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Heat and mass transfer characteristics of carbon nanotube nanofluids: A review

Muhammad Noor Afiq Witri Muhammad Yazid[a,*], Nor Azwadi Che Sidik[a,b], Wira Jazair Yahya[b]

[a] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia
[b] Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

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ABSTRACT

The pursuit of superior working fluids for heat and mass transfer systems in the industry is on the rise, inspired by not only to maximize revenue but also to accommodate heat dissipation or chemical separation under extreme conditions. The addition of a small amount of nanoparticle, a product called nanofluid, has been initiated over the last decade. In particular, researchers have employed carbon nanotubes (CNTs) into conventional fluids as their preferred nanoparticles due to the merits of having a remarkable thermal conductivity compared to other nanoparticles. Here, we present a comprehensive and up to date review of this incredible fluid being applied in various heat transfer (convective and boiling) and mass transfer systems such as heat exchangers and separators. Other critical parameters associated with the practicality of the CNT nanofluids such as pumping power and efficiency are also discussed. We surveyed a remarkable range of results of some of the heat and mass transfer studies that strongly depend on the inherent CNT nanofluid characteristics and operating conditions such as CNT treatment, size, concentration, Reynolds number, and so on. A major conclusion that can be drawn from this review is the significantly higher heat transfer coefficient at lower pressure drop or pumping power of the CNT nanofluid compared to other nanofluids, which implied better thermal performance of the heat transfer system. Besides that, the concentration of CNT is the influential factor to achieve optimum boiling heat transfer while the mass transfer performance of the CNT nanofluid is moderately good against other nanofluids. Additionally, CNT treatment using covalent functionalization is crucial for the overall stability and performance of the CNT nanofluid. However, several issues that inhibit their widespread use such as possible corrosion-erosion in systems, lack of risk assessments, and high cost of CNT nanofluid must be thoroughly addressed in future studies.

1. Introduction

Equipments that involve heat and mass transfer processes, for examples, heat exchanger and chemical separator, are already widely used in the industry. For the heat transfer system, some of the important attributes of their practical use in the industry include higher efficiency and compactness. In order to fulfil this, a heat transfer system must be able to transfer more heat at the expense of low pressure drop. There are three strategies that could be adopted to make the heat transfer system more efficient and compact, which are active, passive, and compound techniques. Among these, the passive technique has been the focus of many as it can operate without an external power. This method generally uses surface or geometrical modifications to the flow channel or by adding an additive to the working fluid [1,2]. However, recent research activities concerning the development of passive devices to further enhance heat transfer have reached its full prospectivity as the recent devices require highly complex techniques to fabricate which ultimately become more expensive to be produced [3]. Meanwhile, an efficient mass transfer in a separation unit requires a better absorption rate. In order to achieve this, a conventional

Abbreviations: AC, Activated carbon; Al_2O_3, Aluminum oxide; BHTC, Boiling heat transfer coefficient; CHF, Critical heat flux; CNT, Carbon nanotube; CTAB, Cetyl trimethyl ammonium bromide; CTAC, Cetyl trimethyl ammonium chloride; Cu, Copper; CuO, Copper(II) oxide; CO_2, Carbon dioxide; DWCNT, Double-walled carbon nanotube; EF, Efficiency factor; EG, Ethylene glycol; EO, Ethylene oxide; f-MWCNT, Functionalized multiwalled carbon nanotube; GA, Gum Arabic; H_2O, Water; HEG, Hydrogen exfoliated graphene; f-HEG, Functionalized hydrogen exfoliated graphene; Fe, Iron; Fe_2O_3, Iron(III) oxide; Fe_3O_4, Iron(II,III) oxide; LiBr, Lithium bromide; LNG, Liquefied natural gas; LED, Light emitting diode; MWCNT, Multiwalled carbon nanotube; NH_3, Ammonia; PEG, Polyethylene glycol; PEO, Polyethylene oxide; PO, Propylene oxide; PVP, Polyvinyl pyrrolidone; rGO, Reduced graphene oxide; sG, Solar graphene; SDBS, Sodium dodecylbenzenesulfonate; SDS, Sodium dodecyl sulfate; SiO_2, Silicon dioxide; SSA, Specific surface area; SWCNT, Single-walled carbon nanotube; TFPEG, Tetrahydrofurfuryl polyethylene glycol; TiO_2, Titanium dioxide; TPCT, Two-phase closed thermosyphon; TSP, Trisodium phosphate; Zn, Zinc; ZnO, Zinc oxide

* Corresponding author.
E-mail address: mnafiqwitri@utm.my (M.N.A.W.M. Yazid).

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Nomenclature

AR	Strip aspect ratio
C_f	Skin friction coefficient
C_k	Thermal conductivity enhancement coefficient
C_p	Specific heat [J/(kg K)]
C_μ	Viscosity enhancement coefficient
D	Pipe inner diameter [m]
D_h	Pipe hydraulic diameter [m]
e	Wire diameter [m]
e_c	Corrugation depth [m]
f	Friction factor
Gr	Grashof number
Gz	Graetz number
h	Convective heat transfer coefficient [W/(m^2 K)]
H	Helix length [m]
He	Helical coil number
k	Thermal conductivity [W/(m K)]
L	Pipe length [m]
m	Empirical constant
Mo	Mouromtseff number
$\overline{\mathrm{Nu}}$	Average Nusselt number
p	Wire coil pitch [m]
P	Pumping power [W]
p_c	Corrugation pitch [m]
Pr	Prandtl number
TR	Twist ratio
$\dot{Q}$	Heat exchange capacity [kW]
r	Absorption rate [g/s]
R	Absorption ratio
Re	Reynolds number
S	Inner surface area of the pipe [m^2]
x	Axial distance [m]

Greek symbol

Δp	Pressure drop [Pa]
δT	Thermal boundary layer thickness [m]
η	Thermal-hydraulic performance factor
η_T	Heat transfer rate per pump power and per temperature difference [K^{-1}]
θ	Pipe inclination angle
μ	Dynamic viscosity [kg/(s m)]
μ_b	Bulk dynamic viscosity [kg/(s m)]
μ_w	Wall dynamic viscosity [kg/(s m)]
ρ	Density [kg/m^3]
φ	Nanoparticle concentration [wt% or vol%]

Subscript

b	Bulk
bf	Base fluid
c	Corrugation
sp	Smooth pipe
w	Wall

separation process usually adopts the physical or chemical process such as changing the flow mode or the addition of surfactant.

In recent decades, there is an upward trend in the research pertaining to the addition of additives into the working fluid as part of the passive technique to enhance heat transfer. Comparable to the heat transfer, mass transfer also benefited from the use of additives so as to decrease the interfacial tension between two adjacent species or fluid phases. Initially, solid particles made from metal are employed as additives to improve the inherently poor thermophysical properties of liquids. However, a solid particle having a diameter of mili or micrometer often fails to perform as it quickly sedimented after it is added into a fluid. In conjunction with the progress on the development in nanoscience and nanotechnology, a small amount of ultra-small particles known as nanoparticles (< 100 nm in size) are dispersed into a conventional fluid producing nanofluids has been shown to remarkably improve heat and mass transfer while maintaining homogenous and stable state for a longer period of time. Consequently, a lot of research efforts have been invested in the literature in applying different nanofluids in energy harvesting system [4,5] and cooling system [6–16]. Some of the studies on this subject have focused extensively on carbon nanotube (CNT) as an additive in the base fluid as it exhibits the highest thermal conductivity compared to other nanoparticles. Based on the Scopus database, as displayed in Fig. 1, the research trends for nanofluid and CNT nanofluid to be specific, are rising steadily over the past decade.

So far, several papers have comprehensively reviewed the performance of nanofluids on heat and mass transfer [17-20]. Furthermore, there are a few reviews that focus on the thermal performance of CNT nanofluids [21,22]. However, the discussion of these reviews has been on heat transfer only and none of the reviews describe researches pertaining to the use of CNT nanofluids on pumping power and efficiency of various systems and its performance in mass transfer system. Therefore, this review aims to contribute to this rapidly growing area of nanofluid research by exploring the latest research findings on the performance of CNT nanofluids in various heat and mass transfer systems. This review also discusses some challenging issues that impede the widespread use of the CNT nanofluids and provide an exciting opportunity to advance our knowledge in understanding the mechanistic and promising performance of CNT nanofluids.

1.1. Preparation of CNT nanofluids

Nanofluids can be produced through a single or two-step method. For CNT nanofluids, the latter method is commonly adopted. The procedure for this method starts firstly by producing the dry nanoparticle using techniques discussed [23–25] before dispersing it into the host fluid. Although this method is cost efficient, as the CNT powder synthesis techniques have already been scaled up for mass production, there are challenging issues to obtain a long-term stability of the CNT

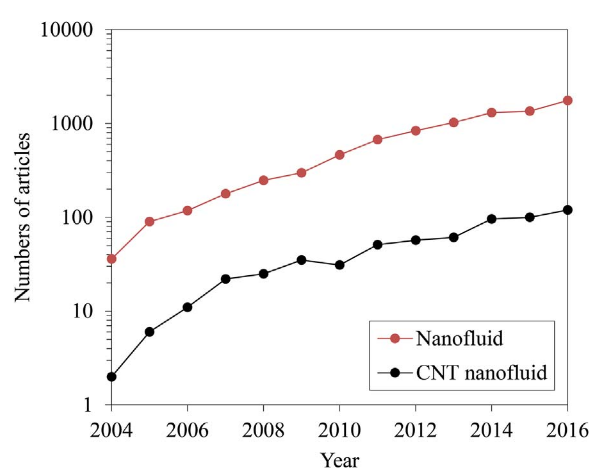

Fig. 1. Number of articles on nanofluid and CNT nanofluid published from 2004 to 2016. Records retrieved from Scopus as of 21 January 2017 using 'nanofluid' or 'nanofluid carbon nanotube' as the keywords.