INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 17, ISSUE 1, 7719 – 7733
DOI: https://doi.org/10.15282/ijame.17.1.2020.19.0574

REVIEW ARTICLE

Heat Transfer Augmentation in Heat Exchanger by using Nanofluids and Vibration Excitation - A Review

N. F. D. Razak[1], M. S. M. Sani[1,3*] and W. H. Azmi[2,3]

[1]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan Pahang, Malaysia
[2]College of Engineering, Department of Mechanical Engineering, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
[3]Automotive Engineering Centre, Universiti Malaysia Pahang, 26600 Pekan Pahang, Malaysia.
Phone: +6-09-4246325; Fax: +6-09-4246222

ABSTRACT – Nanofluids are used in heat exchanger system as efficient heat transfer fluids to improve heat transfer performance by passive method. Besides, another special active technique by implementing the low or high frequency vibration, which was used in heat exchanger to enhance the heat transfer performance. This paper reviews the heat transfer augmentation in heat exchanger by using nanofluids, vibration excitation of low and high frequency vibration. The use of nanofluids in heat exchanger system can provide better effective thermal conductivity compared to the conventional coolants. The presence of nanosize particles in nanofluids performed better mixing flow with higher thermal properties compared to pure fluids. Additionally, the active method by inducing low and high frequency vibration technology was applied in heat exchanger system. The heat transfer augmentation by vibration excitation was resulted from the mitigation of the fouling resistance on the surface of the tube wall. It was found that vibration excitation not only increase the heat transfer rate, but also might be a solution for fouling reduction. Hence, there is a great potential of using nanofluids together with vibration excitation simultaneously in heat exchanger system to improve the heat transfer performance.

ARTICLE HISTORY
Revised: 21st Nov 2019
Accepted: 6th Dec 2019

KEYWORDS
Heat transfer; Heat exchanger; Nanofluids; Flow-induced vibration; Ultrasound

INTRODUCTION

In a combustion system, heat exchanger played an essential role as a device that exchanges the circulated heated coolant where heat is lost to the atmosphere to return into its ambient temperature. Conventional coolants such as water and ethylene glycol mixture have been used primarily in automobile radiator for many years. However, these provided low thermal conductivity. Recently, in an advanced fluids research area, the new types of coolant fluids, namely nanofluids has been introduced. This nanofluids offer higher thermal conductivity compared to that of conventional coolants. To improve the thermal properties of a liquid, solid particles less than 100 nm are dispersed to the conventional coolants. This resulted in nanofluids being used instead of base fluids [1, 2]. The most commonly used nanoparticles for nanofluids formulation are copper (Cu), aluminium (Al), magnesium (Mg), silicon (Si), silver (Ag), iron (Fe), titanium (Ti), zinc (Zn), carbon nanotubes (CNTs), graphene, graphene oxide, and diamond. Also, the commonly used of base fluids for nanofluid formulation are water, ethylene glycol (EG), EG – H_2O mixtures, and oils [3]. CuO water-based nanofluid has the potential to use as an effective heat transfer fluid as it has been discovered by former research. As the volume fraction of CuO nanoparticles increase, the heat transfer performance increases by 92.71% for 1% CuO water-based nanofluid compared to base fluid water. Also, from the observation, the addition of nanoparticles will increase the conductivity slightly and viscosity greatly [4]. The increased rate of heat transfer was observed with an increase in volume flow rate, nanoparticle concentration. Rate of heat transfer was also found to be increasing with a decrease in temperature of hot nanofluid at the inlet [5]. Moreover, increasing the fluid circulating rate can improve the heat transfer performance. Meanwhile, in comparison with pure water, the application of nanofluid with low concentrations can improve heat transfer efficiency up to 45% [6].

At present, more than 90% of worldwide energy utilisation involves heat transfer process. Therefore, it is a very important researching point to improve heat transfer efficiency. It takes years for scholars to find several efficient methods on the improvement of heat transfer performance, including active and passive technology [7, 8]. As an example, flow-induced vibration enhancing heat transfer is a unique method in passive technology [9,10]. From the literature, the work covered low and high-frequency vibrations, with the low-frequency work between 10 to 3000 Hz and the high-frequency work at above 20 kHz. Despite the harmful factor for causing the heat exchanger damage, the flow-induced vibration in heat exchanger is used by some researchers for its positive role on restraining the fouling, thus reduce the fouling resistance [11, 14]. Additionally, the implemented of low-frequency vibration were found to increase the thermal performance of the heat exchanger by its frequency and amplitude of vibration waves [15]. Vibration can materially increase the coefficient of heat transfer, a quadrupling of the coefficient having been obtained. Holding other variables constant in turn, the heat transfer coefficient increased with both amplitude and frequency

*CORRESPONDING AUTHOR | M. S. M. Sani | mshahrir@ump.edu.my

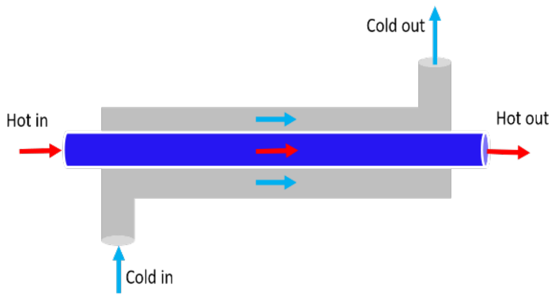
[16]. Overall, the objectives of this paper are to provide scientific and historical backgrounds to the future studies concerning heat transfer enhancement by nanofluids and vibration applications in heat exchanger to bring forward the evolution of this domain with several examples of applications.

BASIC PRINCIPLE OF HEAT EXCHANGER

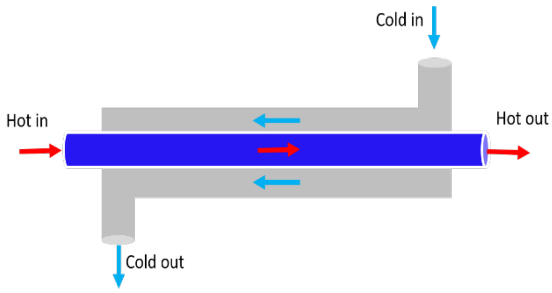
The heat exchanger is a device that exchanges the heat between two fluids at different temperatures without mixing each other. The heat exchanger covers a wide range of applications. Some of the applications are heating and air-conditioning systems in a household, chemical processing, and power production in large plants. Heat transfer in a heat exchanger commonly involves convection in each fluid and conduction through the wall separating the two fluids. In the study of a heat exchanger, it is convenient to work with an overall heat transfer coefficient that accounts for the contribution of all (convection and conduction) effects on heat transfer. In a heat exchanger, the rate of heat transfer between the two fluids at a location depends on the magnitude of the temperature gradient at the location. Besides, the rate of heat transfer varies along with the heat exchanger.

There are different types of heat exchanger in the industry or market. Different heat transfer applications need different types of hardware and configurations of heat transfer equipment. Double-pipe heat exchanger is an example of simplest type of heat exchanger. One fluid flows through the smaller pipe while the other fluid flows through the annular space between the two pipes. Parallel flow, as shown in Figure 1(a) and counterflow, as shown in Figure 1(b) are the two types of possible flow arrangement. Besides that, a compact heat exchanger is another type of heat exchanger that specifically designed to detect a large heat transfer surface per unit volume. In advanced fluids research area, nanofluids have been introduced in a heat exchanger to offer higher thermal conductivity hence increase the rate of heat transfer compared to that of conventional coolants.

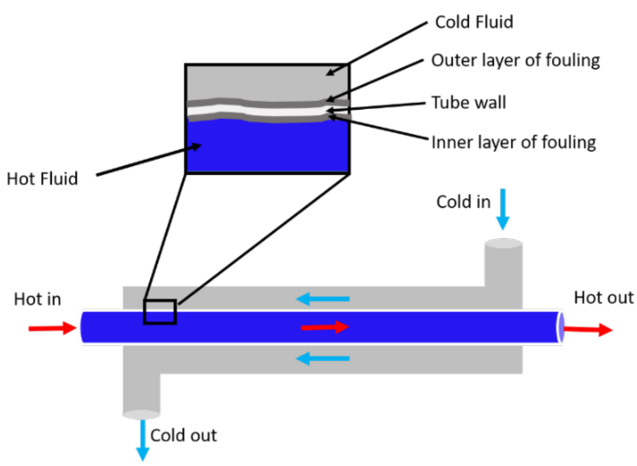
The heat exchanger also experienced with an accumulation of deposits on the heat transfer surface. The performance of heat exchangers usually deteriorates with time because the layer of deposits creates additional resistance to the heat transfer. The fouling layer in heat exchanger is shown in Figure 1(c). Over a transient study, low-frequency vibration was implemented to mitigate the fouling of nanoparticles inside the heat exchanger. By applying the vibration into the system, fouling thermal resistance can be decreased, and via low-frequency vibration, fouling of nanoparticles can be mitigated. A new design of a heat transfer device is proposed in a novel approach to improve heat transfer. The convective heat transfer coefficient can be significantly increased, and the fouling resistance can be decreased by using the new design of heat exchanger.



(a) parallel flow



(b) counter flow



(c) fouling layer in heat exchanger

Figure 1. Double pipe heat exchanger.

APPLICATION OF NANOFLUIDS IN HEAT EXCHANGER

Nanofluids have gained so much attention in these recent years. The nanofluids were proven with significant potential for implementation in many systems and industries. The wide range of application especially in heat exchanger system becomes the main reason for the development of the nanofluids. This section will review the application of nanofluids in the heat exchanger. In addition, the section also highlights the method of preparation and stability mechanisms for nanofluids, thermophysical properties and heat transfer performance of nanofluids specifically for the application in the heat exchanger system.

Preparation of Nanofluids

The proper method of preparation is the key step to improve the thermal conductivity of the nanofluids. Recently, a researcher has been trying to produce stable nanofluids with high capability of heat transfer characteristics based on a different type of nanoparticles [17]. The effect of various chemical surfactants namely sodium dodecyl benzene sulfonate (SDBS), sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB), and gum Arabic (GA) on the stabilisation of the graphene nanoplatelets in water have been investigated by Sarsam, Amiri, Kazi and Badarudin [18]. Ultrasonic has been used by them to homogenize the nanofluid. The results portrayed that the sample containing SDBS surfactant with the ratio of 1:1 and ultrasonic duration of 60 minutes experienced good stability condition for up to 60 days.

Leela Vinodhan, Suganthi and Rajan [19] investigated the heat transfer performance of self-produced water-based nanofluids by using copper oxide (CuO) nanoparticles in a U- shaped tube. The heat transfer rate and the Nusselt number of nanofluids were higher than those of pure water. In another paper, Hemmat Esfe, Saedodin, Biglari and Rostamian [20] did not use surfactants to stabilise the nanoparticles in the base fluids. However, the nanofluids underwent 400 W ultrasonic waves for up to 3 hours to stabilise the suspended nanoparticles. They investigated thermo-physical properties and heat transfer performance of the nanofluids of water and silver (Ag) nanoparticles. The Nusselt number was increased up to 11.8% at 1.0% volume concentration. Imani Mofrad, Saeed and Shanbedi [21] improved the thermal performance of a wet cooling tower by applying the nanofluids of water and zinc oxide (ZnO) nanoparticles. The thermal performance of a wet cooling tower was improved with the use of nanofluids at 0.02 to 0.1% weight concentration. In advanced cooling systems, Ilyas, Pendyala, Narahari and Susin [22] studied the stability and thermal properties of the nanofluids for thermal oil and alumina (Al_2O_3) nanoparticles. Oleic acid has been used by them to stabilise alumina nanoparticles suspended in the base oil.

Furthermore, Ettefaghi, Rashidi, Ahmadi, Mohtasebi and Pourkhalil [23] studied thermal and rheological properties of the nanofluids for engine oil with various carbon nanoparticles, viz. carbon nanotubes, graphene, carbon nanoball, and fullerene. The ultrasonic probe also has been used by them to normalize the suspended nanoparticles in the based fluids. The results indicated a significant thermal conductivity enhancement for up to 18% for nanofluids containing the carbon nanoball particles. Few studies have investigated car radiator coolant (CRC) performance by using nanofluids with a different type of nanoparticles. One of the studies was undertaken by Ali, Ali, Liaquat, Bin Maqsood and Nadir [24]. They used zinc oxide nanoparticles to enhance the performance of a car radiator. For further clarification on the technique of preparation, Table 1 shows the summary of the preparation method of nanofluids using different dispersing equipment undertaken by various scholars in the literature [25-36].

Thermo-Physical Properties of Nanofluids

The convective heat transfer performance strongly depends to the thermo-physical properties such as thermal conductivity, viscosity, density and specific heat of the working fluids. The dispersion of nanoparticles in nanofluids was improved the thermo-physical properties of original based fluids. The level of enhancement was associated with the type of nanofluids and also the physical characteristics of the nanoparticles. Some of the prime factors such as concentration, level of purity, shape and size of suspended nanoparticles were reported by Zhao, Li and Yang [37] which significantly alter the thermo-physical properties of the nanofluids. In addition, the heat transfer coefficient and pressure drop of nanofluids can be characterized quantitatively as a function of thermo-physical properties and thermal-hydraulic performances for application in automotive radiator [37]. The impact of variables namely nanoparticle properties, type, size, concentration and temperature on thermal conductivity and viscosity of nanofluids has dependably been a vital issue for both hypotheses contemplating and building application of nanofluids in an automobile radiator. Therefore, this section presents the thermo-physical properties and heat transfer performance of nanofluids for various types of base fluids and nanoparticles.

Thermal Conductivity of Nanofluids

Numerous experimental works, as well as theoretical investigation, have been performed to investigate the thermal conductivity variation of nanofluids. The enhancement of the thermal conductivity was affected by the addition of nanoparticles. The Brownian motion is found as a key mechanism to control the thermal behaviour of nanoparticles liquid suspensions. Various methods were used to measure thermal conductivity of nanofluids such as transient hot-wire apparatus and hot disk thermal constants analyzer. The measurements were performed for distinctive base liquids (ethylene glycol, propylene glycol, methanol, glycerol, gear oil, engine oil and paraffin) with various type of nanoparticles.

Table 1. Summary of preparation method of nanofluids using different dispersing equipment.

Dispersing equipment	Authors	Durations	Nanofluids	stabilisers / pH control
Ultrasonic vibrator	Duangthongsuk and Wongwises [25]	3-4	TiO_2/water	CTAB / -
Ultrasonic bath	Zhu et al. [26]	≥ 1	Al_2O_3/water	0.1 wt.% SDBS / pH = 8.0-9.0
	Li et al. [27]	≥ 0.25	Cu/water	0.02 wt.% SDBS / pH = 8.5-9.5
	Ho et al. [28]	≥ 2	Al_2O_3/water	-/pH = 3
	Kathiravan et al. [29]	≥ 10	Cu/water	SDS / -
	Dong et al. [30]	≥ 0.5	CuPc-U (unsulfonated and hydrophobic) and CuPc-S (surface sulfonated and hydrophilic)/(water-NaNO3 mixture)	Triton X-100 / -
Ultrasonic processor	Peng et al. [31]	1	Cu/R113 (refrigerant-based)	CTAB, SDS, Span-80 / -
Ultrasonic disruptor	Yousefi et al. [32]	0.5	MWCNTs/water	Triton X-100 / pH = 3.5, 6.5, and 9.5
	Hwang et al. [33]	2	MWCNTs/water	SDS / -
	Yousefi et al. [34]	0.5	Al_2O_3/water	Triton X-100 / -
Ultrasonic cleanser	Li et al. [35]	≥ 1	CuO/water	TX-10, CTAB, and SDBS / pH = 9.5
Ultrasonicated	Wang et al. [36]	24	Single-walled carbon nanotubes (SWNTs)/heavy water (D2O)	Triton X-100 / -

Sundar et al. [38] investigated thermal conductivity of Fe_3O_4 nanofluids. The experiments were performed at volume concentration up to 2.0% and the temperature range of 20 to 60 °C. Their results were displayed clearly the reliance on thermal conductivity on the particle volume concentration and temperature. A maximum enhancement of thermal conductivity was recorded up to 48% higher than the base fluids with 2.0% volume concentration and 60 °C temperature. The thermal conductivity was increased with increasing of the particle volume concentration. The thermal conductivity of NH_3 and H_2O mixtures (ammonia mass fractions from 0.10 to 0.50) at temperatures between 20 and 40 °C were studied experimentally by Cuenca et al. [39]. The results showed that the thermal conductivity of NH_3+H_2O mixtures was increased with the increase in the temperature and vice versa with the mass fraction.

The thermal conductivity enhancement of ZnO-EG nanofluids with temperature was investigated by Yu et al. [40]. The thermal conductivity was increased with the increase of temperatures from 10 to 60 °C however with constant enhancement ratios of nanofluids. In addition, the thermal conductivity augmentation of ZnO-EG nanofluids was increased nonlinearly with the volume concentration. The maximum improvement of 26.5% was observed for thermal conductivity of ZnO-EG nanofluids with 5.0% volume concentration. In another paper, the thermal conductivity of TiO_2/water nanofluids studied by Duangthongsuk and Wongwises [41]. The TiO_2 nanoparticles were dispersed in water for volume concentration of 0.2 to 2.0%. Similarly, the thermal conductivity of TiO_2 nanofluids was increased with increasing temperature.

The variation of thermal conductivity enhancement for CuO–gear oil nanofluids at different temperature was examined by Kole and Dey [42]. The enhancement of 10.4% was obtained at room temperature and 0.025 volume fraction of CuO nanoparticles. Further, the augmentation of thermal conductivity was increased up to 11.9% for 80 °C temperature. Table 2 summarises thermal conductivity investigation of various nanofluids for a different type of nanoparticles from other scholars [43-63]. The table presents variation of thermal conductivity enhancement for different types of nanofluids, based fluids and particle size from previous researchers.

Dynamic Viscosity of Nanofluids

The viscosity of nanofluids is an important parameter in the heat transfer system. The viscosity of the working fluids directly associated with the pressure drop and the pumping power of the system. The amount of particle loading into the conventional base fluids will increase the relative viscosity of the nanofluids. Besides, the viscosity of nanofluids also influenced by the particle diameter, temperature, and the type of material. Thus, further study on the parameters affecting the viscosity of nanofluids was carried out by various researcher [64]. Some of the instruments are the piston-type rheometer, rotational rheometer and the capillary viscometer were used to measure the viscosity of nanofluids. This section highlights the viscosity of nanofluids for different base fluids.

Table 2. Summary of thermal conductivity of nanofluids for different type of nanoparticles.

Nanoparticles	Based fluid	Particle size (nm)	Enhancement of thermal conductivity (%)	Researchers
Al_2O_3	Water	43	9.7	Chandrasekar [43]
		9	29	Mintsa et al. [44]
		30	1.44	Lee et al. [45]
		36	29	Li and Peterson [46]
		11-150	47	Chon et al. [47]
		38.4	24	Das et al. [48]
		13	32.4	Masuda [49]
	Water/EG	53	35	Vajjha and Das [50]
		8–282	20	Beck et al. [51]
		60.4	23/29	Xie et al. [52]
		28	41	Wang et al. [53]
	EG	12-282	19	Beck et al. [51]
	Transformer oil	650-1000	20	Choi et al. [54]
Cu	Water	50–100	24	Liu et al. [55]
		100–200	12	Liu et al. [55]
	EG	5–10	46	Yu et al. [56]
		23	34/54	Wang et al. [53]
		< 10	41	Eastman et al. [57]
CuO	Water	100	52	Zhang et al. [58]
		29	24	Mintsa et al. [44]
MWCNT	Water	10-30 (dia)×(10–50) µm	30	Ding et al. [59]
		270	7	Karami et al. [60]
		10(diameter) 5–10 µm length	41	Natrajan et al. [61]
		40(diameter)	32	Hwang et al. [62]
TiO_2	Water	15	79	Murshed et al. [63]

The viscosity can be interpreted as the internal resistance of nanofluids to flow [65]. Both the pumping power and convective heat transfer coefficient are affected by viscosity in heat transfer applications [66]. For future understanding on the rheological characteristics of nanofluids, it is important to investigate the influence of nanoparticle on the relative viscosity of the nanofluids. Aladag et al. [67] investigated the effect of temperature and shearing time on viscosity for Al_2O_3 and CNT nanoparticles dispersed in water at low particle loading and temperatures. The hysteresis behaviour is depending on shearing time when the stress was steadily loaded and unloaded. The CNT-water nanofluids showed Newtonian behaviour at a high shear rate, whereas Al_2O_3-water nanofluids exhibited non-Newtonian behaviour in the range of low temperatures.

Elias et al. [68] demonstrated an increase in viscosity with particle loading of Al_2O_3-water and Al_2O_3-water/EG mixture nanofluids, while diminishment in viscosity with increasing of temperature. Moghaddam et al. [68] were prepared the graphene–glycerol nanofluids and experimentally measured the rheological properties of the nanofluids. The viscosity of graphene–glycerol nanofluids increased with increasing the mass fraction and decreased with increasing of temperature. In their investigation, the relative viscosity of glycerol with nanoparticles experienced an enhancement of up to 401.49% at a shear rate of 6.32 s^{-1} and temperature of 20 °C when loading with 2% graphene nanosheets. In another paper, Alawi et al. [69] presented an increase in viscosity with particle loading and decrease with temperature for CuO/R134a nanofluids. Later, Sundar et al. [38] were showed the maximum viscosity ratio of 2.96 times higher than water at 2.0% volume concentration of the Fe_3O_4-water nanofluids. Table 3 shows the summary of viscosity for different nanofluids from other researchers [70-77]. The table presents the viscosity increment of nanofluids for different based fluids, volume concentrations, particle sizes and temperatures undertaken by various scholars.

Heat Transfer Performance using Nanofluids

Numerous experimental investigations have been conducted for vehicle system cooling using nanofluids or nanocoolants with ethylene glycol as the base fluids by different researchers. Teng and Yu [79] investigated the performance of MWCNT nanocoolant. They observed an improvement of efficiency for up to 14.1% by using performance factor ratio of heat exchange capacity to pumping power. Besides, the 50:50 ratio between nanofluids and ethylene glycol was reported as the optimum ratio for the best performance, and it was restricted to a low volume fraction of nanoparticles. The performance was dropped at a high concentration of nanocoolant due to the stability problem of the suspended nanoparticles. In another study, Nieh et al. [80] was achieved an efficiency factor of 27.2% at 0.2% volume concentration of TiO_2 nanofluid in ethylene glycol with 50:50 ratio. Raja et al. [81] and Zhong et al. [82] have examined the performance of alumina water at a different range of nanoparticle volume fractions. Raja et al. [81] obtained the maximum improvement of the heat transfer coefficient up to 25% at 2.0% volume concentration.

Table 3. Summary of viscosity for various types of nanofluids by using different based fluids.

Based fluid	Nanoparticles (volume concentration)	Particle size (nm)	Temperature range (°C)	Viscosity Increment	Authors
Water	Al_2O_3 (1–9.4%)	36,47	22–75	Dynamic viscosity is directly proportional to particle loading, but inversely proportional with the rise of temperature.	Nguyen et al. [70]
	Al_2O_3 (0.33–5%)	43	Room temperature	When volume concentrations of nanoparticles increased, the viscosity also increased. Viscosity and particle loading nonlinear relationship was identified in this study.	Chandrasekar et al. [71]
	Al_2O_3 (0–1%)	13-131	5–20	Viscosity improvement depends on volume fraction of nanoparticles and its temperature.	Mena et al. [72]
	TiO_2 (0.2– 2%)	21	15–35	Viscosity of nanofluids depends upon volume concentration and temperature. In this study, when particle concentration increased, the viscosity increased but decreased when the temperature increased.	Duangthongsuk and Wongwises [73]
	MWCNT (0.25–1.5 wt%)	20–30	Room temperature	Viscosity of nanofluids increased 233% compared with deionized water where it is consisting of MWCNTs and chitosan with particle loading 0.4 wt% and 1.5 wt%.	Hung and Chou [74]
	Fe_3O_4 (0–2%)	40	20–60	Viscosity increased 2.96 times with 2.0% volume concentration at 60 °C compared to base fluid.	Sundar et al. [38]
Ethylene glycol	ZnO (0–5%)	10–20	10–60	The temperature and volume fractions affects the Newtonian and non-Newtonian behavior of the nanofluids.	Yu et al. [40]
Water and EG	CuO (0–6.12%)	29	−35–50	Viscosity increased 4 times with 6.12% volume concentration of the CuO at -35 °C compared to base fluid.	Namburu et al. [75]
	Al_2O_3 (0 to 1 vol%)	13	10–50	Viscosity increased with the increase of volume concentrations but decreased at high temperature.	Elias et al. [78]
Base oil	CuO (0.2–2 wt%)	50	20–70	Viscosity increased about 20% with weight fraction of 2% at the lowest temperature of 20 °C.	Saeedinia et al. [76]
Gear oil	Cu (0.11–2%)	~40	10−80	Viscosity increased about 71% by 2 vol% of the Cu nanoparticles in gear oil at 30 °C.	Kole and Dey [77]
	CuO (0.005–0.025)	40	10–80	Viscosity increased around 3 times with 0.025 volume fraction of CuO but then decreased when the temperature increased.	Kole and Dey [42]

Nevertheless, Zhong et al. [82] reported a lower improvement of 6.52% compared to water at 5.0% volume concentration. Hence from the two observations indicate the declination of heat transfer performance at high volume concentration. Further, Table 4 provides a summary of experimental studies for vehicle cooling system using nanofluids from other researchers [83-98].

Advanced growth in numerical methods nowadays has gathered the attention of many researchers in computational analysis. Computational or numerical predictions give more comprehensive research to be conducted at low cost to support and extend the conventional experimental approach. Recently, the numerical and simulation studies of nanofluids were increased significantly to prove the better performance of nanofluids than traditional heat transfer fluids. Lv, Zhou, Bai, Liu and Xu [99] estimated the enhancement of heat transfer in internal combustion engine by the application of 5.0% volume concentration of Cu nanofluids. They found that the enhancement of the heat transfer coefficient was 46% higher than pure fluids by using Star-CD commercial software. Later, Vajjha et al. [100] carried out a numerical prediction on the fluid dynamics and heat transfer performance of Al_2O_3 and CuO nanofluids in the flat tubes of a radiator by using Fluent software. The results revealed an improvement of heat transfer coefficient up to 94% at Reynolds number of 2000 with 10% volume concentration of Al_2O_3 nanofluids. Whereas they presented 89% improvement of heat transfer coefficient using 6.0% volume concentration of CuO nanofluids when compared to pure water. The summary of numerical studies for vehicle cooling system using nanofluids from other scholars [101-106] is shown in Table 5. The table presented the best performance of the cooling system for different nanofluids.

Table 4. Summary of experimental studies for vehicle cooling system using nanofluids.

Authors	Coolants (nanofluids)	Best findings
Zhong et al. [82]	Al_2O_3-water, Al_2O_3-EG, Al_2O_3-EG/water	Increased 6.52% of heat transfer coefficient by 5.0 vol% of nanoparticles concentration compared to pure water.
Ali et al. [83]	Al_2O_3-water	Increased 14.72% of heat transfer coefficient by 1.0 vol% of nanoparticles concentration. Heat transfer rate and Nusselt number increased by 14.79% and 9.51% respectively.
Chougule and Sahu [84]	Al_2O_3-water, CNT-water	Thermal conductivity increased 76% of the CNT-water and 18% of the Al_2O_3-water by 1.0 vol% of nanoparticles concentration.
Tzeng et al. [85]	CuO, Al_2O_3, antifoam-transmission oil	At various speed, CuO enhanced until maximum heat transfer effect and had the lowest heat transfer distribution.
Vasheghani [86]	AlN-engine oil, α-Al_2O_3-engine oil, γ-Al_2O_3-engine oil	Thermal conductivity increased 75.23% of the AlN nanofluid, 37.49% of the γ- Al_2O_3 (20 nm) nanofluid, 31.47% of the α-Al_2O_3 (20 nm) nanofluid and 26.10% of the α-Al_2O_3 (100 nm) by 3.0 vol% of nanoparticles concentration.
Saripella et al. [87]	CuO-EG/water(50:50)	Lower coolant and engine temperature are resulted from heat transfer coefficient enhancement and hence improved the automotive engine cooling system.
Ettefaghi et al. [88]	MWCNT-engine oil	Increased 12.7% of thermal conductivity of the MWCNT by 0.5 vol% of nanoparticles concentration at 20 °C.
Peyghambarzadeh et al. [89]	Al_2O_3-water	Increased 3.0% of thermal conductivity of the Al_2O_3 by 1.0 vol% of nanoparticles concentration.
Chavan and Pise [90]	Al_2O_3-water	Increased 3.0% of thermal conductivity of the Al_2O_3-water by 1.0 vol% of nanoparticles concentration. Increased 40-45% of heat transfer of the Al_2O_3-water by adittion of 1.0 vol% of nanoparticles concentration when compared to pure fluid.
Elias et al. [78]	Al_2O_3-EG/water (50:50)	Increased 8.3% of thermal conductivity of the Al_2O_3 by 1.0 vol% of nanoparticles concentration at 50 °C.
Peyghambarzadeh et al. [91]	Al_2O_3-water, Al_2O_3-EG, Al_2O_3-EG/water (5–20 vol% of EG)	Increased 40% of heat transfer of the nanofluids by 1.0 vol% of nanoparticles concentration when compared to pure fluid.
Nieh et al. [80]	Al_2O_3-EG/water (50 vol% of EG), TiO_2 EG/water (50 vol% of EG)	Increased around 24-39% of thermal conductivity of the Al_2O_3 and similar to TiO_2 at all nanoparticles concentrations. Increased 27.2% of efficiency factor of the TiO_2-EG/water by 2.0 vol% nanoparticles concentrations also increased 14.4% when using Al_2O_3−EG/water compared to EG/water.
Sarkar and Tarodiya [92]	CuO, SiC, Al_2O_3, TiO_2-EG/water (80% water, 20% EG)	I Increased 15.34%, 14.33% and 14.03% of heat transfer rate of the SiC, Al_2O_3, and TiO_2 respectively by 1.0 vol% of nanoparticles concentration when compared to base fluid.
Liu et al. [93]	Nanodiamond-engine oil	Increased up to 1.15% of engine power and 1.18% of the torque by using nanofluid hence decreasing 1.18% fuel consumption compared to the engine oil.
Ebrahimi et al. [94]	SiO_2−water	Increased 9.3% of heat transfer of the nanofluid by 0.4 vol% of nanoparticles concentration at 60 °C.
Naraki et al. [95]	CuO−water	Increased 8.0% of heat transfer coefficient of the CuO by 0.4 vol% of nanoparticles concentration compared to pure water.
Hussein et al. [96]	SiO_2−water	Increased 46.0% of heat transfer of nanofluid by 2.5 vol% of nanoparticles concentration.
Hussein et al. [97]	SiO_2−water, TiO_2−water	Increased 11.0% of Nusselt number of the TiO_2 and 22.5% of SiO_2 compared to pured water.
Hussein et al. [98]	TiO_2−water, SiO_2−water	Increased 20.0% of heat transfer rate of the TiO_2 and 32.0% of SiO_2 nanofluid.

Table 5. Summary of numerical studies for vehicle cooling system using nanofluids.

Authors	Coolants (nanofluids)	Best findings
Lv et al. [99]	Cu−water, Cu−oil engine	Increased up to 46% of heat transfer coefficient and 43.9% of heat dissipating capacity of the Cu-water nanofluid by 5.0 vol% of nanoparticle concentration when compared to pure water.
Vajjha et al. [100]	Al_2O_3-EG/water (60:40), CuO-EG/water (60:40)	I Increased up to 94% of heat transfer coefficient by addition of 10 vol% Al_2O_3 and achieved up to 89% by 6 vol% CuO compared to base fluid.
Huminic and Huminic [101]	Cu-EG	Increased up to 82% of heat transfer coefficient of the nanofluid when Reynolds number was 125.
Vajjha et al. [102]	Al_2O_3-EG/water (60:40), CuO-EG/water (60:40)	Increased up to 36.6% and 49.7% of heat transfer coefficient of the Al_2O_3 and CuO nanofluid respectively by 3 vol% of nanoparticle concentration when Reynolds number was 5500.
Huminic and Huminic [103]	CuO-EG	The convective heat transfer coefficient of nanofluid is higher compared to pure EG. The heat transfer coefficient for flattened tubes was higher than circular and elliptic tubes in all nanoparticle concentrations and Reynolds number.
Abbasi and Baniamerian [104]	Al_2O_3, Au, CuO, TiO_2-water/vapor	As the vapor quality increases, the heat transfer coefficient decreases along the flow. Al_2O_3 has highest heat transfer coefficient followed by TiO_2, Au, and CuO nanofluids in two-phase flow.
Hatami et al. [105]	CuO-water, Fe_2O_3 water, TiO_2-water, EG/water (50:50)	Increased up to 10% of heat transfer rate by using TiO_2-water followed by Fe_2O_3-water and CuO-water nanofluid compared to EG/water without any pressure drop.
Delavari et al. [106]	Al_2O_3-water, Al_2O_3-EG	About 10–45% of Nusselt number for two-phase approach was greater than the single phase approach hence two-phase approach was closer to the experimental data.

APPLICATION OF VIBRATION EXCITATION IN HEAT EXCHANGER

Flow-induced vibration generated by the high flow velocities in a flow system. The vibration will cause problems by decreasing the structural rigidity. Tube failures by fretting-wear or, less likely, by fatigue, can be caused by excessive flow-induced vibration. At the tube supports or midspan, the fretting-wear might happen if the tubes vibrate at appropriate amplitude when contacting each other. Most flow-induced vibration problems can be avoided although there are still areas of uncertain. The components of heat exchanger need to be analysed properly at the design stage and supported by adequate testing and development work.

Low Frequency Vibration in Heat Exchanger

The vibration amplitude is strongly influenced by structural parameters. Duan et al. [11] reported the average fluctuation of 81.85% and 19.55% for vibration amplitude and frequency, respectively. Vibrational Reynolds number is a dimensionless parameter with a combination of amplitude and frequency. The parameter controls the heat transfer enhancement. Duan et al. [11] presented the minimum heat transfer coefficient ratio of 1.08 and the maximum heat transfer coefficient ratio of 1.29. Later, Ji et al. [107] stated that the out-plane vibration was mainly vibration of each tube bundle and induced by the shell-side fluids. The vibration amplitudes of the two stainless steel blocks are essentially predictable when the shell-side fluids inlet velocity is lower. The vibration amplitude of the stainless steel block III is more extreme when the shell-side fluids inlet with high velocity. Furthermore, the heat transfer coefficient of each elastic tube bundle has increased significantly at a low flow rate (low Reynolds number) when the shell-side flow-induced the elastic tube bundle vibration.

Mechanical force vibration greatly influences the heat transfer in a heated pipe flow, as suggested by Duan et al. [11]. The Nusselt number increased indistinctively with the vibration acceleration augmentation. Meanwhile, the enhancement in the Nusselt number was weakened with increasing of the inlet velocity. The Nusselt number increased rapidly when increasing vibration frequency up to resonance frequency value of 400 Hz. Then the Nusselt number decreased sharply at the frequency of 1500 Hz. Finally, a new correlation was obtained by using the key parameters of vibration frequency, vibration acceleration, and Reynolds number. From the previous discussion, it should be noted that flow-induced vibration can play an important role in heat transfer enhancement, although it also contributed a negative impact on the fatigue life of planar elastic tube bundle. Heat transfer can be improved by increasing vibration intensity, but the fatigue life of the vibrating structure will be decreased. Therefore, flow-induced vibration should also satisfy the requirement of fatigue strength along with the enhancement of the heat transfer. Table 6 shows a summary of low-frequency vibration applications for heat transfer enhancement from other researchers [10, 11, 13, 15, 16, 107, 108].

Table 6. A summary of low-frequency vibration applications for heat transfer enhancement.

Authors	Research description	Frequency, Hz (amplitude, mm)	Findings
Duan et al. [11]	Numerical study, flow-induced vibration for heat transfer enhancement and fatigue life of heat exchanger.	16.26 to 23.23	Heat transfer enhancement increased by the combination effect of vibration amplitude and frequency. Maximum heat transfer coefficient ratio is 1.29 and minimum is 1.08.
Ji et al. [107]	Numerical study, shell-side flow-induced vibration, heat transfer characteristics of elastic tube bundle.	21.24 to 29.8	Heat transfer coefficient of each elastic tube bundle increases with increasing shell-side water inlet velocity and at low Reynolds number.
Liu et al. [108]	Experimental study, effects of mechanical vibration, characteristics of tubular laminar flow.	158 to 3000	Heat transfer enhancement increased by mechanical force excitation of vibration in a heated pipe flow. Vibration frequency increases to 400 Hz caused the Nusselt number increased.
Sarafraz et al. [15]	Experimental study, a plate heat exchanger, flow-induced vibration for fouling mitigation and intensification of thermal performance, working with CuO/water nanofluid as coolants.	30 and 60 (1 and 5)	Heat transfer enhancement increased when the fouling of nanoparticles is mitigated hence decreased the fouling thermal resistance.
Cheng et al. [13]	Experimental and theoretical study, flow-induced vibration application for new designed heat transfer device.	8.75 to 192.6	Heat transfer coefficient can be increased by pulsation flow of flow-induced vibration for nonlinear heat transfer device.
Yakut and Sahin [10]	Experimental study of conical rings, flow-induced vibration	200 to 220	Maximum heat transfer enhancement increased when conical-ring turbulators occur with small pitches produced maximum amplitudes.
Lemlich [16]	Experimental, effect of vibration on natural convective heat transfer	39 to 122 (0.0076)	Heat transfer enhancement increased when the coefficient of heat transfer increased by vibration.

High Frequency Vibration Application in Heat Exchanger

High-frequency vibration or ultrasound is beneficial in engineering applications for improvement of system efficiency. There are various possible applications of ultrasonic waves, such as intensifying chemical reactions, drying, welding, and cleaning. Since the last decades, ultrasound application has gained attention from the industry. Hence, it resulted in the development of several specific applications. It appeared as an interesting way to improve the process productivity. In heat transfer studies, ultrasound can also be used as a possible technical solution for heat exchange improvement [109].

Benzinger et al. [110] developed an electrically heated microstructured heat exchanger. They applied an ultrasonic pulse of 1 min duration into the system to mitigate the fouling layer. The layer occurred because of the precipitation of solid calcium carbonate on the surface of the microstructured device which related to temperature. They found that the heat transfer coefficient of the heat exchanger was recorded similar to the original values when the fouling layer was eliminated by ultrasonic pulse. Bott and Tianqing [111] investigated the effects of mutuality between 20 kHz of ultrasound and oxidizing biocide ozone for the control of biofouling. The results indicated that the biofilm accumulation was reduced up to 70%. Table 7 shows a summary of numerous high-frequency vibration (ultrasound) studies [112-116] for heat transfer enhancement.

CHALLENGES AND POTENTIAL OF NANOFLUIDS WITH VIBRATION EXCITATION

Numerous engaging properties of nanofluids have been presented in the literature. Thermal conductivity has received the maximum interest in the previous studies, but many researchers have recently started studies on other heat transfer properties as well. The use of nanofluids in various thermal applications appears engaging. Yet, the challenges in the development of the nanofluids for engineering applications are ruined by (i) absence of agreement of results acquired by various scholars; (ii) poor portrayal of suspensions; (iii) lack of hypothetical comprehension of the components in charge of changes in properties. So, this paper deduces some important matters that should receive greater attention in the near future [117].

One of the factors that hinder the application of nanofluids in the industry is the high production cost. This has also emphasised by Lee and Mudawar and Pantzali et al. [118, 119]. There are two methods to produce nanofluids. It is either one step or two steps methods. Yet both methods require advanced and sophisticated equipment. Past endeavours to produce nanofluids have frequently utilised either a solitary advance that all the while makes and scatters the nanoparticles into base liquids or a two-advance approach that includes creating nanoparticles and in this manner scattering them into a base liquid. Utilising both methodologies, nanoparticles are inalienably created from reduction reactions or ion exchange. Besides, the base fluids contain different ions and reaction that are troublesome or difficult to isolate from the liquids.

Table 7. Summary of high-frequency vibration (ultrasound) applications for heat transfer enhancement.

Authors	Research Description	Frequency (kHz)	Power / Intensity	Interesting Result
Benzinger et al. [110]	Experimental study, investigations of antifouling, microstructured heat exchanger	20	35 W	Fouling layer decreased by 1 min of pulses hence increased the heat transfer coefficient.
Bott and Tianqing [111]	Experimental study, ultrasound and ozone application to clean heat exchangers	20	2357.8 kWm^{-2}	Biofilm thickness reduced up to 70 % by 2357.8 kWm^{-2}, 3 × 1min pulse/day.
Larson [112]	Experimental study, acoustic streaming of a sphere within a cavitation, cylinder, toluene, and water	20–1000	up to 6 Wcm^{-2}	Nusselt number increase about 4 times. However, it is not adequate to warrant authorise the technology.
Nomura et al. [113]	Experimental study, intensity of turbulence, square channel, transducer at the bottom	25	0–50 W	Ultrasound increased turbulence intensity about 3 times and increased locally up to 5 times.
Gondrexon et al. [114]	Experimental study, vibration application for shell-and-tube heat exchanger	35	80 W	Overall heat transfer coefficient enhanced up to 257%.
Nomura et al. [115]	Experimental study, natural convection, acoustic streaming, obstacle in front of a heating surface using different materials	60.7	5–20 W	Heat transfer increased up to 3 times with using acrylic plate at 20W.
Nomura et al. [116]	Experimental study, acoustic streaming, downward facing surface, ultrasound from below, and cavitation	60.7	5–20 W	Heat transfer coefficient enhanced up to 10-fold.

Vibration waves show up as a fascinating method to enhance forms efficiency particularly to beat transfer limitations. For the concerns in heat transfer, vibration can likewise be viewed as a conceivable specialized answer for heat exchange enhancement. Subsequently, a great deal of productions managing basic investigations can be found in the literature. Be that as it may, the majority of these works are performed at the research facility scale, including scholarly setups and as a rule utilising established low-frequency vibration. Surely understood ultrasonically initiated effects, for example, acoustic cavitation, acoustic streaming, and fluid particles oscillations are in charge of heat transfer enhancement. It is likewise imperative to note here that it is extremely hard to recognize the impact of these effects since they frequently happen all the while. One may along think about the positive impact of ultrasound as a general impact.

The deposition of nanoparticles is a major problem in the application of nanofluids in the heat exchanger system. The nanoparticles might cause a fouling effect and attach on the inner wall in the tube, especially in a tube of a heat exchanger. If so, the nanoparticle deposit layer might present an additional thermal resistance at the wall and thus deteriorates the heat transfer performance. In addition, the fouling layer apparently can increase the surface roughness, friction factor and pressure drop of the heat exchanger system. In order to overcome this problem, the low-frequency vibration can be introduced in the heat exchanger system to lessen the fouling of nanoparticles from the inner wall. The use of frequency of vibration at higher values is not only capable of eliminating the fouling from the inner wall of the heat exchanger but also will cause local agitation of adjacent fluids to the wall. Consequently, this condition will enhance the overall heat transfer coefficient. Higher thermal performance of the system was achieved with increasing of vibration amplitude [15].

In recent work, the vibration induced by the pulsation flow was increased the convective heat transfer coefficient of the nonlinear heat transfer device at low flow velocity [13]. Additional energy is not required by the flow-induced vibration. The heat transfer coefficient on the heat surface is less dependent on the flow velocity, although the vibration may increase the flow friction coefficient. Hence, the low flow velocity could be utilised, which would bring about low energy consumption [13]. Therefore, the heat transfer coefficient can be increased by vibration. Heat transfer coefficient increased with both amplitude and frequency when other variables are kept constant. The bearing of vibration was without critical effect [15].

FUTURE RECOMMENDATION

Heat transfer enhancement by nanofluids, low and high frequency vibrations was investigated in this article. All of the experimental, numerical and theoretical approaches were considered in this paper. Since the nanofluids and vibration frequency and amplitude can influence the heat transfer augmentation results, the future research can be extended by the combination of using high thermal conductivity of nanofluids and the application of vibration frequency. Also, a new design of heat exchanger using vibration can be modelled by a moving boundary and dynamic mesh modelling.

CONCLUSION

Amid the most recent decades, nanofluids and vibrations application either low or high-frequency excitation have picked up a developing enthusiasm from industry, bringing about the improvement of a few particular applications. This audit exhibited logical and chronicled foundations to the future studies concerning heat transfer enhancement by nanofluids and vibration applications in the heat exchanger to present the advancement of this space with a few cases of utilisations. It can be reasoned that the heat transfer coefficient can be enhanced up to half contrasted with the original coolant. Be that as it may, there are still a few issues and difficulties with respect to the systems of heat transfer enhancement and the real applications on the heat exchanger. Despite the fact that vibration waves show up as an intriguing method to enhance processes productivity particularly to defeat transfer limitations. For what concerns heat transfer, flow-induced vibration and ultrasound can likewise be viewed as a conceivable specialized answer for heat exchange enhancement. Local heat transfer coefficient was appeared to be increased in the vicinity of 2 and 5 times within sight of an ultrasonic field. Therefore, in the literature, a great deal of productions dealing with fundamental studies can be found. Be that as it may, the greater part of these works is performed at the research centre scale, including scholastic setups. As nitty-gritty in this paper, the impact of ultrasound on convection remains the significant subject of intrigue.

REFERENCES

[1] Finn J, Ewing D J, Ma L and Wagner J 2011 Nanofluid augmented coolant rail thermoelectric cooling of electronic systems—modeling and analysis. In: American Control Conference, (San Francisco, CA, USA: IEEE) pp 3077-83

[2] Oliet C, Pérez-Segarra C D and Oliva A 2008 Thermal and Fluid Dynamic Simulation of Automotive Fin-and-Tube Heat Exchangers, Part 2: Experimental Comparison Heat Transfer Engineering 29 495-502

[3] Suganthi K, Rajan K J R and reviews s e 2017 Metal oxide nanofluids: Review of formulation, thermo-physical properties, mechanisms, and heat transfer performance 76 226-55

[4] Patel H V, Subhedar D G and Ramani B 2017 Numerical investigation of performance for car radiator oval tube Materials Today: Proceedings 4 9384-9

[5] Kannan C, Jayasingh T R, Vinoth M and Vijayakumar T 2014 An experimental study on the influence of operating parameters on the heat transfer characteristics of an automotive radiator with nano fluids International Journal of Recent Trends in Mechanical Engineering 2 7-11

[6] Bhimani V L, Ratho P P and Sorathiya A S 2013 Experimental study of heat transfer enhancement using water based nanofluids as a new coolant for car radiators International Journal of Emerging Technology and Advanced Engineering 3 295-302

[7] Pawar S S and Sunnapwar V K 2014 Experimental and CFD investigation of convective heat transfer in helically coiled tube heat exchanger Chemical Engineering Research and Design 92 2294-312

[8] Tang X Y, Jiang G and Cao G 2015 Parameters study and analysis of turbulent flow and heat transfer enhancement in narrow channel with discrete grooved structures Chemical Engineering Research and Design 93 232-50

[9] Kim D H, Kim Y K, Won D I, Shin S and Suh J S 2008 Assessment of hemorheological deformability of human red cells exposed to tert-butyl hydroperoxide, verapamil and ascorbate by ektacytometer The Korean Journal of Laboratory Medicine 28 325-31

[10] Yakut K and Sahin B 2004 Flow-induced vibration analysis of conical rings used for heat transfer enhancement in heat exchangers Applied Energy 78 273-88

[11] Duan D, Ge P and Bi W 2018 Numerical study on the heat transfer enhancement and fatigue life by flow-induced vibration Chemical Engineering Research and Design 132 652-63

[12] Duan D, Ge P and Bi W 2016 Numerical investigation on heat transfer performance of planar elastic tube bundle by flow-induced vibration in heat exchanger International Journal of Heat and Mass Transfer 103 868-78

[13] Cheng L, Luan T, Du W and Xu M 2009 Heat transfer enhancement by flow-induced vibration in heat exchangers International Journal of Heat and Mass Transfer 52 1053-7

[14] Chen Y N 1968 Flow-induced vibration and noise in tube-bank heat exchangers due to von Karman streets Journal of Engineering for Industry 90 134-46

[15] Sarafraz M M, Nikkhah V, Madani S A, Jafarian M and Hormozi F 2017 Low-frequency vibration for fouling mitigation and intensification of thermal performance of a plate heat exchanger working with CuO/water nanofluid Applied Thermal Engineering 121 388-99

[16] Lemlich R 1955 Effect of vibration on natural convective heat transfer Industrial and Engineering Chemistry 47 1175-80

[17] Ettefaghi E, Ghobadian B, Rashidi A, Najafi G, Khoshtaghaza M H and Pourhashem S 2017 Preparation and investigation of the heat transfer properties of a novel nanofluid based on graphene quantum dots Energy Conversion and Management 153 215-23

[18] Sarsam W S, Amiri A, Kazi S N and Badarudin A 2016 Stability and thermophysical properties of non-covalently functionalized graphene nanoplatelets nanofluids Energy Conversion and Management 116 101-11

[19] Leela Vinodhan V, Suganthi K S and Rajan K S 2016 Convective heat transfer performance of CuO–water nanofluids in U-shaped minitube: Potential for improved energy recovery Energy Conversion and Management 118 415-25

[20] Hemmat Esfe M, Saedodin S, Biglari M and Rostamian H 2016 An experimental study on thermophysical properties and heat transfer characteristics of low volume concentrations of Ag-water nanofluid International Communications in Heat and Mass Transfer 74 91-7

[21] Imani Mofrad P, Saeed Z H and Shanbedi M 2016 Experimental investigation of filled bed effect on the thermal performance of a wet cooling tower by using ZnO/water nanofluid Energy Conversion and Management 127 199-207

[22] Ilyas S U, Pendyala R, Narahari M and Susin L 2017 Stability, rheology and thermal analysis of functionalized alumina- thermal oil-based nanofluids for advanced cooling systems Energy Conversion and Management 142 215-29

[23] Ettefaghi E, Rashidi A, Ahmadi H, Mohtasebi S S and Pourkhalil M 2013 Thermal and rheological properties of oil-based nanofluids from different carbon nanostructures International Communications in Heat and Mass Transfer 48 178-82

[24] Ali H M, Ali H, Liaquat H, Bin Maqsood H T and Nadir M A 2015 Experimental investigation of convective heat transfer augmentation for car radiator using ZnO–water nanofluids Energy 84 317-24

[25] Duangthongsuk W and Wongwises S 2009 Heat transfer enhancement and pressure drop characteristics of TiO2–water nanofluid in a double-tube counter flow heat exchanger International Journal of Heat and Mass Transfer 52 2059-67

[26] Zhu D, Li X, Wang N, Wang X, Gao J and Li H 2009 Dispersion behavior and thermal conductivity characteristics of Al2O3–H2O nanofluids Current Applied Physics 9 131-9

[27] Li X F, Zhu D S, Wang X J, Wang N, Gao J W and Li H 2008 Thermal conductivity enhancement dependent pH and chemical surfactant for Cu-H2O nanofluids Thermochimica Acta 469 98-103

[28] Ho C J, Wei L C and Li Z W 2010 An experimental investigation of forced convective cooling performance of a microchannel heat sink with Al2O3/water nanofluid Applied Thermal Engineering 30 96-103

[29] Kathiravan R, Kumar R, Gupta A and Chandra R 2010 Preparation and pool boiling characteristics of copper nanofluids over a flat plate heater International Journal of Heat and Mass Transfer 53 1673-81

[30] Dong J, Chen S, Corti D S, Franses E I, Zhao Y, Ng H T and Hanson E 2011 Effect of Triton X-100 on the stability of aqueous dispersions of copper phthalocyanine pigment nanoparticles Journal of Colloid and Interface Science 362 33-41

[31] Peng H, Ding G and Hu H 2011 Effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based nanofluid Experimental Thermal and Fluid Science 35 960-70

[32] Yousefi T, Shojaeizadeh E, Veysi F and Zinadini S 2012 An experimental investigation on the effect of pH variation of MWCNT–H2O nanofluid on the efficiency of a flat-plate solar collector Solar Energy 86 771-9

[33] Hwang Y J, Ahn Y C, Shin H S, Lee C G, Kim G T, Park H S and Lee J K 2006 Investigation on characteristics of thermal conductivity enhancement of nanofluids Current Applied Physics 6 1068-71

[34] Yousefi T, Veysi F, Shojaeizadeh E and Zinadini S 2012 An experimental investigation on the effect of Al_2O_3-H_2O nanofluid on the efficiency of flat-plate solar collectors Renewable Energy 39 293-8

[35] Li X, Zhu D and Wang X 2007 Evaluation on dispersion behavior of the aqueous copper nano-suspensions Journal of Colloid and Interface Science 310 456-63

[36] Wang H, Zhou W, Ho D L, Winey K I, Fischer J E, Glinka C J and Hobbie E K 2004 Dispersing single-walled carbon nanotubes with surfactants: a small angle neutron scattering study Nano Letters 4 1789-93

[37] Zhao N, Li S and Yang J 2016 A review on nanofluids: Data-driven modeling of thermalphysical properties and the application in automotive radiator Renewable and Sustainable Energy Reviews 66 596-616

[38] Syam Sundar L, Singh M K and Sousa A C M 2013 Investigation of thermal conductivity and viscosity of Fe3O4 nanofluid for heat transfer applications International Communications in Heat and Mass Transfer 44 7-14

[39] Cuenca Y, Salavera D, Vernet A and Vallès M 2013 Thermal conductivity of ammonia + water mixtures over a wide range of concentrations International Journal of Refrigeration 36 998-1003

[40] Yu W, Xie H, Chen L and Li Y 2009 Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid Thermochimica Acta 491 92-6

[41] Duangthongsuk W and Wongwises S 2010 An experimental study on the heat transfer performance and pressure drop of TiO2-water nanofluids flowing under a turbulent flow regime International Journal of Heat and Mass Transfer 53 334-44

[42] Kole M and Dey T K 2011 Effect of aggregation on the viscosity of copper oxide–gear oil nanofluids International Journal of Thermal Sciences 50 1741-7

[43] Chandrasekar M, Suresh S and Senthilkumar T 2012 Mechanisms proposed through experimental investigations on thermophysical properties and forced convective heat transfer characteristics of various nanofluids – A review Renewable and Sustainable Energy Reviews 16 3917-38

[44] Mintsa H A, Roy G, Nguyen C T and Doucet D 2009 New temperature dependent thermal conductivity data for water-based nanofluids International Journal of Thermal Sciences 48 363-71

[45] Lee J H, Hwang K S, Jang S P, Lee B H, Kim J H, Choi S U S and Choi C J 2008 Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al_2O_3 nanoparticles International Journal of Heat and Mass Transfer 51 2651-6

[46] Li C, Zhang X and Zhang S 2006 Environmental Benign Design of DMC Production Process Chemical Engineering Research and Design 84 1-8

[47] Chon C H, Kihm K D, Lee S P and Choi S U S 2005 Empirical correlation finding the role of temperature and particle size for nanofluid (Al_2O_3) thermal conductivity enhancement Applied Physics Letters 87 153107

[48] Das S K, Putra N, Thiesen P and Roetzel W 2003 Temperature dependence of thermal conductivity enhancement for nanofluids Journal of heat transfer 125 567-74

[49] Masuda H, Ebata A and Teramae K 1993 Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles. Dispersion of Al_2O_3, SiO_2 and TiO_2 ultra-fine particles Netsu Bussei 7 227-33

[50] Vajjha R S and Das D K 2009 Experimental determination of thermal conductivity of three nanofluids and development of new correlations International Journal of Heat and Mass Transfer 52 4675-82

[51] Beck M P, Yuan Y, Warrier P and Teja A S 2009 The effect of particle size on the thermal conductivity of alumina nanofluids Journal of Nanoparticle Research 11 1129-36

[52] Xie H, Wang J, Xi T, Liu Y and Ai F 2002 Dependence of the thermal conductivity of nanoparticle-fluid mixture on the base fluid Journal of Materials Science Letters 21 1469-71

[53] Wang X, Xu X and Choi S U S 1999 Thermal conductivity of nanoparticle-fluid mixture Journal of Thermophysics and Heat Transfer 13 474-80

[54] Choi C, Yoo H S and Oh J M 2008 Preparation and heat transfer properties of nanoparticle-in-transformer oil dispersions as advanced energy-efficient coolants Current Applied Physics 8 710-2

[55] Liu M S, Lin M C C, Huang I T and Wang C C 2006 Enhancement of thermal conductivity with CuO for nanofluids Chemical Engineering and Technology 29 72-7

[56] Yu W, Timofeeva E V, Singh D, France D M and Smith R K 2013 Investigations of heat transfer of copper-in-Therminol 59 nanofluids International Journal of Heat and Mass Transfer 64 1196-204

[57] Eastman J A, Choi S U S, Li S, Yu W and Thompson L J 2001 Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles Applied Physics Letters 78 718-20

[58] Zhang X, Gu H and Fujii M 2006 Experimental Study on the Effective Thermal Conductivity and Thermal Diffusivity of Nanofluids International Journal of Thermophysics 27 569-80

[59] Ding Y, Alias H, Wen D and Williams R A 2006 Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids) International Journal of Heat and Mass Transfer 49 240-50

[60] Karami M, Akhavan Bahabadi M A, Delfani S and Ghozatloo A 2014 A new application of carbon nanotubes nanofluid as working fluid of low-temperature direct absorption solar collector Solar Energy Materials and Solar Cells 121 114-8

[61] Natarajan E and Sathish R 2009 Role of nanofluids in solar water heater The International Journal of Advanced Manufacturing Technology 1-5

[62] Hwang Y, Park H S, Lee J K and Jung W H 2006 Thermal conductivity and lubrication characteristics of nanofluids Current Applied Physics 6 e67-e71

[63] Murshed S M S, Leong K C and Yang C 2005 Enhanced thermal conductivity of TiO_2-water based nanofluids International Journal of Thermal Sciences 44 367-73

[64] Ghadimi A, Saidur R and Metselaar H S C 2011 A review of nanofluid stability properties and characterization in stationary conditions International Journal of Heat and Mass Transfer 54 4051-68

[65] Mahbubul I M, Saidur R and Amalina M A 2012 Latest developments on the viscosity of nanofluids International Journal of Heat and Mass Transfer 55 874-85

[66] Kole M and Dey T K 2010 Viscosity of alumina nanoparticles dispersed in car engine coolant Experimental Thermal and Fluid Science 34 677-83

[67] Aladag B, Halelfadl S, Doner N, Maré T, Duret S and Estellé P 2012 Experimental investigations of the viscosity of nanofluids at low temperatures Applied Energy 97 876-80

[68] Moghaddam M B, Goharshadi E K, Entezari M H and Nancarrow P 2013 Preparation, characterization, and rheological properties of graphene–glycerol nanofluids Chemical Engineering Journal 231 365-72

[69] Alawi O A and Sidik N A C 2014 Influence of particle concentration and temperature on the thermophysical properties of CuO/R134a nanorefrigerant International Communications in Heat and Mass Transfer 58 79-84

[70] Nguyen C T, Desgranges F, Galanis N, Roy G, Maré T, Boucher S and Angue Mintsa H 2008 Viscosity data for Al2O3–water nanofluid—hysteresis: is heat transfer enhancement using nanofluids reliable? International Journal of Thermal Sciences 47 103-11

[71] Chandrasekar M, Suresh S and Chandra Bose A 2010 Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al2O3/water nanofluid Experimental Thermal and Fluid Science 34 210-6

[72] Mena J B, Ubices de Moraes A A, Benito Y R, Ribatski G and Parise J A R 2013 Extrapolation of Al2O3–water nanofluid viscosity for temperatures and volume concentrations beyond the range of validity of existing correlations Applied Thermal Engineering 51 1092-7

[73] Duangthongsuk W and Wongwises S 2009 Measurement of temperature-dependent thermal conductivity and viscosity of TiO2-water nanofluids Experimental Thermal and Fluid Science 33 706-14

[74] Hung Y H and Chou W C 2012 Chitosan for suspension performance and viscosity of MWCNTs International Journal of Chemical Engineering and Applications 3 343-6

[75] Namburu P K, Kulkarni D P, Misra D and Das D K 2007 Viscosity of copper oxide nanoparticles dispersed in ethylene glycol and water mixture Experimental Thermal and Fluid Science 32 397-402

[76] Saeedinia M, Akhavan-Behabadi M A and Razi P 2012 Thermal and rheological characteristics of CuO–Base oil nanofluid flow inside a circular tube International Communications in Heat and Mass Transfer 39 152-9

[77] Kole M and Dey T K 2013 Enhanced thermophysical properties of copper nanoparticles dispersed in gear oil Applied Thermal Engineering 56 45-53

[78] Elias M M, Mahbubul I M, Saidur R, Sohel M R, Shahrul I M, Khaleduzzaman S S and Sadeghipour S 2014 Experimental investigation on the thermo-physical properties of Al2O3 nanoparticles suspended in car radiator coolant International Communications in Heat and Mass Transfer 54 48-53

[79] Teng T P and Yu C C 2013 Heat dissipation performance of MWCNTs nano-coolant for vehicle Experimental Thermal and Fluid Science 49 22-30

[80] Nieh H M, Teng T P and Yu C C 2014 Enhanced heat dissipation of a radiator using oxide nano-coolant International Journal of Thermal Sciences 77 252-61

[81] Raja M, Vijayan R, Suresh S and Vivekananthan R 2013 Effect of heat transfer enhancement and NO_x emission using Al_2O_3/water nanofluid as coolant in CI engine Indian Journal of Engineering and Materials Sciences 20 443-9

[82] Zhong X, Yu X L, Wu J and Jiang P Z 2010 Experimental investigation on alumina nanofluids in vehicle heat exchanger Journal of Zhejiang University (Engineering Science) 4 024

[83] Ali H M, Azhar M D, Saleem M, Saeed Q S and Saieed A 2015 Heat transfer enhancement of car radiator using aqua based magnesium oxide nanofluids Thermal science 19 2039-48

[84] Chougule S S and Sahu S K 2014 Comparative study of cooling performance of automobile radiator using Al_2O_3-water and carbon nanotube-water nanofluid Journal of Nanotechnology in Engineering and Medicine 5 1-6

[85] Tzeng S C, Lin C W and Huang K D 2005 Heat transfer enhancement of nanofluids in rotary blade coupling of four-wheel-drive vehicles Acta Mechanica 179 11-23

[86] Vasheghani M 2012 Enhancement of the thermal conductivity and viscosity of aluminum component– engine oil nanofluids Nanomechanics Science and Technology: An International Journal 3 333-40

[87] Saripella S K, Yu W, Routbort J L and France D M 2007 Effects of nanofluid coolant in a class 8 truck engine SAE Technical Paper 2007-11-01 1-9

[88] Ettefaghi E, Ahmadi H, Rashidi A, Nouralishahi A and Mohtasebi S S 2013 Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant International Communications in Heat and Mass Transfer 46 142-7

[89] Peyghambarzadeh S M, Hashemabadi S H, Jamnani M S and Hoseini S M 2011 Improving the cooling performance of automobile radiator with Al2O3/water nanofluid Applied Thermal Engineering 31 1833-8

[90] Chavan D and Pise A T 2014 Performance investigation of an automotive car radiator operated with nanofluid as a coolant Journal of Thermal Science and Engineering Applications 6 1-5

[91] Peyghambarzadeh S M, Hashemabadi S H, Hoseini S M and Seifi Jamnani M 2011 Experimental study of heat transfer enhancement using water/ethylene glycol based nanofluids as a new coolant for car radiators International Communications in Heat and Mass Transfer 38 1283-90

[92] Sarkar J and Tarodiya R 2013 Performance analysis of louvered fin tube automotive radiator using nanofluids as coolants International Journal of Nanomanufacturing 9 51-65

[93] Liu H, Bai M and Qu Y 2013 The impact of oil-based diamond nanofluids on diesel engine performance. In: The FISITA 2012 World Automotive Congress, (Berlin, Heidelberg: Springer) pp 1313-9

[94] Ebrahimi M, Farhadi M, Sedighi K and Akbarzade S 2014 Experimental investigation of force convection heat transfer in a car radiator filled with SiO_2–water nanofluid International Journal of Engineering Transactions B: Applications 27 333-40

[95] Naraki M, Peyghambarzadeh S M, Hashemabadi S H and Vermahmoudi Y 2013 Parametric study of overall heat transfer coefficient of CuO/water nanofluids in a car radiator International Journal of Thermal Sciences 66 82-90

[96] Hussein A M, Bakar R A and Kadirgama K 2014 Study of forced convection nanofluid heat transfer in the automotive cooling system Case Studies in Thermal Engineering 2 50-61

[97] Hussein A M, Bakar R A, Kadirgama K and Sharma K V 2014 Heat transfer enhancement using nanofluids in an automotive cooling system International Communications in Heat and Mass Transfer 53 195-202

[98] Hussein A M, Bakar R A, Kadirgama K and Sharma K V 2014 Heat transfer augmentation of a car radiator using nanofluids Heat and Mass Transfer 50 1553-61

[99] Lv J, Zhou L, Bai M, Liu J W and Xu Z 2010 Numerical simulation of the improvement to the heat transfer within the internal combustion engine by the application of nanofluids Journal of Enhanced Heat Transfer 17 93-109

[100] Vajjha R S, Das D K and Namburu P K 2010 Numerical study of fluid dynamic and heat transfer performance of Al2O3 and CuO nanofluids in the flat tubes of a radiator International Journal of Heat and Fluid Flow 31 613-21

[101] Huminic G and Huminic A 2012 The cooling performances evaluation of nanofluids in a compact heat exchanger SAE Technical Paper 2012-01-1045 1-8

[102] Vajjha R S, Das D K and Ray D R 2015 Development of new correlations for the Nusselt number and the friction factor under turbulent flow of nanofluids in flat tubes International Journal of Heat and Mass Transfer 80 353-67

[103] Huminic G and Huminic A 2013 Numerical analysis of laminar flow heat transfer of nanofluids in a flattened tube International Communications in Heat and Mass Transfer 44 52-7

[104] Abbasi M and Baniamerian Z 2014 Analytical simulation of flow and heat transfer of two-phase nanofluid (stratified flow regime) International Journal of Chemical Engineering 2014 1-7

[105] Hatami M, Ganji D D and Gorji-Bandpy M 2014 CFD simulation and optimization of ICEs exhaust heat recovery using different coolants and fin dimensions in heat exchanger Neural Computing and Applications 25 2079-90

[106] Delavari V and Hashemabadi S H 2014 CFD simulation of heat transfer enhancement of Al2O3/water and Al2O3/ethylene glycol nanofluids in a car radiator Applied Thermal Engineering 73 380-90

[107] Ji J, Ge P and Bi W 2016 Numerical analysis on shell-side flow-induced vibration and heat transfer characteristics of elastic tube bundle in heat exchanger Applied Thermal Engineering 107 544-51

[108] Liu W, Yang Z, Zhang B and Lv P 2017 Experimental study on the effects of mechanical vibration on the heat transfer characteristics of tubular laminar flow International Journal of Heat and Mass Transfer 115 169-79

[109] Legay M, Gondrexon N, Le Person S, Boldo P and Bontemps A 2011 Enhancement of heat transfer by ultrasound: review and recent advances International Journal of Chemical Engineering 2011 1-17

[110] Benzinger W, Schygulla U, Jäger M and Schubert K 2005 Anti fouling investigations with ultrasound in a microstructured heat exchanger. In: 6th International Conference on Heat Exchanger Fouling and Cleaning - Challenges and Opportunities, ed H Müller-Steinhagen, et al. (Kloster Irsee, Germany: The Berkeley Electronic Press) pp 197-201

[111] Bott T R and Tianqing L 2004 Ultrasound enhancement of biocide efficiency Ultrasonics Sonochemistry 11 323-6

[112] Larson M B 1962 A study of the effects of ultrasonic vibrations on convective heat transfer to liquids The American Society of Mechanical Engineers 62 1-16

[113] Nomura S, Murakami K and Kawada M 2002 Effects of turbulence by ultrasonic vibration on fluid flow in a rectangular channel Japanese Journal of Applied Physics 41 6601

[114] Gondrexon N, Rousselet Y, Legay M, Boldo P, Le Person S and Bontemps A 2010 Intensification of heat transfer process: Improvement of shell-and-tube heat exchanger performances by means of ultrasound Chemical Engineering and Processing: Process Intensification 49 936-42

[115] Nomura S, Nakagawa M, Mukasa S, Toyota H, Murakami K and Kobayashi R 2005 Ultrasonic heat transfer enhancement with obstacle in front of heating surface Japanese Journal of Applied Physics 44 4674

[116] Nomura S, Yamamoto A and Murakami K 2002 Ultrasonic heat transfer enhancement using a horn-type transducer Japanese Journal of Applied Physics 41 3217

[117] Bhogare R A and Kothawale B S 2013 A review on applications and challenges of nano-fluids as coolant in automobile radiator International Journal of Scientific and Research Publications 3 435-41

[118] Lee J and Mudawar I 2007 Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels International Journal of Heat and Mass Transfer 50 452-63

[119] Pantzali M N, Mouza A A and Paras S V 2009 Investigating the efficacy of nanofluids as coolants in plate heat exchangers (PHE) Chemical Engineering Science 64 3290-300