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Periodic natural convection in a nanofluid-filled enclosure with oscillating heat flux

B. Ghasemi [a,*], S.M. Aminossadati [b,1]

[a] Shahrekord University, Faculty of Engineering, PO Box 115, Shahrekord, Iran
[b] The University of Queensland, School of Mechanical and Mining Engineering, QLD 4072, Australia

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ABSTRACT

This paper examines the periodic natural convection in an enclosure filled with nanofluids. Whilst a heat source with oscillating heat flux is located on the left wall of the enclosure, the right wall is maintained at a relatively low temperature and the other walls are thermally insulated. Based upon numerical predictions, the effects of pertinent parameters such as Rayleigh number, solid volume fraction, heat source position, type of nanoparticles and oscillation period are examined. A periodic behaviour is found for the flow and temperature fields as a result of the oscillating heat flux. The utilisation of nanoparticles, in particular Cu, enhances the heat transfer especially at low Rayleigh numbers. In addition, the oscillation period of heat generation affects the maximum operational temperature of the heat source. It is also interesting to observe that the optimum position of the heat source on the left wall is a function of Rayleigh number. The results of this study can be used in the design of an effective cooling system for electronic components to help ensure effective and safe operational conditions.

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1. Introduction

Due to its various applications, buoyancy-driven heat transfer in enclosures filled with clear fluids has been comprehensively studied and documented in the literature in the past [1]. In particular, attention has been given to enclosures with time-dependent thermal boundary conditions due to their relevance in practical situations such as heating or cooling of buildings, food storage facilities and heat removal from electronic components.

For the first time, Lage and Bejan [2] investigated the buoyancy-driven flows in a square enclosure with periodic heat flux and examined the effects of oscillation frequency of heat generation on natural convection. Other researchers carried out similar studies by considering a clear base fluid within the enclosure [3–6]. For an air-filled enclosure, Xia et al. [7] studied the stability of buoyancy-driven laminar flows where sinusoidal perturbation was imposed on the hot vertical wall. They argued that the perturbation destabilises the flow in high amplitudes leading to lower critical Rayleigh numbers for the flow transitions. For a water-filled enclosure, Antohe and Lage [8] experimentally examined the pulsating horizontal heating process and showed that by tuning the heating oscillation period properly, the heat transfer across the enclosure can be enhanced.

Most of the studies on natural convection under oscillating thermal boundary conditions have utilised the base fluid with a low thermal conductivity, which, in turn, limits the heat transfer enhancement. Choi [9] showed that introducing nanofluids containing nanoparticles with substantially higher thermal conductivities improves the heat transfer performance. The results of this study have also been confirmed by other researchers [10–13].

However, contradictory studies can be found which argue that the dispersion of nanoparticles in the base fluid may result in considerable decrease in the heat transfer [14–16]. Ho et al. [17] argued that the enhancement or mitigation of heat transfer depends on the formulas used for the thermal properties for nanofluids. Even though the structure, shape, size, aggregation and anisotropy of the nanoparticles as well as the type, fabrication process, particle aggregation and deterioration of nanofluids are important factors in a comprehensive nanofluid modelling study, many researchers still find the classical models to be appropriate for predicting the physical properties of nanofluids [18–20].

The utilisation of nanofluids for cooling enhancement of systems with an oscillating heat flux can be considered as an area of interest for the designers of heat removal systems in the electronic industry. To the best knowledge of the authors, no study has yet been reported on this topic in the literature. As such, the focus of

* Corresponding author. Tel./fax: +98 381 4424438.
E-mail addresses: behzadgh@yahoo.com, ghasemi@eng.sku.ac.ir (B. Ghasemi), uqsamino@uq.edu.au (S.M. Aminossadati).
[1] Tel.: +61 7 33653676; fax: +61 7 33653888.

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Nomenclature

C_p	specific heat, J/kg K
g	gravitational acceleration, m/s^2
h	convection heat transfer coefficient, W/m^{2}K
h_s	heat source length, m
H_s	dimensionless heat source length (h_s/L)
k	thermal conductivity, W/mK
L	enclosure length, m
Nu_s	local Nusselt number on the heat source
Nu_m	average Nusselt number
p	fluid pressure, Pa
$\bar{p}$	modified pressure ($p+\rho_c g y$)
P	dimensionless pressure ($\bar{p}L^2/\rho_{nf}\alpha_f^2$)
Pr	Prandtl number (ν_f/α_f)
q''	oscillating heat flux, W/m^2
q''_0	amplitude of oscillating heat flux, W/m^2
Ra	Rayleigh number ($g\beta_f L^3 \Delta T/\nu_f\alpha_f$)
S_φ	source term in Eq. (2)
t	time, s
t_p	oscillation period, s
T	temperature, K
u,v	velocity components in x,y directions, m/s
U,V	dimensionless velocity components (uL/α_f, vL/α_f)
x,y	cartesian coordinates, m
X,Y	dimensionless coordinates (x/L, y/L)
y_s	distance of the heat source from the bottom wall, m
Y_s	dimensionless distance of the heat source from the bottom wall (y_s/L)

Greek symbols

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, 1/K
ΔT	temperature difference $\Delta T = q''_0 L/k_f$
ϕ	solid volume fraction
φ	non-dimensional parameter in Eq. (2)
Γ_φ	diffusion term in Eq. (2)
μ	Dynamic viscosity, Ns/m^2
ν	kinematic viscosity, m^2/s
θ	dimensionless temperature $(T-T_c)/\Delta T$
θ_{max}	maximum heat source temperature along its length
$(\theta_{max})_{max}$	the highest value of θ_{max} respect to time
$(\theta_{max})_{min}$	the lowest value of θ_{max} respect to time
ρ	density, kg/m^3
τ	time in dimensionless form ($\alpha_f t/L^2$)
τ_p	oscillation period in dimensionless form ($\alpha_f t_p/L^2$)
ψ_{max}	maximum stream function

Subscripts

c	cold wall
f	fluid (pure water)
nf	nanofluid
np	nanoparticle
s	heat source

the present study is to examine the effects of pertinent parameters such as Rayleigh number, solid volume fraction, heat source position, type of nanoparticles and oscillation period on the natural convection cooling characteristics of an enclosure with an oscillating heat flux.

2. Problem description

Fig. 1 depicts the geometry of the square enclosure filled with nanofluids. The right wall of the enclosure is maintained at a uniform low temperature (T_c) while the other walls are thermally insulated. A partial heat source with an oscillating heat flux (Eq. (1)) is embedded on the left vertical wall of the enclosure. The oscillating heat flux simulates the heat generation by an electronic component having a pulsating input voltage [21].

$$q'' = q''_0\left[1+\cos\left(\frac{2\pi t}{t_p}\right)\right]. \quad (1)$$

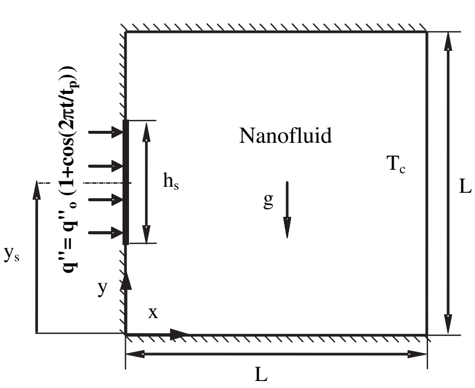

Fig. 1. A schematic diagram of the physical model.

The enclosure is filled with a water-based nanofluid ($Pr=6.2$) containing various spherical nanoparticles (Cu, Al_2O_3 and TiO_2). It is assumed that the base fluid and the nanoparticles are in thermal equilibrium, the nanofluid is Newtonian and incompressible and the flow is laminar. The thermophysical properties of the base fluid and the nanoparticles are given in Table 1. Constant thermophysical properties are considered for the nanofluid except for the density variation in the buoyancy forces determined by using the Boussinesq approximation.

3. Governing equations

The equations that govern the conservation of mass, momentum and energy can be written in a non-dimensional form as shown in Eq. (2).

Table 1
Thermophysical properties of pure water and nanoparticles.

Physical properties	Pure water	Cu	Al_2O_3	TiO_2
ρ (kg/m^3)	997.1	8933	3970	4250
C_P (J/kg K)	4179	385	765	686.2
k (W/mK)	0.613	400	40	8.9538
β (1/K)	21×10^{-5}	1.67×10^{-5}	0.85×10^{-5}	0.9×10^{-5}

Table 2
A summary of the governing non-dimensional equations.

Equations	φ	Γ_φ	S_φ
Continuity	1	0	0
X-momentum	U	$\mu_{nf}/\rho_{nf}\alpha_f$	$-(\partial P/\partial X)$
Y-momentum	V	$\mu_{nf}/\rho_{nf}\alpha_f$	$-(\partial P/\partial Y)+((\rho\beta)_{nf}/\rho_{nf}\beta_f)\ Ra\ Pr\ \theta$
Energy	θ	α_{nf}/α_f	0

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