Journal of Advanced Research in Fluid
Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Enhancing Thermal Conductivity of TiO_2-3%F+/MEG-40 Binary Nanofluid for Sustainable Cooling Systems in Plastic Injection Molding Applications

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ARTICLE INFO

Article history:
Received 15 November 2024
Received in revised form 25 February 2025
Accepted 5 March 2025
Available online 20 March 2025

Keywords:
Binary nanofluid; Brownian motion; electron microscopy; thermal conductivity; TiO_2 rutile; SiO_2 beta-quartz

ABSTRACT

This study explores thermal conductivity enhancement in nanofluids for high-temperature applications (70–120°C), specifically targeting plastic injection molding. The research investigates two formulations: TiO_2-3%/MEG-40 nanofluid, containing 3 vol% TiO_2 nanoparticles, and TiO_2-3%F8/MEG-40 binary nanofluid, comprising TiO_2 rutile and SiO_2 beta-quartz composite nanoparticles in a 92:8 ratio with a total volume fraction of 3 vol%. Both nanofluids were synthesized using the two-step method, with grain size confirmed via scanning and transmission electron microscopy. Thermal conductivity was measured using a TEMPOS Thermal Property Analyzer in a highly insulated heating chamber. Results demonstrated significant enhancements in comparison to the base fluid, with TiO_2-3%/MEG-40 nanofluid and TiO_2-3%F8/MEG-40 binary nanofluid exhibiting an 18% and 22% increase in thermal conductivity at approximately 95°C. Including SiO_2 beta-quartz nanoparticles enhanced dispersion, and thermal conductivity, highlighting their critical role in optimizing performance. These findings demonstrate the potential of TiO_2 rutile and SiO_2 beta-quartz nanofluids to improve thermal management in industrial processes, advancing beyond existing literature by integrating nanoparticle stability with higher temperature thermal performance.

1. Introduction

Plastic manufacturing utilizing plastic injection molding is a widely employed method in which the quality and productivity are significantly influenced by the cooling system, which regulates the mold temperature and prevents excessive heating. This mechanism is very important for regulating the mold temperature because it affects the productivity and quality of the product. However, conventional coolants have shortcomings in terms of their thermal stability and conductivity.

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https://doi.org/10.37934/arfmts.128.2.177187

Therefore, researchers have focused on the use of nanofluids as efficient substitutes. Cooling systems in molding generally operate at high temperatures; therefore, cold fluids such as water are less effective because they have a low boiling point [1-4]. However, glycol-based coolants are limited in terms of heat transfer [5,6]. To improve effective heat transfer, nanofluids, which have higher heat transfer properties than traditional fluids, hold great promise for improving heat dissipation efficiency [7]. However, there is a significant research gap between general mold temperatures and published results on the thermal conductivity (TC) of nanofluids in the 30–80°C range. In plastic injection molding, the mold temperature generally ranges from 70 to 120°C, depending on the material used. Figure 1 shows a schematic representation of the potential applications of nanofluids in plastic injection manufacturing processes.

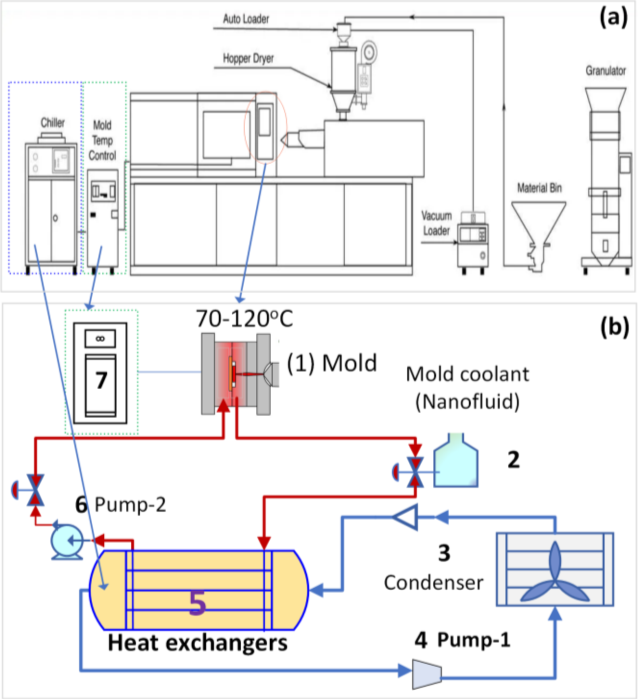

Fig. 1. Potential nanofluid applications: (a) Schematic representation of a plastic injection molding machine, and (b) Utilization of nanofluids as mold coolants [8]

Ideal control of the mold temperature is crucial for meeting the quality criteria of automotive plastic injection molding. Heat exchangers are commonly used to manage cooling, with the required temperature range varying according to the material: 20–70°C for polyvinyl chloride (PVC) and low-density polyethylene (LDPE); 25–80°C for acrylonitrile butadiene styrene (ABS) and high-density polyethylene (HDPE), 70–120°C for polycarbonate (PC), and 80–120°C for liquid crystal polymers (LCP) [2,8-10]. Although suitable thermal management in plastic injection processes is vital, there is still a research gap in nanofluids at high temperatures, owing to the challenges of conducting high-temperature analyses. The lack of sufficient data on the TC of nanofluids at elevated temperatures limits their potential for enhancing the performance of cooling systems in high-temperature applications. Bridging this information gap is essential for facilitating the use of nanofluids to enhance heat transfer efficiency in high-temperature applications, thus improving the plastic molding process [11].

Nanofluids are suspensions containing nanoparticles, generally less than 100 nm in grain size, dispersed in base fluids such as water or ethylene glycol [12-14]. These nanoparticles, including TiO_2,

SiO_2, Al_2O_2, and *ZnO*, substantially improved the TC of the working fluid, thereby improving the heat conveyance performance. This characteristic makes nanofluids particularly beneficial for mechanical processing in plastic injection molding applications.

Several studies have investigated the TC of TiO_2/EG-water nanofluids. Hamid *et al.,* [15] observed a maximum TC enhancement of 15.35% with 50 nm TiO_2 nanoparticles in an EG-40 blend (40% ethylene glycol and 60% water) at a 1.5% volume fraction over a temperature range of 30–80°C. Tertsinidou *et al.,* [16] demonstrated up to a 40% enhancement in EG-based fluids containing nanoparticles ≥15 nm, while TiO_2/water nanofluids with particle sizes of 30–50 nm exhibited an 8% increase. Pak and Cho [17] reported a 19.9% improvement using 27 nm TiO_2 nanoparticles in water at 25°C, and Tseng and Lin [18] reported similar findings with 7–20 nm TiO_2 nanoparticles at 5–12%. However, these studies predominantly focused on temperatures up to 80°C, limiting their applicability to high-temperature processes, such as plastic injection molding.

Studies on nanofluids using TiO_2 and SiO_2 have primarily focused on temperatures ranging from to 25-80°C. However, most TC data for nanofluids are limited to 80°C, which is insufficient for cooling applications in plastic injection molding. Bridging this gap in the elevated-temperature TC data is essential for fulfilling the capacity of nanofluids in this area. This study examined the TC of TiO_2 and SiO_2 nanofluids in the temperature range–30-95°C, which is relevant to plastic injection molding. TiO_2 and SiO_2 were selected because of their exceptional thermal properties and high-temperature stability, which make them suitable for industrial thermal management. Investigations utilized 30 nm TiO_2 (rutile phase) and 15 nm SiO_2 (beta-quartz) nanoparticles dispersed in a 40:60 mixture of monoethylene glycol/distilled water (MEG-40). In this study, two nanofluids were examined. The first was a TiO_2-3%/MEG-40 nanofluid (NF) containing 3% TiO_2 nanoparticles by volume. The second was a TiO_2-3%F8/MEG-40 binary nanofluid (BNF) consisting of TiO_2-SiO_2 composite nanoparticles in a 92:8 ratio, with a total volume fraction of 3%. The nanoparticle grain size analysis was conducted using scanning electron microscopy (SEM). Transmission electron microscopy (TEM) was used to check the dispersion quality, which supported the stability and TC. A TEMPOS thermal property analyzer (TTPA) situated within a well-insulated heating chamber was used for the TC. The results show significant enhancements in the base fluid. The increased TC correlated directly with temperature, indicating that TiO_2 and SiO_2 nanofluids can enhance thermal management efficiency in plastic injection molding.

2. Method

2.1 Preparation of Nanofluids

This study utilized TiO_2 rutile and SiO_2 beta-quartz nanoparticles from Hebei Suoyi New Material and Technology Co. Ltd., with a purity of 99.8% and average particle sizes of 30 nm for TiO_2 and 15 nm for SiO_2. In white powder form and at a temperature of 27 °C, the nanoparticles exhibited a thermal conductivity of 8.4 W/m·K for TiO_2 and 10.4 W/m·K for SiO_2 [19]. PT Indochemical Citra Kimia supplied monoethylene glycol (MEG). Table 1 lists the specifications for the raw materials, including MEG, DW, TiO_2, and SiO_2.

Table 1
Specifications of raw materials at room temperature

Specification’s	Symbol	MEG-40	DW	TiO_2	SiO_2
Thermal conductivity. (W/m.°C)	k	0.408	0.613	8.4	10.4
Purity, (%)	-	99.8	99.8	99.8	99.8
Chemical formulae	-	$C_2H_6O_2$	H_2O	TiO_2	SiO_2
Phase	-	Liquid	Liquid	Rutile	β-quartz
Viscosity, (mPa/s)		2.57	0.907	-	-
Density, (kg/m^3)	ρ	1050.62	997.0	4157	2650
Grain size, (nm)	D	-	-	30	15

A two-step method (TSM) was employed to prepare TiO_2-3%/MEG-40 NF and TiO_2-3%F8/MEG-40 BNF nanofluids for TC measurements by dispersing nanoparticles in EG-40 at 3% volume concentration, as outlined in Eq. (1) [20,21].

$$\phi = \frac{w_s\,\rho_f}{w_s\rho_f + w_f\rho_s} \tag{1}$$

where w denotes the mass in grams, ρ denotes the density in gram/cm^3, and subscripts f and s indicate the base fluid (fluid) and nanoparticles (solid), respectively. The TSM used for preparing the TiO_2-3%/MEG-40 NF and TiO_2-3%F8/MEG-40 BNF are illustrated in Figure 2, and the matrix preparation for both samples is provided in Table 2.

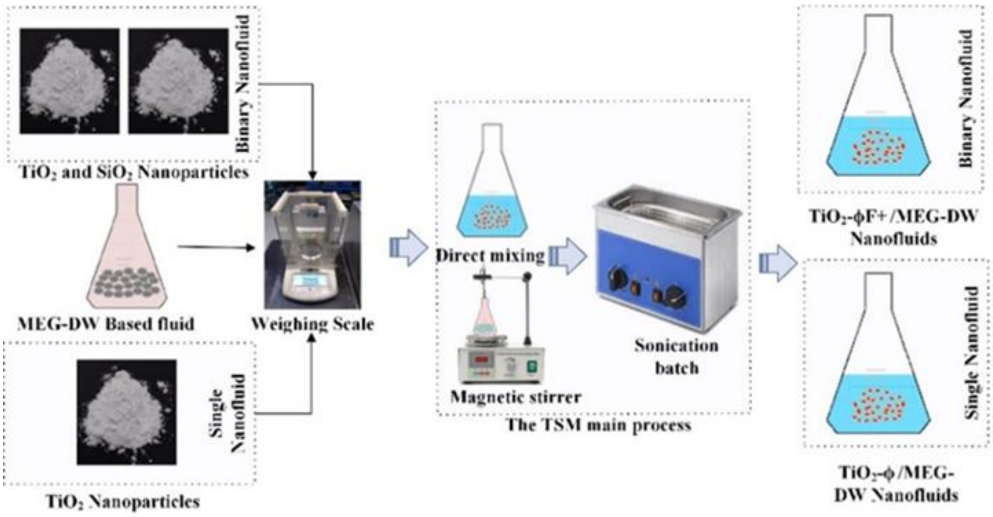

Fig. 2. Two-step method (TSM) for nanofluid preparation

Table 2
Matrix preparation for single and binary nanofluids

Nanofluid Identifications	NPS- vol. factions (ϕ)	TiO_2: SiO_2 (binary ratio)	MEG:DW ratio
TiO_2-3%/MEG-40	3%	100:0 %	40:60
TiO_2-3%F+8/MEG-40	3%	92: 8%	40:60

2.2 Electron Microscopy

Scanning microscopy plays a crucial role in nanomaterial characterization because of its versatility and high spatial resolution. The grain size and morphology of the rutile TiO2 and SiO2 beta-quartz nanoparticles were examined using SEM prior to their incorporation into the base fluid. Images were obtained using a JEOL JSM-IT710 SEM at an accelerating voltage of 5.0 kV. The microscope was set to an operating distance of 2.8 mm, and a magnification of 100,000 × was used to achieve the highest possible resolution. The ImageJ software was used to examine the SEM images and verify the grain size and structural phases. Furthermore, the distribution of the nanoparticles in the base fluid was examined using a JEOL/EO-JEM-1400 TEM instrument operating at 120V with a magnification of 40,000 ×. This technique allows for detailed observations at a scale of 100 nm. The quality of nanoparticle dispersion is influenced by its uniformity of the nanoparticle dispersion, which typically has a direct effect on TC [15,22].

2.3 Thermal Conductivity Measurement

In this study, TTPA was applied to assess the TC properties of TiO_2-3%/MEG-40 NF and TiO_2-3%F8/MEG-40 BNF. A data logger was used to monitor the temperature inside the water tank insulation of the heating chamber. TTPA provides an exact and accurate technique for measuring TC. This study utilized a thermally insulated chamber with a capacity of 1000 mL to submerge the nanofluid for TC analysis with the aim of supporting cooling systems in plastic injection molding applications. The TC examination was conducted while maintaining the relative humidity at approximately 26°C and maintaining the room temperature at approximately 65%. A-50 mL of *the* TiO_2-3%/MEG-40 NF and TiO_2-3%F8/MEG-40 BNF were individually subjected to varying temperature gradients within this setup to evaluate their TC performance under different thermal loads. Real-time TTPA data capture during the experiments allowed the precise quantification and analysis of TC enhancement by the binary nanofluid composite. Figure 3 shows the schematic of the TTPA arrangement.

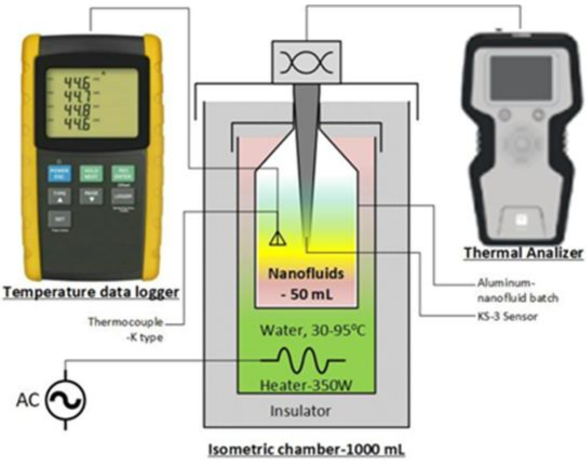

Fig. 3. Thermal conductivity (TC) measurement using TTPA

3. Results and Discussion

3.1 Electron Microscopy Analysis

The grain size and crystallite phase of the TiO_2 rutile and SiO_2 beta-quartz nanoparticles were analyzed using SEM, as shown in Figure 4. The structural phases of rutile TiO_2 rutile and SiO_2 quartz-phase nanoparticles are presented in Figure 4(a) and Figure 4(b), respectively. The rutile phase of the TiO_2 nanoparticles was tetragonal, which is consistent with our previous study in Sukarman *et al.,* [20] and Ulhakim *et al.,* [23] and is in line with the results reported by Fal *et al.,* [24]. The structure of SiO_2 beta-quartz exhibited a regular crystalline pattern in which silicon and oxygen atoms were arranged periodically, which is consistent with the findings reported in Shiga *et al.,* [25]. The average grain size of rutile-phase TiO_2 is approximately 27.65 nm, as reported in previous studies, whereas SiO_2 beta-quartz has an average grain size of approximately 18.5 nm, as shown in Figure 4(b) [20].

TEM images were evaluated to determine the homogeneity of the TiO_2 dispersion in the base fluid. Figure 4(c) shows the distribution of TiO_2 rutile nanoparticles in MEG-40 (TiO_2-3%/MEG-40 NF), which is a critical factor for enhancing the TC of effective particulate heat transfer. This homogeneity suggests that the nanofluid preserves structural stability and decreases particle agglomeration, which is essential for maintaining TC. Figure 4(d) depicts an even more uniform distribution in MEG-40 doped with SiO_2 (TiO_2-3%F8/MEG-40 BNF), where SiO_2 acts as a stabilizer by adhering to TiO_2 rutile nanoparticles. This interaction enhances dispersion and prevents agglomeration more effectively than TiO_2 nanofluids. The SiO_2–TiO_2 composite exhibited an improved TC and long-term stability. This finding aligns with earlier studies that demonstrated that binary nanofluids, particularly those containing SiO_2, enhance the particle dispersion and TC. It underscoring the importance of nanoparticle interactions in the overall performance of nanofluids [26,27].

The SEM analysis also revealed significant findings regarding the dispersal of nanoparticles in different nanofluid mixtures. The titania (TiO_2) rutile nanoparticles showed a homogeneous distribution in MEG-40 (TiO_2-3%/MEG-40 NF), which is essential for enhancing the TC and thermal dissipation. The addition of SiO_2 to the nanofluid (TiO_2-3%F8/MEG-40 BNF) resulted in a more homogeneous distribution, with SiO_2 acting as a stabilizer by bonding rounding TiO_2 rutile nanoparticles. This interaction improved the dispersion more effectively than *the* TiO_2 nanofluids alone. The improved distribution and durability of the SiO_2-TiO_2 mixture led to a superior TC and long-term reliability. This observation aligns with prior research showing that nanofluids containing SiO_2 improve the particle dispersion and TC [15,26,27]. These results emphasize the crucial role of nanoparticle interactions in determining the effectiveness of nanofluids and the potential of binary nanofluid systems in advanced heat-transfer applications.

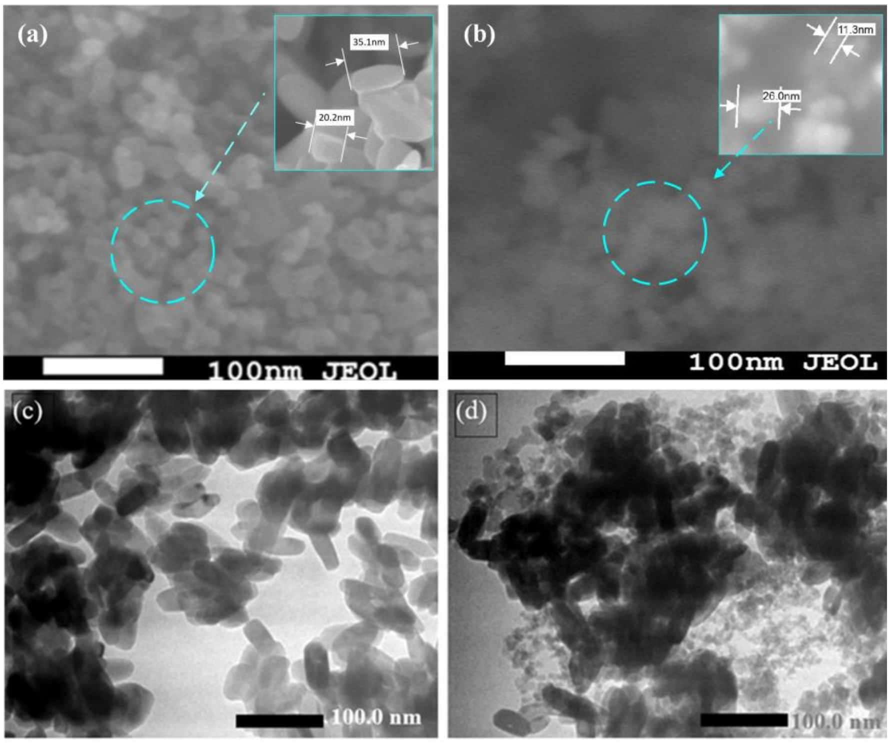

Fig. 4. Electron microscopy of nanofluids: (a) SEM image of TiO2 rutile-phase, (b) SEM image of SiO2 beta-quartz, (c) TEM image of TiO2-3%/MEG-40 NF, and (d) TEM image of TiO2-3%F8/MEG-40 BNF

3.2 Thermal Conductivity Analysis

A comprehensive analysis of the TC of the nanofluids was conducted by comparing the results with established theoretical models and those of a previous study. Maxwell's Effective Medium Theory (EMT) serves as the fundamental theory for the development of TC in nanofluids, as shown in Eq. (2) [28,29].

$$\frac{k_{nf}}{k_f} = 1 + \frac{3\left(\frac{k_s}{k_f}-1\right)\emptyset}{\left(\frac{k_s}{k_f}+1\right)-\left(\frac{k_s}{k_f}-1\right)\emptyset} \tag{2}$$

Hamilton-Crosser developed Maxwell's fundamental theory to determine the correlation between TC and the shape of nanoparticles. The correlation between TC and the shape of the nanoparticles dispersed in the base fluid is given by Eq. (3) [30].

$$\frac{k_{nf}}{k_f} = \frac{k_s+(n-1)k_f-(n-1)\emptyset(k_s-k_f)}{k_s+(n-1)k_f+\emptyset(k_f-k_s)} \tag{3}$$

where *k* represents the TC ratio; ϕ denotes the nanoparticle volume fraction; and the subscripts *nf*, *f*, and *s* correspond to the nanofluid, base fluid, and nanoparticles (solid), respectively. The shape factor (dimensionless unit) is expressed as $n=3/\psi$, where ψ is sphericity (dimensionless). The shape factor varies depending on the particle shape: $\psi=1$ for spherical particles, $\psi=0.75$ for tetragonal nanoparticles, and $\psi=0.5$ for cylindrical particles [29,31,32]. As shown in Eq. (3), the Hamilton–Crosser equation was used to compare the experimental results. Additionally, the TC results from this study were compared with the equations proposed by Hamid *et al.,* [22], which established a correlation between the thermal conductivity, volume fraction, and temperature (*T*), as presented in Eq. (4).

$$\frac{k_{nf}}{k_f} = \left(1+\frac{\emptyset}{100}\right)^{7}\left(\frac{T}{80}\right)^{0.024} \tag{4}$$

The experimental data in Figure 5 demonstrate a significant increase in TC over a temperature range of 30–95°C. Specifically, the TiO_2-3%/MEG-40 NF and TiO_2-3%F8/MEG-40 BNF exhibited enhancements of approximately 18% and 22%, respectively, compared to the MEG-40 base fluid. At a peak temperature of approximately 95°C, the TiO_2-3%/MEG-40 NF exhibited TC enhancement of 18.6%. In contrast, *the* TiO_2-3%F8/MEG-40 BNF exhibited a significant improvement of 22.2% under the same conditions, indicating the effectiveness of the TiO_2 nanoparticle composites and F8 additives (8% SiO_2 nanoparticles) in improving the TC when dispersed in MEG-40. The propensity of TC to increase with increasing temperature accentuates the potential of these nanofluids for high-temperature applications. This enhancement is ascribed to the improved nanoparticle distribution and stability within the base fluid and synergistic effects in the binary nanofluid, facilitating a more efficient heat transfer in the industrial field, especially in plastic injection applications.

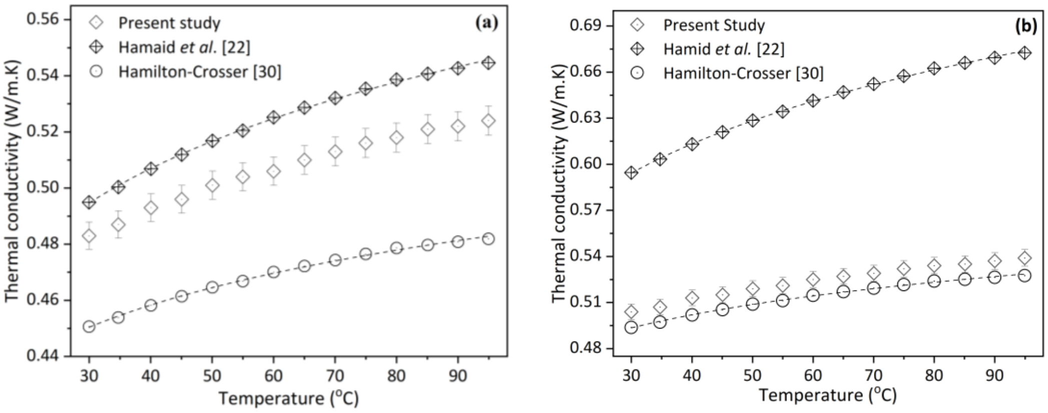

Fig. 5. Thermal conductivity: (a) TiO_2-3%/MEG-40 NF, and (b) TiO_2-3%F8/MEG-40 BNF

The observed enhancement in TC was approximately 2% higher than that predicted by Hamilton and Crosser [30]. However, it remains lower than the predictions made using Eq. (3) [15,22]. The observed difference indicates that, while the Hamilton-Crosser model provides a conservative estimate, the actual performance of these nanofluids is enhanced by additional factors not fully considered in Hamilton's approach, such as nanoparticle interactions and stability effects. Although Hamid's formula may account for more complex interactions, potentially explaining its higher predicted values, it appears less applicable because of issues when used at 0°C. Furthermore, a previous study examined the effects of Brownian motion on the TC of nanofluids. The results of this study indicate that increasing Brownian movement improves the TC of nanofluids. The absence of Brownian motion particle effects in these models can explain the disparities between the experimental and theoretical outcomes [33]. This finding suggests that future models should incorporate Brownian motion to obtain more precise nanofluid TC predictions.

Adding SiO_2 beta-quartz at a concentration of F8 (F+), substituting 8% of the total 3% volume fraction of TiO_2 rutile, significantly enhanced the TC of the nanofluid. Incorporating SiO_2 beta-quartz into TiO_2 nanofluids synergistically combines the TC and stability benefits of SiO_2 beta-quartz, resulting in a more efficient heat transfer medium. This finding aligns with Bergman *et al.,* [19], which demonstrated that SiO_2 beta-quartz exhibits a higher TC than TiO_2 rutile. The inclusion of SiO_2 beta-quartz nanoparticles improved the stability and dispersion of the nanofluid, reduced particle agglomeration, and enhanced heat transfer efficiency. However, in contrast to the findings of Hamid *et al.,* [15], a higher TiO_2 concentration contributed to a greater increase in TC. This discrepancy may be due to the inherently high TC of SiO_2 beta-quartz nanoparticles, approximately 10.2 W/m·K, compared to TiO_2, which has a TC of around 8.4 W/m·K, as reported in Bergman *et al.,* [19]. Future studies should focus on refining the binary mixture to enhance its heat conduction properties and structural integrity.

4. Conclusions

This study effectively evaluated the efficacy of TiO_2 nanofluid by itself against its integration with SiO_2 nanoparticle doping as a binary nanofluid, offering an advanced thermal management approach for contemporary cooling systems in plastic injection molding processes. The key experimental results are summarized as follows:

i. Electron microscopy analysis confirmed the presence of rutile TiO_2 (27.65 nm) and beta-quartz SiO_2 (18.5 nm), which ensured the grain size of the nanoparticles for thermal enhancement.

ii. Analysis of the TEM images revealed that the binary nanofluid consisting of TiO_2 nanoparticles combined with SiO_2 exhibited an improved dispersion of TiO_2 compared to the single TiO_2 nanofluid.

iii. The binary nanofluid demonstrated a 22% increase in TC at 95.1°C, outperforming the 18% increase obtained with *the* TiO_2 nanoparticles alone at 94.9°C. The superior performance of the SiO_2-enhanced mixture underscores the potential of binary nanofluid fluids for heat-transfer applications. The enhanced TC properties significantly benefit industrial settings, particularly in plastic injection molding, where efficient heat management is crucial.

Future research will investigate TiO_2 –SiO_2 binary nanofluids in MEG-10 at a 90:80 ratio to enhance the industrial heat transfer, including energy-efficient plastic injection molding. Studies should assess the long-term stability and thermal conductivity under dynamic conditions to ensure practical and reliable real-world applications.

Acknowledgement

The authors express their gratitude to the Ministry of Research, Technology, and Higher Education for providing full funding for this research through the "Postgraduate Research of Doctoral Dissertation" program with contract number 086/E5/PG.02.00.PL/2024 and 1076.1/UN27.22/PT.01.03/2024. Acknowledgment is also extended to Universitas Sebelas Maret, Surakarta and Universitas Buana Perjuangan Karawang for their continuous support throughout the research, particularly in nanofluid characterization.

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