International Journal of Heat and Mass Transfer 110 (2017) 63–67

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermal instability in a nanofluid saturated horizontal porous layer subjected to g-gitter

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ARTICLE INFO

Article history:
Received 13 February 2017
Received in revised form 6 March 2017
Accepted 6 March 2017

Keywords:
Nanofluid
Porous media
Rayleigh number
Thermophoresis
Brownian motion
Heat transfer
Mathieu equation
g-gitter
Vibration

ABSTRACT

An analytical investigation of the onset of convection in a horizontal porous saturated by a nanofluid, and subjected to g-gitter (or vertical vibration) is presented. The Darcy model is used for the porous layer and a linear stability analysis is used to determine the convection threshold in terms of the key parameters for the nanofluid in a homogenous porous medium. The results are presented for the special case when the porosity to heat capacity ratio is unity. The critical Rayleigh number and wavenumber is presented in terms of the nanofluid parameter.

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1. Introduction

Choi [1] defined a revolutionary fluid which consists of a base fluid and nanoparticles in suspension, known as a nanofluid, has been used to demonstrate a means of improving heat transfer in practical applications such as medicine or engineering. The experimental results by Choi [1] thus far shows substantially improved effective thermal conductivity but seem not to be independently confirmed by any other scientists working in the field. In order to validate the current model presented and previous models in open literature, it seems prudent that the key step is to commission an independent confirmation of the currently available experimental results.

The present paper focuses on applications in engineering and possibility in power generation applications involving heating or cooling enhancement. As an example heat transfer enhancement in nuclear reactor applications using nanofluids has been discussed by Buongiorno [2]. This work involved flow and heat transfer in porous media and included comparative tests between quenching metallic spheres in water and a nanofluid. The quenching process was greatly accelerated when the spheres were quenched in a nanofluid. Essentially this work concluded that nanoparticles enhances the critical heat flux limit and accelerates quenching heat transfer. In relation to water cooled nuclear reactor technologies it is proposed that sizeable power increase in the core are possible with rewards being economic gains and improved safety margins.

Pioneering work on thermal instability in porous media containing nanofluids has been developed and analysed analytically by Nield and Kuznetsov [3,4] for a horizontal porous layer subjected to gravity. Later the paper Nield and Kuznetsov [3] was revised to include the zero flux boundary conditions for the nanofluid which then removed the possibility of the oscillatory mode of convection, Nield and Kuznetsov [5]. The reader is also referred to other works by Kuznetsov and Nield [5–7] for further reading. The mentioned papers presents a comprehensive formulation of the governing equations and provides numerical value ranges for the nanofluid parameters. Numerous interesting features of nanofluids has been explained and a full analytical solution is presented. The reader is referred to Tzou et al. [8] and Vadasz [9] for a review of additional applications of nanofluids. An additional application involving rotation, such as cooling of electronic equipment found in rotating radars or cooling in high speed generators was undertaken by Govender [10,11].

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.018
0017-9310/© 2017 Published by Elsevier Ltd.

Nomenclature

Latin symbols

A	term in Mathieu equation
Da	Darcy number, equals k_{0*}/L_*
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
$\hat{\boldsymbol{e}}_x$	unit vector in the x-direction
$\hat{\boldsymbol{e}}_y$	unit vector in the y-direction
$\hat{\boldsymbol{e}}_z$	unit vector in the z-direction
g_*	gravitational acceleration
H^*	height of porous layer
H	the front aspect ratio of the porous layer, equals H_*/L_*
k_0^*	characteristic permeability
L_*	the length of the porous layer.
N	rank for linear algebraic system of equations
N_A	modified diffusivity ratio, $N_A = D_T(T_1 - T_0)/D_B(\varphi_1 - \varphi_0)$
N_B	the modified particle-density increment, $N_B = \varepsilon(\rho c)_P\varphi_0/(\rho c)_f$
p	dimensionless reduced pressure
Pr	Prandtl number, equals ν_*/λ_*
Q	term in Mathieu equation
$\boldsymbol{V}$	dimensionless filtration velocity vector, equals $u\hat{\boldsymbol{e}}_x + v\hat{\boldsymbol{e}}_y + w\hat{\boldsymbol{e}}_z$
Va	Vadasz number, equals $\varepsilon Pr/Da$
Ra	centrifugal based Rayleigh number, equals $Ra = (1-\varphi^*)\rho_0^*\beta^*\Delta T g^* H_0^* k_0^*/(\lambda^*\mu^*)$
Ra_{np}	nanoparticle based Rayleigh number, equals $Ra_{np} = (\rho_P^* - \rho_0^*)\Delta\varphi H^* g^* k_0^*/(\lambda^*\mu^*)$
R	scaled gravity based Rayleigh number, equals Ra/π^2
R_{np}	scaled rotation based Rayleigh number, equals Ra_{np}/π^2
s	convection wavenumber
t^*	dimensional time
T^*	dimensional temperature
T	dimensionless temperature, equals $(T^* - T_0)/(T_1 - T_0)$
T_0	coldest wall temperature
T_1	hottest wall temperature
u	horizontal x-component of the filtration velocity
v	horizontal y-component of the filtration velocity
w	vertical z-component of the filtration velocity
x	horizontal length coordinate
X	vibration amplitude in scaled Mathieu equation
y	horizontal width coordinate
z	vertical coordinate

Greek symbols

α	a parameter related to the wave number, equals s^2/π^2
β_*	thermal expansion coefficient
δ	related to the vibration amplitude, $\delta = b^*/H^*$
ΔT	characteristic temperature difference
ε	porosity
γ^*	fluid thermal conductivity
η	scaled Vadasz number, $\eta = Va/\pi^2$
φ	volume fraction of nanoparticles
λ_*	effective thermal diffusivity
μ_*	fluid dynamic viscosity
π^*	permeability of the porous matrix
ρ^*	fluid density
σ	exponent for growth/decay of convection
τ	scaled time $t = 2\pi + 2\tau$
ω^*	vibration frequency
ν^*	fluid kinematic viscosity
ξ	ratio of heat capacities, $\xi = (\rho c)_m/(\rho c)_f$

Subscripts

0	related to cold wall
1	related to hot wall
$*$	dimensional values
c	characteristic
P	related to nanoparticles

The author is not aware of any current studies on vibration effects in nanofluids. Gershuni et al. [12] and Gresho and Sani [13] originally used mechanical vibration in mathematical modelling aimed at increasing the stability threshold in pure fluids. Bardan and Mojtabi [14] then used a time average technique to research a confined cavity subjected to vertical vibration in porous media. Govender [15] then used the direct technique using Mathieu charts to consider stability in a horizontal porous layer subjected to vertical vibration. Later Govender [16] then used the direct technique to recover the transition from synchronous to subharmonic modes. Govender [17] then presented a study on the stability of convection in a cylinder subjected to vibration. Pedramrazi et al. [18] discusses the validity of the time averaged formulation in the Horton-Rogers-Lapwood problem using the time average and direct methods.

In this work, we consider the effects of g-gitter (or vertical vibration) on the stability of convection in a nanofluid saturated horizontal porous layer. Readers are also referred to a fairly recent survey of literature on convection in porous media saturated by nanofluids presented by Nield and Kuznetsov [19]. In the current study we will use the linear stability analysis to derive the convection threshold in terms of the critical Rayleigh and wavenumbers in terms of the nanofluid parameters.

2. Problem formulation

A horizontal nanofluid saturated porous subjected to vertical vibration is presented in Fig. 1. The porous layer is constrained between two rigid vertical plates, spaced a distance H^* apart. At $z^* = 0$: $T^* = T_0^*$, $\varphi = \varphi_0$, and at $z^* = 1$: $T^* = T_1^*$, $\varphi = \varphi_1$, where $T_1^* > T_0^*$, and the reference temperature is taken to be T_0^*. In addition, the Boussinesq approximation extended to include the volume fraction of the nanoparticles is applied to account for the effects of the density variations. The following system of dimensional equations for continuity, momentum and energy is proposed, similar to Kuznetsov and Nield [4]:

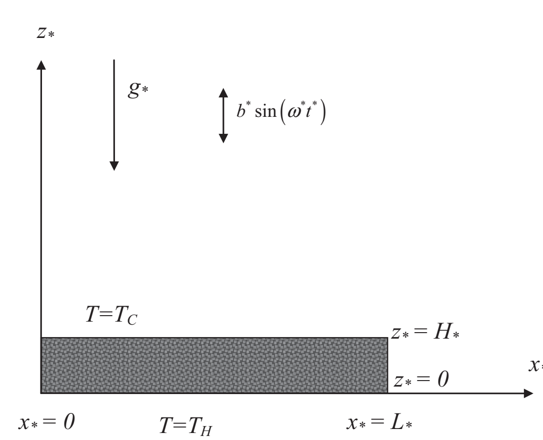

Fig. 1. Nanofluid saturated porous layer subjected to vibration.

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