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A review on applications and challenges of nanofluids

R. Saidur[a,*], K.Y. Leong[b], H.A. Mohammad[c]

[a] Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Mechanical Engineering, National Defense University of Malaysia, Sg Besi Camp, 57000 Kuala Lumpur, Malaysia
[c] Department of Mechanical Engineering, College of Engineering, Universiti Tenaga Nasional, Km 7, Jalan Kajang-Puchong, 43009 Kajang, Selangor, Malaysia

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ABSTRACT

Nanofluids are potential heat transfer fluids with enhanced thermophysical properties and heat transfer performance can be applied in many devices for better performances (i.e. energy, heat transfer and other performances). In this paper, a comprehensive literature on the applications and challenges of nanofluids have been compiled and reviewed. Latest up to date literatures on the applications and challenges in terms of PhD and Master thesis, journal articles, conference proceedings, reports and web materials have been reviewed and reported. Recent researches have indicated that substitution of conventional coolants by nanofluids appears promising. Specific application of nanofluids in engine cooling, solar water heating, cooling of electronics, cooling of transformer oil, improving diesel generator efficiency, cooling of heat exchanging devices, improving heat transfer efficiency of chillers, domestic refrigerator-freezers, cooling in machining, in nuclear reactor and defense and space have been reviewed and presented. Authors also critically analyzed some of the applications and identified research gaps for further research. Moreover, challenges and future directions of applications of nanofluids have been reviewed and presented in this paper. Based on results available in the literatures, it has been found nanofluids have a much higher and strongly temperature-dependent thermal conductivity at very low particle concentrations than conventional fluids. This can be considered as one of the key parameters for enhanced performances for many of the applications of nanofluids. Because of its superior thermal performances, latest up to date literatures on this property have been summarized and presented in this paper as well. However, few barriers and challenges that have been identified in this review must be addressed carefully before it can be fully implemented in the industrial applications.

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* Corresponding author. Tel.: +60 3 79674462; fax: +60 3 79675317.
E-mail address: saidur912@yahoo.com (R. Saidur).

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1. Introduction

Nanofluids are a relatively new class of fluids which consist of a base fluid with nano-sized particles (1–100 nm) suspended within them. These particles, generally a metal or metal oxide, increase conduction and convection coefficients, allowing for more heat transfer out of the coolant [1]. Serrano et al. [2], provided excellent examples of nanometer in comparison with millimeter and micrometer to understand clearly as can be seen in Fig. 1.

In the past few decades, rapid advances in nanotechnology have lead to emerging of new generation of coolants called "nanofluids". Nanofluids are defined as suspension of nanoparticles in a basefluid. Some typical nanofluids are ethylene glycol based copper nanofluids and water based copper oxide nanofluids, Nanofluids are dilute suspensions of functionalized nanoparticles composite materials developed about a decade ago with the specific aim of increasing the thermal conductivity of heat transfer fluids, which have now evolved into a promising nanotechnological area. Such thermal nanofluids for heat transfer applications represent a class of its own difference from conventional colloids for other applications. Compared to conventional solid–liquid suspensions for heat transfer intensifications, nanofluids possess the following advantages [1]:

- High specific surface area and therefore more heat transfer surface between particles and fluids.
- High dispersion stability with predominant Brownian motion of particles.
- Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
- Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization.
- Adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications.

Nanotechnology is being used or considered for use in many applications targeted to provide cleaner, more efficient energy supplies and uses. While many of these applications may not affect energy transmission directly, each has the potential to reduce the need for the electricity, petroleum distillate fuel, or natural gas that would otherwise be moved through energy transmission system. More efficient energy generation and use may decrease the amount of construction, maintenance, repair, and decommissioning activities. Examples of how nanotechnology may be integrated into each of these technological areas are highlighted in the following specific applications [1,3,4]:

- Engine cooling.
- Engine transmission oil.
- In diesel electric generator as jacket water coolant.
- Boiler exhaust flue gas recovery.
- Heating and cooling of buildings.
- Cooling of electronics.
- Cooling of welding.
- Nanofluids in transformer cooling oil.
- Nuclear systems cooling.
- Solar water heating.
- Nanofluids in drilling.
- Refrigeration (domestic refrigerator, chillers).
- Defense.
- Space.
- High-power lasers, microwave tubes.
- Biomedical applications.
- Drilling.
- Lubrications.
- Thermal storage.
- Drag reductions.

These novel and advanced concepts of coolants offer intriguing heat transfer characteristics compared to conventional coolants. There are considerable researches on the superior heat transfer properties of nanofluids especially on thermal conductivity and convective heat transfer. Eastman et al. [5], Liu et al. [6], Hwang et al. [7], Yu et al. [8] and Mintsa et al. [9], observed great enhancement of nanofluids' thermal conductivity compared to conventional coolants. Enhancement of convective heat transfer was reported by Zeinali Heris et al. [10], Kim et al. [11], Jung et al. [12] and Sharma et al. [13]. Applications of nanofluids in industries such as heat exchanging devices appear promising with these characteristics. However, the development and applications of nanofluids may be hindered by several factors such as long term stability,

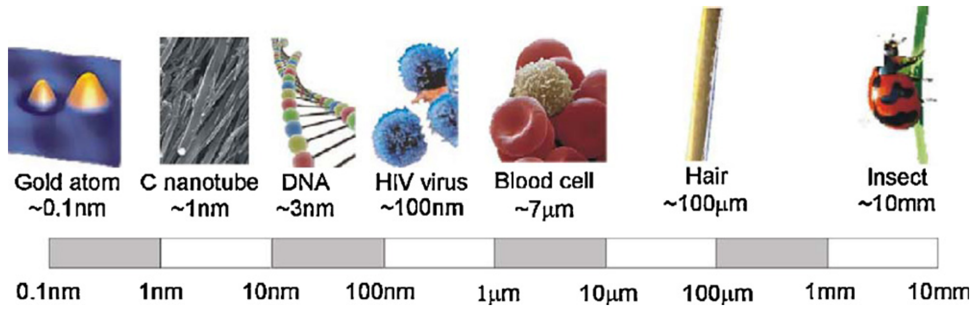

Fig. 1. Length scale and some examples related [2].

increase pumping power and pressure drop, nanofluids' thermal performance in turbulent flow and fully developed region, lower specific heat of nanofluids and higher production cost of nanofluids.

In the literatures a number of reviews on thermal and rheological properties, different modes of heat transfer including boiling one have been reported by many researchers. However, to the best of authors' knowledge, there is no comprehensive literature on the applications and challenges of nanofluids. It is authors' hope that this review will be useful to find other applications with better performances and solutions to overcome these challenges. It is also expected that performances of these identified applications can be improved further.

2. Overview of applications of nanofluids

The advent of high heat flow processes has created significant demand for new technologies to enhance heat transfer. For example, microprocessors have continually become smaller and more powerful, and as a result heat flow demands have steadily increased over time leading to new challenges in thermal management. Furthermore, there is increasing interest in improving the efficiency of existing heat transfer processes. An example is in automotive systems where improved heat transfer could lead to smaller heat exchangers for cooling resulting in reduced weight of the vehicle. Many methods are available to improve heat transfer in processes. The flow of heat in a process can be calculated based on [14]:

$$Q = hA\Delta T \tag{1}$$

where Q is the heat flow, h is the heat transfer coefficient, A is the heat transfer area, and ΔT is the temperature difference that results in heat flow. It can be stated from this equation that increased heat transfer can be achieved by:

(i) increasing ΔT;
(ii) increasing A;
(iii) increasing h.

A greater temperature difference ΔT can lead to increase the heat flow, but ΔT is often limited by process or materials constraints. For example, the maximum temperature in a nuclear reactor must be kept below a certain value to avoid runaway reactions and meltdown. Therefore, increased ΔT can only be achieved by decreasing the temperature of the coolant. However, this would reduce the rate of the nuclear reaction and decrease the efficiency of the process [14].

Maximizing the heat transfer area A is a common strategy to improve heat transfer, and many heat exchangers such as radiators and plate-and-frame heat exchangers are designed to maximize the heat transfer area. However, this strategy cannot be employed in microprocessors and microelectromechanical systems (MEMS) because the area cannot be increased. In aerospace and automotive systems, increasing the heat transfer area can only be achieved by increasing the size of the heat exchanger which can lead to unwanted increases in weight [14].

Heat transfer improvements can also be achieved by increasing the heat transfer coefficient h either by using more efficient heat transfer methods, or by improving the transport properties of the heat transfer material. For example, heat transfer systems which employ forced convection of a gas exhibit a greater heat transfer coefficient than systems which employ free convection of a gas. Alternatively, the heat transfer coefficient can be increased by enhancing the properties of the coolant for a given method of heat transfer. Additives are often added to liquid coolants to improve specific properties. For example, glycols are added to water to depress its freezing point and to increase its boiling point. The heat transfer coefficient can be improved via the addition of solid particles to the liquid coolant (i.e. nanofluids) [1,14–17].

Nanofluids can be used for a wide variety of industries, ranging from transportation to energy production and in electronics systems like microprocessors, Micro-Electro-Mechanical Systems (MEMS) and in the field of biotechnology. Recently, the number of companies that observe the potential of nanofluids technology and their focus for specific industrial applications is increasing. In the transportation industry, nanocars, GM and Ford, among others are focusing on nanofluids research projects [18–20].

Nanofluids can be used to cool automobile engines and welding equipment and to cool high heat-flux devices such as high power microwave tubes and high-power laser diode arrays. A nanofluid coolant could flow through tiny passages in MEMS to improve its efficiency. The measurement of nanofluids critical heat flux (CHF) in a forced convection loop is useful for nuclear applications. If nanofluids improve chiller efficiency by 1%, a saving of 320 billion kWh of electricity or an equivalent 5.5 million barrels of oil per year would be realized in the US alone. Nanofluids find potential for use in deep drilling application. A nanofluid can also be used for increasing the dielectric strength and life of the transformer oil by dispersing nanodiamond particles [21,22].

Kostic [23] reported that nanofluids can be used in following specific areas:

- Heat-transfer nanofluids.
- Tribological nanofluids.
- Surfactant and coating nanofluids.
- Chemical nanofluids.
- Process/extraction nanofluids.
- Environmental (pollution cleaning) nanofluids.
- Bio- and pharmaceutical-nanofluids.
- Medical nanofluids (drug delivery and functional tissue–cell interaction).

Fig. 2 shows the market volume of nanomaterials, tools and devices in past, present and future.

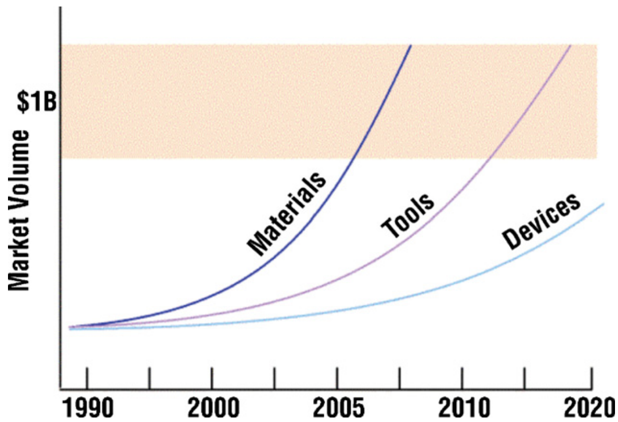

Fig. 2. Nanotechnology is poised to impact dramatically on all sectors of industry [24].

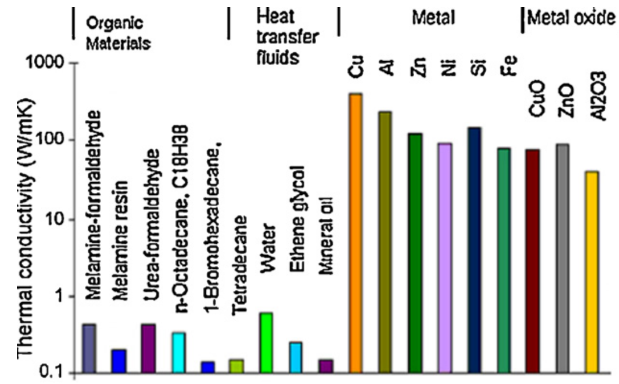

Fig. 3. Comparison of the thermal conductivity of common liquids, polymers and solids [42].

3. Thermal conductivity of nanofluids

Thermal conductivity of nanofluids is found to be an attracting characteristic for many applications. It represents the ability of material to conduct or transmit heat. Considerable researches have been carried out on this topic. Eastman et al. [25], found that thermal conductivity of 0.3% copper nanoparticles of ethylene glycol nanofluids is increased up to 40% compared to basefluid. Authors stressed that, this property plays an important role in construction of energy efficient heat transfer equipment. Liu et al. [26], investigated the thermal conductivity of copper–water nanofluids produced by chemical reduction method. Results showed 23.8% improvement at 0.1% volume fraction of copper particles. Higher thermal conductivity and larger surface area of copper nanoparticles are attributed to this improvement. It is also noted that thermal conductivity increases with particles volume fraction but decreases with elapsed time. Hwang et al. [27], suggested that thermal conductivity enhancement of nanofluids is greatly influenced by thermal conductivity of nanoparticles and basefluid. For instance, thermal conductivity of water based nanofluids with multiwalled carbon nanotube have noticeably higher thermal conductivity compared to SiO_2 nanoparticles in the same basefluid. However, Yoo et al. [28], argued that surface to volume ratio of nanoparticles is a dominant factor that influences the nanofluids thermal conductivity rather than nanoparticles thermal conductivity. Surface to volume ratio is increased with smaller sizes of nanoparticles.

Choi et al. [29], reported a 150% thermal conductivity enhancement of poly(α-olefin) oil with the addition of multiwalled carbon nanotubes (MWCNT) at 1% volume fraction. Similarly, Yang et al. [30], reported a 200% thermal conductivity enhancement for poly(α-olefin) oil containing 0.35% (v/v) MWCNT. It is important to note that this thermal conductivity enhancement was accompanied by a three order of magnitude increase in viscosity. Eastman et al. [25], found a 40% thermal conductivity enhancement for ethylene glycol with 0.3% (v/v) copper nanoparticles (10 nm diameter), although the authors added about 1% (v/v) thioglycolic acid to aid in the dispersion of the nanoparticles. The addition of this dispersant yielded a greater thermal conductivity than the same concentration of nanoparticles in the ethylene glycol without the dispersant. Jana et al. [31] measured the thermal conductivity of a similar copper containing nanofluid, except the base fluid was water and laurate salt was used as a dispersant. Authors observed a 70% thermal conductivity enhancement for 0.3% (v/v) Cu nanoparticles in water. Kang et al. [32] reported a 75% thermal conductivity enhancement for ethylene glycol with 1.2% (v/v) diamond nanoparticles between 30 and 50 nm in diameter. Despite these remarkable results, some researchers have measured the thermal conductivity of nanofluids and have found no anomalous results. Also, those results can often be predicted by conventional thermal conductivity models [33–36].

Lee et al. [37] revealed thermal conductivity of nanofluids is affected by pH level and addition of surfactant during nanofluids preparation stage. Better dispersion of nanoparticles is achieved with addition of surfactant such as sodium dodecylbenzenesulfonate. Optimum combination of pH and surfactant leads to 10.7% thermal conductivity enhancement of 0.1% Cu/H_2O nanofluids. Thermal conductivity of ethylene glycol based ZnO nanofluids measured by transient short hot wire technique is found to be increased non-linearly with nanoparticles volume fraction [38]. Mintsa et al. [9] added thermal conductivity of nanofluids also depend on the nanoparticles size and temperature. Vajjha and Das [39] also agreed that thermal conductivity is dependent not only on the nanoparticles concentration but also on the temperature. Authors concluded that, it will be more beneficial if nanofluids are used in high temperature applications.

It has been noticed that most authors agreed that nanofluids provide higher thermal conductivity compared to basefluids. Its value increases with particles concentration. Temperature, particles size, dispersion and stability do play important role in determining thermal conductivity of nanofluids [40]. Fig. 3 shows the comparison of thermal conductivity of heat transfer fluids and nanofluids. Figs. 4 and 5 show the thermal conductivity of nanofluids at different temperatures. Table 1 also shows the enhanced thermal conductivities of metallic and non-metallic nanofluids as reported by Shen [41]. Table 2 shows the thermal conductivity ratio (i.e. thermal conductivity of solid to liquids) of nanofluids. The ratios are found to be in the range of 3–17,100. This shows an indication that when solid particles are added in conventional liquids/coolants, thermal conductivity can be increased tremendously.

Research has shown that the thermal conductivity and the convection heat transfer coefficient of the fluid can be largely enhanced by suspended nanoparticles [1,15–17]. Choi et al. [29] observed that the thermal conductivity of this nanofluid was 150% greater than that of the oil alone. Tables 1–6 show the thermal performances of different types (metallic, non-metallic, MWCNT) and concentrations of nanofluids.

Recently, tribology research shows that lubricating oils with nanoparticles additives (MoS_2, CuO, TiO_2, diamond, etc.) exhibit improved load-carrying capacity, anti-wear and friction-reduction properties [44,45]. These features made nanofluids very attractive in some cooling and/or lubricating application in many industries including manufacturing, transportation, energy, and electronics, etc.

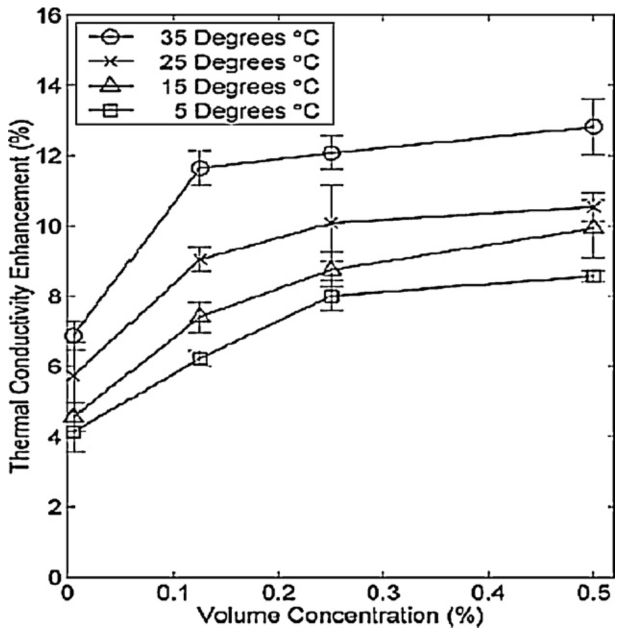

Fig. 4. Thermal conductivity enhancement of 2 nm gold nanoparticle in water as a function of volume concentration [43].

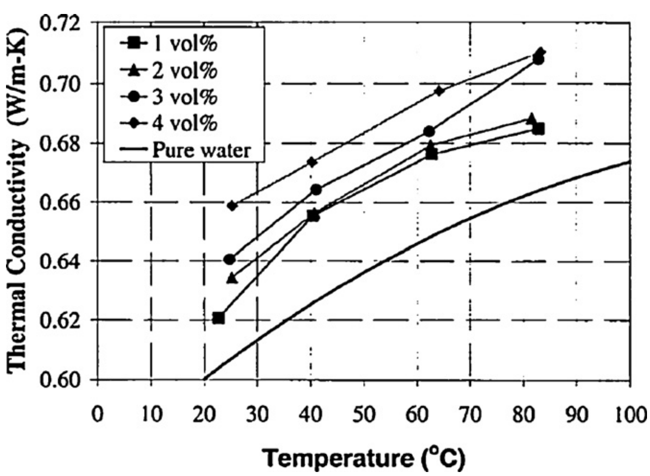

Fig. 5. Thermal conductivity with temperature [41].

Table 2
Thermal conductivities ratio of different types of nanofluids.

Nanoparticle	k_2/k_1[a]	Fluid
Al_2O_3	66	Water [58,59,35,51,60,33,34,61,28,50,36,53]
	156	Ethylene glycol [51,60,61,50,36,53]
	140	Glycerol [53]
	342	Oil [51,61,53,62]
CuO	127	Water [58,59,35,33,61,50,7]
	300	Ethylene glycol [61,50,7,51]
TiO_2	14	Water [35,60,33,28]
	33	Ethylene glycol [60,47]
Fe_3O_4	11.5	Water [63]
ZrO_2		Water [33]
WO_3		Ethylene glycol [28]
ZnO	48	Water [60]
	113	Ethylene glycol [60]
SiO_2	2.2	Water [32,27]
	5.2	Ethylene glycol [32]
Cu	655	Water [26,31]
	1550	Ethylene glycol [25,56]
		Water + ethylene glycol [64]
Ag	697	Water [32]
Au	518	Water [62,31]
	1830	Ethanol [65]
	2370	Toluene [35,34,65]
Fe	132	Water [47]
	311	Ethylene glycol [28,47]
Alxcuy		Water [66,67]
		Ethylene glycol [66,67]
Agxcuy		Oil [68]
Agxaly		Water [67]
		Ethylene glycol [68]
Carbon nanotubes	3290	Water [7,31,56,69,70]
	7780	[56,71]
	17,100	Antifreeze [28]
	14,300	Oil [29,72,56]
Carbon nanofibers	21	Water [34]
	111	Oil [72]
	3	Toluene [65]
Graphite	1020	Oil [72]
Diamond	3500	Ethylene glycol [32]

[a] k_1, thermal conductivity of liquid; k_2, thermal conductivity of solid.

Table 1
Summary of literature review for thermal conductivity of nanofluids.

	Particle	Base fluid	Average particle size	Volume fraction	Thermal conductivity enhancement	References
Metallic nanofluids	Cu	Ethylene glycol	10 nm	0.3%	40%	[16]
	Cu	Water	100 nm	7.5%	78%	[46]
	Fe	Ethylene glycol	10 nm	0.55%	18%	[47]
	Au	Water	10–20 nm	0.026%	21%	[48]
	Ag	Water	60–80 nm	0.001%	17%	[48]
Non-metallic nanofluids	Al_2O_3	Water	13 nm	4.3%	30%	[49]
	Al_2O_3	Water	33 nm	4.3%	15%	[50]
	Al_2O_3	Water	68 nm	5%	21%	[51]
	CuO	Water	36 nm	3.4%	12%	[50]
	CuO	Water	50 nm	0.4%	17%	[52]
	SiC	Water	26 nm	4.2%	16%	[53]
	TiO_2	Water	15 nm	5%	30%	[54]
	MWCNT	Synthetic oil	25 nm in diameter 50 μm in length	1%	150%	[29]
	MWCNT	Decene/ethylene glycol/water	15 nm in diameter 30 μm in length	1%	20%/13%/7%	[55]
	MWCNT	Water	100 nm in diameter 70 μm in length	0.6%	38%	[56]

Main source: [41].

Table 3
The augmentation factor (α_{cond}) of $A1_2O_3$ nanofluids.

Particle material	Particle size (nm)	Base fluid material	α_{cond}	References
Al_2O_3	33	Water	6	[5]
Al_2O_3	24.4	Water	2.5	[50]
Al_2O_3	28	Water	4	[61]
Al_2O_3	38.4	Water	2.5	[58]
Al_2O_3	36	Water	6	[59]
Al_2O_3	47	Water	5	[59]
Al_2O_3	20	Water	1.3	[33]
Al_2O_3	11	Water	12	[74]
Al_2O_3	47	Water	6	[74]
Al_2O_3	150	Water	3	[74]
Al_2O_3	Not reported	Water	4.6	[55]
Al_2O_3	24.4	Ethylene glycol	3	[50]
Al_2O_3	28	Ethylene glycol	3.4	[61]
Al_2O_3	Not reported	Ethylene glycol	6	[55]
Al_2O_3	28	Pump fluid	2.4	[61]
Al_2O_3	Not reported	Pump oil	7.6	[55]
Al_2O_3	28	Engine oil	4	[61]
Al_2O_3	Not reported	Glycerol	5.4	[55]

Main source: [78].

Table 4
The augmentation factor (α_{cond}) of oxide nanofluids.

Particle material	Particle size (nm)	Base fluid material	α_{cond}	References
CuO	36	Water	12	[5]
CuO	18.6	Water	4	[50]
CuO	23	Water	3.8	[61]
CuO	28.6	Water	3.8	[58]
CuO	33	Water	3	[34]
CuO	18.6	Ethylene glycol	5	[50]
CuO	23	Ethylene glycol	3.9	[61]
CuO	12	Ethylene glycol	6	[75]
CuO	29	Ethylene glycol	4.5	[6]
TiO_2	15	Water	6	[54]
TiO_2	40	Water	2.4	[34]
ZrO_2	20	Water	2.5	[34]
Fe_3O_4	9.8	Water	8	[63]

Main source: [78].

Table 5
The augmentation factor (α_{cond}) metal nanofluids.

Particle material	Particle size (nm)	Base fluid material	α_{cond}	References
Cu	18	Water	6	[5]
Cu	100	Water	10.1	[46]
Cu	100–200	Water	232	[6]
Cu	10	Ethylene glycol	133	[5]
Cu	100	Transformer oil	5.9	[46]
Au	10–20	Toluene	818	[48]
Fe	10	Ethylene glycol	32.7	[47]
Bi_2Te_3	100	FC72	10	[76]

Main source: [78].

Table 6
The augmentation factor (α_{cond}) CNT nanofluids.

Particle material	Tube size diameter (nm)/length (μm)	Base fluid material	α_{cond}	References
CNT	15/30	Water	7.5	[55]
CNT	150/10	Water	44	[34]
CNT	40/50	Water	37	[77]
CNT	15/30	Ethylene glycol	12	[55]
CNT	15/30	Decene	818	[55]

Main source: [78].

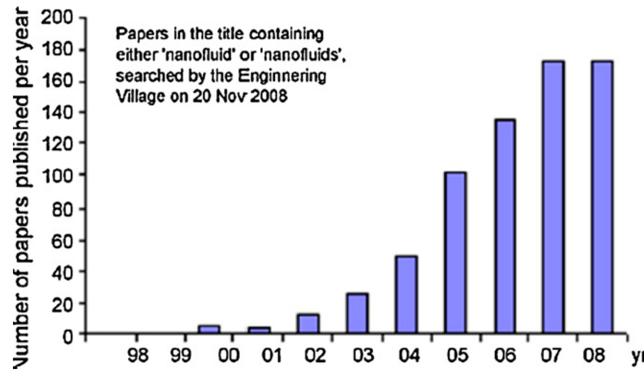

Fig. 6. Growth of publications by the nanofluids community [42].

Fig. 6 shows the rapid growth of nanofluids research in recent years, including US, EU, and China, and more recently, India and South Korea. The potential market for nanofluids for heat transfer applications is estimated to be over 2 billion dollars per year worldwide [57], with prospect of further growth in the next 5–10 years.

The enhanced thermal conductivity of nanofluids offer several benefits such as higher cooling rates, decreased pumping power needs, smaller and lighter cooling systems, reduced inventory of heat transfer fluids, reduced friction coefficients, and improved wear resistance. Those benefits make nanofluids promising for applications like coolants, lubricants, hydraulic fluids, and metal cutting fluids [73].

Fig. 7 shows the boundary of properties of nanofluids for different applications.

4. Applications of nanofluids

This section explains applications of nanofluids in industrial, commercial, residential and transportation sectors based on available literatures.

4.1. Cooling of electronics

Due to the rapid development of modern technology, recent electronics generate an enormous amount of heat, which disturbs the normal performance of the devices, reduces reliability and expected life. According to international technology road map

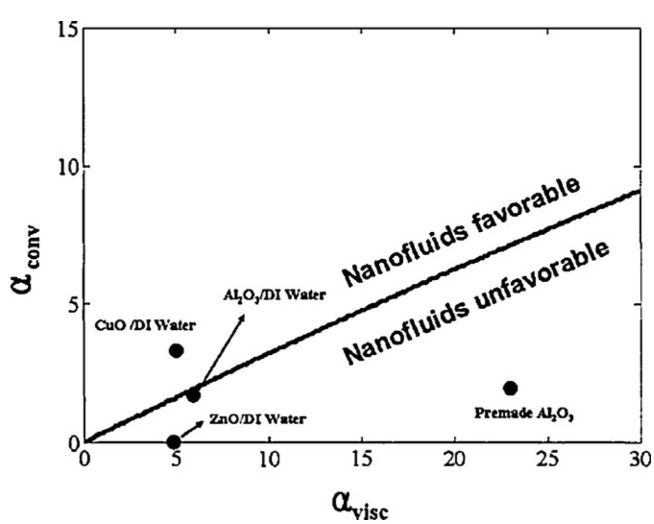

Fig. 7. The data summary of oxide nanofluids and the boundary line of nanofluid effectiveness [78].

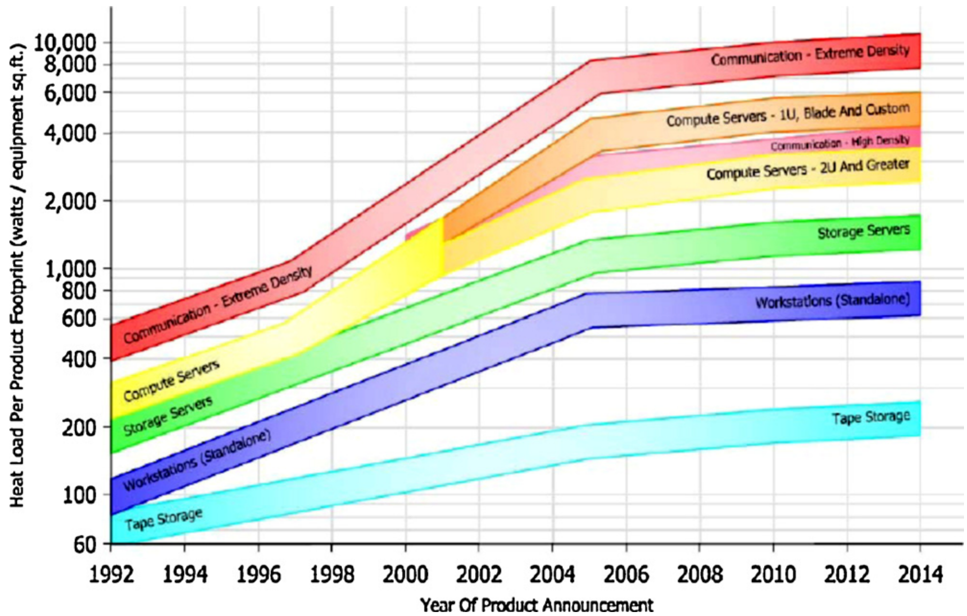

Fig. 8. Power density chart.

for semiconductors, the heat flux generated from a single chip is expected to increase from 330 W/cm^2 in 2007 to 520 W/cm^2 in 2011 for high performance chips [78]. Therefore, an efficient cooling system is one of the most important problems in designing electronic components. There have been numerous attempts to remove high heat flux effectively including air cooling, liquid cooling and two-phase cooling [78].

Due to the high level of heat generation, space limitation for setting up of the cooling system, and air-cooling limitation, the liquid cooling in the mini-rectangular fin channel heat sink for CPU of PC has been investigated by Naphon et al. [79]. Authors found a reasonable agreement between the predicted and experimental results. Authors reported that the results of their study are expected to lead to guidelines that will allow the design of the cooling system with improved cooling performance of the electronic equipments with increasing reliable operation of these devices [79]. Effect of channel width of heat sink, coolant flow rate and operating conditions of PC on the CPU temperatures were investigated by the authors. Authors found that flow structure and temperature distributions are not uniform. The temperature non-uniformity of the heat sink is a serious problem for the electronic devices. The results of this study are expected to lead to guidelines that will allow the design of the cooling system with improved heat transfer performance to ensure that the operating temperature of electronic devices is lower than the critical temperature [79].

Fig. 8 shows the power per product footprint for all levels of packaging covering most of the applications in electronic packages. Owing to the increasing high power trend, it is becoming a challenge to manage the thermal loading without compromising the efficiency and power capabilities of the electronic packages [80].

Figs. 9 and 10 present the power trends for the chip and chip heat flux, respectively. It has been observed that the chip power and heat flux increased and expected to increase for days to come. With continuous trend toward increase in power, efficient thermal management with mechanical reliability are the challenges limiting the technological development in electronic packaging industry [80].

Decreasing the temperature of a component increases its performance as well as reliability. In addition to lowering the junction temperatures within a component, it is sometimes also important to reduce the temperature variation between components that are

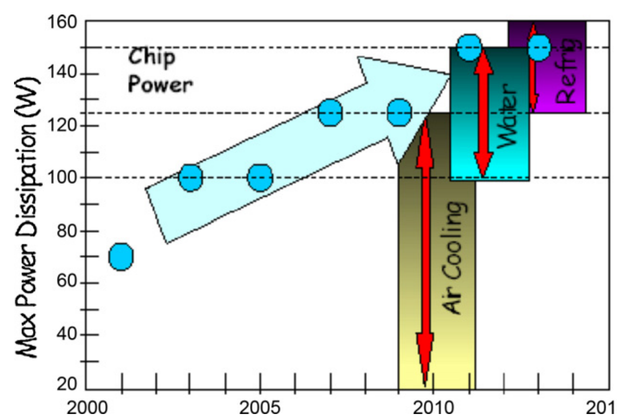

Fig. 9. Chip power dissipation chart [80].

electronically connected in order to obtain optimum performance. Thermal considerations become an important part of electronic equipment because of increased heat flux. Thermal management of electronic components may employ different heat transfer modes simultaneously and acting at different levels [80].

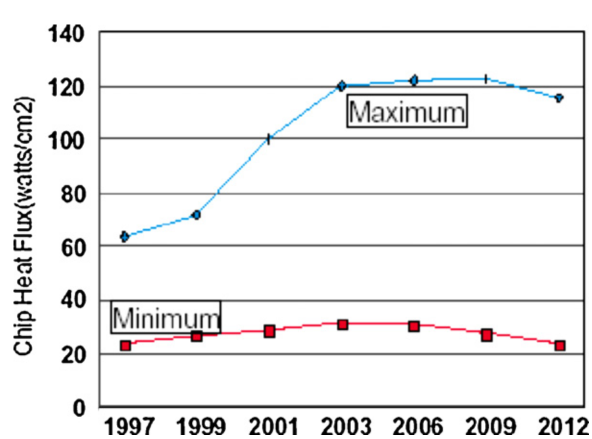

Fig. 10. Chip heat flux chart [80].

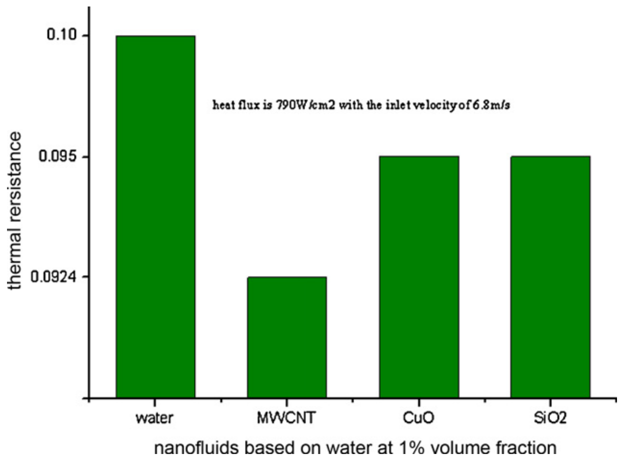

Fig. 11. Thermal resistance of different nanofluids [83].

Technology development in microelectronic systems (MEMS) provide faster operating speed electronic devices shown in Fig. 9, which have tremendous thermal load and require sophisticated cooling strategy. Recently, the customary method for increasing heat diffusion is to enlarge the contact area between the hot device and heat transfer fluid. However, this approach results in an undesirable cooling system size and impedes the efficiency of heat exchangers. Therefore, an innovative coolant with improved heat transfer performance is needed. The notion of nanofluids heat transfer fluids has been proposed to overcome these challenges. Nanotechnology has been widely used in traditional industry because materials with grain size of nanometers posses unique optical, electrical and chemical properties. An innovative utility of this emerging technology is that nanoparticles can be dispersed in conventional heat transfer fluids such as water, glycol or oil to produce a new class of high efficiency heat exchange media [1].

Technological developments such as microelectronic devices with smaller (sub-100 nm) features and faster (multi-GHz) operating speeds, higher-power engines and brighter optical devices are driving increased thermal loads, requiring advances in cooling [21]. Vasu et al. [81] reviewed nanofluids thermal performance for cooling of electronics. However, authors did not make a correlation between naofluids properties and cooling/heat transfer. Authors' focus was on the preparation of nanofluids, investigation of thermal conductivity by experimental and comparing with model which have been carried out by many authors.

Lai et al. [82] reported that heat transfer coefficient depends on the Reynolds number, the nanofluid volume fraction, temperature, the base fluid thermal properties and the nanoparticle purity. In general, the heat transfer coefficients exceeded those predicted by classical analyses in the laminar flow region, and those from well-known correlations like the Dittus–Boelter correlation in turbulent conditions. Thus, the use of nanofluids in electronics packaging appears promising as reported by Lai et al.

As the technical development of very-large-scale integrated (VLSI) circuits, the advanced electronic devices require better cooling systems because of the high level of heat dispassion. Authors found out the very compact water-cooled heat sink can make a minimum thermal resistance of 0.09 °C/W over 1-cm^2 area as can be seen in Fig. 11 [83].

4.2. Nanofluids in cameras, microdevices, and displays

A new study by Tasciuc [84] has demonstrated that liquids embedded with nanoparticles show enhanced performance and stability when exposed to electric fields, which could lead to new types of miniature camera lenses, cell phone displays, and other microscale fluidic devices. This study reported that this type of study may open up a new vista for using nanofluids in microscale and nanoscale actuator device applications [84].

The manipulation of small volumes of liquid is critical for fluidic digital display devices, optical devices, and microelectromechanical systems (MEMS) such as lab-on-chip analysis systems. Most research into such systems has been conducted with regular liquids, but not with nanofluids. Tasciuc's team placed droplets of water-based solutions containing bismuth telluride nanoparticles onto a Teflon-coated silicon wafer. When an electric field was applied to the droplet, the researchers observed a strong change in the angle at which the droplet contacted the wafer. This change was much higher than that observed in liquids without the nanoparticles when tested under the same conditions.

The ability to easily change the contact angle of droplets of nanofluids has potential applications for efficiently moving liquids in microsystems, creating new methods of focusing lenses in miniature cameras, or cooling computer chips.

Nguyen et al. [85] experimentally investigated the behavior and heat transfer enhancement of an Al_2O_3/water nanofluid flowing inside a closed system that is used for cooling of micro-electronic components. Results showed that the inclusion of nanoparticles into distilled water produced a considerable enhancement of the cooling block convective heat transfer coefficient. For a 6.8 vol.% concentration, the heat transfer coefficient has been found to increase as much as 40% compared to that of the base fluid. Experimental results also showed that a nanofluid with 36 nm particle size provides higher convective heat transfer coefficients than the ones given by a nanofluid with 47 nm particles. These positive results are promoting the continued research and development of nanofluids for such applications. Authors explored microchannel cooling using Al_2O_3/water nanofluids. The high thermal conductivity of nanoparticles is only shown to enhance the single-phase heat transfer coefficient, especially for laminar flow. Higher heat transfer coefficients were achieved mostly in the entrance region of microchannels. However, the enhancement was weaker in the fully developed region, proving that nanoparticles have an appreciable effect on thermal boundary layer development. Higher concentrations also produced greater sensitivity to heat flux. Despite this enhancement, the overall cooling effectiveness of nanoparticles was quite miniscule because of the large axial temperature rise associated with the decreased specific heat for the nanofluid compared to the base fluid. For two-phase cooling, nanoparticles cause catastrophic failure by depositing into large clusters near the channel exit due to localized evaporation once boiling commenced. These and other practical disadvantages bring into question the overall merit of using nanofluids in microchannel heat sinks [18].

4.3. Application in chillers

Many reported that 40% increase in thermal conductivity for 0.4% volume fraction of nanofluids. This gives an opportunity for improving performance of chillers in air conditioning systems. Surprisingly, the cooling capacity of the nanofluids could be increased by 4.2% at the standard rating conditions. A 6.7% increase in the capacity was encountered at a flow rate of 60 L/min. The unexpected rise in the cooling capacity of the nanofluids was related to the dynamic interaction of the flow field and the nanopowder. The nanopowders were capable of absorbing the fluctuation of the turbulent kinetic energy, giving rise to a better heat transfer characteristic under dynamic conditions, thereby leading to better system performance. At the standard rating conditions, the introduction of nanofluids gave rise to an increase in the COP by 5.15%, relative to a condition without nanofluids. Furthermore, the pressure drop penalty of the addition of nanofluids was almost negligible [86].

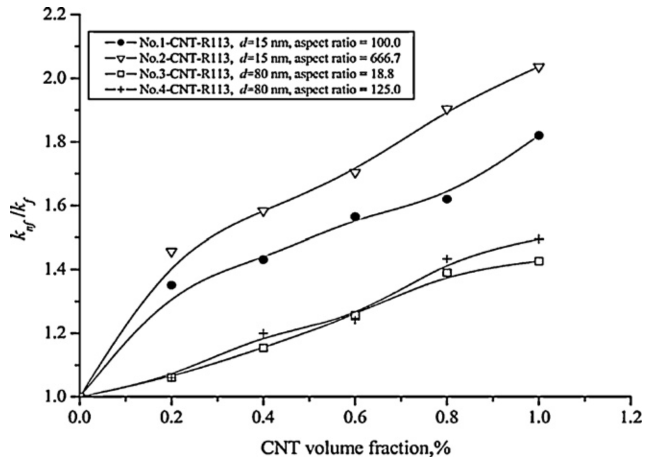

Fig. 12. Effective thermal conductivity of different concentrations of CNT [88].

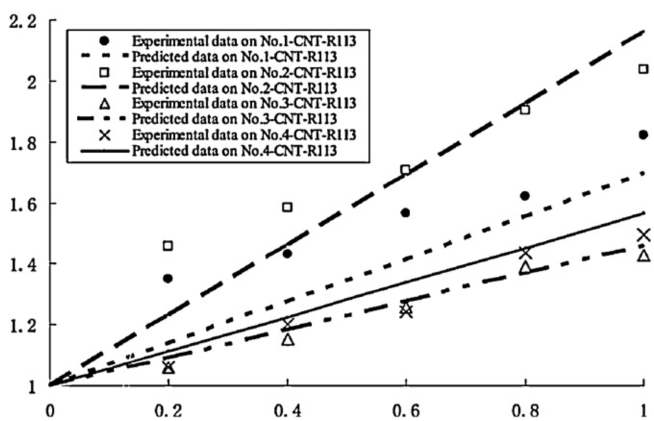

Fig. 13. Experimental data vs. predicted data of the modified Yu–Choi model [88].

This study [87] aimed to evaluate the potential of Al_2O_3–H_2O nanofluids as a new phase change material for the thermal energy storage of cooling systems. The photographic results suggest that the freezing rate of nanofluids was enhanced. Only adding 0.2 wt% Al_2O_3 nanoparticles into water, the total freezing time can be saved by 20.5%. Thus, the application of nanofluids in cooling industry can improve the performance of refrigeration systems and save the running time for refrigeration systems.

4.4. Application in domestic refrigerator

The experimental results by Jiang et al. [88] showed that the thermal conductivities of carbon nanotube (CNT) nanorefrigerants are much higher than those of CNT–water nanofluids or spherical-nanoparticle-R113 nanorefrigerants. Authors reported that the smaller the diameter of CNT is or the larger the aspect ratio of CNT is, the larger the thermal conductivity enhancement of CNT nanorefrigerant is as can be seen in Fig. 12.

Fig. 13 shows the comparison between the experimental data and the predicted results of the modified Yu–Choi model. The mean and maximum deviations of the modified Yu–Choi model are 5.5% and 15.8%, respectively, which shows that the modified Yu–Choi model is better than the existing models in predicting thermal conductivities of CNT nanorefrigerants.

Some investigations were carried out with nanoparticles in refrigeration systems to use advantageous properties of nanoparticles to enhance the efficiency and reliability of refrigerators. For example, Wang et al. [89] found that TiO_2 nanoparticles can be used as additives to enhance the solubility of the mineral oil in the hydrofluorocarbon (HFC) refrigerant. In addition, refrigeration systems using a mixture of HFC134a and mineral oil with TiO_2 nanoparticles appear to give better performance by returning more lubricant oil back to the compressor with similar performance to systems using HFC134a and POE oil. Wang et al. [90] carried out an experimental study of the boiling heat transfer characteristics of R22 refrigerant with Al_2O_3 nanoparticles and found that the nanoparticles enhanced the refrigerant heat transfer characteristics with reduced bubble sizes that moved quickly near the heat transfer surface.

Li et al. [91] investigated the pool boiling heat transfer characteristics of R11 refrigerant with TiO_2 nanoparticles and showed that the heat transfer enhancement reached 20% at a particle loading of 0.01 g/L. Park and Jung [92] investigated the effects of carbon nanotubes (CNTs) on the nucleate boiling heat transfer of R123 and HFC134a refrigerants. Authors test results showed that CNTs increase the nucleate boiling heat transfer coefficients for these refrigerants. Large enhancements of up to 36.6% were observed at low heat fluxes of less than 30 kW/m^2. Thus, the use of nanoparticles in refrigeration systems is a new, innovative way to enhance the efficiency and reliability of refrigerators. This study analyzes the use of nanoparticles in domestic refrigerators by measuring the refrigeration performance of a domestic refrigerator charged with HFC134a and mineral oil mixed with nanoparticles (Table 7).

The refrigerator performance with the nanoparticles was then investigated using energy consumption tests and freezer capacity tests. The results indicate that HFC134a and mineral oil with TiO_2 nanoparticles works normally and safely in the refrigerator. The refrigerator's performance was better than the HFC134a and POE oil system, with 26.1% less energy consumption used with 0.1% mass fraction of TiO_2 nanoparticles compared to the HFC134a and POE oil system. The same tests with Al_2O_3 nanoparticles showed that the different nanoparticles properties have little effect on the refrigerator performance. Thus, nanoparticles can be used in domestic refrigerators to considerably reduce energy consumption as reported by Bi et al. [97].

Peng et al. [98] investigated the influence of nanoparticles on the heat transfer characteristics of refrigerant-based nanofluids flow boiling inside a horizontal smooth tube, and presented a correlation for predicting heat transfer performance of refrigerant-based nanofluids. For the convenience of preparing refrigerant-based nanofluids, R113 refrigerant and CuO nanoparticles were used by the authors. Authors reported that the heat transfer coefficient of refrigerant-based nanofluids is higher than that of pure refrigerant, and the maximum enhancement of heat transfer coefficient found to be about 29.7%. Naphon et al. [99] reported that the heat pipe with 0.1% nanoparticles concentration gave efficiency 1.40 times higher than that with pure refrigerant as can

Table 7
Summary of research on nanoparticles and refrigerants.

Year	Investigator	Refrigerant	Nanoparticles	Size of nanoparticles	Volume concentrations
2007	[93]	R141b	Au	3 nm	0.09%, 0.4%, 1.0%
2007	[92]	R123, R134a	Carbon nanotubes	20 nm × 1 μm	1.0%
2009	[94]	R141b	TiO_2	21 nm	0.01%, 0.03%, 0.05%
2009	[95]	R113	CuO	40 nm	0.15–1.5%
2009	[96]	R134a	CuO	30 nm	0.5%, 1.0%, 2.0%

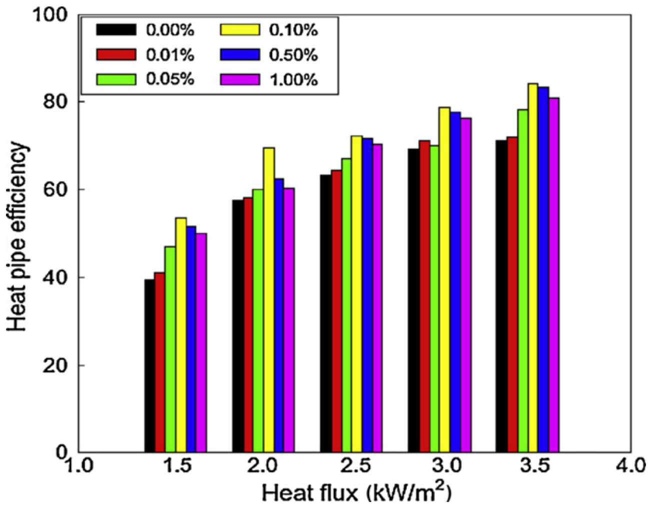

Fig. 14. Effect of nanoparticles concentrations on the heat pipe efficiency [99].

be seen in Fig. 14. Fig. 15 shows heat transfer enhancement of nanorefrigerants.

Heat pipe technology has been used in wide variety of applications in the various heat transfer devices especially in the electronic components. However, the heat transfer capability is limited by the working fluid transport properties. The basic idea is to enhance the heat transfer by changing the fluid transport properties and flow features with nanoparticles suspended. New experimental data on the efficiency enhancement of heat pipe with nanofluids are presented. Effects of nanoparticles concentrations on the heat pipe efficiency are considered. The optimum condition that results in maximum efficiency is obtained [99].

4.5. Engine cooling/vehicle thermal management

Vehicle thermal management is a crosscutting technology because it directly or indirectly affects engine performance, fuel economy, safety and reliability, aerodynamics, driver/passenger comfort, materials selection, emissions, maintenance, and component life. It follows that an effective and responsive thermal management system is critical to the design and operation of over-the-road trucks that are fuel-efficient and that meet increasingly stringent emissions standards [100].

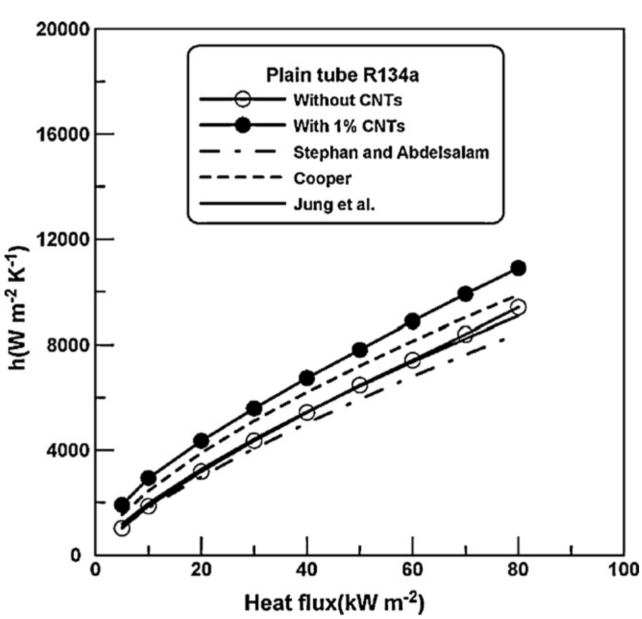

Fig. 15. Boiling heat transfer coefficients with 1.0 vol.% CNTs for R134a [92].

Choi et al. [101] showed that nanofluids have the potential of being recognized as a new generation of coolants for vehicle thermal management due to their significantly higher thermal conductivities than the base fluids. The heat rejection requirements of automobiles and trucks are continually increasing due to trends toward more power output.

Ollivier et al. [102] numerically investigated the possible application of nanofluids as a jacket water coolant in a gas spark ignition engine. Authors performed numerical simulations of unsteady heat transfer through the cylinder and inside the coolant flow. Authors reported that because of higher thermal diffusivity of nanofluids, the thermal signal variations for knock detection increased by 15% over that predicted using water alone.

Thermal management of heavy vehicle engines and support systems is a technology that addresses reduction in energy usage through improvements in engine thermal efficiency and reductions in parasitic energy uses and losses.

An ethylene glycol and water mixture, the nearly universally used automotive coolant, is a relatively poor heat transfer fluid compared to water alone. Engine oils perform even worse as a heat transfer medium. The addition of nanoparticles to the standard engine coolant has the potential to improve automotive and heavy-duty engine cooling rates. Such improvement can be used to remove engine heat with a reduced-size coolant system. Smaller coolant systems result in smaller and lighter radiators, which in turn benefit almost every aspect of car and economy. This may reduce the coefficient of drag and thus resulting in less fuel consumption. Alternatively, improved cooling rates for automotive and truck engines can be used to remove more heat from higher horsepower engines with the same size of coolant system.

A promising nanofluids engine coolant is pure ethylene glycol with nanoparticles. Pure ethylene glycol is a poor heat transfer fluid compared to a 50/50 mixture of ethylene glycol and water, but the addition of nanoparticles will improve the situation. If the resulting heat transfer rate can approach the 50/50 mixture rate, there are important advantages. Perhaps one of the most prominent is the low pressure operation of an ethylene-glycol-based nanofluids compared with a 50/50 mixture of ethylene glycol and water. This nanofluid also has a high boiling point, which is desirable for maintaining single-phase coolant flow. In addition, a higher boiling point coolant can be used to increase the normal coolant operating temperature and then reject more heat through the existing coolant system. More heat rejection allows a variety of design enhancements including engines with higher horsepower. Tzeng et al. [103] dispersed CuO and Al_2O_3 nanoparticles into engine transmission oil. The experimental platform was the transmission of a four-wheel-drive vehicle. The temperature distribution on the exterior of the rotary-blade coupling transmission was measured at four engine operating speeds. The temperature distribution on the exterior of the rotary-blade-coupling transmission was measured at four engine operating speeds (400, 800, 1200, and 1600 rpm), and the optimum composition of nanofluids with regard to heat transfer performance was investigated. Authors reported that CuO nanofluids produced the lowest transmission temperatures at both high and low rotating speeds. Thus, use of nanofluids in the transmission has a clear advantage from the thermal performance viewpoint. As in all nanofluids applications, however, consideration must be given to such factors as particle setting, particle agglomeration, and surface erosion. In automotive lubrication applications, surface modified nanoparticles stably dispersed in mineral oils are reported to be effective in reducing wear and enhancing load-carrying capacity. Results from a research project involving industry and university points to the use of nanoparticles in lubricants to enhance tribological properties such as load-carrying capacity, wear resistance, and friction reduction between moving mechanical components. Such results are encouraging for improving heat transfer rates in automotive systems through the use of nanofluids [18]. Ollivier et al. [102] reported that the use of the nanofluids leads to increased thermal signal variations by around 15% over that predicted using water alone. Authors employed a CFD numerical simulation method to analyze the application value of nanofluids in engine cooling. The simulation results indicated that nanofluids could enhance engine heat dissipating capacity and Cu–water nanofluids had better heat-transfer capability. It was also found that the more concentrations of the nanoparticles, the more enhancement of the engine heat dissipating capacity. When the concentration reached 5%, the heat dissipating capacity increased by 44.1%. With a remarkable enhancement on heat-transfer capability, the workload of the pump of engine cooling system only increased by 6%, which could be acceptable [104].

The trend toward higher engine power and EGR inevitably leads to larger radiators and increased frontal areas, resulting in additional aerodynamic drag and increased fuel consumption. Therefore, cooling is one of the top technical challenges facing the truck industry [43,105,106].

Choi [43] reported the limitations of existing technologies as follows:

- Liquid-side: traditional coolants and oils have inherently poor heat transfer properties.
- Air-side: current radiator designs for increasing air-side heat transfer have already adopted extended surface technology to its limits.
- Therefore, there is a steadily increasing need for new concepts and technology for improving HV cooling system performance.

Choi [43] reported that in US a project was initiated to target fuel savings for the HV industry through the development of energy efficient nanofluids and smaller and lighter radiators. A major goal of the nanofluids project is to reduce the size and weight of the HV cooling systems by >10% thereby increasing fuel efficiency by >5%, despite the cooling demands of higher-power engines and EGR. Nanofluids enable the potential to allow higher temperature coolants and higher heat rejection in HVs. A higher temperature radiator could reduce the radiator size by perhaps 30%. This translates into reduced aerodynamic drag and fluid pumping and fan requirements, leading to perhaps a 10% fuel savings.

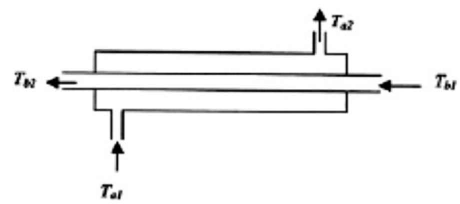

Fig. 16. Fluid flows in a radiator.

The new radiator design will be used in new general motors hybrid vehicles. These hybrid vehicles have multiple cooling systems for the internal combustion engine, electric engine, and batteries. The popularity of these hybrid vehicles is on the rise due to the decreasing fossil fuel supply, increasing the importance of a new radiator design that can possibly replace these multiple cooling systems.

These properties would be very beneficial to allow for an increased amount of heat to be removed from the engine. This is important because it will allow for a greater load to be placed on the fluid for cooling. However, these nanofluids do not show considerable improvement in heat transfer when used with current radiator designs. This is because there are several limitations to current radiator designs.

A steady-state heat exchanger consists of a fluid flowing through a pipe or system of pipes, where heat is transferred from one fluid to another. Heat exchangers are very common in everyday life and can be found almost anywhere. Some common examples of heat exchangers are air conditioners, automobile radiators, and a hot water heater. A schematic of a simple heat exchanger is shown in Figs. 16 and 17. Fluid flows through a system of pipes and takes heat from a hotter fluid and carries it away. Essentially it is exchanging heat from the hotter fluid to the cooler fluid as can be seen in Fig. 16.

Almost all automobiles in the market today have a type of heat exchanger called a radiator. The radiator is part of the cooling system of the engine as shown in Fig. 17. As can be can be seen in the figure, the radiator is just one of the many components of the complex cooling system.

Ma and Liu [107] reported that having the highest conductivity, being electromagnetically drivable, the liquid metal with low melting point is expected to be an idealistic base fluid for making

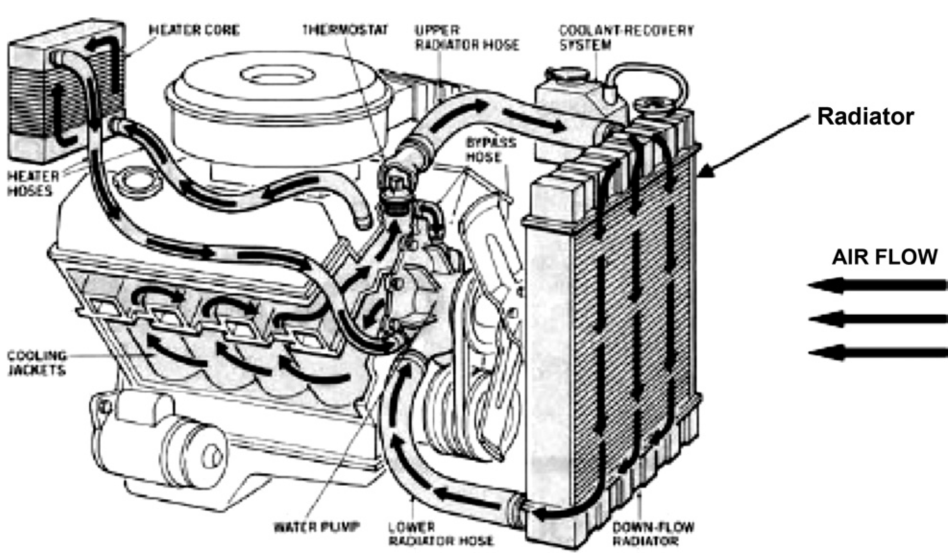

Fig. 17. Radiator of an engine.

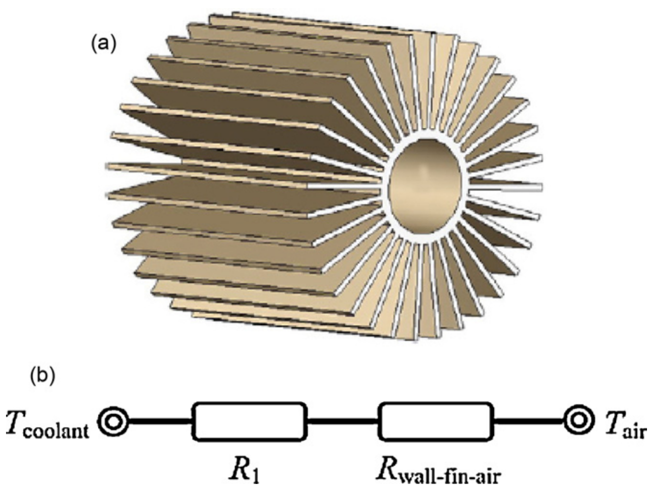

Fig. 18. Heat transfer for flowing liquid running inside a tube radiator ($T_{coolant}$ and T_{air} are temperatures for coolant and surrounding air, respectively). (a) Cylindrical tube radiator with fin structure. (b) Thermal resistance between coolant and ambient air [107].

super conductive solution which may lead to the ultimate coolant in a wide variety of heat transfer enhancement area. Fig. 18 shows heat transfer through a radiator.

Leong et al. [108] applied nanofluids in engine cooling and found that overall heat transfer coefficient and heat transfer rate increased with the usage of nanofluids in engine cooling compared to ethylene glycol (i.e. basefluids). Authors reported that about 3.8% of heat transfer enhancement can be achieved with the addition of 2% copper particles at 6000 and 5000 Reynold number for air and coolant, respectively. In addition, 18.7% reduction of air frontal area has been estimated. It has been found that heat transfer rate is increased with the increase of volume fraction of copper particles.

4.6. Detection of knock occurrence in a gas SI engine

Ollivier et al. [102] reported that a 5% water/Al_2O_3 nanofluids was numerically tested and their results show that the use of the nanofluids leads to increased thermal signal variations by around 15% over water as can be seen in Fig. 19.

4.7. Application as a coolant in machining

Heat liberated and the friction associated with the cutting process ever pose a problem in terms of tool life. Cutting fluids have been the conventional choice to address the problem. However, environmental hazards posed by the fluids have limited their usage,

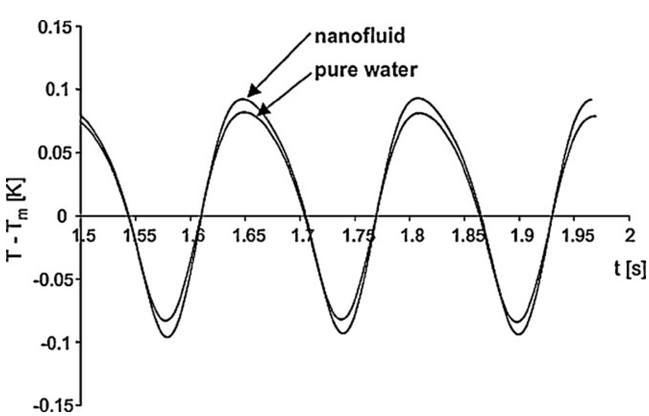

Fig. 19. Temperature variation recorded 0.5 mm from the internal side of the cavity (point 1), with nanofluid and with pure water [102].

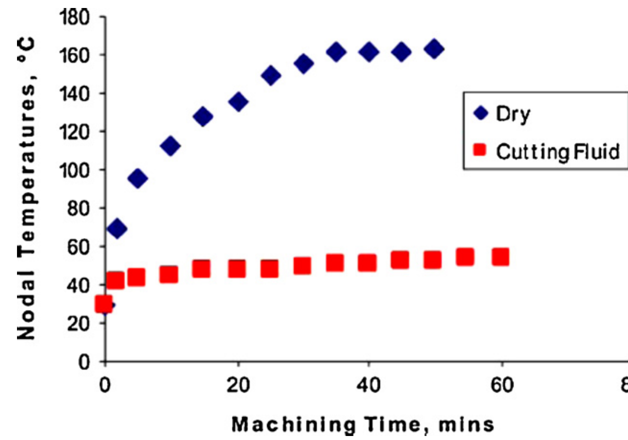

Fig. 20. Nodal temperature of nanofluids with time [109].

giving rise to minimum quantity lubrication. Nevertheless, its capability to carry away the heat and provideadequate lubrication is limited. In view of the above problems, nanofluids have gained renewed interest. Nanofluids, with their cooling and lubricating properties, have emerged as a promising solution [109]. Authors reported the characterizing changes in the heat transfer capacities of nanofluids with the inclusion of nanoparticles in the cutting fluids. To estimate the prevalent temperatures in machining, a facing operation was carried out by the authors under constant cutting conditions in a dry state and using conventional cutting fluid as coolant. Heat transfer coefficients were estimated using the analogy for flowover flat plates in all lubricating conditions. The temperatures calculated using the estimated heat transfer coefficient for conventional cutting fluid were compared with the experimental observations to validate the methodology. Temperature profiles were simulated using ANSYS 5.4 to infer on the suitability of the coolants in enhancing machining performance. Figs. 20 and 21 show the nodal temperature distributions for dry, cutting fluids and nanofluids with different concentrations. Nanoparticle inclusion was found to be beneficial in improving the coolant properties. Nevertheless, the high cost of nanoparticles may appear to be prohibitive and hence minimum requirement of inclusion was estimated. Cutting fluids with inclusion of nanoparticles have enhanced heat transfer capacity up to 6% [109]. Heat transfer coefficient for cutting fluids with inclusion of nanoparticles is shown in Table 9.

4.8. Cooling of diesel electric generator [110]

The investigation by Devdatta et al. [110] showed that applying nanofluids resulted in a reduction of cogeneration efficiency. Authors reported that this is due to the decrease in specific heat, which influences the waste heat recovery from the engine. However, it was found that the efficiency of waste heat recovery heat exchanger increased for nanofluids, due to its superior convective heat transfer coefficient. Authors reported that the heat exchanger efficiency increased with nanofluids. This is due to the higher heat transfer coefficient of nanofluids compared to the base fluid. For example the heat exchanger efficiency with ethylene glycol–water mixture of 78.1% increased to 81.11% for 6% Al_2O_3 nanofluids.

The cogeneration efficiency with various concentrations of Al_2O_3 nanofluid is shown in Fig. 22. From this experimental study, it is observed that with increased Al_2O_3 nanoparticle concentration, the diesel engine cogeneration efficiency decreased. This is mainly attributed to a decrease in the specific heat associated with an increase in Al_2O_3 nanoparticle concentration. As a typical value, the cogeneration efficiency of EG/W mixture of 79.1%, dropped to 76.11% with 6% Al_2O_3 nanofluids [110].

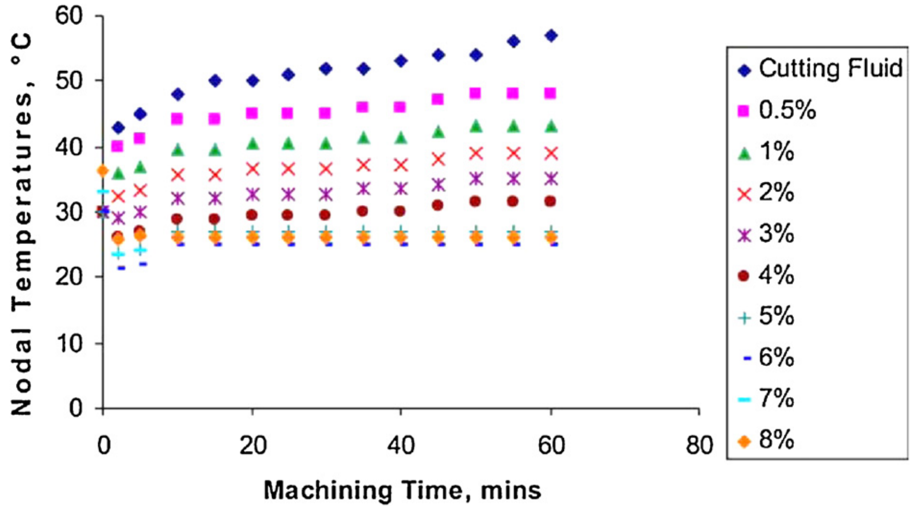

Fig. 21. Nodal temperatures for cutting fluids with varying nanoparticle inclusions [109].

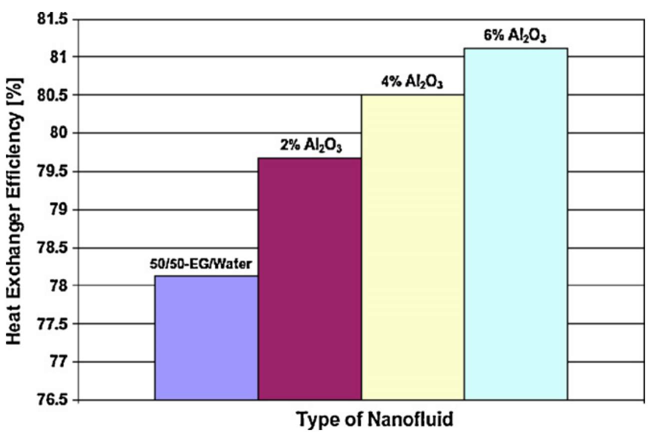

Fig. 22. Heat exchanger efficiency of the heat recovery system with various concentrations of Al_2O_3 nanofluid [110].

Table 9
Heat transfer coefficients for the cutting fluids.

Inclusion of nanoparticles (%)	Heat transfer coefficient (W/m^2 K)
0.0	1774.46
0.5	1857.42
1.0	1885.80
2.0	1941.84
3.0	1990.08
4.0	2018.61
5.0	2032.58
6.0	2099.79
7.0	2066.90
8.0	2058.06

[109].

4.9. Diesel combustion

The addition of nanoparticles to solid fuels and propellants has been part of several studies [111–115]. Such studies have shown that there are multiple advantages of adding nanoparticles to propellants and solid fuels, such as shorted ignition delay increased energy density, and high burn rates [111]. Few studies have also shown that the addition of nanoparticles to a fluid can enhance its physical properties such as thermal conductivity [116–118], mass diffusivity [119] and radiative heat transfer [120,121]. As a result it is possible in principle to achieve the desired properties of a fluid by adding some specifically tailored nanoparticles. However, little work has been reported in the past on the effect of adding nanoparticles to liquid fuels.

4.10. Boiler flue gas temperature reduction

Saidur et al. [122] proposed that heat transfer rate of flue gases can be enhanced by using nanofluids. Energy and bill savings associated with these savings has been shown in Table 8 for total boiler populations in Malaysia.

4.11. Solar water heating

Due to its renewable and nonpolluting nature, solar energy is often used in applications such as electricity generation, thermal heating, and chemical processing. The most cost-effective solar heaters are of the “flat-plate” type, but these suffer from relatively low efficiency and outlet temperatures. Tyagi et al. [123] theoretically investigated the feasibility of using a nonconcentrating direct absorption solar collector (DAC) and compared its performance with that of a typical flat-plate collector. Here a nanofluid—a mixture of water and aluminum nanoparticles—was used as the absorbing medium. A two-dimensional heat transfer analysis was developed in which direct sunlight was incident on a thin flowing film of nanofluids. The effects of absorption and scattering within the nanofluids were accounted for. In order to evaluate the temperature profile and intensity distribution within the nanofluid, the energy balance equation and heat transport equations were solved numerically. It was observed that the presence of nanoparticles increases the absorption of incident radiation by more than nine

Table 8
Total boiler energy and bill savings for Malaysian industries.

Energy savings (MJ) for savings of				Bill savings (RM) for			
2%	4%	6%	8%	2%	4%	6%	8%
167, 978	335, 957	503, 935	671, 913	10, 965, 250	21, 930, 501	32, 895, 751	43, 861, 002

times over that of pure water. According to the results obtained from this study, under similar operating conditions, the efficiency of a DAC using nanofluid as the working fluid is found to be up to 10% higher than that of a flat-plate collector. Generally a DAC using nanofluids as the working fluid performs better than a flat-plate collector. However, much better designed flat-plate collectors might be able to match or outperform a nanofluids based DAC under certain conditions [123,124].

Heat transfer enhancement in solar devices is one of the key issues of energy saving and compact designs. Researches in heat transfer have carried out over the previous several decades, leading to the development of the currently used heat transfer enhancement techniques. The use of additives is a technique applied to enhance the heat transfer performance of base fluids. Recently, as an innovative material, nanosized particles have been used in suspension in conventional heat transfer fluids. The fluids with nanosized solid particles suspended in them are called "nanofluids." The suspended metallic or nonmetallic nanoparticles change the transport properties and heat transfer characteristics of the base fluid. Nanofluids are expected to exhibit superior heat transfer properties compared to conventional heat transfer fluids [125].

Solar energy has the greatest potential of all the sources of renewable energy especially when other sources in the country have depleted. There are so many methods introduced to increase the efficiency of the solar water heater. But the novel approach is to introduce the nanofluids in solar water heater instead of conventional heat transfer fluids. The poor heat transfer properties of these conventional fluids compared to most solids are the primary obstacle to the high compactness and effectiveness of the system. The essential initiative is to seek the solid particles having thermal conductivity of several hundred times higher than those of conventional fluids. An innovative idea is to suspend ultrafine solid particles in the fluid for improving the thermal conductivity of the fluid [125]. Authors reported that thermal conductivity enhancement depends on the volume fraction of the suspended particles and thermal conductivities of the particles and base fluids, and the experiment proves that the nanofluid is more effective than the conventional fluids. If these fluids are used as a heat transport medium, it increases the efficiency of the traditional solar water heater.

4.12. Cooling and heating in buildings

Various nanofluids can be employed in conventional heat exchangers used in buildings. Analysis shows that nanofluid applications could result in volumetric flow reduction, reduction in the mass flow rate and pumping power savings. Nanofluids also require smaller heating systems in order to be capable of delivering the same amount of thermal energy, thus reducing the size and the initial cost of equipment. This will reduce the release of pollutants to the environment due to a reduction in power consumption and the waste produced at the end of the heat transfer system lifecycle. In cooling systems, nanofluids can be used in place of chilled water, which is commonly used in coils of air conditioning ducts. This application has not been explored extensively in the technical literature [38].

4.13. Application in transformer

Nanometer-sized, low-cost, readily available, particulate nanodiamond can be used as an additive to the mineral oil used in electrical power transformers and other oil-cooled electrical equipment to enhance the thermal conductivity (TC) and dielectric properties of the oil without compromising the oil's required electrical insulation, such that failures are suppressed, oil life is greatly extended and load boundaries are elevated. This could extend transformer life and allow increases to transformer MVA ratings [126].

The oil used to cool operating transformers has served the industry well, but suffers from excessive maintenance, replacement costs, environmental jeopardy and catastrophic failure incidence directly traceable to overheating. Transformer oil itself is a very poor thermal conductor; hence local hot spots lead to cracking of the oil's molecular composition and insulation collapse. Nanosize particles that are suspended in liquids will increase the overall TC and do so in much more than an additive manner. Several researchers conducted tests on nanoparticle suspensions and found a significant increase in thermal conductivity with very small particle volume fraction (less than 1.0%)—a result that is much higher than that predicted by traditional theory [126]. Transformer cooling is important to the power generation industry with the objective of reducing transformer size and weight. The ever-growing demand for greater electricity production can lead to the necessity of replacing and/or upgrading transformers on a large scale and at a high cost. A potential alternative in many cases is the replacement of conventional transformer oil with a nanofluid. Such retrofits can represent considerable cost savings. It has been demonstrated that the heat transfer properties of transformer oils can be significantly improved by using nanoparticle additives [2].

Choi et al. [101] prepared and evaluated the dispersions of nanosized Al_2O_3 and AlN powder in transformer oil with small amounts of oleic acid as a dispersant. As the transformer oil has relatively low thermal conductivity, thermally driven failures from instantaneous overload are common. Therefore, if it can be increased the thermal conductivity of the transformer oil, considerable extension in transformer lifetime and increment in load/cooling capacity may be achieved. Authors chose ceramic nano particles to make high efficiency transformer oil because they have an electric insulation property. Thermal conductivities of dispersions were measured by the transient hot-wire technique and the experimental results show a maximum 8% enhancement of thermal conductivity and 20% improvement of the overall heat transfer coefficient for 0.5% volumetric loading of AlN particles as can be seen in Fig. 23. From the natural convection test using a prototype transformer, the cooling effect of Al_2O_3/AlN-oil nanofluids on the heating element and oil itself was confirmed [101].

4.14. Heat exchanger

Cooling is one of the important challenges faced by many industries. The conventional way to increase cooling rates is increasing the heat transfer area. There is a balance between pumping costs and heat transfer. As the area goes up, so does the energy needed to pass the fluid through the exchanger. Further increase of heat transfer area requires increasing the size of thermal management system. An attractive approach to heat exchanger design is to develop new, high efficiency heat transfer fluids [30].

Nanotechnology may help accelerate the development of energy-efficient central heating. When added to water, CNTs disperse to form a nanofluid. Researchers have developed nanofluids whose rates of forced convective heat transfer are four times better than the norm by using CNTs. When added to a home's commercial water boiler, such nanofluids could make the central heating device 10% more efficient [3].

The new experimental data concerning the use of nanofluids in a commercial heat exchanger confirmed that, besides the physical properties, the type of flow (laminar or turbulent) inside the heat exchanging equipment plays an important role in the effectiveness of a nanofluid. When the heat exchanging equipment operates under conditions that promote turbulence, the use of nanofluids is beneficial if and only if the increase in their thermal conductivity is accompanied by a marginal increase in viscosity, which

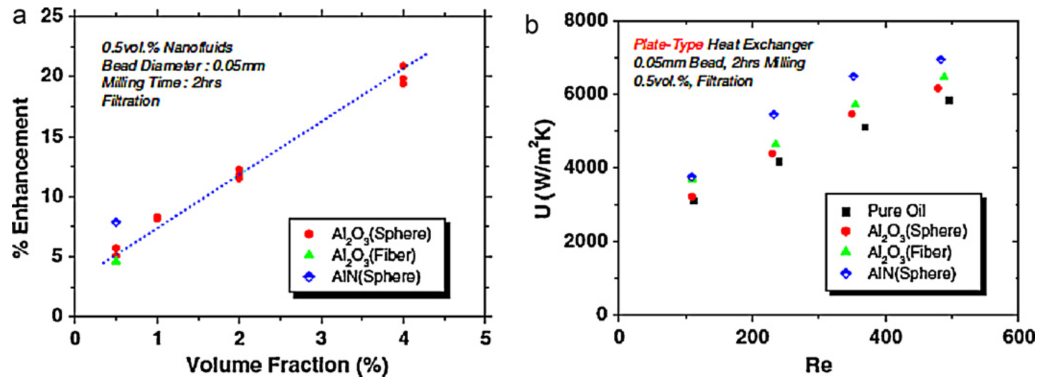

Fig. 23. (a) Thermal conductivity as a function of volume fraction for the nanoparticles–oil suspensions and (b) plot of overall heat transfer coefficient versus Reynolds number for oil-based nanofluids [101].

seems very difficult to be achieved. On the other hand, if the heat exchanger operates under laminar conditions, the use of nanofluids seems advantageous, the only disadvantages so far being their high price and the potential instability of the suspension. The empirical correlations characterizing the heat transfer processes seem to be reliable for the convective heat transfer coefficient prediction in the case of nanofluids under the condition that accurate values of physical properties are provided. In conclusion, in industrial heat exchangers, where large volumes of nanofluids are involved and turbulent flow is usually developed, the substitution of conventional fluids by nanofluids seems inauspicious. However, in micro-scale equipment with increased thermal duties, where also volume is a matter, and especially in laminar flow, the use of a nanofluid instead of a conventional fluid seems advantageous. In each case the nanofluid properties should be defined carefully in order to evaluate its efficacy in a specific heat exchanger [127].

In this study, analysis demonstrates that a nanofluid-cooled microchannel heat exchanger can extract heat from the silicon crystal mirror to a working fluid faster than present cooling technology. The benefits of nanofluid cooling are clear, including dramatic enhancement of cooling rates while operating the advanced cooling system at room temperature. Furthermore, the possibility of thermal distortion and flow-induced vibration will be eliminated by passing the nanofluids through microchannels within the silicon mirror itself. Future experimental work on the nanofluid-cooled microchannel heat exchanger will advance the art of cooling high-heat-load X-ray monochromators. For the high aspect ratio microchannels, power densities of 3000 W/cm^2 should be achievable with the use of nanofluids as can be seen in Fig. 24 [20,38]. Fig. 25 shows the enhanced heat flow rate for nanofluids compared to basefluid (i.e. water).

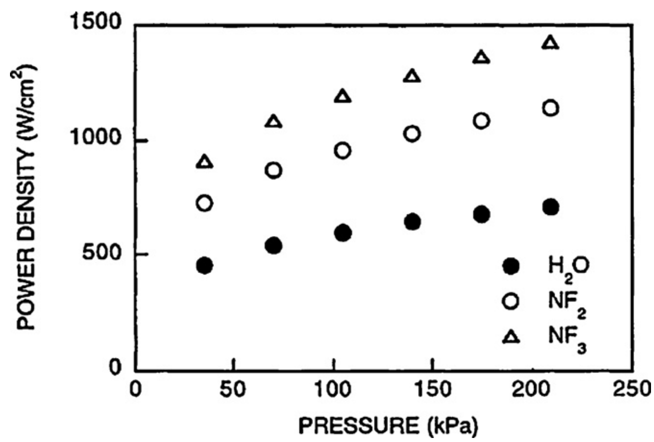

Fig. 24. Power density with pressure for nanofluids and water [20].

4.15. In oscillating heat pipes

It was found that nanofluids significantly increase the heat transport capability in an OHP. In order to determine the primary factors affecting the heat transfer enhancement of the OHP,

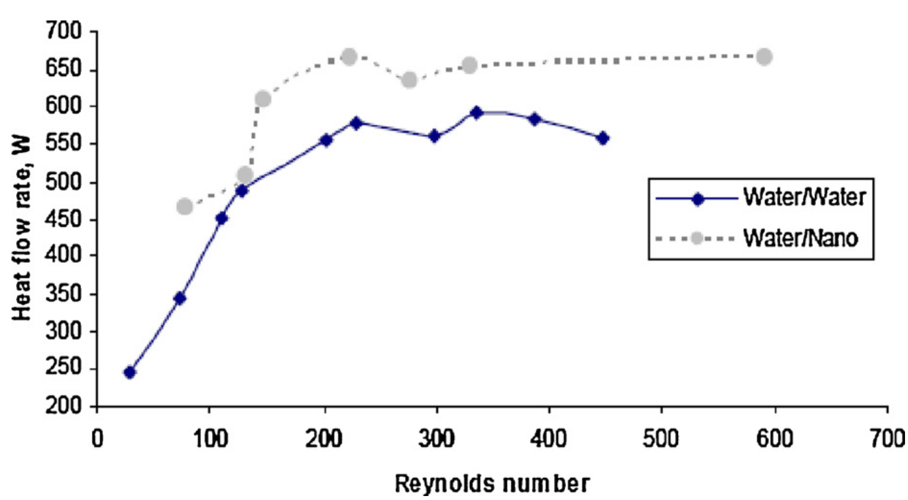

Fig. 25. Reynolds number versus heat transfer rate [128].

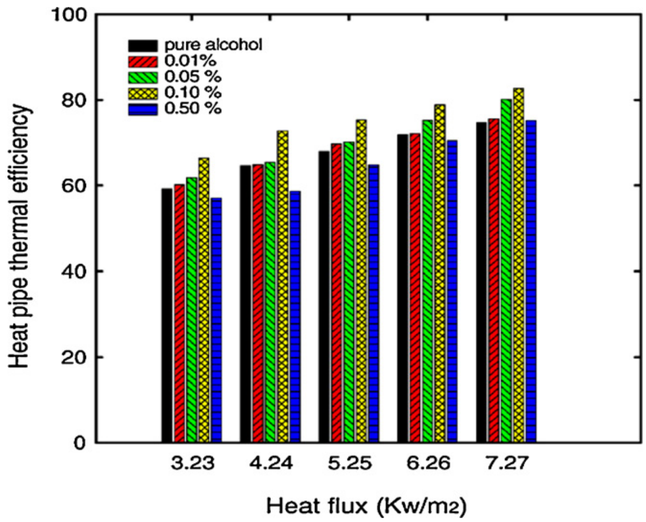

Fig. 26. Variation of heat pipe thermal efficiency with heat flux for different % nanoparticles volume concentrations [130].

the thermal conductivity of the motionless nanofluids was measured. Experimental results show that the diamond nanoparticles can enhance the thermal conductivity of nanofluids. At an ambient temperature of 21 °C, the thermal conductivity for nanofluid was determined to be 1.0 W/m K comparing with the thermal conductivity of 0.6 W/m K for HPLC grade water. Therefore, the nanofluid provided a significant increase in thermal conductivity, which is a primary reason for the significantly increased heat transport capability in the OHP. Another factor investigated was the operating temperature that influence the performance of OHP. It was shown that increased operating temperatures significantly increase the heat transport capability of the investigated OHPs. Thus, the nanofluids OHP investigated provides a new approach in designing a highly efficient heat pipe cooling device [129].

Naphon et al. [130] conducted experiment with titanium nanofluids to investigate the performance of heat pipes and results have been presented in Fig. 26.

In general, the suspension of nanoparticles in the fluid has significant effect on the enhancement of heat transfer due to: higher heat capacity, higher thermal conductivity of working fluid and higher mixing fluctuation. Therefore, the heat pipe thermal efficiency increases with increasing nanoparticles concentrations. For the particular nanofluids with 0.10% nanoparticles volume concentration, the thermal efficiency of heat pipe increases as much as 10.60% compared to that of the base working fluid. However, as the nanoparticles concentrations exceed a value of 0.10%, the properties of the nanofluids seem to be a solid phase thereby lower evaporation rate of working fluid in the evaporator section. Therefore, the heat pipe thermal efficiency also decreases [130].

4.16. Space, defense and ships

A number of military devices and systems require high-heat-flux cooling to the level of tens of MW/m^2. At this level, cooling with conventional fluids is challenging. Examples of military applications include cooling of power electronics and directed energy weapons. Directed-energy weapons involve high heat fluxes (>500–1000 W/cm^2), and providing adequate cooling of them and the associated power electronics is a critical need. Nanofluids have the potential to provide the required cooling in such applications as well as in other military systems, including military vehicles, submarines, and high-power laser diodes. In some cases, nanofluids research for defense applications includes multifunctional nanofluids with added thermal energy storage or energy harvesting through chemical reactions. Wang and Mujumdar [18] reported order of magnitude increase in the critical heat flux in pool boiling with naofluids compared to the base fluid alone. Such levels present the possibility of raising chip power in electronic components or simplifying cooling requirements for space applications. High critical heat fluxes allow boiling to higher qualities with increased heat removal and wider safety margin from the film boiling. This feature makes nanofluids attractive in general electronic cooling as well as space applications where power density is very high [18].

The US Department of Defense (DoD) is developing new generations of pulsed power weapons, all electric warships and advanced electrical systems, all of which produce large amounts of heat. Waste heat from these systems may be of the order of megawatts, which can be transported by nanofluids to the hull of a ship. Therefore, the thermal management of weapons and hull heating can be accomplished simultaneously by circulating nanofluids to transport the heat from critical high heat flux components, in excess of 1000 W/cm^2 and deliver it to the ship hull. This heating of the ship hull will reduce the drag of the ship ultimately saving fuel costs [38].

4.17. Medical applications

Nanofluids and nanoparticles have many applications in the biomedical industry, but there are some side effects in traditional cancer treatment methods. Iron based nanoparticles could be used as delivery vehicles for drugs or radiation without damaging nearby healthy tissue. Such particles could be guided in the blood stream to a tumor using magnets external to the body. Nanofluids could also be used for safer surgery by producing effective cooling around the surgical region and thereby enhancing the patient's chance of survival and reducing the risk of organ damage. Magnetic nanoparticles in biofluids can be used as delivery vehicles for drugs or radiation, providing new cancer treatment techniques. Magnetic nanoparticles absorb much more power than microparticles at AC magnetic fields tolerable to humans. Nanoparticles are more adhesive to tumor cells than normal cells, therefore, magnetic nanoparticles excited by an AC magnetic field is promising for cancer therapy. The combined effect of radiation and hyperthermia is due to the heat induced malfunction of the repair process right after radiation induced DNA damage [21,38].

4.18. The antibacterial activities

The antibacterial activities of ZnO nanofluids were evaluated by estimating the reduction ratio of the bacteria treated with ZnO. The results showed that the ZnO nanofluids stored for 120 days under the light had the best antibacterial behavior against *Escherichia coli* DH5a [131]. Different from the antibacterial activity of TiO_2 under UV light, newly developed ZnO ceramics have been found to exhibit the sustainable antibacterial activity even in the dark sunshade [132].

4.19. Application in nuclear reactor

Buongiorno and Hu [133] carried out a project in nuclear reactor to investigate the CHF of nanofluids and mechanisms of enhanced heat transfer. Authors reposted that the project findings were significant and new because they expanded the nanofluids CHF database to include a flow situation, which is the situation of interest for nuclear applications. The development of viable nanofluids for use in water-cooled nuclear systems could result in a significant improvement of their economic performance and/or safety margins. The experimental data generated in the project are also a contribution to heat transfer research, and have been widely disseminated and recognized.

It was determined that the system has a reasonably low failure probability, and that, once injected, the nanofluid would be delivered effectively to the reactor vessel surface within seconds. It was also shown analytically that the increase in decay power removal through the vessel using a nanofluid is about 40%, which could be exploited to provide a higher in-vessel retention (IVR) safety margin or, for a given margin, to enable IVR at higher core power.

Finally, the colloidal stability of a candidate alumina-based nanofluids in an IVR environment was experimentally investigated, and it was found that this nanofluid would be stable against dilution, exposure to gamma radiation, and mixing with boric acid and lithium hydroxide, but not trisodium phosphate [133].

4.20. Application in grinding

The grinding process generates an extremely high input of energy per unit volume of material removed. Virtually all this energy is converted to heat, which can cause high temperatures and thermal damage to the work piece such as work piece burn, phase transformations, undesirable residual tensile stresses, cracks, reduced fatigue strength, and thermal distortion and inaccuracies. The recent development of nanofluids provides alternative cutting fluids which can be used in MQL grinding. The advanced heat transfer and tribological properties of these nanofluids can provide better cooling and lubricating in the MQL grinding process, and make in production-feasible [41].

4.21. New sensors for improving exploration

In high-temperature/high-pressure conditions, old electrical sensors and other measuring tools often are not reliable. But researchers currently are developing a set of reliable and economical sensors from optical fibers for measuring temperature and pressure, oil-flow rate, and acoustic waves in oil wells. These new sensors are small in size, work safely in the presence of electromagnetic fields, are able to work in high temperatures and pressures, and can be changed at a sensible cost without interfering in the procedure of oil exploration.

Changing and displacing old sensors in oil wells is very costly. But this technology could, with its accurate and reliable measurements, make a great improvement in oil exploration. In the future, the industry may be using nanoscale sensors for probing properties deep in the reservoir, allowing us to unravel the complex nature of the rock/fluid interactions and their effects on multiphase flow and providing the ability to design a suitable exploitation plan for the asset.

Another area of significant challenge lies in the upgrading of bitumen and heavy crude oil. Because of their high density and viscosity, it is difficult to handle and transport them to locations where they could be converted into valuable products. Significant resources and intense research activities have been devoted to develop processes and specifically designed catalysts for on-site field upgrading combined with hydrogen/methane production. These processes would incorporate a minimized and controlled carbon rejection, in conjunction with a catalytically enhanced hydrogen generation performed on the rejected carbon from the upgrading process. This central activity will be complemented with an effort to integrate the research for ultradispersed catalytic formulas for the in situ upgrading of bitumen as well as for hydrogen generation from coal/coke or petroleum pitch. The former requires research on specifically designed adsorbents and catalysts to be introduced into the reservoir porous media in nanosized form.

The latter requires extensive research on both catalytic active phases and process setup as well as adopting different catalytic forms for effective contact with the gasifying materials. This research has the potential to generate significant technology to convert bitumen and heavy-oil reserves into products cost effectively [134,135].

4.22. Application of nanofluids in thermal absorption systems

The thermally driven absorption system is an alternative to the vapor compression system, which may lead to environmental problems such as global warming and ozone layer depletion due to the use of certain refrigerants. The absorber is the most critical component in the absorption system. In order to improve the performance of the absorber, several studies have been carried out. Kim et al. [136] showed that by adding nanoparticles such as Cu, CuO and Ah03 to a NH31H20 solution improved the absorption performance by 5.32 times. Whenever there are cooling baths using glycol water mixtures, methanol and silicon oil, exploratory studies should be performed on nanofluids to determine if any advantages may be gained [38].

4.23. Application in fuel cell

Fuel cells are new developments in the power generation field which involve notable amounts of heat and mass exchange. Whenever the heat exchange phenomenon occurs within a fuel cell or in its auxiliary heat recovery systems, nanofluids can be employed to enhance heat transfer and raise the fuel cell efficiency [1,3,137].

4.24. Other applications

There are unending situations where an increase in heat transfer effectiveness can be beneficial to the quality, quantity, and/or cost of a product or process. In many of these situations, nanofluids are good candidates for accomplishing the enhancement in heat transfer performance. For example, nanofluids have potential application in building where increases in energy efficiency could be realized without increased pumping power. Such an application would save energy in a heating, ventilating, and air conditioning system while providing environmental benefits. Nanofluids coolants also have potential application in major process industries, such as materials, chemical, food and drink, oil and gas, paper and printing, and textiles.

Nanotechnology could help improve oil and gas production by making it easier to separate oil and gas in the reservoir—for instance, through improved understanding of processes at the molecular level. There are many other potential clean energy sources that could be enhanced through the use of nanotechnology. The practical application of nanotechnology in the oil sector is, fortunately, less frightening. It opens interesting prospects for improved oil recovery, not least through better understanding of processes at the interface between liquids and solids. The aim is to understand how oil and water can be separated more effectively. Nanotechnology could be applied to improved oil recovery in the form of tailoring surfactants. These can then be added to the reservoir in a more controlled way than with existing substances, thereby releasing more oil. It could also help develop new metering techniques with tiny sensors to provide improved information about the reservoir.

Scientists at China's Shandong University are researching ways in which nanotechnology can be used to improve the drilling process. Their specialized petroleum laboratory has developed an advanced fluid mixed with nanosized particles and superfine powder that significantly improved drilling speed. This blend eliminates damage to the reservoir rock in the well, making it possible to extract more oil [138].

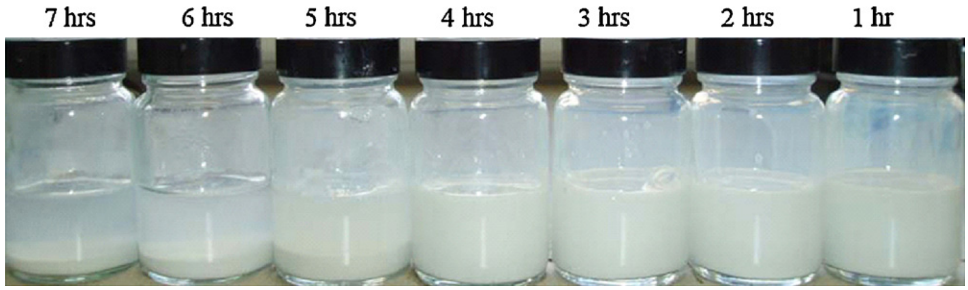

Fig. 27. Samples of Al_2O_3 nanofluids (without any stabilizer) stability change with time [142].

5. Challenges of nanofluids

Many interesting properties of nanofluids have been reported in the review. In the previous studies, thermal conductivity has received the maximum attention, but many researchers have recently initiated studies on other heat transfer properties as well. The use of nanofluids in a wide variety of applications appears promising. But the development of the field is hindered by (i) lack of agreement of results obtained by different researchers; (ii) poor characterization of suspensions; (iii) lack of theoretical understanding of the mechanisms responsible for changes in properties. Therefore, this paper concludes several important issues that should receive greater attention in the near future. Experimental studies in the convective heat transfer of nanofluids are needed. Many issues, such as thermal conductivity, the Brownian motion of particles, particle migration, and thermophysical property change with temperature, must be carefully considered with convective heat transfer in nanofluids. Though, all the convective studies have been performed with oxide particles in high concentrations (for example Pak and Cho [139] used 10 vol.% of Al_2O_3 which increased the viscosity and pumping power of the fluid, it is interesting to know the energy transport in low concentration(<1 vol.%) nanofluids with metallic particles, since the thermal conductivity of pure metallic nanoparticles is more than 100 times higher than that of the oxide nanoparticles. Future convective studies must be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulentregions. The use of nanofluids in heat pipes has shown enhancement in performance and considerable reduction in thermal resistance. However, recent studies indicate particle aggregation and deposition in micro-channel heat sinks. Further study is required in these areas to identify the reasons for and the effects of particle deposition. Finally, there appears to be hardly any research in the use of nanofluids as refrigerants. Nanoparticle-refrigerant dispersions in two-phase heat transfer applications can be studied to explore the possibility of improving the heat transfer characteristics of evaporators and condensers used in refrigerationand air-conditioning appliances. Applied research in nanofluids which will define their future in the field of heat transfer is expected to grow at a faster pace in the near future [140].

5.1. Long term stability of nanoparticles dispersion

Preparation of homogeneous suspension remains a technical challenge since the nanoparticles always form aggregates due to very strong van der Waals interactions. To get stable nanofluids, physical or chemical treatment have been conducted such as an addition of surfactant, surface modification of the suspended particles or applying strong force on the clusters of the suspended particles. Dispersing agents, surface-active agents, have been used to disperse fine particles of hydrophobic materials in aqueous solution [141].

On the other hand, if the heat exchanger operates under laminar conditions, the use of nanofluids seems advantageous, the only disadvantages so far being their high price and the potential instability of the suspension [127].

Generally, long term stability of nanoparticles dispersion is one of the basic requirements of nanofluids applications. Stability of nanofluids have good corresponding relationship with the enhancement of thermal conductivity where the better dispersion behavior, the higher thermal conductivity of nanofluids [142]. However the dispersion behavior of the nanoparticles could be influenced by period of time as can be seen in Figs. 27 and 28. As a result, thermal conductivity of nanofluids is eventually affected. Eastman et al. [25] revealed that, thermal conductivity of ethylene glycol based nanofluids containing 0.3% copper nanoparticles is decreased with time. In their study, the thermal conductivity of nanofluids was measured twice: first was within 2 days and second was two months after the preparation. It was found that fresh nanofluids exhibited slightly higher thermal conductivities than nanofluids that were stored up to two months. This might due to reduced dispersion stability of nanoparticles with respect to time. Nanoparticles may tend to agglomerate when kept for long period of time. Lee and Mudawar [143] compared the Al_2O_3 nanofluids stability visually over time span. It was found that nanofluids kept for 30 days exhibit some settlement and concentration gradient compared to fresh nanofluids. It indicated long term degradation in thermal performance of nanofluids could be happened. Particles settling must be examined carefully since it may lead to clogging of coolant passages.

Choi et al. [145] reported that the excess quantity of surfactant has a harmful effect on viscosity, thermal property, chemical stability, and thus it is strongly recommended to control the addition of the surfactant with great care. However, the addition of surfactant would make the particle surface coated, thereby resulting in the screening effect on the heat transfer performance of nanoparticles. Authors also mentioned that the surfactant may cause physical and/or chemical instability problems.

5.2. Increased pressure drop and pumping power

Pressure drop developed during the flow of coolant is one of the important parameter determining the efficiency of nanofluids application. Pressure drop and coolant pumping power are closely associated with each other. There are few properties which could influence the coolant pressure drop: density and viscosity. It is expected that coolants with higher density and viscosity experience higher pressure drop. This has contributed to the disadvantages of nanofluids application as coolant liquids. Lee et al. [146] and Yu et al. [38] investigated viscosity of water based Al_2O_3 nanofluids and ethylene glycol based ZnO nanofluids. Results clearly show, viscosity of nanofluids is higher than basefluid. Namburu et al. [147] in their numerical study reviewed that density of nanofluids is greater than basefluid. Both properties are found pro-

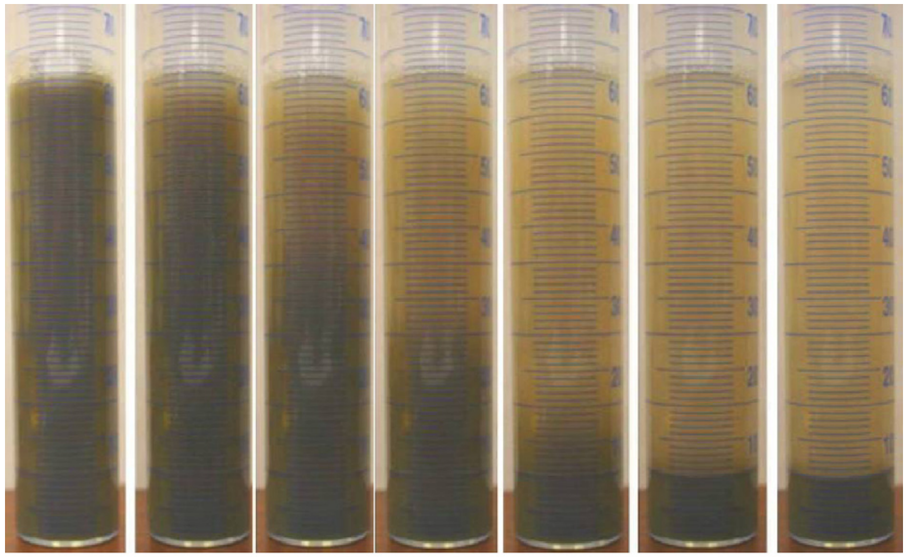

Fig. 28. The sedimentation of diamond nanoparticles at settling times of (a) 0 min, (b) 1 min, (c) 2 min, (d) 3 min, (e) 4 min, (f) 5 min, and (g) 6 min [144].

portional with nanoparticles volume fraction. Several literatures have indicated that there is significant increase of nanofluids pressure drop compared to basefluid. Lee and Mudawar [143] revealed that single phase pressure drop of Al_2O_3 nanofluids in microchannel heat sink increases with nanoparticles concentration. Vasu et al. [81] studied the thermal design of compact heat exchanger using nanofluids. In this study, it is found that pressure drop of 4% $Al_2O_3 + H_2O$ nanofluids is almost double of the basefluid. Pantzali et al. [127] reported there was substantial increase of nanofluids pressure drop and pumping power in plate heat exchanger. About 40% increase of pumping power was observed for nanofluids compared with water.

Peng et al. [148] reported that the frictional pressure drop of refrigerant-based nanofluids flow boiling inside the horizontal smooth tube is larger than that of pure refrigerant, and increases with the increase of the mass fraction of nanoparticles. The maximum enhancement of frictional pressure drop can reach 20.8% under the experimental conditions.

An important parameter in the application of nanofluids in heat exchanging equipment is the pressure drop developed during the flow through the Plate Heat Exchanger (PHE). In Fig. 29 the total pressure drop *P*, measured inside the PHE, is plotted versus the cooling liquid volumetric flow rate for both the water and the nanofluid. Pantzali et al. [127] observed that the measured viscosity of the suspension (i.e. nanofluids) exhibits a twofold increase compared to water. This leads to a significant increase in the measured pressure drop and consequently in the necessary pumping power when the nanofluids are applied. Authors calculated that the pumping power increased about 40% compared to water for a given flow rate. Authors observed that for a given heat duty the required volumetric flow rates for both the water and the nanofluid are practically equal, while the necessary pumping power in the case of the nanofluid is up to two times higher than the corresponding value for water due to the higher kinematic viscosity of the fluid [127].

5.3. Nanofluids thermal performance in turbulent flow and fully developed region

Apart from thermal conductivity, convective heat transfer performance of the nanofluids also attracted maximum attention from the researchers. Most of the literatures reported that this property is greatly enhanced with the application of nanofluids. However, there is an issue that must be addressed carefully especially on the thermal performance of nanofluids in turbulent flow. Recently, there was inconsistence of results reported by the researchers. For instance [136] revealed that no convective heat transfer improvement was noticed for amorphous carbonic nanofluids in turbulent flow despite 8% improvement in laminar flow. However, Duangthongsuk and Wongwises [149] reported that heat transfer coefficient of TiO_2–water nanofluids is higher than basefluid. This property increases with the increase of Reynold numbers and particle concentrations ranging from 0.2% to 2%. Although the study revealed that 26% enhancement can be observed for nanofluids with 1% of TiO_2 nanoparticles, it showed contradictory results at 2.0% volume fraction. Study indicated that heat transfer coefficient of nanofluids at this condition was 14% lower than basefluid. Pantzali et al. [127] added substitution of conventional coolants by nanofluids seemed beneficial for laminar flow compared to turbulent flow. Another

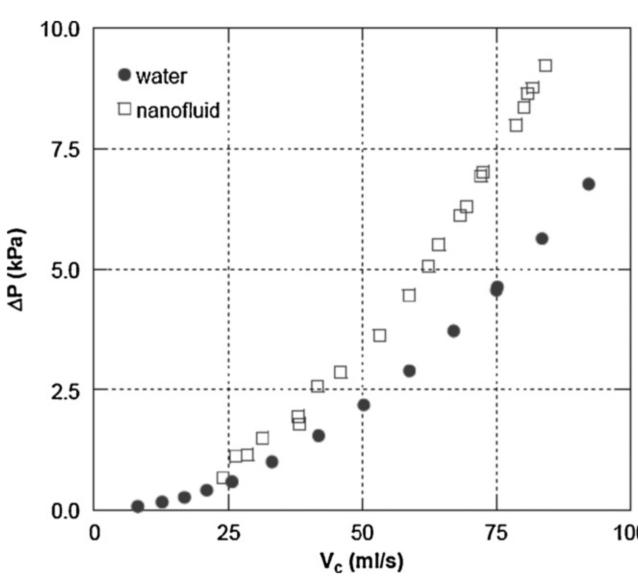

Fig. 29. Pressure drop of the cooling liquid inside the PHE versus the respective volumetric flow rate [127].

weakness of nanofluids is its thermal performance at fully developed region. Ding et al. [150] found that convective heat transfer coefficient of nanofluids at low Reynold number has the highest value at the entrance length of the tube, starts decreasing with axial distances and eventually reaches constant value in fully developed region.

5.4. Higher viscosity

The viscosity of nanoparticle–water suspensions increases in accordance with increasing particle concentration in the suspension. So, the particle mass fraction cannot be increased unlimitedly [87]. Pantzali et al. [127] concluded that in industrial heat exchangers, where large volumes of nanofluids are necessary and turbulent flow is usually developed, the substitution of conventional fluids by nanofluids seems inauspicious. Lee [78] reported that the viscosity increased so rapidly with increasing particle loading that volume percentages of CNTs are limited to less than 0.2% in practical systems.

5.5. Lower specific heat

From the literatures, it is found that specific heat of nanofluids is lower than basefluid. Namburu et al. [147] reported that CuO/ethylene glycol nanofluids, SiO_2/ethylene glycol nanofluids and Al_2O_3/ethylene glycol nanofluids exhibit lower specific heat compared to basefluids. An ideal coolant should possess higher value of specific heat which enable the coolant to remove more heat.

5.6. Thermal conductivity

The existing models for predicting thermal conductivities of CNT nanofluids, including Hamilton–Crosser model, Yu–Choi model and Xue model, cannot predict the thermal conductivities of CNT nanorefrigerants within a mean deviation of less than 15% [151].

5.7. High cost of nanofluids

Higher production cost of nanofluids is among the reasons that may hinder the application of nanofluids in industry. Nanofluids can be produced by either one step or two steps methods. However both methods require advanced and sophisticated equipments. Lee and Mudawar [143] and Pantzali et al. [127] stressed that high cost of nanofluids is among the drawback of nanofluids applications.

5.8. Difficulties in production process

Previous efforts to manufacture nanofluids have often employed either a single step that simultaneously makes and disperses the nanoparticles into base fluids, or a two-step approach that involves generating nanoparticles and subsequently dispersing them into a base fluid. Using either of these two approaches, nanoparticles are inherently produced from processes that involve reduction reactions or ion exchange. Furthermore, the base fluids contain other ions and reaction products that are difficult or impossible to separate from the fluids.

Another difficulty encountered in nanofluid manufacture is nanoparticles' tendency to agglomerate into larger particles, which limits the benefits of the high surface area nanoparticles. To counter this tendency, particle dispersion additives are often added to the base fluid with the nanoparticles. Unfortunately, this practice can change the surface properties of the particles, and nanofluids prepared in this way may contain unacceptable levels of impurities. Most studies to date have been limited to sample sizes less than a few hundred milliliters of nanofluids. This is problematic since larger samples are needed to test many properties of nanofluids and, in particular, to assess their potential for use in new applications [152].

Yet the fact that nano-fluids have more points in favor of them than against, for usage as cooling fluid, has emerged as an undisputed view. This calls for a more intensified effort in the research on nano-fluids. In contrast to the traditional unilateral approach, this research needs to examine closely a variety of issues, such as synthesis, characterization, thermo-physical properties, heat and mass transport, modeling, and device- as well as system-level applications. Hence, a multi-disciplinary approach comprising researchers such as thermal engineers, chemical technologists, material scientists, chemists, and physicists needs to be undertaken. Only such an approach can ensure a "cooler future" with nano-fluids [153].

6. Conclusions

- Based on literatures, it has been found that the improved thermal conductivities of nanofluids are the one of the driving factors for improved performance in different applications. It was found that thermal conductivity of nanofluids with MWCNT can be increased up to 150% [154].
- It has been observed that nanofluids can be considered as a potential candidate for many applications.
- Authors also found that some of the reported articles just reported the improved thermal, rheological, and heat transfer performances without correlating these performances with the specific applications.
- As heat transfer (i.e. conduction, convective, boiling) can be enhanced by nanofluids, heat exchanging devices can be made energy efficient and compact. Reduced or compact shape may results in reduced drag for example in automobile and similar applications.
- It was also found that there are inconsistencies in the reported results published by many researchers. Few researchers reported the inconsistencies between model and experimental results of thermal conductivity of nanofluids.
- Exact mechanism of enhanced heat transfer for nanofluids is still unclear as reported by many researchers.
- However, it should be noted that many challenges need to be identified and overcome for different applications.
- Nanofluids stability and its production cost are major factors that hinder the commercialization of nanofluids. By solving these challenges, it is expected that nanofluids can make substantial impact as coolant in heat exchanging devices.

7. Recommendations for future work

This work focused on the characterization and the convection of various nanofluids, however further research is required for better understanding of nanofluids. The current results imply most of the oxide nanofluids are ineffective as heat transfer liquids and certain CNT nanofluids are effective. A traditional effective medium theory failed to explain the results. More research on the oxide nanofluids may not be needed but there may be some controlling parameter which increases the thermal conductivity we did not recognize.

Future research needs to focus on finding out the main parameters affecting the thermal conductivity of nanofluids. The thermal conductivity of nanofluids can be a function of parameters such as particle shape, particle agglomeration, particle polydispersity, etc. In order to clarify these variables, a number of experiments will be necessary as varying only one parameter among the selected parameters. The possible main parameters are the aspect ratio of the particle and the polydispersity of particles based on the results of CNT nanofluids in this work. We acquired significantly higher thermal conductivity with CNT nanofluids consisting of long, monodisperse tube shapes and no change in the thermal conductivity with CNT nanofluids with short, irregular tube shape. The thermal conductivity of oxide nanofluids may also be affected by the particle shapes. The challenging point is to obtain the desirable nanoparticle product. Currently, the available nanoparticles are limited and their specifications are not accurate. The development of the nanoparticle production technique will be very helpful for the nanofluid research. Finally, a theoretical model needs to be developed which explains the empirical data [78].

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