

# A brief survey of preparation and heat transfer enhancement of hybrid nanofluids

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*Investigation of domestic application of heat flux dissemination is in incredible request. The best strategy in getting the coolant with an ideal execution is by including particular sorts of nanoparticles to the base fluid. The utilize of nanofluids is to escalate heat transfer coefficient through the enhancement of base fluid's thermal conductivity. An advanced coolant (Hybrid nanofluid) was delivered by blending two or more different types of nano size particles with conventional fluid. This article mainly aims to cover the recent publications in hybrid nanofluids on different aspects such as preparation, thermophysical properties, and heat transfer enhancement. In common, the culminate combination of different nanoparticle properties results in an excellent thermal conductivity and heat transfer coefficient improvement were reached up to 148% compared to the base fluid. Moreover, moderate increase on pressure drop has been detected due to presence of composite nanoparticles. In any case, the anticipated results for both thermal conductivity and viscosity values utilizing classical relationships were distinctive from the experimental results.*

**Keywords:** Hybrid nanofluids, Nusselt number, Thermal conductivity, Viscosity, Thermal applications

## Highlights:

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

## 0 INTRODUCTION

High heat flux dissipation is one of the most prominent reasons which has motivated many researchers to put their best efforts in producing new cooling system ( or what so-called new coolant).

Finally in 1995, Choi presented the term “nanofluid” as an expression for base fluid that contains very small particles(<100nm) 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 system. However, issues such as clogging, erosion, nanoparticles sedimentation, and high cost are the main challenges in extending nanofluid within

industrial sector [2]. For example, metallic nanoparticles have high thermal conductivity and good electric properties but they produce low stability and chemically inert fluid. On the other hand, metals oxide nanoparticles have low thermal conductivity with high stability in the fluid. The combination of these two nanoparticles types was the preferred characteristics for a favorable coolant. Therefore, many researchers were 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 is an abrupt demand for research in hybrid nanofluids that, enhance

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thermophysical and heat transfer properties. Thus a sincere attempt was made in preparing an article that may come in handy to fulfill those demands. Many researches focused only on thermophysical properties of hybrid nanofluids, and some focused on its application especially 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 nanofluids preparation, thermophysical properties, and heat transfer coefficient enhancement.

An Introduction should provide a review of the recent literature on the topic and sufficient background information to allow the results of the article to be understood and evaluated.

## 1 PREPARATION OF HYBRID NANOFLUIDS

There are many methods for nanomaterials synthesis such as Chemical Vapor Deposition (CVD), Vacuum Deposition and Vaporization, and Sol-Gel Techniques [4, 5]. There are two methods used in preparing hybrid nanofluids known as one-step and two-step methods. Most scholars utilize the two-step method in preparing hybrid nanofluids, but some of them synthesize the nanocomposite (NC) particles before they are dispersed in base fluids. The NC particles could be synthesized through several methods such as pure chemical reaction [6], thermochemical method [7], and in-situ method [8].

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

While Megatiff et al. [10] prepared  $\text{TiO}_2$ –CNT nanocomposite by using hydrolysis technique. They obtained CNTs dispersion by mixing the CNTs with  $\text{HNO}_3$ – $\text{H}_2\text{SO}_4$ , followed by EG and 20 mL of 2-propanol. Subsequently,  $\text{Ti}(\text{OBu})_4$  was added into the suspension for a special treatment. Nanocomposite was obtained after vacuum filtering, washing in 2-propanol, and drying of CNT– $\text{TiO}_2$ . Suresh et al. [7] synthesized  $\text{Al}_2\text{O}_3$ –Cu nanocomposite particles by using 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-MWCNTs– $\text{Fe}_3\text{O}_4$ /EG hybrid nanofluid. Dry f-MWCNTs and  $\text{Fe}_3\text{O}_4$  nanoparticles were mixed in ethylene glycol and were prepared in different volume fractions. Ultrasonic vibration instrument was used to get a good stability as shown in Fig. 2. Akilu et al. [12] utilized wet-mixing method to synthesize titanium oxide-copper oxide/carbon ( $\text{TiO}_2$ – $\text{CuO}$ /C) based nanocomposites. After that, they prepared stable EG based hybrid nanofluids through two step method to develop the thermophysical properties of base fluid. Sundar et al. [13] synthesized nanodiamond-nickel (ND–Ni) nanocomposite materials through in-situ growth and chemical co-precipitation method.

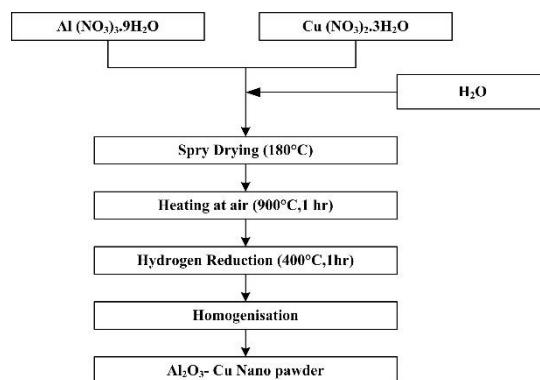


Fig 1. Schematic diagram of  $\text{Al}_2\text{O}_3$ –Cu synthesis through the thermochemical procedure.

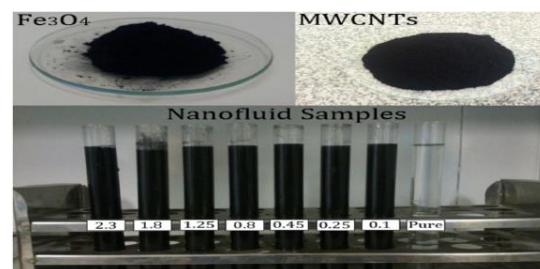


Fig 2. f-MWCNTs– $\text{Fe}_3\text{O}_4$ /EG hybrid nanofluid with different volume concentration[11].

Table 1 shows that, researchers preferred to combine metallic or metallic oxide with carbon

nanoparticles families (CNTs, MWCNTs, GNPs, and diamonds) because of their high thermal conductivities, low densities, and better performance in electric behavior. Table 1 describes the recent works done in hybrid nanofluids. In this shown 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.

Moreover, comprehensive reviews on hybrid nanofluids preparation is conducted by

Sundar et al. [38], Takabi and Salehi [39] and Babu et al. [40]. They summarized all the work that is related to preparation of such nanofluids in the past few decades.

It is important to mention here that in order to reach a stable hybrid nanofluid, the absolute zeta potential of the hybrid nanofluid must be more to the extent possible. As the zeta potential diverges from the iso-electric point, strong repulsive forces develop among nanoparticles and reduce agglomeration. [40].

In the next section, thermophysical and rheological properties of the hybrid nanofluids is dealt.

**Table 1.** The preparation methods of hybrid nanofluids

Reference	Hybrid nanoparticle	Dispersant fluid	Vol. %	Stability methods	Main Objective
Han et al. [14]	(NC)Al <sub>2</sub> O <sub>3</sub> +Fe <sub>2</sub> O <sub>3</sub> +CNT	poly-alpha-olefin (PAO)	0.1,0.2 vol. %	Sonication and surfactant (Span-80)	Studying the effective thermal conductivity
Chen et al. [15]	(NC)Ag/MWNT	Water	1.0vol. %	Sodium dodecyl sulfate (SDS)	Studying the effective thermal conductivity
Suresh et al. [16]	(NC)Al <sub>2</sub> O <sub>3</sub> -Cu	Water	0.1 vol. %	ultrasonic vibrator, and sodium lauryl sulfate (SLS)	Enhancing convective heat transfer and pressure drop
Khosravifard et al. [17]	TiO <sub>2</sub> -CNTs	propylene glycol + water		ultrasonic Agitator, and (SDS)	Studying the characterization and thermophysical properties
Selvakumar and Suresh [18]	(NC)Al <sub>2</sub> O <sub>3</sub> -Cu	Water	0.1vol. %	ultrasonic vibrator, and (SLS)	Enhancing convective heat transfer
Safi et al. [19]	(NC)MWCNT-TiO <sub>2</sub>	Water	0.02 - 0.08 wt. %	ultrasonic agitator	Enhancing convective heat transfer
Nine et al. [20]	Al <sub>2</sub> O <sub>3</sub> -MWCNTs	water	1- 4 wt. %	ultrasonic vibrator	Studying the characterization and thermophysical properties
Sundar et al. [21]	(NC)Diamond+Ni	water and EG	0.1- 0.3vol. %	ultrasonic vibrator, and NanoSpere AQ	Enhancing convective heat transfer and pressure drop
Madhesh et al. [22]	(NC)Cu-TiO <sub>2</sub>	Water	0.1-2.0 vol. %	ultrasonic vibrator without surfactant	Enhancing convective heat transfer
Esfe et al. [23]	Ag-MgO	water	0-2.0 vol. %	ultrasonic vibrator and CetylTrimethyl Ammonium Bromide (CTAB)	Studying the effective thermal conductivity
Esfe et al. [24]	CNTs-Al <sub>2</sub> O <sub>3</sub>	Water	0.02-1 vol. %	ultrasonic vibrator	Studying the effective thermal conductivity
Yarmand et al. [9]	(NC) GNP-Ag	Water	0-0.1vol. %	ultrasonic vibrator	Enhancing convective heat transfer and pressure drop
Baghbanzadeh et al. [25]	silica + MWCNTs	Water	1.0 wt. %	SDBS	Studying the rheological properties.

Sundar et al. [26]	(NC)CNT-Fe <sub>3</sub> O <sub>4</sub>	Water	0.1-0.3 vol.%	(situ method) and NanoSpere AQ	Enhancing convective heat transfer and pressure drop
Madhesh et al. [27]	Ag+CuO	water	1.0 vol.%	ultrasonic vibrator	Enhancing convective heat transfer and pressure drop
Eshgarf and Afrand [28]	MWCNTs-SiO <sub>2</sub>	EG, Water	0.0625- 2 vol.%	carboxyl (COOH) - functionalized	Studying the rheological properties.
Harandi et al. [11]	F-MWCNTs-Fe <sub>3</sub> O <sub>4</sub>	EG	0-2.3vol.%	ultrasonic vibrator	Studying the effective thermal conductivity
Ramachandran [29]	Al <sub>2</sub> O <sub>3</sub> + CuO	Water	0.1 vol.%	ultrasonic vibrator	Enhancing convective heat transfer
Asadi and Asadi [30]	MWCNT+ZnO	Engine oil	0.125- 1 vol.%	ultrasonic vibrator	Studying the rheological properties.
Huang et al. [31]	MWCNT+Al <sub>2</sub> O <sub>3</sub>	Water	MWCNT0 .0111 vol. % , Al <sub>2</sub> O <sub>3</sub> 1.89vol.%	ultrasonic vibrator	Enhancing convective heat transfer and pressure drop
Esfe et al. [32]	MWCNTs-SiO <sub>2</sub>	Engine oil	0-2.0vol%	ultrasonic vibrator	Studying the rheological properties.
Afrand [33]	Fe <sub>3</sub> O <sub>4</sub> -Ag	EG	0.6-1.2vol.%	ultrasonic vibrator	Studying the rheological properties.
Afrand [34]	SiO <sub>2</sub> -MWCNTs	Engine oil	0.625-1 vol.%	ultrasonic vibrator	Studying the rheological properties.
Allahyar et al. [35]	(NC) Al <sub>2</sub> O <sub>3</sub> -Ag	Water	0.1-0.4 vol%	Sol-gel method	Studying the effective thermal conductivity
Megatif et al. [10]	(NC)TiO <sub>2</sub> -CNT	Water	0.1-0.2 vol.%	Hydroxyl (-OH) and carboxyl (-COOH) functionalized	Enhancing convective heat transfer
Toghraie et al. [36]	ZnO-TiO <sub>2</sub>	EG	0-3.5 %	ultrasonic vibrator	Studying the effective thermal conductivity

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

Reference	Hybrid nanofluids type	The proposed correlations
Sunder et al. [21]	Diamond+Ni/water,EG	$\frac{k_{nf}}{k_{bf}} = 1 + 4.01\phi$ , $\frac{\mu_{nf}}{\mu_{bf}} = 1.35e^{12.83\phi}$
Esfe et al. [23]	Ag-MgO/water	$\frac{k_{nf}}{k_{bf}} = \frac{0.1747 \times 10^5 + \phi}{0.1747 \times 10^5 - 0.1498 \times 10^6 \phi + 0.1117 \times 10^7 \phi^2 + 0.1997 \times 10^8 \phi^3}$ $\frac{\mu_{nf}}{\mu_{bf}} = 1 + 32.795\phi - 7214\phi^2 + 714600\phi^3 - 0.1941 \times 10^8 \phi^4$
Harandi et al. [11]	F-MWCNTs-Fe <sub>3</sub> O <sub>4</sub> /EG	$\frac{k_{nf}}{k_{bf}} = 1 + 0.0162\phi^{0.7038}T^{0.6009}$
Asadi and Asadi [30]	MWCNT+ZnO/engine oil	$\mu_{nf} = 796.8 + 76.26\phi + 12.88T + 0.7695\phi T + \frac{-196.9T - 16.53\phi}{\sqrt{T}}$
Afrand et al. [34]	SiO <sub>2</sub> -MWCNTs/ engine oil	$\frac{\mu_{nf}}{\mu_{bf}} = a_0 + a_1\phi + a_2\phi^2 + a_3\phi^3 + a_4\phi^4$ , where a's are factors depend on T..
Toghraie et al. [36]	ZnO-TiO <sub>2</sub> /EG	$\frac{k_{nf}}{k_{bf}} = 1 + 0.004503\phi^{0.8717}T^{0.7972}$
Esfahani et al. [37]	ZnO-Ag /water	$\frac{k_{nf}}{k_{bf}} = 1 + 0.0008974\phi^{0.5899}T^{1.345}$

## 2 THERMOPHYSICAL PROPERTIES OF HYBRID NANOFLUIDS

Studying the thermophysical and rheological properties of hybrid nanofluids is essential for continuous development and determination of their usage in various applications. Also, a significant amount of combination between nanofluids types can be done in preparing hybrid nanofluids. Therefore, a lot of researches worked on investigating thermophysical and rheological properties, in addition to the main parameters which has an effect on hybrid nanofluids.

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

$$\rho_{hy} = \phi_{np1}\rho_{np1} + \dots + \phi_{npn}\rho_{npn} + (1 - \phi_{np}) \quad (1)$$

$$c_{hy} = \frac{\phi_{np1}\rho_{np1}c_{np1} + \dots + \phi_{npn}\rho_{npn}c_{npn} + (1 - \phi_{np})\rho_{bf}c_{bf}}{\rho_{hy}} \quad (2)$$

where  $\phi_{np}$  is the volume concentration of all nanoparticles

$$\phi_{np} = \sum_{i=1}^n \phi_{npi} \quad (3)$$

The thermal conductivities and viscosity of nanofluids can be predicted by traditional models, such as: Hamilton and Crosser Model (1962) for predicting thermal conductivity[41]:

$$k_{eff} = k_{bf} \frac{k_p + (n-1)k_{bf} + (n+1)(k_p - k_{bf})\phi}{k_p + (n-1)k_{bf} - (k_p - k_{bf})\phi} \quad (4)$$

Where n is the shape factor

$n: 3 \leq n \leq 3.13$  and for spherical shape  $n=3$ .

For hybrid nanofluids the thermal conductivity can be calculated using Eq. (5), and Batchelor correlation (1977) (Eq. (6)) for the viscosity[42].

$$k_p = \frac{\phi_{np1}k_{np1} + \phi_{np2}k_{np2} + \dots + \phi_{npn}k_{npn}}{\phi_{np}} \quad (5)$$

$$\mu_{eff} = (1 + 2.5\phi + 6.2\phi^2)\mu_{bf} \quad (6)$$

Some researchers have indicated that viscosity and thermal conductivity of the hybrid nanofluid 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 thermophysical properties of EG-water based  $Al_2O_3/CuO$  hybrid nanofluids at different concentrations. They revealed that conventional correlations need to consider the interfacial

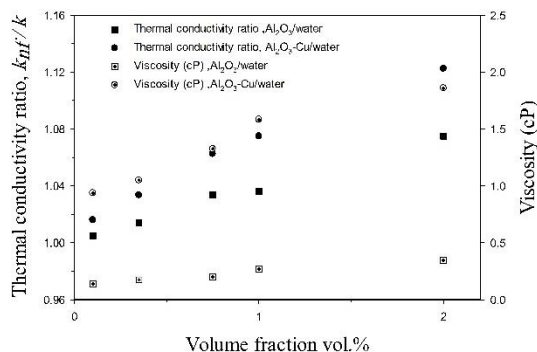
chemical interactions between nanomaterials and base fluids.

Correlations for specific hybrid nanofluids types depend on experimental data collection, whereby general correlations were predicted by using methods such as curve fitting, the Predicted Residual Sum of Squares (PRESS) or any regression software. Table 2 introduces some correlations which were derived from recent experimental works. Esfe et al. [24] had predicted a correlation to predict the thermal conductivity of CNTs-  $Al_2O_3$ /water hybrid nanofluid. 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+ $SiO_2$ /engine oil hybrid nanofluid. Also, Newtonian behavior 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 investigation to ensure that the simulations are more reliable, cost effective and time saving.

Recently Esfe et al. [44] has studied the thermal conductivity of dispersing SWCNT and ZnO particles in a solution contains 30% EG and 70% water. They proposed a new correlation to thermal conductivity ratio of the nanofluid. They also concluded that the thermal conductivity is more sensitive to concentration variations more than to temperature changes.

Hybrid nanofluids were proven to highly enhance the effective thermal conductivity and viscosity, compared to the mono nanofluids. Sundar et al. [21] concluded that thermal conductivity of nano diamond and nickel (ND-Ni)/EG enhances 21% more when compared to the base fluid. They have also observed a 28.46% enhancement of MWCNT- $Fe_3O_4$ /water compared to the base fluid [8]. Additionally, Suresh et al. [7] found some enormous enhancement in the effective thermal conductivity and viscosity of  $Al_2O_3-Cu$ /water hybrid nanofluids in comparison to  $Al_2O_3$ /water nanofluid. Fig. 3 indicates that as the particle concentration increased, thermal conductivity ratio and viscosity also increased, respectively. The maximum enhancement of thermal conductivity was 12.11%, and significant enhancement in viscosity reached up to 115% in comparison with the water. Baghbanzadeh et al. [25] investigated the rheological properties of silica-MWCNT/water hybrid nanofluid 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 thermophysical properties of  $\text{TiO}_2\text{-Cu}$ /water hybrid nanofluid.



**Fig. 3.** Thermal conductivity ratio and viscosity of the nanofluids as a function of volume concentrations [7].

Parameters that control the thermophysical properties enhancement of hybrid nanofluids are mainly the solid volume concentration and the temperature, in addition to the nanoparticles shapes and sizes. The Brownian motion contributes to a great impact on this enhancement as well, which is even more significant when temperature increases. This behavior is similarly observed on mono nanofluids. However, thermal conductivity is more sensitive towards the nanoparticle concentration than the temperature, contrary to the temperature effect on viscosity [34, 46].

It is of great importance to mention here and based on the previous literature review that few research articles consider thermophysical properties to be temperature independent such as [21, 45]. Whereas, many research papers consider thermophysical properties to be temperature dependent such as [7, 8, 11, 24, 25, 30, 32, 34, 36, 37]

### 3 HEAT TRANSFER ENHANCEMENT USING HYBRID NANOFLUIDS

The main objective in studying the thermophysical properties of hybrid nanofluids is to involve in and further improve its various

applications especially these 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.

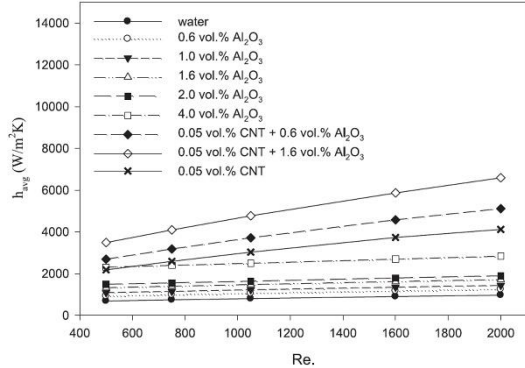
Based on the literature review, one can classify the work done to investigate heat transfer enhancement using hybrid nanofluids into two major categories. Namely, numerical and experimental works. The next subsections summarizes the work done that is related to the enhancement of heat transfer employing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

#### 3.1 Numerical Studies

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

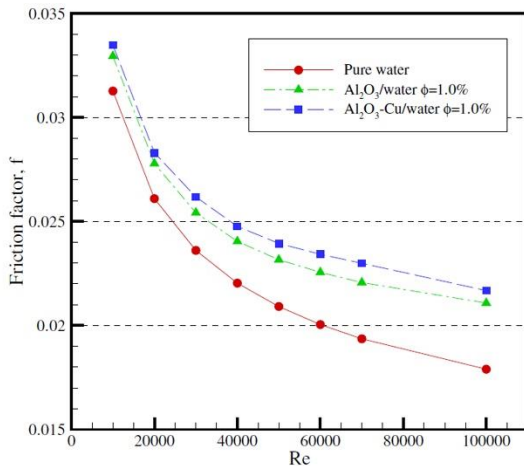
Takabi and Shokouhmand [49] had numerically analyzed the turbulent forced convective heat transfer of  $\text{Al}_2\text{O}_3\text{-Cu}$ /water hybrid nanofluid. Uniform heat flux was applied on the external walls of circular tubes. They compared the results obtained from hybrid nanofluid with  $\text{Al}_2\text{O}_3$ /water nanofluid, and hybrid nanofluid with water. Their results show that the use of hybrid

nanofluids could increase the average Nusselt number, on the other hand the increase in pressure drop is one of the main obstacles.



**Fig. 4.** Effect of particle concentration and Reynolds number of average heat transfer coefficient of mono and hybrid nanofluids[44].

Fig. 5 clearly indicates the increment in friction factor for  $\text{Al}_2\text{O}_3$ -Cu/water hybrid nanofluid over  $\text{Al}_2\text{O}_3$ /water nanofluid. Takabi et al. [50] used the same hybrid nanofluid to investigate the thermal effect in laminar regime and found 7.20% enhancement in the average Nusselt number compared to water, with only 10.94% increase in pressure drop.



**Fig. 5.** The effect of Hybrid nanofluid on the pressure factor [46]

Nimmagadda and Venkatasubbaiah[51] shared their results which reflect an enormous enhancement in heat transfer coefficient which had reached up to 148%. They used 3.0 vol.%  $\text{Al}_2\text{O}_3$ +

Ag/water hybrid nanofluids 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  $\text{Al}_2\text{O}_3$ +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 ( $\text{Re} < 2300$ ), and the results were compared to the same concentration of  $\text{Al}_2\text{O}_3$ /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 laminar flow of the Cu+CuO/water hybrid nanofluid in 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 30-35% enhancement of Nusselt number ratio with a notice of pressure drop. The pressure drop was also increased with the increase of the Reynolds number, volume concentration of nanoparticles, and the density of nanoparticle materials. In addition, Takabi and Salehi [39] concluded numerically 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- $\text{Fe}_3\text{O}_4$  nanocomposite particles were used in preparing hybrid nanofluids in different volume concentration (0-0.3vol.%). The results highlight the increase of Nusselt number dependent on the increase of particle concentration. Fortunately, a negligible increase of 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 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  $5000 \leq Re \leq 15,000$  within fully developed turbulent flow regime. The outcome indicates an improvement in heat transfer performance with an increase of pumping power requirement to overcome pressure drop.

Recently, Hussien et al. [58, 59, 60] studied the thermal performance of MWCNTs/water nanofluid and MWCNTs/GNPs hybrid nanofluid in minitube. Their experimental results show high enhancement of heat transfer coefficients with an increase in pressure drop when using low weight concentration of MWCNTs/GNPs. They concluded that the increase of 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 horizontal tube. They found that hybrid nanofluids enhanced heat transfer better than mono nanofluids.

Hamid et al. [62] investigated experimentally the role of  $TiO_2$ - $SiO_2$ /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 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 surrounding.

On the other side, the continuous movement of nanoparticles in the base fluid specially at the layers near the walls increases the chance of collision with the wall required for heat transfer.

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 give 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, 66], and automotive cooling system [67, 68].

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

In their experimental research, Selvakumar and Suresh [18] used  $Al_2O_3$ -Cu/water hybrid nanofluid for cooling of electrical component through a thin-channelled copper heat sink. Fig.6 shows the flow of  $Al_2O_3$ -Cu/water inside the heat sink. 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 on observations along with utilizations of hybrid nanofluids.



Fig. 6. Thin channel copper heat sink[18].



Bahiraei and Heshmatian [66] utilized hybrid nanofluid that contains graphene nanoplatelets decorated with silver nanoparticles in CPU cooler. Their results show a higher thermal performance and irreversibility rates than the normal CPU cooler. They strongly suggest hybrid nanofluids as a promising coolant for electrical devices.

Sozen et al.[69] studied the role of fly ash water based nanofluid in increasing the efficiency of concentric tube heat exchanger. They prepared 2wt.% nanofluid through direct synthesis. The maximum improvement of the efficiency was 31.2% for parallel flow concentric tube heat exchanger. Safi et al. [19] investigated experimentally the use of MWCNT-TiO<sub>2</sub>/water hybrid nanofluid in 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 occurs when using Cu-TiO<sub>2</sub>/water hybrid nanofluid, after testing it as a coolant inside a tubular heat exchanger. The heat transfer coefficient enhanced at 48.4% more compared with water. In their study, 0.1-1.0 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 Al<sub>2</sub>O<sub>3</sub>+MWCNT/water hybrid nanofluid in a plate heat exchanger. In that experiment, a mixture of 0.0111% MWCNT/water nanofluid with 1.89% Al<sub>2</sub>O<sub>3</sub>/water nanofluid was used, and subsequently detected a very low enhancement in heat transfer coefficient compared to Al<sub>2</sub>O<sub>3</sub>/water with a slight increase in pressure drop. Since these results may contradict with previous researches, it was considered as erroneous because the enhancement is within the range of experimental errors. However, it was still recommended for hybrid nanofluids to be used in heat transfer applications.

In order to improve engine oil as a coolant and lubricant fluid, Asadi et al. [68] added Mg (OH)<sub>2</sub>/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 cylindrical screen mesh heat pipe by Ramachandran et al. [29, 71]. They combined Al<sub>2</sub>O<sub>3</sub> and CuO nanoparticles in different ratios and obtained results showing 44.25% maximum reduction in thermal resistance for the ratio Al<sub>2</sub>O<sub>3</sub> 25% – CuO 75%. Based on the results, it can be concluded that hybrid nanofluids are worth to be strongly considered as a substitute for conventional fluid.

Moreover, nanofluids and hybrid nanofluids are used to enhance the performance of the 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 economic and ecologic of nanofluid based solar systems. In addition, Hader and Al-Kouz [73] investigated numerically 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. Also, 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 the efficiency. Moreover, they 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, 76].

It is worth mentioning here that few researches had been conducted on dispersing nanofluid in rarefied gases. For instance, Al-Kouz et al. [77] investigated the effect of dispersing nanosolid particles of Al<sub>2</sub>O<sub>3</sub> into the air base fluid in cavities equipped with solid fins. Effects of Knudsen number, volume fraction of the nanosolid particles, Rayleigh number on both heat transfer and pressure drop were analyzed. 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/ $\text{Al}_2\text{O}_3$  nanofluid. Effects of Knudsen number and volume fraction of the nanosolid particles on the total entropy generation were shown and analyzed. In addition, 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/ $\text{Al}_2\text{O}_3$  flow in pipes. Effects of the aspect ratio, Knudsen number, Reynolds number and the nanosolid particles volume fraction on the heat transfer characteristics were presented and a correlation of Nusselt number among all the investigated parameters is introduced. It is highly recommended and for future work to investigate rarefied flows with hybrid nanofluids which is and up to the authors knowledge have not been tackled yet.

## 5 CONCLUSION

This article constitutes a brief review of preperation and heat transfer enhancement of hybrid nanofluids. Recent publications that deal with preperation, synthesis, thermophysical properties, experimental aspects and numerical studies of hybrid nanofluids in thermal applications were summarized and appropriately shared. 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 researches working in such field. For instance, higher pumping power is needed to overcome pressure drop, stability analysis, 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

$k$	W/m.K	Thermal conductivity
$c_p$	J/kg.K	Specific heat capacity

CNTs	-	Carbon nanotubes
EG		Ethylene glycol
MWCNTs	-	Multiwall carbon nanotubes
GNPs		Graphene nanoplatelets
$Re$	-	Reynolds number
$T$	K	Bulk fluid temperature
$\mu$	N.s/m <sup>2</sup>	Dynamic viscosity
$\phi$	Vol.%	Nanoparticles volume fraction
$\rho$	Kg/m <sup>3</sup>	Density

### Subscripts

$bf$	Base fluid
$nf$	Nanofluid
$hy$	Hybrid nanofluids
$np$	Nanoparticles
$eff$	Effective

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