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The effect of g-jitter on double diffusion by natural convection from a sphere

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Abstract

This paper specifically considers the generation of steady streaming induced by g-jitter on double diffusion from a sphere immersed in a viscous and incompressible fluid. The governing equations of motion are first written in dimensionless forms and the resulting equations obtained after the introduction of the stream function are solved analytically and numerically. Analytical results using the matched asymptotic method are presented for the case when the Reynolds number, Re, is small ($Re \ll 1$), while numerical results using the Keller-box method are given for ($Re \gg 1$), or the boundary layer approximation. Both the cases of assisting and opposing thermal and concentration buoyancies are considered. Table and graphical results for the skin friction and heat and mass transfer from the sphere are presented and discussed for various parametric physical conditions. It is shown that for opposing buoyant forces the skin friction and heat and mass transfer rates follow complex trends depending on the buoyant ratio parameter, Prandtl and Schmidt numbers.

Keywords: g-Jitter; Heat and mass transfer; Stokes layer; Boundary layer; Matched asymptotic expansion; Numerical results

1. Introduction

Various studies to investigate the effect of g-jitter, which is a term to describe fluctuating gravitational fields induced by machine vibrations and crew motions onboard a spacecraft have been addressed recently. For example, Alexander [1] carried out a numerical investigation on the effect of g-jitter on dopant concentration in a modeled crystal growth reactor. He concluded that low-frequency g-jitter can have a significant effect on dopant concentration. Li [2,3], Pan and Li [4], Suresh et al. [5] and Chamkha [6] reported analytical results for the g-jitter induced flows in microgravity under the influence of a transverse magnetic field for a simple system consisting of two vertical plates held at different temperatures. Results showed that the g-jitter frequency, applied magnetic field and temperature gradients all contribute to affect the convective flow. Rees and Pop [7–9] discussed g-jitter induced free convection effects in porous media and in viscous and incompressible fluids (non-porous media) were under the boundary layer approximation. Biringen and Danabasoglu [10] solved the full non-linear, time-dependent Boussinesq equations for g-jitter in a rectangular cavity. Their results showed the response to consist of a harmonic

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Nomenclature

a	radius of a sphere
C	concentration
C_∞	ambient concentration
g^*	g-jitter gravity field
g_0	magnitude of g-jitter
$\boldsymbol{k}$	unit vector pointing vertically upward
N	buoyancy ratio parameter
p	non-dimensional pressure
p_∞	ambient pressure
Pr	Prandtl number
q_{w}	wall heat flux
r	non-dimensional radial coordinate
Re	Reynolds number
t	non-dimensional time
T	non-dimensional fluid temperature
T_∞	ambient temperature
U_{c}	characteristic velocity
v_r, v_θ	non-dimensional velocity components along r and θ axes
$\boldsymbol{v}$	non-dimensional velocity vector

Greek symbols

β_C	concentration expansion coefficient
β_T	thermal expansion coefficient
θ	polar angle
η, $\overline{\eta}$	non-dimensional inner variables
υ	kinematic viscosity
ε	non-dimensional small quantity
ψ	non- dimensional stream function
ω^*	frequency of g-jitter oscillation

Superscripts

*	dimensional variables
′	differentiation with respect to $\overline{\eta}$
s	denotes steady part of the solution
u	denotes unsteady part of the solution

Subscripts

w	condition at the wall
∞	ambient condition

time-dependent component superposed over a steady streaming. The results of Farooq and Homsy [11,12] were complementary to those reported by Biringen and Danabasoglu [10], since by a weakly non-linear calculation, Farooq and Homsy [11,12] were able to explore parametric dependencies that explain physical mechanism and scaling.

All these studies have shed some light on the basic nature of g-jitter effects and have provided a thrust to devise useful mechanism by which the g-jitter induced convective flows may be suppressed. Also a fundamental understanding of some isolated aspects of fluid dynamic systems in an unsteady gravitational environment has been given. Given that perturbed accelerations exist in the microgravity environment, an estimation of the critical frequency ranges that drive a significant amount of convective motion, critical directions of modulation, and effects of random forcing have been estimated. Although these studies are useful in illustrating the basic features of g-jitter induced convection in a single component system, very little information seems to be available on the fundamental understanding of double diffusive convection in a microgravity environment [13].

In this paper, we consider the effect of g-jitter on the problem of double diffusion from an isothermal sphere that is immersed in a viscous and incompressible fluid. Double diffusive convection is referred to fluid flow generated by combined temperature and concentration gradients. It occurs in a wide range of scientific fields such as oceanography, astrophysics, geology, biology and chemical processes [14]. The study of double diffusion convection can be of critical importance in binary alloy solidification systems, because the quality of the final products is strongly correlated to the concentration distribution in the melt during processing.

Shu et al. [13] presented a numerical analysis of double diffusive convection induced by g-jitter in a cavity. Extensive simulations were carried out for temperature distribution and solutal (concentration) transport alloy system in space flights. The computations using finite element include the use of idealized single-frequency and multi-frequency g-jitter as well as real g-jitter data. These numerical results indicate that with an increase in g-jitter force (or amplitude), the non-linear convective effects become much more obvious, which in turn drastically change the concentration fields.

Our present work involves the generation of steady streaming for a double diffusion by natural convection from a sphere placed in a viscous and incompressible fluid under the influence of g-jitter of high frequency. The methodology here follows closely that of Amin [15] who investigated the heat transfer from a sphere immersed in an infinite fluid medium in a zero-gravity environment under the influence of g-jitter. Analytical results are presented for the case when the Reynolds number, Re, is small ($Re \ll 1$) and the Prandtl and Schmidt numbers are of O(1). Further, for the case ($Re \gg 1$), or the boundary layer approximation, and the Prandtl and Schmidt numbers are of O(1), numerical solutions are obtained using a very efficient implicit finite-difference method known as Keller-box method. The cases for assisting and opposing thermal and