International Journal of Thermal Sciences 123 (2018) 58–72

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Dissipative particle dynamics investigation of heat transfer mechanisms in Al_2O_3-water nanofluid

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ARTICLE INFO

Article history:
Received 16 April 2017
Received in revised form
29 August 2017
Accepted 5 September 2017

Keywords:
Dissipative particle dynamics
Nanofluid
Brownian motion
Variable properties of nanofluids

ABSTRACT

The current paper applied dissipative particle dynamics (DPD) approach to investigate the effect of nanoparticles on the heat transfer mechanisms in natural convection using Al_2O_3-water nanofluids. The study investigated in detail the effect of nanoparticle concentration on the random heat flux (i.e., Brownian motion) and the total heat flux. The DPD model considered the viscosity and the thermal conductivity of the Al_2O_3-water nanofluid to be dual function of temperature and volume fraction of nanoparticles. The study covered a wide range of nanoparticles ($1\% \leq \varphi \leq 7\%$) and three Rayleigh numbers were considered, which are $Ra = 10^4$, $Ra = 5 \times 10^4$, and $Ra = 10^5$. The DPD results predicted an enhancement in heat transfer due to the addition of nanoparticles. However, the results revealed that the relative of enhancement of the total heat flux in the cavity is more effective at low Rayleigh numbers than at high Rayleigh numbers. The regions around the hot wall of the cavity are found to experience the maximum enhancement in heat transfer in the cavity whereas the region adjacent to the cold wall experienced a deterioration in heat transfer due to the addition of nanoparticles. Also, the DPD results revealed that the role of Brownian motion in the vicinity of hot and cold walls was negligible where the ratio of random heat flux to the total heat flux was below 5%. However, this ratio reached a very large value around the center of the cavity and the bottom wall of the cavity, where this value at low Rayleigh number and high volume fraction of nanoparticles exceeded 65%. Moreover, the study revealed that the random heat flux enhances with increase of volume fraction of nanoparticles.

1. Introduction

Nanofluids are considered very attractive in enhancing intrinsic thermal conductivity of heat transfer fluids (HTF) by suspending certain concentration of nanoparticles in a base fluid [1,2]. Nanofluids are proven to be very effective in enhancing heat transfer in forced convection applications, but their role on heat transfer enhancement in natural convection applications is still debatable. There is discrepancy between most of theoretical studies and experimental findings, where early theoretical studies reported augmentation in heat transfer as a result of the addition of nanoparticles which conflicts with some experimental results, for example Putra et al. [3] and Wen and Ding [4]. Recently, numerical results of Abu-Nada et al. [5] and Abu-Nada [6] related such deterioration in heat transfer, observed experimentally, to the increase in nanofluids' viscosity particularly at high concentration of nanoparticles, which adversely affects the heat transfer in natural convection applications.

Theoretically speaking, most of theoretical studies on nanofluids use continuum models such as Navier-Stokes Equations (NES) to investigate nanoparticles' energy transport in base fluids. But, the main concern is whether at such nanoscale dimension the continuum theory is still applicable. In reality, spatial scales and temporal scales of the energy transport within nanofluids are much larger than those of discrete models (for example, molecular dynamics (MD)) and they are also much smaller than the continuum scales. Such intermediate scales can be tackled using mesoscopic (scales between micro to nanoscale) methods through coarse graining where each meso-particle represents a group of real fluid molecules.

Hoogerbrugge and Koelman [7] introduced dissipative particle dynamics (DPD) method as a coarse-grained mesoscopic computational model to tackle physical processes that are encountered at mesoscale. The method consists of randomly dispersed DPD particles with interaction among them governed by the conservation laws (conservation of mass and momentum) and at ultimately at

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.09.005
1290-0729/

Nomenclature

a	repulsion parameter
C_v	specific heat at constant volume, J/kg.K
C_{RM}	random motion velocity of a nanoparticle, m/s
c_s	speed of sound
D_o	Einstein's molecular diffusion coefficient, m^2/s
d	nanoparticle diameter, m
e	unit vector
f	force, N
g	gravity vector
H	enclosure height, m
h	heat transfer coefficient, $W/m^2.K$
K	thermal conductivity function, W/m.K
k	thermal conductivity, W/m.K
k_B	Boltzmann constant
k_o	parameter controlling the thermal conductivity of the DPD particle
m	mass of DPD particle
Nu	Nusselt number, $Nu=hH/k_{nf}$
Nu^*	modified Nusselt number defined in Eq. (29)
n	normal vector
p	dimensional pressure, N/m^2
Pr	Prandtl number, $Pr = \nu_C/\alpha_C$
Pr_T	Prandtl number based on local temperature, $Pr = \mu_{bf}(T)/(\rho_{bf}\alpha_{bf}(T))$
q	heat flux, W/m^2
Q_{cell}	total heat flux in the "averaging cell", $Q_{cell} = Q^{cond} + Q^{visc} + Q^R$
Q^{cond}	conduction heat flux in the "averaging cell"
Q^{visc}	viscous heat flux in the "averaging cell"
Q^R	random heat flux in the "averaging cell"
r	position vector
r_c	cut-off radius
Ra	Rayleigh number, $Ra = g\beta(T_H\text{-}T_C)H^3/(\nu_C\,\alpha_C)$
T	dimensional temperature, °C
t	time, s
v	velocity vector, m/s
V	dimensionless velocity, $V = vH/\alpha$
w	weight function
x, y	dimensional coordinates, m
X, Y	dimensionless coordinates, $X = x/H$, $Y = y/H$
α	thermal diffusivity, m^2/s
α_{ij}	random heat flux parameter
β	thermal expansion coefficient, 1/K
β'	constant
γ	dissipative force parameter
Γ_{cell}	ratio of random heat flux to total heat flux at the "averaging cell", $\Gamma_{cell} = Q^R/Q_{cell}$
Δ	relative enhancement of the total heat flux at the "averaging cell" for any volume fraction of nanoparticles
ζ	random number for the momentum equation
ζ^e	random number for the energy equation
θ	dimensionless temperature, $\theta = (T\text{-}T_C)/(T_H\text{-}T_C)$
κ	collisional heat flux parameter
λ	random heat flux parameter
Λ	relative enhancement of the average random heat flux at any volume fraction of nanoparticles
μ	dynamic viscosity, $N.s/m^2$
ν	kinematic viscosity, m^2/s
ρ	DPD number density
σ	amplitude of the random force
φ	volume fraction of nanoparticles (%)
Ω	variable weight function, $\Omega(T,\varphi)$

Subscripts

avg	average
bf	base fluid
C	cold
H	hot
i, j	indices
max	maximum
nf	nanofluid
p	particle
ref	reference
s	isentropic

Superscripts

C	conservative
cell	a computational square cell of a half cut-off radius side size, where any heat flux quantity of interest is averaged
cond	conduction
D	dissipative
R	random
visc	viscous

the macroscopic level the DPD system would represent bulk fluid flow [8,9]. Español [9] and Avalos and Mackie [10] extended the DPD model to account for energy conservation and it was further advanced by various researches to mimic heat transport in many applications. Chaudhri and Lukes [11] recently conducted a detailed and critical review of the DPD studies in heat transfer. Although the number of studies carried out using DPD in heat transfer has increased considerably in recent years, but most of the studies were limited to pure fluids. Therefore, it is very crucial to advance the DPD method to mimic convective heat transfer in nanofluids. Recently, Abu-Nada [12] applied DPD approach to simulate heat transfer in CuO-water nanofluid. The focus of his study was on the enhancement of heat transfer in CuO-water nanofluid and no attention was given on analysing the mechanism of such enhancement. Therefore, the scope of the present work is to extend the applicability of DPD to investigate heat transport in other nanofluids such as Al_2O_3-water nanofluid. Also, to examine the energy transport mechanisms within nanofluids such as random heat fluxes attributed to Brownian motion in addition to other mechanisms such as conductive and convective heat fluxes. The problem considered in this study is natural convection in a differential heated cavity having Al_2O_3-water nanofluid as the working fluid. The viscosity and the thermal conductivity of the DPD nanofluid model are considered variable and are devised from available experimental data. The DPD model is evaluated over a wide range of Rayleigh numbers and volume fraction of nanoparticles. The role of Brownian motion on heat transfer within the cavity will be also assessed in the current study.

2. Governing equations

Simulation of heat transfer in a differential heated cavity filled