10. Because of the thinning of the fluid boundary layer by raising the Reynolds number, the friction factor of nanofluids decreases. The results show that with raising the

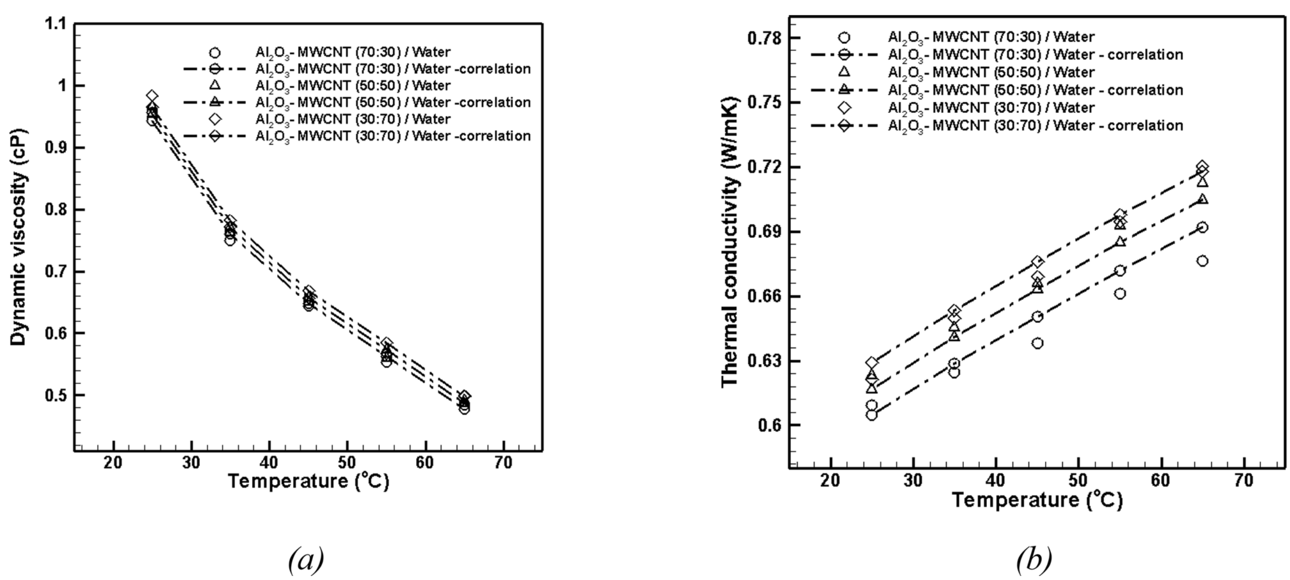


Fig. 7 A comparison of the proposed empirical correlation and experimental data for **a** dynamic viscosity, and **b** thermal conductivity of Al_2O_3-MWCNT/water hybrid nanofluids at a 0.1% volumetric concentration

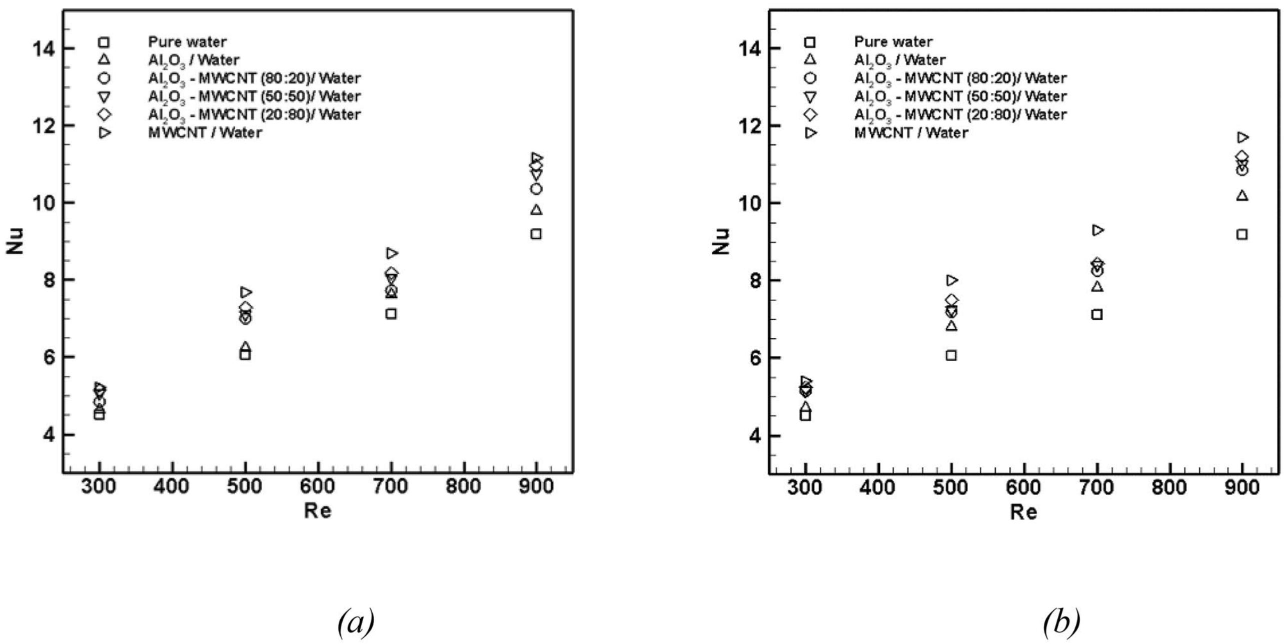


Fig. 8 Nusselt number as a function of Reynolds number for different nanofluids at **a** 0.05% and **b** 0.1% volume concentration

concentration of nanoparticles as well as increasing the ratio of MWCNT nanoparticles in hybrid nanofluids, the friction factor increases.The reason is MWCNT nanoparticles cause a greater pressure drop than Al_2O_3 nanoparticles.

3.5 Performance evaluation criteria (PEC)

To determine whether the use of nanofluids is useful or not, it is not sufficient to examine the heat transfer rate or pressure drop penalty independently. The PEC is defined

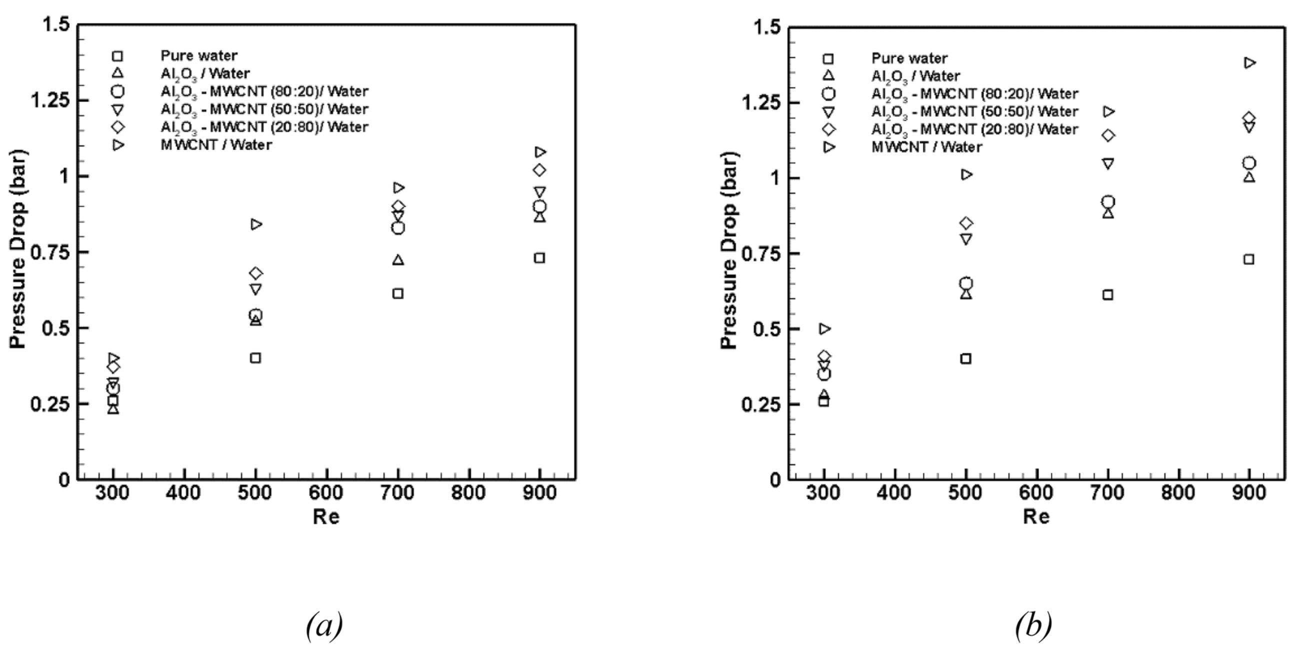
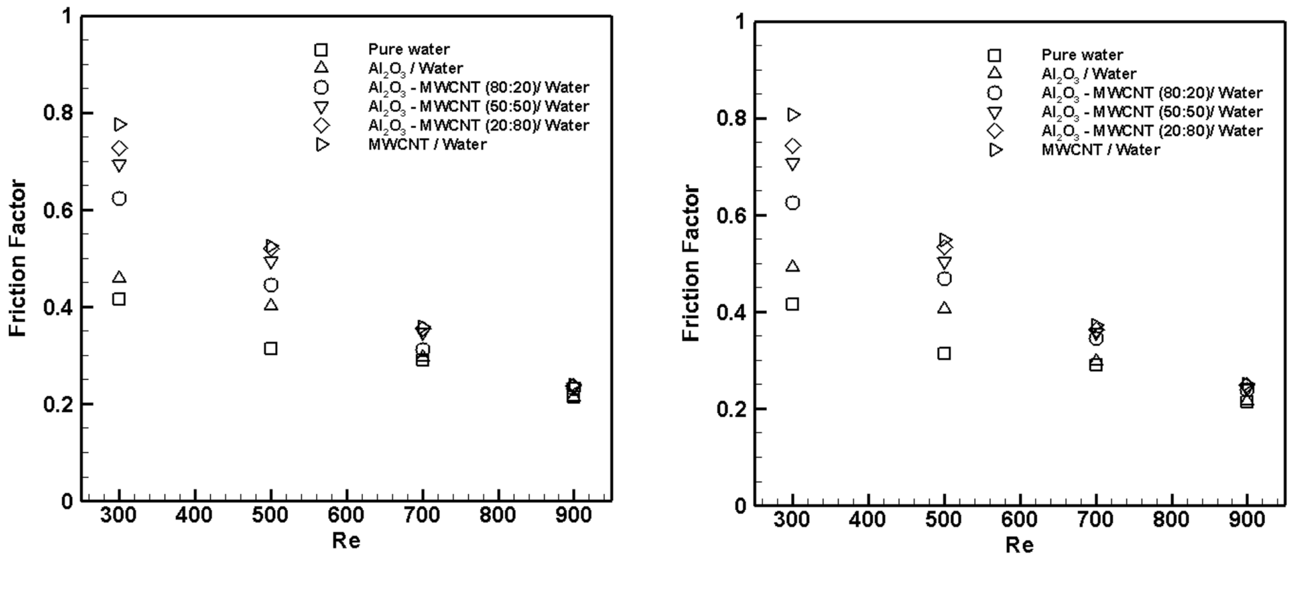


Fig. 9 Pressure drop as a function of Reynolds number for different nanofluids at (a) 0.05% and (b) 0.1% volume concentration



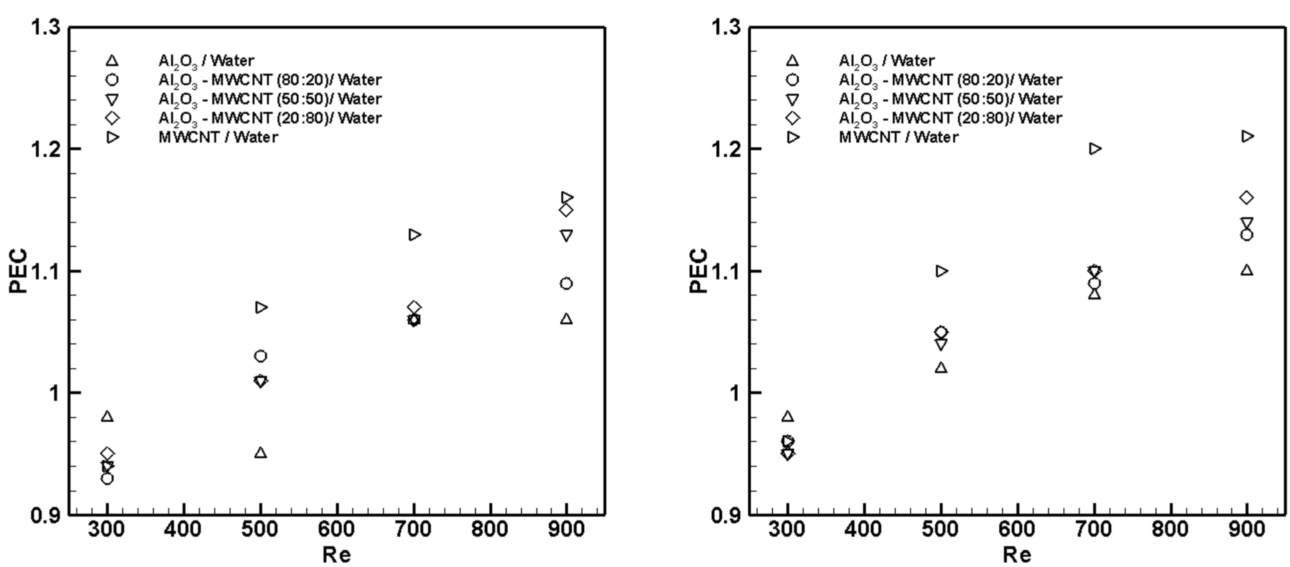
(a) (b)

Fig. 10 Friction factor in terms of Reynolds number for different nanofluids at **a** 0.05% and **b** volume concentration

to assess the justification for the use of nanofluids as follows:

$$\mathrm{PEC} = \frac{\frac{NU_{nf}}{NU_{bf}}}{\left(\frac{f_{nf}}{f_{bf}}\right)^{\frac{1}{3}}} \tag{13}$$

The PEC values greater than one indicate that the raises in the heat transfer rate dominates the rise in the pressure drop penalty, and the use of nanofluids is reasonably justified. Figure 11 shows the PEC values for studied nanofluids at volumetric concentration of 0.05% and 0.1%. The results indicate that at higher Reynolds numbers, the use of nanofluids is more justifiable than lower ones. As shown



(a) (b)

Fig. 11 PEC index in terms of Reynolds number for different studied nanofluids at **a** 0.05% **b** 0.1% volume concentration in Fig. 11a, the results reveal that at a Reynolds number of 900, the PEC index for Al_2O_3–MWCNT (20:80)/water hybrid nanofluid is 1.16, while it is 0.95 at a Reynolds number of 300.

4 Conclusion

Heat transfer efficiency of microchannel heat sinks using mono and hybrid nanofluids in two volume fractions of 0.05 and 0.1% was studied in the present investigation. In this regard, to calculate the convective heat transfer coefficient and pressure drop penalty, thermophysical properties of the different hybrid nanofluids were measured at 25–65 °C. The following results are obtained:

- The highest rise in the Nusselt number, which was equal to 27.41% than the base fluid, was observed for the MWCNT/water nanofluids in 0.1% a volumetric concentration.
- The Al_2O_3-MWCNT (80:20)/water nanofluid improves the heat transfer rate by about 7 and 6% compared to the Al_2O_3/water at concentrations of 0.1 and 0.05%.
- The results revealed that the heat transfer rate of Al_2O_3-MWCNT (80:20)/water at 0.05% vol. are higher than the Al_2O_3/water at a 0.1% volume fraction.
- The MWCNT/water nanofluid at 0.1% volumetric concentration had 89% higher pressure drop than to the water. However, the pressure drop of Al_2O_3-MWCT (20:80)/water was 64% higher compare the base fluid.
- The Al_2O_3-MWCNT /water hybrid nanofluid at composition ratio of (80:20) and 0.05% vol. had the highest PEC value.
- The viscosities of Al_2O_3-MWCNT/water hybrid nanofluids at composition ratios of (30:70), (50:50), and (70:30) were 14.76%, 13.23%, and 11.28% higher compare to the water, respectively. In addition, the viscosity of the Al_2O_3/water at 25 °C, compare to the base fluid was 4.08% higher.
- The MWCNT/water nanofluids at 0.1% volumetric concentration can improve the thermal conductivity 16.28%. Also the results indicated that the Al_2O_3/water had the lowest thermal conductivity improvement of 3.08% compared to other nanofluids. The Al_2O_3-MWCNT/water hybrid nanofluids at composition ratios of (70:30), (50:50), and (30:70), had the higher thermal conductivities by 5.96%, 8.8%, and 11.72% than the base fluid, respectively.
- The study also provides two experimental correlations to estimate the thermal conductivity and viscosity of Al_2O_3-MWCNT/water. The proposed thermal conductivity correlation was a function of volume fraction, thermal conductivity of each components, temperature, and composition ratio of nanoparticles. Similarly, temperature, density, composition ratio, and volume concentration of nanoparticles were important factors in the proposed viscosity correlation for Al_2O_3-MWCNT/water hybrid nanofluids.

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Author contributions Data collection and analysis were performed by Paria Changizi and Soroush Azartakin. The first draft of the manuscript was written by Mohammad Mahdi Heyhat and Mohammad Zabetian Targhi commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Narendran G, Mallikarjuna B, Nagesha BK et al (2023) Experimental investigation on additive manufactured single and curved double layered microchannel heat sink with nanofluids. Heat Mass Transfer. https://doi.org/10.1007/s00231-022-03336-6
2. Dominic A, Devahdhanush VS, Suresh S (2022) An experimental investigation on the effect of relative waviness on performance of minichannel heat sinks using water and nanofluids. Heat Mass Transfer 58:247–262. https://doi.org/10.1007/s00231-021-03096-9
3. Rubbi F, Das L, Habib KH, Aslfattahi N, Saidur R, Ul Alam S (2021) A comprehensive review on advances of oil-based nanofluids for concentrating solar thermal collector application. J Mol Liq 338:116771
4. Bigham S, Moghaddam S (2015) Microscale study of mechanisms of heat transfer during flow boiling in a microchannel. Int J Heat Mass Transf 88:111–121
5. Alihosseini Y, Zabetian Targhi M, Heyhat MM, Ghorbani N (2020) Effect of a micro heat sink geometric design on thermo-hydraulic performance: A review, Appl Therm Eng 170:114974
6. Kambli A, Dey P (2023) A critical review on recent developments and applications of microchannels in the field of heat transfer and energy. Heat Mass Transfer. https://doi.org/10.1007/s00231-023-03358-8
7. Tuckerman DB, Pease RFW (1981) High-performance heat sinking for VLSI. IEEE Electron Device Lett 2(5):126–129. https://doi.org/10.1109/EDL.1981.25367
8. Choi SUS, Eastman J (1995) Enhancing thermal conductivity of fluids with nanoparticles, No. ANL/MSD/CP-84938; CONF-951135–29. Argonne National Lab.(ANL), Argonne, IL (United States)
9. Ho CJ, Wei LC, Li ZW (2010) An experimental investigation of forced convective cooling performance of a microchannel heat sink with Al2O3/water nanofluid. Appl Therm Eng 30:96–103
10. Vinoth R, Senthil Kumar D (2017) Channel cross section effect on heat transfer performance of oblique finned microchannel heat sink. Int Commun Heat Mass Transf 87:270–276
11. Mohd-Ghazali N, Estellé P, Halelfadl S, Maré T, Siong TC, Abidin U (2019) Thermal and hydrodynamic performance of a microchannel heat sink with carbon nanotube nanofluids: Effect

of concentration and channel section. J Therm Anal Calorim 138:937–945
12. Ho CJ, Huang JB, Tsai PS, Yang YM (2010) Preparation and properties of hybrid water-based suspension of Al 2 O 3 nanoparticles and MEPCM particles as functional forced convection fluid. Int Commun Heat Mass Transf 37:490–494
13. Pourrajab R, Noghrehabadi A, Behbahani M, Hajidavalloo E (2021) An efficient enhancement in thermal conductivity of water-based hybrid nanofluid containing MWCNTs-COOH and Ag nanoparticles: experimental study. J Therm Anal Calorim 143:3331–3343
14. Ho CJ, Chen WC, Yan WM (2014) Experiment on thermal performance of water-based suspensions of Al 2O3 nanoparticles and MEPCM particles in a minichannel heat sink. Int J Heat Mass Transf 69:276–284
15. Ho CJ, Chang PC, Yan WM, Amani P (2018) Efficacy of divergent minichannels on cooling performance of heat sinks with water-based MEPCM suspensions. Int J Therm Sci 130:333–346
16. Sundar LS, Singh MK, Sousa ACM (2014) Enhanced heat transfer and friction factor of MWCNT-Fe3O4/water hybrid nanofluids. Int Commun Heat Mass Transf 52:73–83
17. Kumar V, Sarkar J (2019) Numerical and experimental investigations on heat transfer and pressure drop characteristics of Al 2 O 3 -TiO 2 hybrid nanofluid in minichannel heat sink with different mixture ratio. Powder Technol 345:717–727
18. Vinoth R, Sachuthananthan B (2021) Flow and heat transfer behavior of hybrid nanofluid through microchannel with two different channels. Int Commun Heat Mass Transf 123:105194. https://doi.org/10.1016/j.icheatmasstransfer.2021.105194
19. Kumar V, Sarkar J (2020) Particle ratio optimization of Al 2 O 3 -MWCNT hybrid nano fl uid in minichannel heat sink for best hydrothermal performance. Appl Therm Eng 165:114546
20. Xu C, Xu S, Wang Z, Feng D (2021) Experimental investigation of flow and heat transfer characteristics of pulsating flows driven by wave signals in a microchannel heat sink. Int Commun Heat Mass Transf 125:105343. https://doi.org/10.1016/j.icheatmasstransfer.2021.105343
21. Analyzer, KD2 Pro Thermal Properties (1999) Operator's Manual. Aminco, Division of Travenol Laboratories Inc., Silver Spring, Maryland
22. Kline S, McClintock F (1953) Describing uncertainties in single-sample experiments. Mech Eng 75:3–8
23. Raznjevic K (1975) Handbook of Thermodynamic Tables and Charts, Mc-GRAW HILL, 1975