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An analytical study of linear and non-linear double diffusive convection with Soret and Dufour effects in couple stress fluid

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Abstract

The onset of double diffusive convection in a two component couple stress fluid layer with Soret and Dufour effects has been studied using both linear and non-linear stability analysis. The linear theory depends on normal mode technique and non-linear analysis depends on a minimal representation of double Fourier series. The effect of couple stress parameter, the Soret and Dufour parameters, and the Prandtl number on the stationary and oscillatory convection are presented graphically. The Dufour parameter enhances the stability of the couple stress fluid system in case of both stationary and oscillatory mode. The effect of positive Soret parameter is to destabilize the system in case of stationary mode while it stabilizes the system in case of oscillatory mode. The negative Soret parameter enhances the stability in both stationary and oscillatory mode. The couple stress parameter enhances the stability of the system in both stationary and oscillatory modes. The Dufour parameter increases the heat transfer while the couple stress parameter has reverse effect. The Soret parameter has negligible influence on heat transfer. Both Dufour and Soret parameters increases the mass transfer while the couple stress parameter has dual effect depending on the value of the Rayleigh number.
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Keywords: Double diffusive convection; Dufour parameter; Soret parameter; Couple stress fluid

1. Introduction

If the gradients of two stratifying agencies, such as heat and salt, having different diffusivities are simultaneously present in a fluid layer, a variety of interesting convective phenomena can occur which are not possible in a single component fluid. Convection in a fluid layer with two or more stratifying agencies has been the subject of extensive theoretical and experimental investigations in the last few decades. Excellent reviews of these studies have been reported by Turner [1–3], Huppert and Turner [4] and Platten and Legros [5]. The interest in the study of two or multi-component convection has developed as a result of the marked difference between single component and multi-component systems. In contrast to single component system, convection sets is even when density decreases with height, that is, when the basic state is hydrostatically stable. The double diffusive convection is of importance in various fields such as high quality crystal production, liquid gas storage, oceanography, production of pure medication, solidification of molten alloys, and geothermally heated lakes and magmas.

Convection in a two-component fluid is characterized by well-mixed convecting layers, which are separated by relatively sharp density steps. These steps may be of the ‘finger’ or ‘diffusive’ kind and both types of interface must enable a net release of potential energy preferentially transporting the destabilizing property. Salt fingers will occur when warm salty fluid overlies cooler fresher fluid and diffusive instability will occur when warm salty fluid underlies the fresh cooler fluid. In two-component system, in the absence of cross-diffusion, instability can occur only if, at least one of the components is destabilizing. However, in the presence of cross-diffusions produced by the simultaneous interference of two transport properties e.g., Soret and Dufour effects the situations may be quite different [6–8].

Typically, the energy transport is described adequately by Fourier diffusion and the mass transport by Fickian diffusion alone. Otherwise, several investigators [9–12] have shown both

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Nomenclature

A_i	amplitude of streamline perturbation
B_i	amplitudes of thermal perturbation ($i = 1, 2$)
E_i	amplitudes of concentration perturbation ($i = 1, 2$)
C	couple stress parameter, $\mu_1/\mu d^2$
d	height of the fluid layer
Du	Dufour parameter ($=\beta_T \kappa_{12}/\beta_S \kappa_{11}$)
$\mathbf{g}$	gravitational acceleration
H	rate of heat transport per unit area
J	rate of mass transport per unit area
K^2	$\pi^2(\alpha^2 + 1)$
Nu	thermal Nusselt number
Nu^S	solute Nusselt number
p	pressure
Pr	Prandtl number ($=\nu/k_{11}$)
$\mathbf{q}$	velocity vector (u, v, w)
R	thermal Rayleigh number ($Ra = \beta_T g \Delta T\, d^3/\nu\kappa_{11}$)
R_S	solute Rayleigh number ($R_S = \beta_S g \Delta S\, d^3/\nu\kappa_{11}$)
S	solute concentration
Sr	Soret parameter ($=\beta_S \kappa_{21}/\beta_T \kappa_{11}$)
ΔS	salinity difference between the walls
T	temperature
ΔT	temperature difference between the walls
t	time (s)
x, y, z	space coordinates

Greek symbols

α	wavenumber
β_S	solute expansion coefficient
β_T	thermal expansion coefficient
Φ	dimensionless amplitude of concentration perturbation
η	$1 + CK^2$
κ_{11}	thermal diffusivity
κ_{12}	cross-diffusion due to S component
κ_{21}	cross-diffusion due to T component
κ_{22}	solute diffusivity
μ	dynamic viscosity
μ_1	couple stress viscosity
ν	kinematic viscosity, μ/ρ_0
Θ	dimensionless amplitude of temperature perturbation
ρ	density
σ	growth rate
τ	diffusivity ratio ($=\kappa_{22}/\kappa_{11}$)
ω	frequency
ψ	stream function
Ψ	dimensionless amplitude of stream function

Subscripts

b	basic state
c	critical
0	reference value

Superscripts

$*$	dimensionless quantity
$'$	perturbed quantity
osc	oscillatory
st	stationary

analytically and experimentally that both Soret and Dufour effects can be important contributions to the total mass and energy transfer, respectively. The thermal-diffusion (Soret) effect, for instance, has been utilized for isotope separation, and in mixture between gases with very light molecular weight (H_2, He) and of medium molecular weight (N_2, air) the diffusion-thermo (Dufour) effects was found to be of order of considerable magnitude such that it cannot be ignored [13]. In view of the importance of above-mentioned effects Atimtay and Gill [14] have shown that Soret and Dufour diffusion to be appreciable for convection on a rotating disc. Weaver and Viskanta [15] studied the influence of species interdiffusion, Soret and Dufour effects on the natural convection heat and mass transfer in a cavity due to combined temperature and concentration gradients. They have shown that contributions to the total mass flux through the cavity due to Soret diffusion can be as much as 10–15% and energy transfer due to Dufour effects can be appreciable compared to heat conduction. Kafoussias and Williams [16] studied thermal-diffusion and diffusion-thermoeffects on mixed free-forced convective and mass transfer boundary layer flow with temperature-dependent viscosity. Thermal convection in a binary fluid driven by the Soret and Dufour effects has been investigated by Knobloch [17]. He has shown that equations are identical to the thermosolutal problem except for a relation between the thermal and solute Rayleigh numbers. Mc Dougall [6] has made an in-depth study of double diffusive convection caused by molecular diffusion in a solute–solute pair for which both Soret and Dufour effects are important. Of particular interest, crystal growth from the vapour is sometimes carried out under conditions conducive to Soret and Dufour effects. As greater demands are made for tighter control of industrial process, second order effects such as Soret and Dufour diffusion must be considered. Because of the limited number of studies available, the knowledge concerning the influence of these effects on the heat and mass transfer and fluid flow is incomplete.

With the growing importance of non-Newtonian fluids in modern technology and industries, the investigations on such fluids are desirable. During recent years the theory of polar fluids has received much attention and this is because the traditional Newtonian fluids cannot precisely describe the characteristics of the fluid flow with suspended particles. The study of

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