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Superior thermal features of carbon nanotubes-based nanofluids – A review

S.M. Sohel Murshed *, C.A. Nieto de Castro

Centro de Ciências Moleculares e Materiais, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

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ABSTRACT

Recent progresses in research on several key thermal features and potential applications of carbon nanotubes-laden nanofluids are reviewed and addressed. Besides briefing on the preparation of these nanofluids, available studies on conduction, convection and boiling heat transfers of this specific class of nanofluids are discussed in detail. Effects of different parameters such as concentration of carbon nanotube and temperature on thermal conductivity, convective heat transfer coefficient, and boiling critical heat flux are also demonstrated. It is found that despite inconsistencies among available data and inconclusive heat transfer mechanisms, substantial increase in these thermal features of carbon nanotubes-nanofluids compared to their base fluids remain undisputed. In addition to the work on specific heat and thermal diffusivity, available theoretical models and heat transfer mechanisms of this particular type of nanofluids are presented and discussed. Research on a new class of nanofluids termed as "ionanofluids" is also reported. Review reveals that ionanofluids exhibit superior thermal properties compared to their base ionic liquids and these properties further increase with increasing concentration of carbon nanotube as well as fluid temperature to some extent. Carbon nanotubes based both nanofluids and ionanofluids show great potential as advanced heat transfer fluids in many important applications.
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* Corresponding author. Tel.: +351 217 500 913; fax: +351 217 500 088.
E-mail address: smmurshed@fc.ul.pt (S.M.S. Murshed).

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Nomenclature

c_p	specific heat (J/kg K)
d	diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
q	heat flux (W/m^2)
r	radius (m)
t	thickness of interfacial layer (m)
T	temperature (K or °C)
R_k	Kapitza resistance (K m^2/W)

Greek symbols

ϕ	particle volume fraction
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
ψ	sphericity

Subscripts

f	base fluid
eff	effective
inf	ionanofluid
il	ionic liquid
lr	layer
nf	nanofluid
p	particle

Abbreviations

BHTC	boiling heat transfer coefficient
CHF	critical heat flux
CNT	carbon nanotubes
DIW	deionized water
EG	ethylene glycol
EO	engine oil
MWCNT	multi-wall carbon nanotubes
NF	nanofluids
PAO	poly-alpha-olefin
SO	silicone oil
SWCNT	single wall carbon nanotubes
THWM	transient hot-wire method
W	water

1. Introduction

Carbon nanotubes (CNT) are often known as wonder nanomaterials which have very large aspect ratio and a very broad range of unique thermal, mechanical, chemical, optical and electronic properties. The remarkable and unique properties of carbon nanotubes have placed them right among the hottest topics in multidisciplinary fields, particularly in materials sciences. Thus research on carbon nanotubes has become a hot topic in multidisciplinary fields. Although innovation of CNT is attributed to a Japanese scientist, Iijima in 1991 [1], Endo and co-workers [2] first reported TEM images of CNT in 1976. Iijima [1] demonstrated synthesizing of needle-like nano-sized (diameter ranging between 4 and 30 nm) carbon tubes using arc-discharge evaporation technique. Later in 1993 the growth process of single walled CNT was reported by two research groups, one by Iijima and Ichihashi [3] and the other by Bethune and co-workers [4]. Since its revolutionary discovery in early 1990s carbon nanotubes have attracted immense interest from both the academic and the industrial communities due to their fascinating properties and potential applications in numerous fields such as aerospace, automotive, electronic, optical, and energy conversion [5,6]. These nanotubes can behave like metals or semiconductors and can conduct better electricity and heat compared to copper and diamond, respectively. Thus they can be used in nanoelectronics like diodes and transistors and in supercapacitors as electromechanical actuators and sensors, in lithium-ion batteries, as well as fillers in composite materials such as polymer-based composites [6–8]. The remarkable thermal property of carbon nanotube is their ultra-high thermal conductivity (2000–6000 W/m K) which is order of magnitude higher compared to those of the metallic or oxide nanomaterials such as aluminum (237 W/m K) and aluminum oxide (40 W/m K) that are commonly used in nanofluids as heat transfer enhancer. Thus like carbon nanotube, nanofluids (NF) which are a new class of advanced heat transfer fluids have attracted great interest from researchers worldwide because of their anomalously high thermophysical properties and potentials applications in numerous important fields such as microelectronics, MEMS, microfluidics, transportation, manufacturing, instrumentation, medical, and HVAC systems [9–19]. Even after almost two decades of innovation of these new fluids (i.e., nanofluids) [20] and having extensive research performed thereafter, reported data are still scattered and the underlying mechanisms for anomalous thermal features particularly thermal conductivity of nanofluids are still inconclusive and not well understood [9–12,19]. Researchers are still debating and facing enormous challenges to uncover the true mechanisms behind such anomalously thermal properties of nanofluids.

With such ultrahigh thermal conductivity of carbon nanotubes, their nanofluids exhibit much higher thermal features such as thermal conductivity, heat transfer coefficient and boiling heat flux as compared to their base fluids as well as nanofluids containing other types of nanomaterials [9–13,20–31]. With a very large aspect ratio carbon nanotubes also exhibit excellent dispersion behavior in most of the commonly used solvents. In order to fully utilize these superior thermal characteristics, it is very important to prepare CNT-nanofluids that show long term stability and well-dispersion of CNT. Literature results on the thermal features of CNT-nanofluids reveal their great potentials as advanced heat transfer fluids. There is

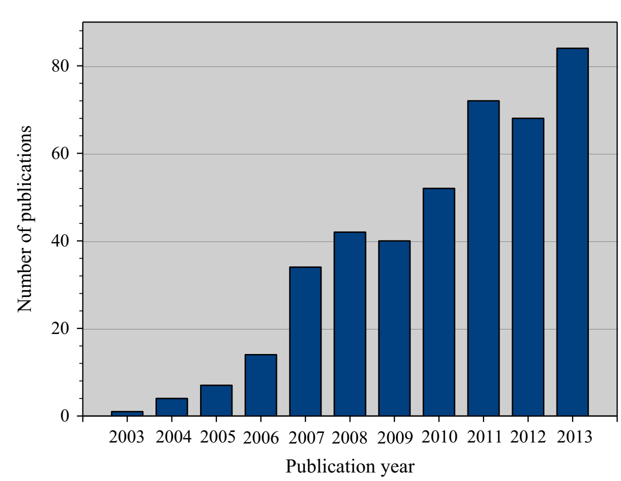

Fig. 1. Year-wise publications on CNT-nanofluids (publications searched by topic "nanofluids" and refined by "carbon nanotubes" in Web of Science on December 20, 2013).

therefore an increasing research interest on conductive, convective and phase change performances of this particular type of nanofluid. This can be evidenced from the reported growth of annual publications on this nanofluid shown in Fig. 1. According to Web of Science searched results, out of total 2964 publications on nanofluids 418 carbon nanotubes-related publications have appeared until December 20, 2013. Note that publications include all types of journals and conference articles, patent, news, letter and others. This publications record reveals that despite the largest enhancement in thermophysical properties and recent growing interest, research activities on CNT-nanofluids are not very promising as compared to other nanofluids containing oxide or metallic nanoparticles. The main reason could be the comparatively higher price of CNT. Nevertheless, while most of the studies dealt with the concentration dependence of thermal conductivity, research efforts on this nanofluid are scattered and findings from different research groups lack consistencies. Given the prospect and potentials of CNT-nanofluids, it is imperative and timely to provide an informative review of available research findings on this special type of nanofluids.

This paper aims to review and address the recent research progress in various thermal features of CNT-nanofluids. Besides discussing the sample preparation and stability, findings from the literature studies on conduction, convection and boiling heat transfer characteristics of this type of nanofluids are thoroughly reviewed and discussed. Effects of various parameters such as concentration of CNT and fluid temperature on these thermal properties and features are demonstrated. In addition, recent research and development on carbon nanotubes-dispersed ionanofluids [32] which are an innovative class of nanofluids are discussed. Being the pioneer in the research and innovation of this new class of fluids (ionanofluids), our group from the forefront is conducting wide range of research on this topic [32–35] and results particularly on thermal conductivity and heat capacity of CNT-ionanofluids mainly from our studies are presented and analyzed.

2. Preparation of CNT and CNT-nanofluids

2.1. Synthesis of CNT

Most CNT production today is used in thin films and as fillers in bulk composite materials. Recently application of CNT in nanofluids as heat transfer enhancer has also increased tremendously. However, like other nanoparticles there are two general approaches for synthesizing and fabrication of carbon nanotubes. These are bottom-up and top-down approaches. Bottom-up approaches begin with atoms or molecules and build up to nanostructures. Since nature creates everything by this approach (self-assembly), it is also known as natural approach. During self-assembly the physical forces operating at nanoscale are used to combine basic units into larger stable structures. On the other hand, top-down approaches use macroscopic initial materials or structures which are miniaturized up to nano-scale structures. This is simply scaling down of a structure from macroscale to nanoscale and typical examples are etching, milling, lithography, and so on. At the moment, the most commonly used top-down approach is photolithography which is known for its application in manufacturing computer chips.

Vapor deposition technique particularly chemical vapor deposition (CVD) is the most widely used method for producing high-volume CNT and it uses fluidized bed reactors systems. The arc discharge method and laser ablation (vaporization) are also commonly used for CNT production nowadays. Techniques used to synthesize CNT are depicted in Fig. 2. Details about CNT synthesis can be found elsewhere [36] and will not be elaborated further.

2.2. Preparation of CNT-nanofluids

A nanofluid does not mean a simple mixture of liquid and nanoparticles. Proper dispersion and stabilization of the CNT in base fluids (BF) are essential in order to prepare CNT-nanofluids. Homogenization of dispersed nanomaterials is commonly performed using ultrasonication which is very effective in breaking the larger clusters into smaller ones. There are two types of techniques commonly used to synthesize nanofluids and they are the one-step method and the two-step method. The two-step method, which is the dispersion of purchased or produced dry CNT in base fluids, is widely used to prepare nanofluids. The one-step method is directly synthesizing CNT in base fluids by applying various chemical or physical methods such as chemical vapor deposition. Fig. 3 depicts flow chart of preparation of CNT-nanofluids. It shows both the one-step and two-step methods of sample nanofluids preparation. Although the one-step method yields better dispersion and stability of nanofluids, it is less popular in preparing nanofluids mainly due to the complexity in

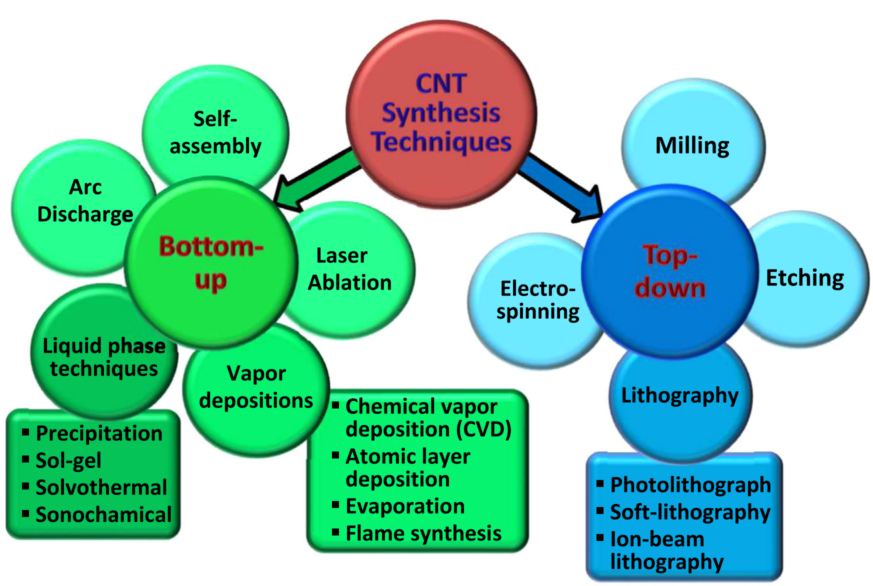

Fig. 2. Techniques used to synthesize CNT.

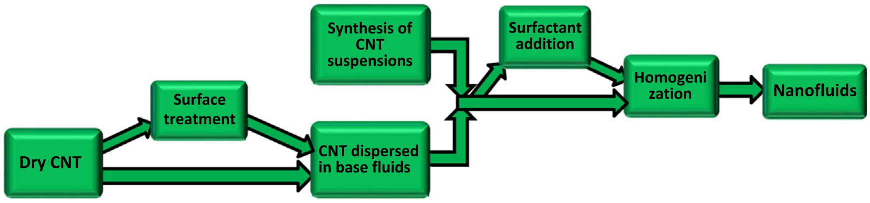

Fig. 3. Flow diagram of CNT-nanofluids preparation processes.

Table 1
Various CNT-nanofluids and their stabilization techniques used in the literature studies.

Carbon nanotubes/ base fluids	Sample preparation techniques	Surfactant/surface treatment	References
MWCNT/EG	Two-step	12-3-12,2Br^{-1} surfactant	[13]
MWCNT/Olefin oil	Two-step	None	[21]
MWCNT/W	Two-step	Surface treatment	[22]
MWCNT/W/EG	Two-step	Surface treatment	[23]
MWCNT/W	Two-step	SDS surfactant	[24]
CNT/W	Two-step	GA surfactant	[25]
MWCNT/W	Two-step	SDS surfactant	[26]
MWCNT/EG/W	Two-step	None	[27,38]
MWCNT/EO	Two-step	NHS surfactant	[27]
SWCNT/EG	Two-step	None	[28]
MWCNT/SO	Two-step	HMDS/ functionalization	[39]
MWCNT/W/EG	Two-step	Functionalization	[40]
MWCNT/W	Two-step	PVP surfactant	[41]
MWCNT/W	One-step	SDS surfactant	[42]
MWCNT/EG	Two-step	SDS surfactant	[43]
MWCNT/W	Two-step	CTAB and Triton X-100	[43]
MWCNT/W + EG	Two-step	Chitosan dispersant	[44]
CNT/R113	One-step	None	[45]
MWCNT/W	Two-step	Plasma-treatment of MWCNT	[46]
MWCNT/W	Two-step	Functionalization/ SDS	[37]

directly synthesizing suspensions of CNT. Nonetheless, most of the studies employed the two-step method to prepare CNT-nanofluids. As mentioned previously, with very large aspect ratio carbon nanotubes usually show excellent dispersion behavior in most of the commonly used conventional heat transfer fluids like water (W), ethylene glycol (EG), decene (DE), silicon oil (SO) and engine oil (EO). Thus, researchers used various types of host fluids-based CNT-nanofluids. While most studies used multiwalled carbon nanotubes (MWCNT) dispersed in water or ethylene glycol, a very few studies used single-walled carbon nanotubes (SWCNT) and other types of base fluids. As proper dispersion of CNT and long term stability of nanofluids are of utmost importance for their optimum properties; most of the studies added surfactants as well as functionalized or surface treated dry CNT in order to obtain desired stability of sample nanofluids. Sometimes functionalization of CNT is found to be more effective for stability of their nanofluids. For example, Nasiri et al. [37] reported that compared to surfactant added CNT-nanofluids the functionalized CNT-nanofluids showed better stability and higher thermal conductivity. The surfactants commonly used in CNT-nanofluids include sodium dodecyl sulfate (SDS), cetyltrimethyl ammonium bromide (CTAB), hexamethyldisiloxane (HMDS), sodium dodecyl benzene sulfonate (SDBS), polyvinyl pyrrolidone (PVP) and gum arabic (GA). In addition, regardless of addition of surfactant and functionalization of CNT, sonication is always employed for breaking the agglomerations of any nanoparticles including CNT dispersed in base fluids. Sonication time can be varied from tens of minutes to several hours depending on the CNT concentration, base fluids, power or frequency setting of the sonicator. Studies showed that through the state of dispersion sonication time also influences the thermal conductivity of any nanofluids [9,10,13]. A summary of preparation of various sample CNT-nanofluids and CNT treatment for better dispersion from the literature is provided in Table 1.

3. Research on CNT-nanofluids

3.1. Thermal and heat transfer characteristics

3.1.1. Thermal conductivity

As mentioned before, CNT-nanofluids exhibit higher thermal conductivity as compared to their base fluids and they further increase with increasing temperature. In addition to different types of CNT-nanofluids, researchers employed different techniques to measure the thermal conductivity of their nanofluids. A summary of room temperature thermal conductivity results on CNT-nanofluids from literature is presented in Table 2 which clearly agrees with the above statement on the enhanced thermal conductivity of these nanofluids. Fig. 4 also demonstrates that regardless of some inconsistencies in literature data, the significant enhancement of thermal conductivity of nanofluids with CNT concentration is obvious. Interestingly, the enhanced thermal conductivity increases even more pronouncedly with the temperature as evidenced from Fig. 5. Such increase in thermal conductivity with temperature makes these nanofluids more attractive for their applications at elevated temperatures.

In addition to summarizing available results (Table 2), some representative experimental investigations on thermal conductivity of CNT-nanofluids are elaborated here.

Yang et al. studied the effect of MWCNT and dispersant concentrations, as well as dispersing energy on thermal conductivity and steady shear viscosity of CNT/poly (α-olefin) oil-based nanofluids [55]. Polyisobutene succinimide (PIBSI) dispersant was also used in their study. The thermal conductivity and viscosity of these nanofluids correlate with each other and vary with the size of large scale agglomerates of nanoparticles as nanofluids with large scale agglomerates have high thermal conductivities. Nonetheless, both the thermal conductivity and viscosity were found to increase substantially with increasing concentration of MWCNT in this oil. The effect of dispersion energy i.e., ultra-sonication power on the thermal conductivity of nanofluids was found to be significant as the thermal conductivity was decreasing almost exponentially with increasing specific dispersing energy.

Following their previous work [24] Assael et al. [50] measured the thermal conductivity of aqueous MWCNT and double-walled CNT (DWCNT) nanofluids and a maximum 34% enhancement of thermal conductivity was observed at 0.6 vol% loading of MWCNT in CTAB surfactant added water.

Using a 3ω-wire method Han et al. [51] measured the thermal conductivity of a new type of nanofluid containing hybrid sphere/CNT nanoparticle in poly-alpha-olefin (PAO) over a temperature range 10–90 °C. At room temperature the effective thermal conductivity of this nanofluid increased 21% for 0.2% loading of their hybrid sphere/CNT. They also found that the enhanced thermal conductivity increased almost linearly with increasing temperature.

Table 2
Summary of thermal conductivity (TC) results of CNT-nanofluids at room temperature from the literature.

Nanofluids	Measurement method	Main findings (maximum enhancement of TC)	References
MWCNT/Oil	THWM	TC increased 160% at 1 vol.% of CNT	[21]
MWCNT/W	THWM	At 1 vol% of CNT, TC increased 7%	[22]
MWCNT/W	THWM	TC increased 12% at 1 vol% of CNT	[23]
MWCNT/EG	THWM	TC increased 17.5% at 1 vol% of CNT	[23]
MWCNT/W+0.1 wt% SDS	THWM	At 0.6 vol% of CNT, TC increased 38%	[24]
MWCNT/W+1 wt% CTAB	THWM	TC increased 34% at 0.6 vol% of CNT	[43]
MWCNT/EG+0.35 wt% SDS	THWM	At 0.6 vol% of CNT, TC increased 21%	[43]
MWCNT/W+Triton X-100	THWM	At 0.6 vol% of CNT, TC increased 13%	[43]
CNT/W+0.25 wt% GA	KD2 Pro	TC increased 25% at 0.5 wt% of CNT	[25]
MWCNT/W+SDS	THWM	TC increased 11.3% at 1 vol% of CNT	[26]
MWCNT/EO+5 vol% NHS	Modified THWM	At 2 vol% of CNT, TC increased 30%	[27,38]
SWCNT/EG	Steady method	At 2.5 vol% of CNT, TC increased 20%	[28]
MWCNT/SO+HMDS	TSHWM	TC increased 19% at 1 vol% of CNT	[39]
MWCNT/EG	THWM	TC increased 12.4% at 1 vol% of CNT	[38]
MWCNT/W/EG	Lambda Instruments (THWM)	At 0.03 vol% of CNT, TC of water and EG increased up to 33% and 40%, respectively	[40]
SWCNT/EG	THWM	TC increased 14.8% at 0.2 vol% of CNT	[47]
MWCNT/W+SDS	THWM	TC increased 7% at 1 vol% of CNT	[48]
SWCNT/EG/PAO	Transient planar source technique	At 1.1 vol% of CNT, TC of EG and PAO increased 35% and 12%, respectively	[49]
MWCNT/W+CTAB	THWM	TC increase 34% at 0.6 vol% of CNT	[50]
Hybrid sphere/CNT/PAO	3ω-wire (THWM)	TC increased 21% at 0.2 vol% of hybrid sphere/CNT particles	[51]
MWCNT/W+GA	Steady state	At 3 wt% of CNT, TC increased 64%	[52]
Ag-MWCNT/W	KD2 Pro	At 0.03 vol% of CNT, TC increased 37.3%	[53]
CNT/R113	Thermal constants analyzer	At 1 vol% of CNT, TC increased 104%	[45]
MWCNT/W	THWM	TC increased 25% at 0.01 vol% of CNT	[46]

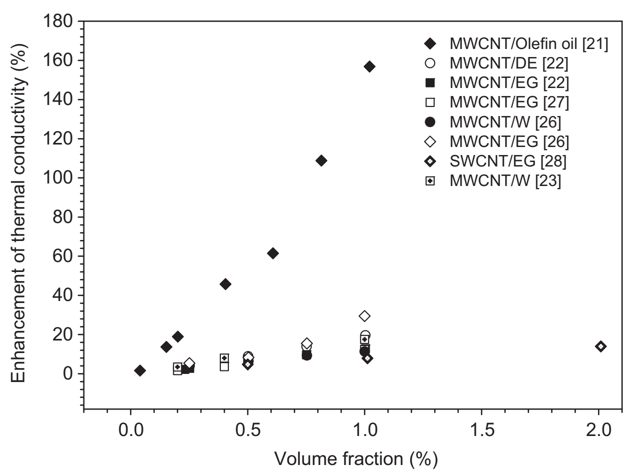

Fig. 4. Effect of CNT concentration on the enhancement of thermal conductivity of nanofluids.

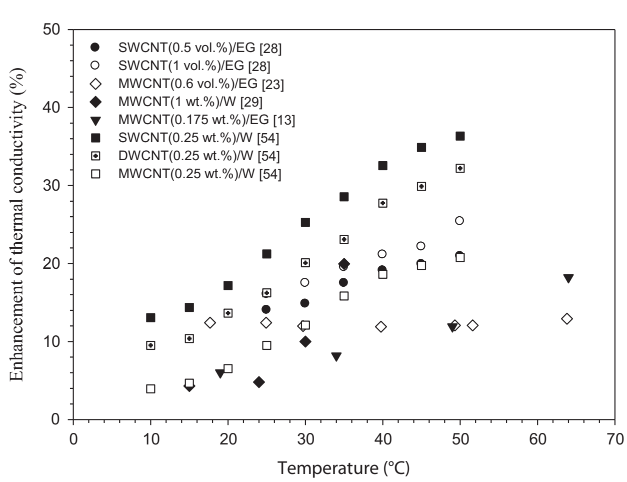

Fig. 5. Enhancement of thermal conductivity of CNT-nanofluids as a function of temperature.

Jana et al. [56] experimentally determined the thermal conductivity of one CNT/w nanofluid and two hybrid CNT nanofluids which are Au and Cu nanoparticles mixed with CNT in water. Their results showed a nonlinear dependence of thermal conductivity of these nanofluids with volume fraction and a maximum increase in thermal conductivity was 34% at CNT volumetric loading of 0.8%. However, no obvious enhancement of thermal conductivity of these nanofluids was found due to addition of CNT to Au and Cu nanoparticles.

Using a thermal constants analyzer which is a transient plane source method Jiang et al. [45] measured the thermal conductivity of nanofluids containing CNT of various aspect ratios and concentrations in refrigerant R113. They found that at 1 vol% of CNT the maximum enhancement of thermal conductivity of refrigerant was 104%. Results of their study also revealed that the aspect ratio and diameter of CNT significantly influence the thermal conductivity of CNT-nanofluids.

Using a short hot-wire method (TSHWM) Chen et al. measured the thermal conductivity of treated multiwalled carbon nanotubes (TCNT) dispersed in ethylene glycol and they observed up to 17.5% enhancement of thermal conductivity of this nanofluid at TCNT volume fraction of 0.01 [23]. In order for better dispersion, their nanotubes were treated by using the mechanochemical reaction method. They however did not observe any obvious effects of temperature on thermal conductivity enhancement. Same group later used silicone oil as base fluid and reported thermal conductivity and viscosity of SO-based nanofluid containing the same TCNT [39]. They reported substantial increase in thermal conductivity of this nanofluid which further increased with increasing TCNT loading as well as temperature. Employing a THWM-based Lambda instrument the thermal conductivity of nanofluids having oxidized MWCNT dispersed in two base fluids (DIW and EG) was measured by Aravind et al. [40]. At a volume fraction of 0.03% the maximum thermal conductivity enhancements for MWCNT/DI water and MWCNT/EG were found to be 33% and 40%, respectively. The enhanced thermal conductivity of these nanofluids was further increased with increasing temperature.

In another study, Amrollahi et al. [28] investigated the effects of temperature, volume fraction, and vibration time on the thermo-physical properties of a SWCNT/EG nanofluid. For 2.5 vol

% concentration of SWCNT the thermal conductivity of ethylene glycol was observed to increase up to 20%. They also reported a strong influence of temperature on the enhanced thermal conductivity of this nanofluid.

Nasiri et al. [54] investigated the effect of CNT structures on thermal conductivity and stability of nanofluids. They used several different structures, single-wall, double-wall (DWCNT), few-wall (FWCNT) and two different multiwall carbon nanotubes in water. Their results showed that both the stability and thermal conductivity of nanofluids decrease with increasing the number of walls of the carbon nanotube. However, all these CNT nanofluids exhibited enhanced thermal conductivity which further increases with increasing temperature. Same group previously reported another work [37], where they studied the effect of the dispersion method on thermal conductivity and stability of nanofluids containing five different CNT structures. Their results showed that the effective thermal conductivity of these nanofluids increases with temperature over a temperature range of 10–50 °C and the best stability and thermal conductivity were associated with the functionalized CNT dispersed nanofluids.

Thermal conductivity, viscosity, and stability of MWCNT-nanofluids were studied by Phuoc et al. [57]. Chitosan dispersant of different concentrations was used for better stability of nanofluids. The thermal conductivity of water increased up to 13% for 3 wt% loading of MWCNT and the Maxell model under-predicted the enhanced thermal conductivity. Surprisingly they also demonstrated that MWCNT can be used either to enhance or reduce the viscosity of base fluid and up to 20% reduction of viscosity was reported.

Many studies also reported significant enhancement of thermal conductivity of CNT-nanofluids with increasing loading of CNT and temperature [46,48,49,53,58–60].

Very recently Gu et al. [61] measured thermal conductivity of three different nanofluids including CNT-nanofluids and showed that nanofluids containing higher aspect ratio fillers exhibit larger thermal conductivity enhancement. When the volume fraction is 0.2%, the CNT-nanofluids showed only 3.7% enhancement of thermal conductivity. This enhancement was much smaller as compared to Ag-nanofluids also used in their study. Their results demonstrated that the particle shape has a substantial effect on the effective thermal conductivity of suspension.

Despite inconsistent data and controversy regarding the heat transfer mechanisms of nanofluids, the reported thermal conductivity enhancements justify their applications as advanced heat transfer and thermal storage fluids.

3.1.2. *Convective heat transfer characteristics*

In the past decade, extensive research work has been conducted on the convective heat transfer performance of nanofluids [9–11]. However, in spite of having ultra-high thermal conductivity and good dispersion behavior of CNT, very limited investigations have been made on convective heat transfer of CNT-nanofluids.

Ding et al. [25] were the first to investigate the heat transfer performance in laminar flow of aqueous CNT nanofluids through a horizontal tube. A significant enhancement of the convective heat transfer in comparison with water was reported in their study. For example, at CNT mass fraction of 0.5% and Reynolds number of 800 an intriguingly high 350% enhancement of heat transfer coefficient (h) was observed. The first convective heat transfer experiment with aqueous CNT-nanofluid in a microchannel with hydraulic diameter of 355 μm at Reynolds numbers between 2 and 17 was conducted by Faulkner et al. [62]. They found considerable enhancement in heat transfer coefficient of this nanofluid at CNT concentration of 4.4%. From a different study Garg et al. [29] showed that heat transfer performance of GA dispersant added MWCNT/water nanofluid increased until an optimum ultrasonication time was reached and decreased on further ultrasonication. However, the maximum enhancement of convective heat transfer was found to be 32%. Amrollahi et al. [63] studied convective heat transfer of aqueous MWCNT-nanofluids under laminar and turbulent flow conditions and reported up to 40% increase in heat transfer coefficient at MWCNT concentration of 0.25 wt%.

Another investigation on convection heat transfer of aqueous CNT nanofluid flowing through a horizontal copper tube under constant heat flux and laminar flow conditions was performed by Rashidi and Nezamabad [64]. A significant enhancement in heat transfer coefficient which further increased with increasing concentration of CNT and Reynolds number was reported. The enhancement was found particularly significant at entrance region and decreases with axial distance from the inlet.

Maré et al. [65] investigated the thermal performances of two aqueous alumina and CNT dispersed nanofluids in two plate heat exchangers. Comparing between heat transfer enhancements and pumping power loss nanofluids containing carbon nanotubes showed better thermal-hydraulic performance than the base fluid.

Lotfi et al. [66] experimentally studied the heat transfer enhancement of MWCNT/water nanofluid in a horizontal shell and tube heat exchanger. Carbon nanotubes used in their study were synthesized by the catalytic chemical vapor deposition (CCVD) method over Co–Mo/MgO nanocatalyst. Results showed that the presence of multi-walled nanotubes enhances the heat transfer rate in a shell and tube heat exchanger.

In an experimental investigation with functionalized CNT (f-MWCNT)-nanofluids Aravind et al. [40] found almost the same trend of the heat transfer coefficient profiles for EG/f-MWCNT and DIW/f-MWCNT nanofluids used in their study. For a volume concentration of 0.03% and flow rate of 56 mL/s, the maximum enhancements of heat transfer coefficient of MWCNT/DIW and MWCNT/EG-based nanofluids were respectively 65% and 180%. These enhancements of heat transfer coefficient were several times larger than their thermal conductivity enhancements.

Convective heat transfer characteristics of water and ethylene glycol-based MWCNT nanofluids in an intertube falling-film flow system were studied by Ruan and Jacobi [67]. They reported that while the heat transfer coefficient of water-based nanofluids first decreases and then increases with increasing concentration of CNT, the heat transfer coefficient of ethylene glycol-based nanofluids only decreases with increasing CNT concentration. They also introduced a model for the prediction of heat transfer enhancement of the nanofluids for their flow systems.

Very recently Kumaresana et al. [68] performed experiments on convective heat transfer characteristics of water/EG mixture (70/30 by volume)-based MWCNT nanofluid in a tubular heat exchanger. The convective heat transfer coefficient of this nanofluid was found to increase to a maximum of 160% at 0.45 vol% MWCNT. They ascribed several factors such as nanotube rearrangement and high aspect ratio as well as delay in boundary layer development for the observed heat transfer enhancement of their nanofluid.

Although limited studies have been conducted to develop model for the anomalously high thermal conductivity of CNT-nanofluids [9,10], almost no rigorous work has been performed to understand and identify the real mechanisms for the observed significant enhancement of convective heat transfer of these specific nanofluids [11].

3.2. *Mechanisms and models for thermal conductivity of CNT-nanofluids*

At the early stage of nanofluids research, several heat transfer mechanisms for nanofluids were proposed and analyzed by

Wang et al. [69] and Keblinski et al. [70]. These mechanisms include nanoparticles Brownian motion, interfacial nanolayer at the nanoparticle/fluid interface, nature of heat transport in the nanoparticle, and nanoparticle clustering. However, these mechanisms were mainly proposed for the observed anomalously high thermal conductivity of nanofluids containing spherical shape nanoparticles. Later it was found that the contributions of some of these factors particularly Brownian motion and nature of heat transport in nanoparticle to the enhanced thermal conductivity of nanofluids are not significant. Although interfacial nanolayer and nanoparticles clustering are recently considered as key factors for the thermal conductivity of nanofluids, there still remain controversies about their actual heat transfer mechanisms. Nevertheless, due to different dominant mechanisms, theoretical models for nanofluids containing spherical nanoparticles and cylindrical nanoparticles (nano-rod or tube) are different. With large aspect ratio and complex morphologies of CNT, heat transfer mechanisms for CNT-nanofluids are far more complicated. Compared to theoretical efforts for nanofluids containing spherical nanoparticle very limited research work has been devoted to identify the heat transfer mechanisms and to develop model for the anomalously high thermal conductivity of CNT-nanofluids [9,10]. Thus, heat transfer mechanisms for the anomalous thermal conductivity of nanorods or CNT-nanofluids are not yet well-understood and conclusive.

Even though most literatures showed that the classical effective medium theory-based models are unable to predict the thermal conductivity of nanofluids, the well-known classical model of Hamilton and Crosser [71] which was developed by modifying Maxwell's model [72] is commonly used for the prediction of the effective thermal conductivity of nanofluids having cylindrical nanoparticles including CNT-nanofluids. The Hamilton and Crosser model [71] considers the thermal conductivities of both solid and liquid phases, volume fraction, and the shape of the dispersed particles. This model shows that increase in thermal conductivity for non-spherical particles is higher compared to the spherical particles.

Some of the representative existing models used to predict the thermal conductivity of nanofluids containing nanorods or nanotubes are elaborated here. Taking a part of their previous model [73] for spherical nanoparticles, Patel et al. [74] later reported a simple model for thermal conductivity of carbon nanotube nanofluids. Strauss and Pober developed geometric models which considered periodic lattices with equal surface-to-surface distances between the nanotubes and their nearest neighbors in all directions [75]. A combination of series model in the direction of the thermal gradient and a parallel model perpendicular to it is used along with averaging over all orientations to derive an effective bulk thermal conductivity model.

The model developed by the lead author [17] for the effective thermal conductivity cylindrical nanoparticles-laden nanofluids takes into account the effects of particle size, concentration, and interfacial nanolayer. Unlike the two-phase system as used in the Hamilton and Crosser model [71], this model was developed considering nanofluids as combination of three phases which are nanoparticle, interfacial layer and base fluid.

Sastry et al. [76] presented a different modeling approach which was based on 3-D CNT chain formation in the base fluid and a thermal resistance network. They used probability density functions for random CNT orientation and CNT–CNT contact determination. Several parameters of this model are to be obtained by random number generators.

Recently Walvekar et al. [77] proposed a simple thermal conductivity model for CNT-based nanofluids. This model has been derived from Kumar et al.'s [73] model, which is valid for only spherical particles. However, the main drawback of this model is that it assumed the liquid medium as particles which are surrounded by other nanoparticles.

A detailed summary of classical and recently developed models used to predict the effective thermal conductivity of nanofluids containing cylindrical nanoparticles (nanorods) and nanotubes (CNT) is presented in Table 3. Models reported in Table 3 have their limitations and are unable to accurately predict the thermal conductivity of CNT-nanofluids. Except those classical models most of the recent models are validated using very limited data which are mainly from own experiments. These models also contain unknown parameters which are either used to fit the experimental data or cannot be obtained directly. Thus these models are not widely accepted. There is therefore an urgent need to identify the real heat transfer mechanisms and to develop model for the prediction of the enhanced thermal conductivity of CNT-nanofluids.

3.3. Boiling heat transfer

Boiling is a very efficient mode of heat transfer in various energy conversion and heat exchange systems. In order for practical applications of nanofluids particularly CNT-nanofluids it is important to perform rigorous investigation on their boiling heat transfer performance. In boiling heat transfer CNT-nanofluids showed high critical heat flux (CHF) and caused no fouling on the heat transfer surface. Due to significant enhancement in boiling heat transfer performance, there is a growing interest on boiling particularly pool boiling investigations of nanofluids. However, most of the boiling heat transfer studies used oxide or metallic nanoparticles-laden nanofluids and very few investigations dealt with boiling of CNT nanofluids [11,13].

Park and Jung [30] studied nucleate boiling of R22/CNT and water/CNT nanofluids and reported a maximum 28.7% enhancement of boiling heat transfer coefficients (BHTC) at 1 vol% of CNT. For aqueous CNT nanofluids the same group [41] later showed that the BHTC of the aqueous solutions with CNTs are lower than those of pure water in the entire nucleate boiling regime. However, the critical heat flux of water was increased up to 200% for very low CNT concentration of 0.001%.

In a pool boiling heat transfer study using surface treated SWCNT/deionized water-based nanofluids in the Ni–Cr wire heater system the lead author [87] previously reported that the maximum enhancements of critical heat flux and burnout heat flux (BHF) can respectively reach as high as 492% and 265% at a SDBS surfactant to SWCNT concentration ratio of 1:5. Besides deposition of nanotubes on heater surface, surface tension of nanofluids was also attributed for such astounding increase in boiling heat fluxes.

Liu et al. [31] performed an experimental study on pool boiling heat transfer of water/CNT nanofluid on a flat copper surface under atmospheric and sub-atmospheric pressures. They demonstrated that the pressure has great impacts on both the BHTC and the CHF enhancements and both increase significantly with decreasing the pressure. For instance, at CNT mass fraction of 2.0%, the BHTC and the CHF were enhanced by about 60% and 63%, respectively at atmospheric pressure. Whereas at a sub-atmospheric pressure of 7.4 kPa, the enhancements of BHTC and the CHF were respectively about 130% and 200% as compared to those of water.

Kathiravan et al. [42] studied nucleate pool boiling heat transfer of MWCNT/water nanofluids over a stainless steel flat plate heater. The MWCNT were produced using the DC arc discharge graphite evaporation technique and SDS surfactant was used to assess its effect on boiling performance. The maximum enhancement of BHTC of surfactant free nanofluid containing 1 vol% of MWCNT was 200%. The addition of SDS surfactant decreases the enhancement of BHTC as at 0.5 vol% the maximum increase in BHTC was about 70% while for same concentration of MWCNT and without any surfactant BHTC

Table 3
Summary of existing models for the effective thermal conductivity of nanofluids having nanotubes or cylindrical nanoparticles.

Researchers	Models	Remarks
Maxwell [72]	$k_{eff}/k_f = \left[\frac{k_p(1+2\phi)+2k_f(1-\phi)}{k_p(1-\phi)+k_f(2+\phi)}\right]$	The effective thermal conductivity of this popular model depends on thermal conductivities of both phases and volume fraction of solid. Non-interacting and uniform size particles of homogenous dispersion.
Hamilton and Crosser (H–C) [71]	$k_{eff}/k_f = \left[\frac{k_p(1+5\phi)+5k_f(1-\phi)}{k_p(1-\phi)+k_f(5+\phi)}\right]$	This form is for cylindrical particles and it used shape factor $n=6$ for cylindrical particle in original expression.
Nan et al. [78]	$k_{eff}/k_f = \frac{3+\phi k_p/k_f}{3-2\phi}$	This model is for carbon nanotube-based composites when k_p (p=CNT) is much larger than k_f.
Xue [79]	$9(1-\phi_c)\frac{k_{eff}-k_f}{2k_{eff}+k_f}+\phi_c\left[\frac{k_{eff}-k_{c,x}}{k_{eff}+B_{2,x}(k_{c,x}-k_{eff})}+4\frac{k_{eff}-k_{c,y}}{2k_{eff}+(1-B_{2,x})(k_{c,y}-k_{eff})}\right]=0$	Maxwell theory [72] and the average polarization theory with the interfacial shell effect were the base of this model where ϕ_c is the volume fraction of complex nanoparticles.
Xue [80]	$k_{eff} = k_f\left[\frac{1-\phi+2\phi((k_p)/(k_p-k_f))\ln((k_p+k_f)/2k_f)}{1-\phi+2\phi((k_f)/(k_p-k_f))\ln((k_p+k_f)/2k_f)}\right]$	This model is developed based on the Maxwell model [72] for thermal conductivity of CNT-nanofluids and it included the effect of axial ratio and space distribution of CNT.
Xue [81]	$9(1-\phi)\frac{k_{eff}-k_f}{2k_{eff}+k_f}+\phi\left[\frac{k_{eff}-k_{33}^c}{k_{eff}+0.14\frac{d}{L}(k_{33}^c-k_{eff})}+4\frac{k_{eff}-k_{11}^c}{2k_{eff}+0.5(k_{11}^c-k_{eff})}\right]=0$ where $k_{11}^c=\frac{k_p}{1+(2R_K k_p/d)}$ and $k_{33}^c=\frac{k_p}{1+(2R_K k_p/L)}$	This model took into account the effect of interfacial resistance and was derived from his previous model [79]. Here k_{11}^c and k_{33}^c are the transverse and longitudinal equivalent thermal conductivities of the composite unit cell of a nanotube with length L and diameter d respectively.
Yu and Choi [82]	$k_{eff}/k_f = 1+\frac{n\phi_{eff}A}{1-\phi_{eff}A}$, where $A=\frac{1}{3}\sum_{j=a,b,c}\frac{k_{pj}-k_f}{k_{pj}+(n-1)k_f}$	This model considered interfacial layer and renovated Hamilton and Crosser model [71]. It introduced shape factor $n=3\psi^{-\alpha}$.
Strauss and Pober [75]	Parallel model: $k_{eff}/k_f = 1+\frac{\phi_{ep}\{[1-(k_f/k_{n-a})]-(2R_k k_f/\alpha d_n)\}}{\{(k_f/k_{n-a})+(1/\phi_{nep})-[1+(2R_k k_f/\alpha d_n)]\}}$ Perpendicular model: $k_{eff}/k_f = 1+\frac{\phi_{ep}\{[1-(k_f/k_{n-r})]-(8R_k k_f/\pi d_n)\}}{\{(k_f/k_{n-r})+(1/\phi_{nep})-[1+(8R_k k_f/\pi d_n)]\}}$	Series of models parallel and perpendicular to the direction of thermal gradient were developed. Here $k_{n\text{-}a}$ and $k_{n\text{-}r}$ are the axial and radial thermal conductivities of nanotubes, respectively and ϕ_{ep} is the volume fraction of the effective particles and ϕ_{nep} is the volume fraction of nanotube in the effective particles.
Kumar et al.[73]	$k_{eff}/k_f = 1+c\frac{2K_BT}{\pi\eta d_p^2}\frac{\phi r_f}{k_f(1-\phi)r_p}$	This model was derived based on kinetic theory and Fourier's law.
Patel et al. [74]	$k_{eff}/k_f = 1+\frac{k_p\phi r_f}{k_f(1-\phi)r_p}$	Ignoring the kinetic contribution in their previous model [73] it is particularly developed for CNT-nanofluids.
Sastry et al.[76]	$k_{eff}=\frac{L_{cell}}{R_{net}A_{cell}}$ where $R_{net}=\sum_{i=1}^{N}\frac{((R_{CNTi,p}+2R_c)/M)\times R_{Fi.p}}{((R_{CNTi,p}+2R_c)/M)+R_{Fi.p}}$ and $L_{cell}=\sum_{i=1}^{N}L_{i,p}\sin\varnothing_i\ \cos\ \theta_i$	This model is based on 3-D CNT chain formation in the base fluid and a thermal resistance network. They used probability density functions for random CNT orientation and CNT–CNT contact determination. Several parameters of this model are to be obtained by random number generators. Here Ø and θ are the orientation angles of each CNT.
Clancy and Gates [83]	$k_{eff}/k_f=\frac{3+\phi(\beta_x+\beta_z)}{2-\phi\beta_x}$ where $\beta_x=\frac{2(k_{11}^c-k_f)}{k_{11}^c-k_f}$ and $\beta_z=k_{33}^c/k_f-1$	This model was derived for SWCNT and considered the effect of interfacial thermal resistance which was determined using molecular dynamic simulations. They used polymer matrix as base medium.
Gao et al. [84]	$9(1-\phi)\frac{k_{eff}-k_f}{2k_{eff}+k_f}+\phi\left[\frac{k_{eff}-k_{c,x}}{k_{eff}+L_x(k_{c,x}-k_{eff})}+4\frac{k_{eff}-k_{c,y}}{2k_{eff}+(1-L_x)(k_{c,y}-k_{eff})}\right]=0$	This model is basically the same as Xue model [79] developed for CNT-nanofluids.
Sabbaghzadeh and Ebrahimi [85]	$k_{eff}=k_f\left[1-\phi(1+M')\right]+\phi(k_p+k_{lr}M')+\phi(1+M')\frac{d_f}{\mathrm{Pr}D}(0.35+0.56\mathrm{Re}_f^{0.52})\mathrm{Pr}_f^{0.3}k_f$ where $M'=\left[\left(\frac{t}{r_p}+1\right)^2-1\right]$, d_f is the diameter of base fluid molecule, t is nanolayer thickness, and D is the diameter of complex nanoparticle.	This model took into account four possible heat transfer modes (base fluids, nanparticle, nanolayer and micro-convection) for carbon nanotubes suspensions. The idea of this model was followed from a previous similar work by Jang and Choi [86].
Murshed et al. [17]	$k_{eff}=\frac{(k_p-k_{lr})\phi_p k_{lr}[\gamma_1{}^2-\gamma^2+1]+(k_p+k_{lr})\gamma_1{}^2[\phi_p\gamma^2(k_{lr}-k_f)+k_f]}{\gamma_1{}^2(k_p+k_{lr})-(k_p-k_{lr})\phi_p[\gamma_1{}^2+\gamma^2-1]}$ where $\gamma=1+\frac{t}{r_p}$ and $\gamma_1=1+\frac{t}{d_p}$.	Effects of particle size, concentration, and interfacial layer were considered in this model which is developed based on three phases (nanoparticle, nanolayer and base fluid) concept.
Walvekar et al. [77]	$k_{eff}=k_f\left[1+\frac{k_p((2\phi(r_p+l_p)/r_pl_p)}{k_f((3(1-\phi)/r_f)}\right]+\frac{C\phi(T-T_0)}{r_p^2l_p^2\mu_f}\ln\left(\frac{l_p}{d_p}\right)$	This model was derived from Kumar et al.'s [73] model and it assumed the liquid as particles which are surrounded by other nanoparticles. Here constants $C=2\times10^{-27}$ and $T_0=273$ K.

was increased up to 160%. They also reported a decrease in critical heat flux with increasing concentration of MWCNT and surfactant added nanofluids showed lower critical heat flux in comparison to pure water as well as surfactant free nanofluid. Literature results of enhancement and decrease of boiling heat transfer coefficient of CNT-nanofluids as a function of heat flux are presented in Fig. 6. It can be seen that with increasing concentration of CNT, BHTC of base fluid increases. However, addition of surfactant to nanofluids showed negative effect as it decreases the BHTC of nanofluids. Interestingly, at low pressure the BHTC of CNT nanofluids is significantly higher as compared to the same nanofluid at higher pressure.

A summary of available studies on boiling heat transfer of CNT-nanofluids is also presented in Table 4 which clearly shows that these nanofluids exhibit substantially higher boiling heat transfer characteristics compared to their base fluids.

3.4. Specific heat and thermal diffusivity

Specific heat capacity is very important in determining other heat transfer properties, heat transfer rates under flow conditions, evaluating heat storage capacity of thermal management systems as well as enthalpy calculations in various processes. However, only a couple of studies were performed for investigating specific heat of CNT-nanofluids. Using ethylene glycol-based SWCNT nanofluids Amrollahi et al. [28] demonstrated that the volumetric heat capacity of ethylene glycol increased with volume fraction of SWCNT and with temperature as well. Liu et al. [38] measured the specific heat of MWNT/water nanofluid using differential scanning calorimetry (DSC) and found that due to addition of 0.1 vol% of MWNT the specific heat of city water at 20 °C increased slightly.

In investigating the heat dissipation performance of MWCNT nanofluids in a motorcycle radiator, Teng and Yu [44] have recently measured temperature (80–95 °C) and concentration dependence of specific heat of their CNT-nanocoolants. The cationic chitosan dispersant was also added into the base fluid which was a mixture (1:1 volumetric ratio) of water and EG. Their results showed that while the specific heat of nanofluids increased with temperature, it however decreased gradually with increasing MWCNT concentration. Results also revealed that adding dispersant to nanofluid increased the specific heat. Such results trends were believed to be because both the dispersant and MWCNT have respectively higher and lower values of specific heat compared to that of base fluid (W/EG). Although enhanced specific heat was reported for all these CNT-nanofluids, no solid conclusions can be made based on these results and thus more studies on this important feature are of great importance.

Wu et al. [88] measured the thermal diffusivity of MWCNT-high-density polyethylene (HDPE) composites. The thermal diffusivity of the composites found to increase with increasing MWCNT loading and a maximum three folds increase in thermal diffusivity was observed at 38% volumetric loading of MWCNT in HDPE. They also reported that the thermal diffusivity decreases substantially (non-linearly) with increasing temperature. Based on effective medium approach for thermal conductivity [78], a model was also introduced for the prediction of thermal diffusivity of MWCNT/HDPE nanofluids. No other work on specific heat and thermal diffusivity of CNT-nanofluids can be found in the literature. Thus it is imperative to conduct more investigation on these important properties of this particular type of nanofluids.

4. Research on CNT-ionanofluids

4.1. Ionanofluids

In 2003, Fukushima and co-workers [89] discovered that carbon nanotubes and room-temperature ionic liquids can be blended to form gels termed as "bucky gels of ionic liquids" which can potentially be used in many engineering or chemical processing applications like making novel electronic devices, coating materials, and antistatic materials [89,90]. However, the concept of ionanofluids (INF), which has recently been devised by our group [32], is defined as the dispersion of nanoparticles in ionic liquids (IL). The CNT blended "bucky gels" of ionic liquids prepared by Fukushima et al. [89] were in fact CNT-laden ionanofluids. This novel type of nanofluids also found to exhibit high thermal conductivity, high heat capacity, non-volatile, designable, and green solvent characteristics. Thus ionanofluids can be used as advanced heat transfer fluids in numerous cooling technologies, heat exchangers, chemical engineering and green energy-based applications [19,33]. Other attractive features of ionanofluids are that they are designable and fine-tunable through their base ionic liquids for desired properties and tasks. These fluids can also be used for the development of new pigments for solar energy-based applications [91].

4.2. Thermophysical properties of CNT-ionanofluids

Since ionanofluid is a recently innovated topic, except the work from our group only a couple of studies from other researchers have been conducted on this new fluids. Results from our research showed that ionanofluids containing MWCNT exhibit enhanced thermal conductivity and specific heat capacity compared to their base ionic liquids [32–35]. These properties further increase with concentration of nanoparticles and fluid temperature to some extent.

Very recently, our group measured the thermal conductivities of ionanofluids containing different mass concentrations of MWCNT in $[C_4mim][(CF_3SO_2)_2N]$ and $[C_2mim][EtSO_4]$ ionic liquids at temperature between 20 and 70 °C and at pressure of 0.1 MPa [35]. The effective thermal conductivity of these two MWCNT-ionanofluids (k_{inf}) increases considerably over base ionic

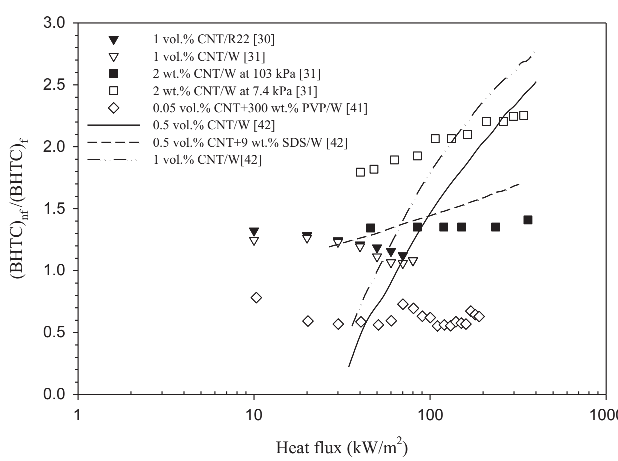

Fig. 6. Boiling heat transfer coefficients of CNT-nanofluids with respect to heat flux.

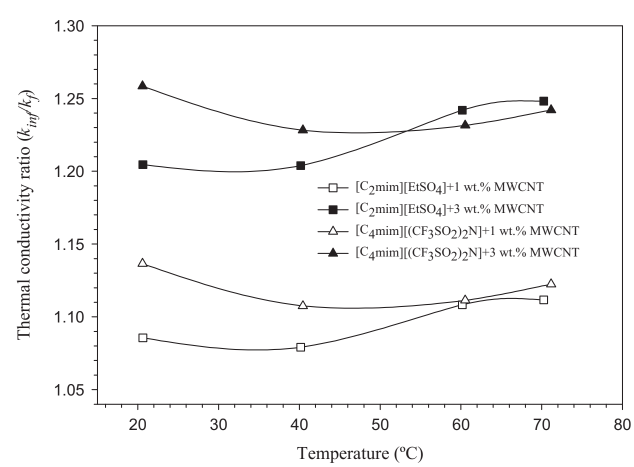

Fig. 7. Temperature and MWCNT concentration dependence of thermal conductivity of two ionanofluids [35].

Table 4
Summary of boiling heat transfer studies of CNT-nanofluids from literature.

Nanofluids	Heat geometry	Main findings	References
MWCNT/R22/W	Cartridge heater	BHTC increased up to 28.7% at 1 vol%	[30]
MWCNT/W	Flat copper heater	BHTC decreased but CHF increased 200%	[41]
SWCNT/W	Ni–Cr wire	CHF increased 492%, BHF increased 265%	[87]
CNT/W	Flat copper heater	At 2 mass%, BHTC and CHF increased 130% and 200%, respectively	[31]
MWCNT/W	Stainless steel flat plate heater	At 1 vol%, maximum increase in BHTC was 200%	[42]

Table 5
Enhancement of thermal conductivity of CNT (1 wt%)-ionanofluids at room temperature.

CNT-ionanofluids	k_{il} (W/m K)	k_{inf} (W/m K)	k_{inf} increase (%)
$[C_4mim][NTf_2]+MWCNT$	0.121	0.164	35.5
$[C_4mim][CF_3SO_3]+MWCNT$	0.142	0.155	9.4
$[C_6mim][NTf_2]+MWCNT$	0.122	0.130	6.8
$[C_8mim][NTf_2]+MWCNT$	0.121	0.129	6.6
$[C_4mim][BF_4]+MWCNT$	0.163	0.173	6.1

liquids (k_f) with MWCNT concentration as shown in Fig. 7. It can be seen that $[C_4mim][(CF_3SO_2)_2N]$-based ionanofluids exhibit larger enhancement of thermal conductivity as compared to other ionanofluids. The results (Fig. 7) surprisingly showed a mixed trend of slight decrease and increase of thermal conductivity of both nanofluids at moderate temperature (20–50 °C) and higher temperature (50–70 °C), respectively. Nevertheless, the effect of temperature on the thermal conductivity of these ionanofluids was not very significant.

The thermal conductivity data of several MWCNT-ionanofluids from our previous work [34] are presented in Table 5. Except for $[C_4mim][NTf_2]$-based ionanofluid, all other ionanofluids showed small increase in thermal conductivity at 1 wt% of MWCNT. This indicates that not all ionic liquids can yield high thermal conductivity when CNT or any other nanoparticles are dispersed into them. Very recently a more comprehensive study on thermal conductivity of MWCNT/imidazolium cation-based ionanofluids was reported and results showed higher thermal conductivity of this ionanofluids compared to base ionic liquid. The increase in thermal conductivity of ionanofluids was attributed to the interactions between the ionic liquid and the MWCNT resulting change in the structure of the liquid phase. In an effort to interpret the results, existing classical and recent models developed for nanofluids were also used [92]. However, none of these models were able to predict the low enhancement (less than 10% for 7.3 vol%) of thermal conductivity of these ionanofluids. Thus there is a need to develop new model that can explain the mechanisms and can predict the thermal conductivity of CNT-ionanofluids.

In our previous study, the specific heat capacity of MWCNT/$[C_4mim][PF_6]$/-ionanofluid was found to increase considerably over base fluid with increasing temperature in the range of 60–90 °C [34]. Regardless of MWCNT loading there was a dome-shaped jump of the specific heat capacity at temperature range of 60–110 °C. Three distinct temperature ranges were observed where heat capacity of this ionanofluid behaved very differently and the reason for such behavior is not fully understood. There was also little enhancement in specific heat capacity of ionanofluids with increasing loading of MWCNT [34]. Nonetheless, any increase in heat capacity of such suspensions or fluids is of great importance for their practical applications as heat transfer fluids.

Very recently Ferreira et al. [93] measured thermal and transport properties of few ionic liquids and ionanofluids containing MWCNT in ionic liquids. Effects of temperature and MWCNT concentration on the effective thermal conductivity, viscosity, and heat capacity of these fluids were investigated. Their results demonstrated that thermal conductivity of $[(C_6)_3PC_{14}][Phosph]$ and $[(C_6)_3PC_{14}][NTf_2]$-based MWCNT ionanofluids increase slightly and decrease linearly with increasing MWCNT concentration and temperature, respectively. Rheological data showed non-Newtonian shear thinning behavior of their ionic liquids as well as ionanofluids. Interestingly the viscosity of ionanofluids was found significantly lower as compared to the base ionic liquid. For example, due to addition of only 0.1 wt% of MWCNT the viscosity of $[(C_6)_3PC_{14}][Phosph]$ decreased about 82%. The reason for such large decrease in viscosity was not well understood. On the other hand the heat capacity of ionic liquids increased up to a maximum 13% for the addition of 0.2 wt% of MWCNT in ionic liquids. Although heat capacity of ionic liquids was found to increase almost linearly with increasing temperature, ionanofluids showed different trends in the enhancement of their heat capacity value. For instance, while the enhanced heat capacity of $[(C_6)_3PC_{14}][Phosph]$-based ionanofluid increases negligibly with temperature, the enhancement of heat capacity (13%) was found almost constant for $[(C_6)_3PC_{14}][NTf_2]$-based ionanofluid over the entire temperature range of their study. They further demonstrated that like ionic liquids the studied ionanofluids are also thermally stable.

5. Advantages of CNT-nanofluids

As thermal properties of fluid play a vital role in the development of energy efficient heat transfer equipment, it is of paramount importance to develop fluids having high heat transfer and transport properties to meet the demands of many high-tech industries and advanced thermal management systems. Nanofluids are superior over suspensions of millimeter-or micrometer-sized particles as even microparticles are not suitable for microsystems. In addition, the major problems of such suspensions are the rapid settling of these particles, clogging the flow channel, and increased pressure drop in the fluid. On the other hand, besides being orders of magnitude smaller compared to the microsystems nanoparticles remain in suspension reducing erosion and clogging. Thus, having well-dispersed nanoparticles nanofluids can flow smoothly through mini- or micro-channels. Another advantage is the mobility of the nanoparticles, which may bring about nanoscale dynamic mechanisms and hence can enhance the heat transfer performance of nanofluids. Because the nanoparticles are small, they weigh less and chances of sedimentation are also less making nanofluids more stable.

Given that the heat transfer performance of heat exchangers or cooling devices is vital in numerous industries, the impact of nanofluid technology is expected to be remarkable. Compared to traditional fluids and suspensions of milli- or micro-sized particles properly engineered CNT-nanofluids offer numerous advantages which include high heat transfer and stability due to large aspect ratio and specific heat transfer surface areas of dispersed CNT, microchannel flow and cooling without clogging, miniaturized systems, and reduction in pumping power [9,10,94]. The better stability of CNT-nanofluids will prevent rapid settling and reduce clogging in the walls of heat transfer devices. High thermal conductivity, convective and boiling heat transfers of nanofluids translate into higher energy efficiency, better performance, and lower operating costs. They can reduce energy consumption for pumping heat transfer fluids and can enhance the performance of solar energy technologies and devices. Miniaturized systems require smaller inventories of fluids where nanofluids can be used. Thermal systems can be smaller and lighter. In vehicles, smaller components result in better gasoline mileage, fuel savings, lower emissions, and a cleaner environment.

One of the major advantages of using CNT suspensions in practical applications is the control of properties and applications through changing the size and concentration of the CNT, synthesizing any number of walls, and surface treatment of CNT.

6. Applications of CNT-nanofluids

With those aforementioned highly desirable thermal properties and potential benefits, it is considered that CNT-nanofluids have wide range of industrial, electronics and medical applications. These nanofluids can be applied for better heat transfer and other performances of systems or technologies in many engineering applications including engine cooling, vehicle thermal managements, solar energy technologies, micro-electromechanical systems (MEMS), electronics and instrumentations, heat exchangers, heating–ventilating and air-conditioning, cooling electronics, microfluidics systems, defense, medical and other applications such as heat pipes, thermal storage, cooling nuclear systems, fuel cells, lubrications, chillers, refrigerator, and so on. Nanofluids have shown great promise as waste heat collectors [95], and in the medical and biomedical fields such as cancer treatment, drug delivery, and control of biofluids motion [96,97]. It is believed that nanofluids will open multi-billion dollar markets in near future. An estimation of the potential world-wide market for nanofluids only in heat transfer applications was recorded to be over 2 billion dollars per year and it is expected to grow further and rapidly over the next several years [98]. Details of the applications of nanofluids have been discussed in the literature [10,94,96,98,99], particularly in a recent article by Taylor et al. [97]. Thus except applications in solar energy technologies no other potential applications of these new fluids will be discussed further.

Due to enhanced absorption, scattering and optical properties as well as other thermophysical properties such as heat capacity nanofluids possess great potentials for their application in solar energy technologies. Importantly, these properties can be changed significantly by changing the CNT size, structure and concentration. However, only a handful of efforts have been devoted on the application of nanofluids in this highly demanding energy sector.

In addition to many other beneficial features nanofluids offer several key advantages in solar power plants including passing through pumps and plumbing of minisystems without any adverse effects, directly absorption solar energy, high absorption in the solar range and low emittance in the infrared, enhanced heat convection and radiation transfer, and enhancing absorption efficiency by changing the size and concentration of CNT used [100].

Taylor et al. [100] demonstrated that the power tower solar collectors can be benefited from the potential efficiency improvements by using a nanofluid as working fluid. Their experiments on a laboratory-scale nanofluid dish receiver indicated that up to 10% increase in efficiency relative to a conventional fluid is possible. By comparing the energy and revenue generated in a conventional solar thermal plant to a nanofluid-based one, they found that a 100 MWe capacity solar thermal power tower operating in a solar resource could generate about $3.5 million more per year by incorporating a nanofluid receiver. Efficiency improvement on the order of 5–10% is possible with a nanofluid receiver. Their findings revealed that nanofluids have excellent potential for tower solar thermal power plants.

The efficiency of solar collectors in low-temperature (<100 °C) can be improved by using nanofluids [101]. Tyagi et al. [101] showed that under similar operating conditions, the efficiency of a nonconcentrating direct absorption solar collector (DAC) using nanofluid as the working fluid is up to 10% higher than that of a flat-plate collector on an absolute basis. Generally a DAC using nanofluids as the working fluid performs better than a flat-plate collector.

Typical solar thermal-energy storage facilities such as solar thermal power plants require the storage medium to have high heat capacity and thermal conductivity. Thus applying CNT-nanofluids and ionanofluids with their higher thermal conductivity as well as heat capacity as compared to their base fluids can remarkably enhance the capability and performance of solar thermal power plants [102].

An experimental study by Vieira et al. [91] showed that MWCNT-ionanofluids can potentially be used in the development of the pigments for paints in solar collector applications. An increase up to 11% in the absorbance and a net gain in efficiency of 0.45–0.57 were obtained. They concluded that the paint coatings with ionanofluids have spectrally selective behavior and the addition of 2.5% (w/w) of pigment enhances the solar absorbance, and does not greatly affect the thermal emittance.

In addition to enhanced thermal and transport properties of CNT dispersed nanofluids as well as ionanofluids above discussion revealed that like many other applications these new fluids can revolutionize the solar energy technologies for harvesting solar energy for numerous applications. However, more application based investigations of these fluids are to be conducted.

7. Conclusions and outlook

Several important thermal features of CNT-laden nanofluids and ionanofluids are presented and reviewed in this study. Results showed that CNT-nanofluids exhibit significantly higher thermal features such as thermal conductivity, convective heat transfer coefficient and boiling critical heat flux compared to their base fluids as well as other nanofluids. These enhanced properties of these nanofluids further increase with increasing CNT concentration and temperature. CNT-ionanofluids also showed superior thermophysical and heat transfer properties compared to base ionic liquids.

Based on the exciting research findings, CNT based nanofluids as well as ionanofluids with their ultra-high thermal conductivity can potentially be the next generation heat transfer fluids. However, research work is mainly focusing on their anomalous thermal conductivity whereas other heat transfer and thermophysical properties are also very important in order for their practical applications particularly as coolants in thermal management systems as well as solar energy based applications.

This review clearly demonstrates that despite inconsistent data, substantial increases in thermal features of this particular type of nanofluids compared to their base fluids are undisputed. However, reported data are still limited and scattered to clearly understand the underlying mechanisms of nanofluids. It is therefore imperative to conduct more comprehensive studies on these thermal characteristics under various important conditions or factors such as concentration, temperature, pressure, flow conditions, heater and tube geometry.

It is also found that most studies used aqueous or ethylene glycol-based MWCNT nanofluids. Thus other types of carbon nanotubes such as single- or double-walled CNT and different types of base fluids like silicone oil and refrigerants-based systems need to be investigated explicitly.

Though extensive theoretical efforts have been devoted to the development of models for the prediction of thermal conductivity of nanofluids containing mainly spherical-shape nanoparticles, very limited attempts have been made to identify the actual heat transfer mechanisms and to develop model for the enhanced thermal conductivity of CNT-nanofluids. Most of the existing models have limitations and are unable to accurately predict the thermal conductivity of CNT-nanofluids. These models are mainly validated using very limited data and most of them also contain unknown parameters and thus are not widely accepted. On the other hand, almost no rigorous analytical work is performed to understand and identify the mechanisms for the enhanced convective heat transfer characteristics of these nanofluids. There is therefore an urgent need to perform more extensive work to identify the actual mechanisms and to develop models for the predictions of the enhanced conductive and convective heat transfer properties of these nanofluids.

Based on the findings from our own studies, ionanofluids containing MWCNT are found to exhibit higher conductivity and heat capacity compared to base ionic liquids. These properties further increase with concentration of CNT and temperature to some extent. Thus, CNT-ionanofluids also showed great potential to be used as advanced heat transfer fluids in numerous important applications. This is a very new class of fluids and more investigations are to be performed in order to explore more uncovered potential applications of this fluid.

Since neither classical models nor recent models developed for nanofluids are able to predict the effective thermal conductivity of ionanofluids, there is an urgent need to develop model for ionanofluids. It is crucial to characterize and understand the relation between the structures and properties in order to develop new models that can explain the anomalous thermal features of CNT-ionanofluids.

Besides having superior thermophysical and heat transfer properties and benefits compared to base fluids, like many other applications these novel fluids show great promises to be applied in solar energy technologies.

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