A Brief Survey of Preparation and Heat Transfer Enhancement of Hybrid Nanofluids


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The investigation of the domestic application of heat flux dissemination is in high demand. The best strategy to obtain a coolant with an ideal execution is by including particular sorts of nanoparticles in the base fluid. The utilization of nanofluids escalates the heat transfer coefficient through the enhancement of the base fluid’s thermal conductivity. An advanced coolant (hybrid nanofluid) was delivered by blending two or more different types of nano-sized particles with conventional fluid. This article mainly aims to cover the recent publications on hybrid nanofluids on different aspects, such as preparation, thermophysical properties, and heat transfer enhancement. In general, the combination of different nanoparticle properties results in excellent thermal conductivity: improvement in heat transfer coefficient was up to 148% compared to the base fluid. Moreover, a moderate increase on pressure drop has been detected due to the presence of composite nanoparticles. In any case, the anticipated results for both thermal conductivity and viscosity values utilizing conventional relationships were distinctive from the experimental results.

Keywords: hybrid nanofluids, Nusselt number, thermal conductivity, viscosity, thermal applications

Highlights
- Hybrid nanofluids are produced by mixing two or more nanoparticles types with a base fluid, via physical or chemical processes.
- Using hybrid nanofluids provides an enormous enhancement in thermophysical and rheological properties.
- A significant enhancement in the heat transfer coefficient for hybrid nanofluid compared to water base fluid is presented.
- The effect of hybrid nanofluids in reducing the pressure drop is observed.

INTRODUCTION

High heat flux dissipation is one of the most prominent reasons that has motivated many researchers to put their best efforts into producing new cooling systems (or new coolants).

In 1995, Choi presented the term “nanofluid” as an expression for base fluid that contains very small particles (<100 nm) called “nanoparticles” [1]. This advanced method was introduced mainly to prevent overheating in many common applications, such as electronic cooling, solar cells, and automotive cooling systems. However, issues such as clogging, erosion, nanoparticles sedimentation, and high cost are the main challenges in extending nanofluid within the industrial sector [2]. For example, metallic nanoparticles have high thermal conductivity and good electrical properties, but they produce low stability and chemically inert fluid. In contrast, metals oxide nanoparticles have low thermal conductivity with high stability in the fluid. The combination of these two nanoparticles types provides the preferred characteristics for a favourable coolant. Therefore, many researchers aspired to mix two or more nanoparticles types with a base fluid to produce hybrid nanofluids, via physical or chemical processes. Hybrid nanofluids may have higher thermal conductivity that can further improve heat transfer and pressure drop properties [3].

Recently, there has been a sharply increased demand for research in hybrid nanofluids that enhance thermophysical and heat transfer properties. Thus, attempts have been made to prepare an article that may come in handy in fulfilling those demands. Many research studies focused only on the thermophysical properties of hybrid nanofluids, and some focused on its application mainly in enhancing the heat transfer coefficient. However, this article considers a systematic approach, focusing on recently published articles related to hybrid nanofluids, specifically in hybrid nanofluid preparation, thermophysical properties, and heat transfer coefficient enhancement.

PREPARATION OF HYBRID NANOFLOIDS

There are many methods for nanomaterial synthesis, such as chemical vapour deposition (CVD), vacuum deposition and vapourisation, and sol-gel techniques.
There are two methods used in preparing hybrid nanofluids, known as one-step and two-step methods. Most scholars utilise the two-step method in preparing hybrid nanofluids, but some synthesize the nanocomposite (NC) particles before they are dispersed in base fluids. The NC particles could be synthesized through several methods such as a pure chemical reaction [6], a thermochemical method [7], and an in-situ method [8].

Yarmand et al. [9] presented a new synthesis method in preparing graphene nanoplatelets (GNP)–Ag/water hybrid nanofluid, which produces silver on functionalized GNP through a simple chemical reaction process.

Megatif et al. [10] prepared TiO$_2$–carbon nanotube (CNT) nanocomposite by using hydrolysis technique. They obtained a CNT dispersion by mixing the CNTs with HNO$_3$–H$_2$SO$_4$, followed by ethylene glycol (EG) and 20 ml of 2-propanol. Subsequently, Ti(OBu)$_4$ was added into the suspension for special treatment. The nanocomposite was obtained after vacuum filtering, washing in 2-propanol, and drying of CNT–TiO$_2$. Suresh et al. [7] synthesized Al$_2$O$_3$–Cu nanocomposite particles by using the thermochemical method as described in Fig.1. Hybrid nanofluids were prepared by dispersing the nanocomposite particles in the deionized water together with sodium lauryl sulphate (SLS). The stability of the prepared powder was then observed in different volume concentrations of hybrid nanofluid. Some researchers prepare hybrid nanofluids by mixing two nanoparticles types, which separately synthesized within the base fluid. Harandi et al. [11] employed the two-step method in preparing f- multiwall carbon nanotubes (MWCNTs)–Fe$_3$O$_4$/EG hybrid nanofluid. Dry f-MWCNTs and Fe$_3$O$_4$ nanoparticles were mixed in ethylene glycol and were prepared in different volume fractions. Ultrasonic vibration instrument was used to obtain good stability, as shown in Fig. 2. Akilu et al. [12] utilized the wet-mixing method to synthesize titanium oxide-copper oxide/carbon (TiO$_2$–CuO/C)-based nanocomposites. After that, they prepared stable EG based hybrid nanofluids through the two-step method to develop the thermophysical properties of the base fluid. Sundar et al. [13] synthesized nanodiamond-nickel (ND-Ni) nanocomposite materials through the in-situ growth and chemical co-precipitation method.

Table 1 shows that researchers preferred to combine metallic or metallic oxide with carbon nanoparticles families (CNTs, MWCNTs, GNP$s$, and diamonds) because of their high thermal conductivities, low densities, and better performance in electric behaviour. Table 1 describes the recent works done in hybrid nanofluids. In this table, the majority used one or more of these methods (adding surfactants, using ultrasonic vibration, fictionalizations agent, and controlling pH value methods) to stabilize the hybrid nanofluids. The main intention was to prepare hybrid nanofluids in order to study the thermophysical and rheological properties and the convective heat transfer enhancement in selected applications.
Table 1. The preparation methods of hybrid nanofluids

<table>
<thead>
<tr>
<th>Reference</th>
<th>Hybrid nanoparticle</th>
<th>Dispersant fluid</th>
<th>vol.% / wt.%</th>
<th>Stability methods</th>
<th>Main objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Han et al. [14]</td>
<td>(NC) Al2O3+Fe2O3+CNT</td>
<td>poly-alpha-olefin (PAO)</td>
<td>0.1, 0.2 vol.%</td>
<td>sonication and surfactant (Span-80)</td>
<td>studying the effective thermal conductivity</td>
</tr>
<tr>
<td>Chen et al. [15]</td>
<td>(NC)Ag/MWNT</td>
<td>water</td>
<td>1.0 vol.%</td>
<td>Sodium dodecyl sulphate (SDS)</td>
<td>studying the effective thermal conductivity</td>
</tr>
<tr>
<td>Suresh et al. [16]</td>
<td>(NC)Al2O3-Cu</td>
<td>water</td>
<td>0.1 vol.%</td>
<td>ultrasonic vibrator, and sodium lauryl sulphate (SLS)</td>
<td>enhancing convective heat transfer and pressure drop</td>
</tr>
<tr>
<td>Khosravifard et al. [17]</td>
<td>TiO2-CNTs</td>
<td>propylene glycol + water</td>
<td></td>
<td>ultrasonic agitator, and (SDS)</td>
<td>studying the characterization and thermophysical properties</td>
</tr>
<tr>
<td>Selvakumar and Suresh [18]</td>
<td>(NC)Al2O3-Cu</td>
<td>water</td>
<td>0.1 vol.%</td>
<td>ultrasonic vibrator, and (SLS)</td>
<td>enhancing convective heat transfer</td>
</tr>
<tr>
<td>Safi et al. [19]</td>
<td>(NC)MWCNT-TiO2</td>
<td>water</td>
<td>0.02 wt.% to 0.08 wt.%</td>
<td>ultrasonic agitator</td>
<td>enhancing convective heat transfer</td>
</tr>
<tr>
<td>Nine et al. [20]</td>
<td>Al2O3-MWCNTs</td>
<td>water</td>
<td>1 wt.% to 4 wt.%</td>
<td>ultrasonic vibrator</td>
<td>studying the characterization and thermophysical properties</td>
</tr>
<tr>
<td>Sundar et al. [21]</td>
<td>(NC)Diamond+Ni</td>
<td>water and EG</td>
<td>0.1 vol.% to 0.3 vol.%</td>
<td>ultrasonic vibrator, and NanoSperse AQ</td>
<td>enhancing convective heat transfer and pressure drop</td>
</tr>
<tr>
<td>Madhesh et al. [22]</td>
<td>(NC)Cu–TiO2</td>
<td>water</td>
<td>0.1 vol.% to 2 vol.%</td>
<td>ultrasonic vibrator without surfactant</td>
<td>enhancing convective heat transfer</td>
</tr>
<tr>
<td>Esfe et al. [23]</td>
<td>Ag–MgO</td>
<td>water</td>
<td>0 vol.% to 2.0 vol.%</td>
<td>ultrasonic vibrator and CetylTrimethyl Ammonium Bromide (CTAB)</td>
<td>studying the effective thermal conductivity</td>
</tr>
<tr>
<td>Esfe et al. [24]</td>
<td>CNTs-Al2O3</td>
<td>water</td>
<td>0.02 vol.% to 1 vol.%</td>
<td>ultrasonic vibrator</td>
<td>studying the effective thermal conductivity</td>
</tr>
<tr>
<td>Yarmand et al. [9]</td>
<td>(NC)GNP–Ag</td>
<td>water</td>
<td>0 vol.% to 0.1 vol.%</td>
<td>ultrasonic vibrator</td>
<td>enhancing convective heat transfer and pressure drop</td>
</tr>
<tr>
<td>Baghbanzadeh et al. [25]</td>
<td>silica + MWCNTs</td>
<td>water</td>
<td>1.0 wt.%</td>
<td>SDS</td>
<td>studying the rheological properties.</td>
</tr>
<tr>
<td>Sundar et al. [26]</td>
<td>(NC)CNT-Fe3O4</td>
<td>water</td>
<td>0.1vol.% to 0.3 vol.%</td>
<td>(situ method) and NanoSperse AQ</td>
<td>enhancing convective heat transfer and pressure drop</td>
</tr>
<tr>
<td>Madhesh et al. [27]</td>
<td>Ag + CuO</td>
<td>water</td>
<td>1 vol.%</td>
<td>ultrasonic vibrator</td>
<td>enhancing convective heat transfer and pressure drop</td>
</tr>
<tr>
<td>Estgarf and Afrand [28]</td>
<td>MWCNTs–SiO2</td>
<td>EG, water</td>
<td>0.0625 vol.% to 2 vol.%</td>
<td>carboxyl (COOH) -functionalized</td>
<td>studying the rheological properties.</td>
</tr>
<tr>
<td>Harandi et al. [11]</td>
<td>F-MWCNTs–Fe3O4</td>
<td>EG</td>
<td>0 vol.% to 2.3 vol.%</td>
<td>ultrasonic vibrator</td>
<td>studying the effective thermal conductivity</td>
</tr>
<tr>
<td>Ramachandran [29]</td>
<td>Al2O3+CuO</td>
<td>water</td>
<td>0.1 vol.%</td>
<td>ultrasonic vibrator</td>
<td>enhancing convective heat transfer</td>
</tr>
<tr>
<td>Asadi and Asadi [30]</td>
<td>MWCNT + ZnO</td>
<td>engine oil</td>
<td>0.125 vol.% to 1 vol.%</td>
<td>ultrasonic vibrator</td>
<td>studying the rheological properties</td>
</tr>
<tr>
<td>Huang et al. [31]</td>
<td>MWCNT + Al2O3</td>
<td>water</td>
<td>MWCNT 0.0111 vol.%, Al2O3 1.89 vol.%</td>
<td>ultrasonic vibrator</td>
<td>enhancing convective heat transfer and pressure drop</td>
</tr>
<tr>
<td>Esfe et al. [32]</td>
<td>MWCNTs–SiO2</td>
<td>engine oil</td>
<td>0 vol.% to 2 vol.%</td>
<td>ultrasonic vibrator</td>
<td>studying the rheological properties</td>
</tr>
<tr>
<td>Afrand et al. [33]</td>
<td>Fe3O4–Ag</td>
<td>EG</td>
<td>0.6 vol.% to 1.2 vol.%</td>
<td>ultrasonic vibrator</td>
<td>studying the rheological properties</td>
</tr>
<tr>
<td>Afrand et al. [34]</td>
<td>SiO2–MWCNTs</td>
<td>engine oil</td>
<td>0.625vol.% to 1 vol.%</td>
<td>ultrasonic vibrator</td>
<td>studying the rheological properties</td>
</tr>
<tr>
<td>Allahyar et al. [35]</td>
<td>(NC)Al2O3–Ag</td>
<td>water</td>
<td>0.1vol.% to 0.4 vol.%</td>
<td>sol–gel method</td>
<td>studying the effective thermal conductivity</td>
</tr>
<tr>
<td>Megatif et al. [10]</td>
<td>(NC)TiO2-CNT</td>
<td>Water</td>
<td>0.1 vol.% to 0.2 vol.%</td>
<td>hydroxyl (–OH) and carboxyl (–COOH) functionalized</td>
<td>enhancing convective heat transfer</td>
</tr>
<tr>
<td>Toghrirae et al. [36]</td>
<td>ZnO–TiO2</td>
<td>EG</td>
<td>0 vol.% to 3.5 vol.%</td>
<td>ultrasonic vibrator</td>
<td>studying the effective thermal conductivity</td>
</tr>
</tbody>
</table>
It is important to mention here that to reach a stable hybrid nanofluid, the absolute zeta potential of the hybrid nanofluid must be increased to the extent possible. As the zeta potential diverges from the isoelectric point, strong repulsive forces develop among nanoparticles and reduce agglomeration.

In the next section, the thermophysical and rheological properties of the hybrid nanofluids are covered. Furthermore, comprehensive reviews on hybrid nanofluids preparation have been conducted by Sundar et al. [38], Takabi and Salehi [39] and Babu et al. [40]. They summarized all the work that is related to the preparation of such nanofluids in recent decades.

### 2 THERMOPHYSICAL PROPERTIES OF HYBRID NANOFLUIDS

Studying the thermophysical and rheological properties of hybrid nanofluids is essential for the continuous development and determination of their usage in various applications. Furthermore, a significant amount of combination between nanofluid types can be done in preparing hybrid nanofluids. Therefore, many researches worked on investigating thermophysical and rheological properties, in addition to the main parameters that affect hybrid nanofluids.

The density and heat capacity of hybrid nanofluids can be calculated using a mixture model, as Eqs. (1) and (2):

\[
\rho_{nf} = \varphi \rho_p + \sum \varphi_{np} \rho_{np} + (1 - \varphi) \rho_f, \quad (1)
\]

\[
c_{nf} = \frac{\varphi}{\rho_p} c_p + \sum \varphi_{np} c_{np} + (1 - \varphi) \rho_f c_f, \quad (2)
\]

where \( \varphi_{np} \) is the volume concentration of all nanoparticles

\[
\varphi_{np} = \frac{\sum \varphi_{np}}{\sum \varphi_{np}}, \quad (3)
\]

The thermal conductivities and viscosity of nanofluids can be predicted with traditional models, as the Hamilton and Crosser model [41] for predicting thermal conductivity:

\[
k_{nf} = k_f \left[ k_p + \frac{(n-1)k_{nf} + (n+1)(k_p - k_{nf})\varphi}{k_p + (n-1)k_{nf} - (k_p - k_{nf})\varphi} \right], \quad (4)
\]

### Table 2. The proposed correlations for thermophysical properties of hybrid nanofluids

<table>
<thead>
<tr>
<th>Reference</th>
<th>Hybrid nanofluids type</th>
<th>The proposed correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunder et al. [21]</td>
<td>Diamond+Ni / water, EG</td>
<td>( \frac{k_{nf}}{k_f} = 1 + 4.01\varphi, \quad \frac{\mu_{nf}}{\mu_f} = 1.35e^{-12.83\varphi} )</td>
</tr>
<tr>
<td>Esfe et al. [23]</td>
<td>Ag–MgO/water</td>
<td>( \frac{k_{nf}}{k_f} = 0.1747 \times 10^3 - 0.1498 \times 10^3 \varphi + 0.1117 \times 10^5 \varphi^2 + 0.1997 \times 10^4 \varphi^3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \frac{\mu_{nf}}{\mu_f} = 1 + 32.795 \varphi - 7240 \varphi^2 + 714600 \varphi^3 - 0.1941 \times 10^5 \varphi^4 )</td>
</tr>
<tr>
<td>Harandi et al. [11]</td>
<td>F-MWCNTs–Fe304/EG</td>
<td>( \frac{k_{nf}}{k_f} = 1 + 0.0162 \varphi^{0.7038}T^{0.6009} )</td>
</tr>
<tr>
<td>Asadi and Asadi [30]</td>
<td>MWCNT+ZnO / engine oil</td>
<td>( \mu_{nf} = 796.8 + 76.26 \varphi + 12.88T + 0.7695T \varphi + \frac{-196.9T - 16.53 \varphi T}{\sqrt{T}} )</td>
</tr>
<tr>
<td>Afrand et al. [34]</td>
<td>SiO2–MWCNTs / engine oil</td>
<td>( \frac{\mu_{nf}}{\mu_f} = a_0 + a_1 \varphi + a_2 \varphi^2 + a_3 \varphi^3 + a_4 \varphi^4 ), where 's are factors depend on T</td>
</tr>
<tr>
<td>Toghraie et al. [38]</td>
<td>ZnO–TiO2/EG</td>
<td>( \frac{k_{nf}}{k_f} = 1 + 0.004503 \varphi^{0.8717}T^{0.7972} )</td>
</tr>
<tr>
<td>Esfahani et al. [37]</td>
<td>ZnO–Ag / water</td>
<td>( \frac{k_{nf}}{k_f} = 1 + 0.0008974 \varphi^{0.5899}T^{1.345} )</td>
</tr>
</tbody>
</table>
where \( n \) is the shape factor: \( 3 \leq n \leq 3.13 \) and for spherical shape \( n = 3 \).

For hybrid nano fluids, the thermal conductivity can be calculated using Eq. (5) and Batchelor correlation [42] (Eq. (6)) for the viscosity.

\[
k_p = \frac{\phi_1 k_{\phi_1} + \phi_2 k_{\phi_2} + \ldots + \phi_n k_{\phi_n}}{\phi}, \quad \text{ (5)}
\]

\[
\mu_{ef} = (1 + 2.5\phi + 6.2\phi^2) \mu_{bf}. \quad \text{ (6)}
\]

Some researchers have indicated that the viscosity and thermal conductivity of the hybrid nano fluid are very high compared to water, and even higher when compared to the theoretical correlations. Kannaiyan et al. [43] proved that the empirical correlations are inadequate when compared to the measurement values. They studied the thermophysical properties of EG-water-based \( \text{Al}_2\text{O}_3/\text{CuO} \) hybrid nano fluids at different concentrations. They revealed that conventional correlations need to consider the interfacial chemical interactions between nanomaterials and base fluids.

Correlations for specific hybrid nano fluids types depend on experimental data collection, whereby general correlations were predicted by using methods such as curve fitting, the predicted residual error sum of squares (PRESS) or any regression software. Table 2 introduces some correlations that were derived from recent experimental works. Esfe et al. [24] predicted a correlation to predict the thermal conductivity of CNTs-\( \text{Al}_2\text{O}_3/\text{water} \) hybrid nano fluid. The effects of volume concentration and temperature were emphasized in their correlation. In the next work, Esfe et al. [32] revealed that traditional models have failed to predict the dynamic viscosity of MWCNT-\( \text{SiO}_2/\text{engine oil} \) hybrid nano fluid. Furthermore, Newtonian behaviour towards the nano-lubricant was at volume fraction up to 1 %, and non-Newtonian are at 1.5 % and 2 %. These predicted correlations are very useful in numerical investigations to ensure that the simulations are more reliable, cost effective and time saving.

Recently Esfe et al. [44] studied the thermal conductivity of dispersing SWCNT and \( \text{ZnO} \) particles in a solution containing 30 % EG and 70 % water. They proposed a new correlation to thermal conductivity ratio of the nano fluid. They also concluded that the thermal conductivity is more sensitive to concentration variations than to temperature changes.

Hybrid nano fluids were proven to highly enhance the effective thermal conductivity and viscosity, compared to the mono-nano fluids. Sundar et al. [21] concluded that the thermal conductivity of nano- diamond and nickel (ND-Ni)/EG enhances 21 % effectively more when compared to the base fluid. They have also observed a 28.46 % enhancement of MWCNT-\( \text{Fe}_3\text{O}_4/\text{water} \) compared to the base fluid [8]. Additionally, Suresh et al. [7] found enormous enhancement in the effective thermal conductivity and viscosity of \( \text{Al}_2\text{O}_3/\text{Cu}/\text{water} \) hybrid nano fluids in comparison to \( \text{Al}_2\text{O}_3/\text{water} \) nano fluid. Fig. 3 indicates that as the particle concentration increased, the thermal conductivity ratio increased. The maximum enhancement of thermal conductivity was 12.1 %. Baghbanzadeh et al. [25] investigated the rheological properties of silica-MWCNT/water hybrid nano fluid, and the results revealed that the structure of nanomaterial is very important in enhancing the viscosity and the density despite the negative effects of MWCNT on the rheological properties development. The same finding has been concluded by Ghadikolaei et al. [45] for the thermophysical properties of \( \text{TiO}_2/\text{Cu} \) hybrid nano fluid. 

![Thermal conductivity ratio of the nano fluids as a function of volume concentrations](image)

Parameters that control the enhancement of the thermophysical properties of hybrid nano fluids are mainly the solid volume concentration and the temperature, in addition to the nanoparticles shapes and sizes. The Brownian motion also contributes to a great impact on this enhancement, which is even more significant when the temperature increases. This behaviour is similarly observed on mono-nano fluids. However, thermal conductivity is more sensitive towards the nanoparticle concentration than the temperature, contrary to the temperature effect on viscosity [34] and [46].
It is of great importance to mention here, based on the previous literature review, that a few research articles consider thermophysical properties to be temperature independent, such as [21] and [45]. In contrast, many research papers consider thermophysical properties to be temperature dependent, such as [7], [8], [11], [24], [25], [30], [32], [34], [36] and [37].

3 HEAT TRANSFER ENHANCEMENT USING HYBRID NANOFLUIDS

The main objective in studying the thermophysical properties of hybrid nanofluids is to involve and further improve its various applications, especially those related to the cooling systems such as electronic cooling, heat exchangers, and automotive cooling systems [3]. Recently, researchers had experimentally studied and numerically observed the profound effects of hybrid nanofluids in enhancing the heat transfer coefficient and reducing the pressure drop in determining the promising coolant.

Based on the literature review, one can classify the work done to investigate heat transfer enhancement using hybrid nanofluids into two major categories: numerical and experimental works. The next subsections summarize the work done that is related to the enhancement of heat transfer employing hybrid nanofluid based on the aforementioned classification.

3.1 Numerical Studies

Labib et al. [47] numerically investigated the convective heat transfer after adding Al$_2$O$_3$ nanoparticles to CNTs/water nanofluids. Their results indicated a 59.86% increase of heat transfer coefficient when utilizing (0.05 vol.% CNTs + 1.6 Al$_2$O$_3$)/water compared to utilizing 0.05 vol.% CNTs/water. They claim that such enhancement for this combination is due to a thinner boundary layer of CNT nanofluid, which may cause significant enhancement in the convection heat transfer coefficient. The hybrid nanofluid particle concentration’s effect on heat transfer performance is reflected in Fig. 4, which shows that the average heat transfer coefficient increases when the nanoparticle fraction and Reynolds number rises. Furthermore, the effects of adding low concentration of GNP$_s$ to Al$_2$O$_3$/water nanofluid on heat transfer performance were studied numerically for different mini-tube sizes and nanoparticle volume fractions by Hussien et al. [48]. Their results noted a high enhancement in heat transfer coefficient for Al$_2$O$_3$+graphene hybrid nanofluid over Al$_2$O$_3$/water nanofluid with extra penalty in pressure drop. Fig. 5 clearly indicates the increment in pressure drop for hybrid nanofluid over mono-nanofluid.

Takabi and Shokouhmand [49] numerically analysed the turbulent forced convective heat transfer of Al$_2$O$_3$-Cu/water hybrid nanofluid. Uniform heat flux was applied on the external walls of circular tubes. They compared the results obtained from hybrid nanofluid with Al$_2$O$_3$/water nanofluid, and hybrid nanofluid with water. Their results show that the use of hybrid nanofluids could increase the average Nusselt number; however, the increase in pressure drop is one of the main obstacles.

Nimmagadda and Venkatasubbaiah [51] shared their results, which reflect an enormous enhancement...
in the heat transfer coefficient, reaching up to 148 %. They used 3 vol.% Al₂O₃+Ag/water hybrid nanofluid flow inside a wide microchannel in the laminar regime. In another numerical study, they investigated the effects of SWCNT+Cu/water hybrid nanofluid in convective heat transfer enhancement [52]. A study by Moghadassi et al. [53] showed that there is an enhancement in the convective heat transfer of Al₂O₃+Cu/water, hybrid nanofluid flow inside a circular tube under uniform heat flux when compared to nanofluid. The flow in the study was assumed to be laminar (Re < 2300), and the results were compared to the same concentration of Al₂O₃/water nanofluid. Their results revealed that by adding Cu nanoparticles, there was a 4.73 % increase in heat transfer. Balla et al. [54] had determined the heat transfer coefficient for the laminar flow of the Cu+CuO/water hybrid nanofluid in a circular tube. The combination of metallic and metal oxide nanoparticles was used and experimented with different ratio and different volume concentrations of hybrid nanofluids. Their results illustrated a 30 % to 35 % enhancement of the Nusselt number ratio with a noticeable pressure drop. The pressure drop was also increased with the increase of the Reynolds number, the volume concentration of nanoparticles, and the density of nanoparticle materials. In addition, Takabi and Salehi [39] concluded that the heat transfer performance can be augmented utilizing hybrid nanofluid for laminar natural convection in a sinusoidal corrugated enclosure.

3.2 Experimental Studies

Sundar et al. [55] experimentally studied the effects of hybrid nanofluid concentration on both heat transfer and friction factors. The MWCNT–Fe₂O₃ nanoparticle nanocomposite particles were used in preparing hybrid nanofluids in different volume concentrations (0 vol.% to 0.3 vol.%). The results highlight the increase of Nusselt number dependent on the increase of particle concentration. Fortunately, a negligible increase in the friction factor was observed.

Zubir et al. [56] used the reduced graphene oxide (RGO), and its hybrid complexes were employed to improve the convective heat transfer performance. They applied a turbulent flow of hybrid complexes solutions inside a closed conduit and observed the heat transfer performance. They recorded a profound enhancement in the Nusselt number that reached 144 %, due to the increase in thermal conductivity. Safaei et al. [57] examined the heat transfer performance when different concentrations of graphene nanoplatelets-silver hybrid nanofluids were used as a coolant. The Reynolds number range used was 5,000 ≤ Re ≤ 15,000 within a fully developed turbulent flow regime. The outcome indicates an improvement in heat transfer performance with an increase of required pumping power to overcome pressure drop.

Recently, Hussien et al. [58] to [60] studied the thermal performance of MWCNTs/water nanofluid and MWCNTs/GNPs hybrid nanofluid in minitubes. Their experimental results show high enhancement of heat transfer coefficients with an increase in pressure drop when using a low weight concentration of MWCNTs/GNPs. They concluded that the increase in pressure drop is insignificant when compared to the gain of the enhancement of heat transfer. Yarmand et al. [61] investigated turbulent forced convective heat transfer for GNP-Platinum (Pt) hybrid nanofluids. Their experimental results reveal that the heat transfer enhancement is dependent on the concentration of the nanocomposite in addition to Reynolds number. Sundar et al. [13] studied the turbulent heat transfer and pressure drop of ND-Ni hybrid nanofluids through a horizontal tube. They found that hybrid nanofluids enhanced heat transfer better than mono nanofluids.

Hamid et al. [62] experimentally investigated the role of TiO₂-SiO₂/water hybrid nanofluids on improving heat transfer performance. Different composite mixture ratios were used under turbulent flow. The highest performance noted was 35.32 % with a negligible pressure drop.

The configuration of the hybrid nanoparticles on the base fluids leads to the generation of high thermal conductivity of the hybrid nanofluid. This superior thermal conductivity increases the ability of working fluid to transfer heat with the surroundings.

In summary, the heat transfer enhancement using hybrid nanofluids depends mainly on nanoparticles concentrations, nanoparticles types, and Reynolds number. From the previous literature review and various research works, it is clear that improvement of the heat transfer will unavoidably be combined with a penalty in terms of pressure drop.

4 THERMAL APPLICATIONS OF HYBRID NANOFLUIDS

The use of mono-nanofluids to increase cooling efficiency in various energy applications plays a vital role in obtaining optimal design along with significant improvement in operation systems, which can have
great impact on thermal applications, leading to magnificent performance in system by using mono nanofluids such as heat exchangers [63], heat pipes [64], cooling electronic devices [65] and [66], and automotive cooling system [67] and [68].

Thermal performance improvement using hybrid nanofluids is in great demand for two reasons. Firstly, there are many other applications that are waiting to be tested, such as automotive cooling systems, solar cells, types of heat exchangers, and mini/micro channels. Secondly (despite all existing studies) there are still a massive number of possible combinations that can be made from nanoparticle materials, which can be used in future studies.

In their experimental research, Selvakumar and Suresh [18] used Al2O3–Cu/water hybrid nanofluid for the cooling of electrical components through a thin-channelled copper heat sink. Fig. 6 show the photographs of copper heat sink with jet plate. Their results reflect a significant enhancement in heat transfer coefficient for hybrid nanofluid compared to water. Pressure drop also increased, although the increase is less than the increase in heat transfer coefficient. Therefore, they recommended the use of hybrid nanofluids as a coolant. Based on this reason, most of the main investigations nowadays emphasize observations along with theutilizations of hybrid nanofluids.

Safi et al. [19] investigated experimentally the use of MWCNT-TiO2/water hybrid nanofluid in a plate heat exchanger (PHE) where the heat transfer performance was studied. There was a 20.2 % increase in the heat transfer coefficient compared with water, and this increase depends on the particle concentration and inlet temperature. In addition Madhesh and Kalaiselvam [70] concluded that an enhancement of heat transfer coefficient also occurred when using Cu-TiO2/water hybrid nanofluid, after testing it as a coolant inside a tubular heat exchanger. The heat transfer coefficient was enhanced by 48.4 % compared with water. In their study, 0.1 vol.% to 1 vol.% nanocomposite volume concentrations were utilized. Most importantly, they had concluded that the development of thermal conductivity and diffusion kinetic of hybrid nanofluids are the main causes of heat transfer coefficient enhancement.

Recently, Huang et al. [31] investigated the new application for testing Al2O3+MWCNT/water hybrid nanofluid in a plate heat exchanger. In that experiment, a mixture of 0.0111 % MWCNT/water nanofluid with 1.89 % Al2O3/water nanofluid was used, and a very low enhancement in heat transfer coefficient compared to Al2O3/water with a slight increase in pressure drop was subsequently detected. Since these results may contradict previous research, it was considered erroneous because the enhancement is within the range of experimental errors. However, it was still recommended that hybrid nanofluids be used in heat transfer applications.

To improve engine oil as a coolant and lubricant fluid, Asadi et al. [68] added Mg(OH)2/MWCNT to engine oil. Their results showed an increase in viscosity and thermal conductivity with a rise in nanomaterials concentration. Therefore, hybrid nano-lubricant could be adopted as a lubricant fluid. The hybrid nanofluids were also used to improve the thermal resistance of a cylindrical screen mesh heat pipe by Ramachandran et al. [29] and [71]. They combined Al2O3 and CuO nanoparticles in different ratios and obtained results showing a 44.25 % maximum reduction in thermal resistance for the ratio Al2O3 25 % and CuO 75 %. Based on the results, it can be concluded that hybrid nanofluids should be strongly considered as a substitute for conventional fluid.

Moreover, nanofluids and hybrid nanofluids are used to enhance the performance of solar energy. For instance, Shah and Ali [72] presented a critical review on applications of hybrid nanofluids in solar energy along with practical limitations and challenges. They also discussed the economics and ecology of
nanofluid-based solar systems. In addition, Hader and Al-Kouz [73] numerically investigated the effect of dispersing nanosolid particles in a hybrid photovoltaic/thermal system. It was shown that dispersing such particles will enhance the overall efficiency of the hybrid system but with a pressure drop penalty. Furthermore, Jin et al. [74] investigated experimentally and numerically the solar photothermal conversion characteristics of hybrid nanofluids. They concluded that hybrid nanofluids with different absorption peaks can enhance efficiency. They also found that there is an optimal mixing volume fraction for hybrid nanofluids.

Finally, a comprehensive review of the recent progress on hybrid nanofluids in heat transfer applications is presented in [75] and [76]. It is worth mentioning here that few research studies had been conducted on dispersing nanofluid in rarefied gases. For instance, Al-Kouz et al. [77] investigated the effect of dispersing nanosolid particles of Al₂O₃ into the air base fluid in cavities equipped with solid fins. The effects of Knudsen number, volume fraction of the nanosolid particles, Rayleigh number on both heat transfer and pressure drop were analysed. It was shown that dispersing nanosolid particles enhances the heat transfer but with a pressure drop penalty. Their results were compared to Al-Kouz et al. [78] to show the enhancement in heat transfer compared to rarefied flows with no dispersed solid particles. Moreover, Al-Kouz et al. [79] studied the entropy generation inside cavities equipped with solid fins and filled with air/Al₂O₃ nanofluid. The effects of Knudsen number and volume fraction of the nanosolid particles on the total entropy generation were shown and analysed. In addition, the correlation for the total entropy generation among all the investigated parameters is proposed. Finally, Al-Kouz et al. [80] conducted a numerical study to investigate heat transfer characteristics in the entrance region of laminar rarefied air/Al₂O₃ flow in pipes. The effects of the aspect ratio, Knudsen number, Reynolds number and the nanosolid particle volume fraction on the heat transfer characteristics were presented, and a correlation of Nusselt number among all the investigated parameters is introduced. Investigating rarefied flows with hybrid nanofluids, which has not been done yet to the authors’ knowledge, is highly recommended.

5 CONCLUSION

This article constitutes a brief review of the preparation and heat transfer enhancement of hybrid nanofluids. Recent publications that deal with preparation, synthesis, thermophysical properties, experimental aspects and numerical studies of hybrid nanofluids in thermal applications were summarized. The main reasons behind the enhanced performance of heat transfer in hybrid nanofluids is the improved effective thermal conductivity and kinetic motion of nanoparticles. Despite the enhanced heat transfer of hybrid nanofluids, many challenges, penalties and obstacles are facing designers and researchers working in this field. For instance, higher pumping power is needed to overcome pressure drop, stability analysis, the effect of sizes and shapes of nanocomposite materials as well as identifying the mechanisms for thermal and rheological properties enhancement. These challenges should be viewed as opportunities to carry out more research. Finally, more effort is required in determining use of hybrid nanofluids to serve as a promising coolant in industrial sector.

6 NOMENCLATURE

\( k \) thermal conductivity, [W/(m·K)]
\( c_p \) specific heat capacity, [J/(kg·K)]
\( Re \) Reynolds number, [-]
\( T \) bulk fluid temperature, [K]
\( \mu \) dynamic viscosity, [N·s/m²]
\( \phi \) nanoparticles volume fraction, [vol.%]
\( \rho \) density, [kg/m³]

Subscripts
\( bf \) base fluid,
\( nf \) nanofluid,
\( hy \) hybrid nanofluids,
\( np \) nanoparticles,
\( eff \) effective.

7 REFERENCES


