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Review

Hybrid nanofluids for heat transfer applications – A state-of-the-art review

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ABSTRACT

In recent years, a novel class of working fluids which consists from two solid materials dispersed in a conventional fluid was developed and intensely studied. These fluids are called hybrid nanofluids. This paper presents a review of the research recent results concerning the thermo-physical properties (thermal conductivity, viscosity, density and specific heat) and the heat transfer and flow characteristics of hybrid nanofluids used in various heat exchangers. The hybrid nanofluids leads to an increased thermal conductivity and finally to a heat transfer enhancement in heat exchangers. Experimental and numerical results shown in this review indicate that the hybrid nanofluids are working fluids which could improve significantly the heat transfer in heat exchangers, but, there are still needed research concerning to the study of different combinations of hybrid nanoparticles, their mixing ratio, the stability of the hybrid nanofluids, and the understanding the mechanisms which contribution to the heat transfer enhancement.

Contents

1. Introduction

Hybrid nanofluids are a new class of working fluids containing very small particles with sizes (under 100 nm) used in heat transfer applications. These fluids consist from two or three solid materials into conventional fluids (water, ethylene glycol or water-ethylene glycol mixture, engine oil, kerosene, vegetable oil and paraffin oil). The solid nanoparticles used for heat transfer enhancement of working fluids are: SWCNT-MgO, MWCNT-Fe_3O_4, MgO-MWCNT, Fe_2O_3-CNT, Fe_3O_4-Graphene, Graphene - Ag, Al_2O_3-CNT, SiO_2-CNT, Al_2O_3 – Cu, Al_2O_3-Ag, Cu–TiO_2, Cu-Cu_2O, Cu-Zn, Ag-SiO-carbon, Ag-TiO_2, Ag-MnO, Ag-CNT, diamond-Ni, ND-Co_3O_4, Al_2O_3-MEPCM, Al_2O_3-SiO_2). In last year's, these hybrid nanofluids were used in various heat transfer applications as heat pipes, micro-channel, minichannel heat sink, plate heat exchanger, air conditioning system, tubular heat exchanger, shell and tube heat exchanger, tube in tube heat exchanger and coiled heat

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Nomenclature

a, A	constants
b, B	constants
d	diameter (m)
D_h	hydraulic diameter (m)
c_p	specific heat (J/kg K)
f	friction factor
k	thermal conductivity (W/m K)
L	length (m)
W	width (m)
Nu	Nusselt number
Ra	Rayleigh number
Re	Reynolds number
Pe	Peclet number
Pr	Prandtl number
Ste^*	Stefan number
Sb^*	modified inlet subcooling parameter
T	temperature (K)

Greek symbol

ϕ	concentration of nanoparticles (%)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
ω	mass fraction (%)

Subscript

bf	base fluid
e	equivalent
EG	ethylene glycol
in	inner
nf	nanofluid
np	nanoparticle
out	outer
p	particle
pcm	phase change material
w	water

exchanger, helical coil heat exchanger. Although researches in this field are still limited, comprehensive reviews were presented in Refs. [1–4].

This review is divided in two parts: first part is dedicated to thermo-physical properties of hybrid nanofluids (thermal conductivity, viscosity, density and specific heat) and in second part are presented possible heat transfer applications which used hybrid nanofluids as working fluids.

2. Thermo-physical properties of hybrid nanofluids

Thermal conductivity and viscosity are two important properties in the study of the hybrid nanofluids. Obtaining some hybrid nanofluids stable in long-term with high thermal conductivities and low viscosities is a research direction which has been studied in last few years (2007-till now) but in especially in the last three years (2015–2017).

2.1. Thermal conductivity

First article about the thermal conductivity of hybrid nanofluids was published in 2007 by Jana et al. [5]. They experimental investigates the thermal conductivity of nanofluids based on carbon nanotubes (CNT), copper (Cu) and gold nanoparticles as well as combinations of thereof (hybrid nanofluids), CNT-Cu/water and CNT-Au/water. Results showed a decrease of thermal conductivity of the hybrid nanofluids with CNT-Au and CNT-Cu compared with thermal conductivity of nanofluids based on Au and Cu nanoparticles (Fig. 1). The main reason was based on the poor interaction between Cu nanoparticles and CNTs such that the addition of CNTs into the Cu nanoparticles suspension degraded the dispersion of both types of nanomaterials resulting in increased agglomeration. Because CNTs are less prone to convection due to their stability, the addition of them to Cu nanoparticles suspension inhibits the natural convection currents causing the lowering of thermal conductivity of suspension.

Later, in 2010, Ho et al. [6] studied the thermal conductivity of the hybrid water-based suspension of Al_2O_3 nanoparticles and MEPCM (microencapsulated phase change material) particles. The experiments were performed at a temperature of 30 °C for various PCM suspension (ω_{pcm} = 0%, 2.0%, 5.0% and 10 wt%) and various mass concentration of Al_2O_3 nanoparticles (ω_{np} = 0%, 2.0%, 4.0%, 6.0% and 10 wt%). Their results showed that the hybrid nanofluids present a higher thermal conductivity with increasing the mass concentration of nanoparticles compared with the PCM suspension.

Suresh et al. [7] measured thermal conductivity of hybrid nanofluids Al_2O_3-Cu/water at the room temperature (32 °C, accuracy ±2%) for volume concentrations of nanoparticles in the range 0.1–2.0%. The average size of nanoparticles was 17 nm. In opposite with the study above-mentioned, Ref. [5], the authors founded that the thermal conductivity of Al_2O_3-Cu/water increases with increasing volume concentration of nanoparticles. Maximum improvement of thermal conductivity was 12.11% at a volume concentration of nanoparticles of 2.0%. The main reason in increase thermal conductivity of Al_2O_3–CuO/water hybrid nanofluid can be due to functionalization of Al_2O_3 nanoparticles and Cu nanoparticles which were higher thermal conductivity than Al_2O_3 nanoparticles.

The thermal conductivity of nanofluids based on MWCNT and SiO_2 nanoparticles as well as of hybrid nanofluids SiO_2-MWCNT/water in two ratios 80%SiO_2-20%MWCNT and 50%SiO_2-50% MWCNT were measured by Baghbanzadeh et al. [8]. Experiments were performed for three mass concentrations of nanoparticles (0.1, 0.5 and 1.0%) at two temperatures 27 °C and 40 °C respectively. Experimental results showed that the values of thermal conductivity of both hybrid nanofluids were between the values of thermal conductivities of nanofluids (Fig. 2). The mechanism that could explain this behavior is due to placing silica nanospheres beside MWCNT which leads to increases the thermal resistance, therefore conduction heat transfer in clusters of hybrid particles will be slower compared to carbon nanotubes alone.

Abbasi et al. [9] investigated the thermal conductivity of hybrid nanofluids based on MWCNT-γ-Al_2O_3 nanoparticles with a volume concentration within the range 0.1–1.0 vol% at the temperature of 25 °C. The hybrid nanofluids were prepared using three methods of synthesis (pure MWCNTs with the average particle size of ~ 37 µm (PS50) and functionalized MWCNTs with the average particle size of 804 nm (S50) and 335 nm (SF50) respectively). Authors founded that the thermal conductivity of MWCNT-γ-Al_2O_3 hybrid nanofluids prepared with first method (S50) was 0.70 W/(m K), the improvement being of approximately 21% compared with the thermal conductivity of distilled water. Also, they stated that the thermal conductivity is dependent on the stability of the hybrid nanoparticles in the nanofluid.