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Research Article

Double Diffusive Surface Driven Convection in a Fluid-Porous System

Y. H. Gangadharaiah

Department of Mathematics, RV Institute of Technology and Management, Bangalore, India

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ABSTRACT

In the present study, double-diffusive surface-driven convective flow in a system composed of a horizontal binary fluid layer overlying an anisotropic porous matrix has been investigated. The boundaries are insulating to temperature perturbations, and the regular perturbation technique is applied to obtain thermal Marangoni number. It is discovered that the solute Marangoni number, the depth of the relative layers, the Darcy number, the diffusivity ratios, thermal and mechanical anisotropy parameters have a significant impact on the system's stability. Increasing the diffusivity ratios, the thermal anisotropy parameter, and decreasing the solute Marangoni number, the mechanical anisotropy parameter leads to stabilization of the system. Besides, the possibility of control of surface-driven convective motion by suitable choice of physical parameters is discussed in detail.

1. Introduction

When the top surface of a liquid-filled enclosure is exposed to a liquid with low viscosity, such as air, the surface tension gradient may cause fluid to flow within the enclosure. Such a flow is called the surface-driven convection or thermocapillary flow. The surface tension effect can be seen in low gravity systems, and it has applications in liquid melting, defect-free crystal formation, glass manufacturing, resolidifying, and welding. Incompressible fluids are suitable for the analysis of Marangoni convection since the flow velocity of such systems is usually in the subsonic range. Other physical phenomena occur as buoyancy develops as a result of both concentration and thermal diffusion of species present in the fluid. Some of the uses of such phenomena include atmospheric convection, earth warming, and the elimination of contaminants from a solution. If the density and surface tension also differ with solute concentration, the phenomenon is called

Corresponding e-mail: gangu.honnappa@gmail.com

Nomenclature

a	horizontal wave number	d	thickness of the porous layer
D	differential operator d/dz	d_m	thickness of the porous layer
Da	Darcy number K_v/d_m^2	p	pressure
M_T	Thermal Marangoni number	T_0	temperature at the interface
W	perturbed vertical velocity	T	temperature
Pr	Prandtl number for fluid layer	Pr_m	Prandtl number
β	slip parameter	$\vec{V}$	velocity vector (u, v, w)
∇_h^2	horizontal Laplacian operator	Ms	Solute Marangoni number
∇^2	Laplacian operator	$\vec{V}$	velocity vector
ε_T	ratio of thermal diffusivities	ϕ	porosity of the porous medium
κ	thermal diffusivity	θ	amplitude of perturbed temperature
μ	fluid viscosity	ρ_0	fluid density
σ	temperature dependent surface tension	v	kinematic viscosity

thermocapillary convection. Double-diffusive surface-driven convection is the study of the relationship between these two types of flows.

There are a variety of circumstances in which a contaminant is removed by a chemical reaction between the contaminant and another chemical agent, according to chemical engineering. Such phenomena are used in a variety of physical applications, including geothermal engineering, nuclear waste disposal, and electrochemical processes.

Surface-induced convective motion in a composite layer system with a fluid layer overlying a porous matrix has gotten a lot of attention recently because of its important geophysical and industrial applications (Nield [1,2], Chen[3] Straughan [4] and Carr [5]), such as oil flow in underground reservoirs, alloy solidification, hydrothermal synthesis in crystalline material growth, mixing, and in ice-covered lakes. A large number of studies on the thermocapillary instability in a two layer system have been published in recent decades(Suma et al.[6], Khalili et al.[[7], Gangadharaiah et al.[8], Shivakumara et al.[9], Gangadharaiah [10], Gangadharaiah and Ananda [11] and Gangadharaiah and Suma [12]).

Sheng Chen et al. [13] used the lattice Boltzmann model to investigate double-diffusive thermocapillary instability in vertical annuluses with contradicting concentration and temperature gradients, which is of vital interest and viable significance. The successive over-relaxation technique was used by Saleem et al. [14] to study the thermocapillary convective motion in a square cavity. Using the perturbation method, Gangadharaiah [15] has examined double-diffusive thermocapillary convection in a composite layer. Sumithra [16] used the perturbation technique to expand the magneto-double-diffusive convection in a composite layer. Massimo Corcione et al.[17] have investigated numerically double-diffusive convective motion in vertical square enclosures caused by horizontal concentration and temperature gradients. Tatyana and Ekaterina[18] examined the onset of double-diffusive instability in a two layers under small-amplitude vibrations and high-frequency. The Kuppers-Lortz convective flow in rotating fluid bounded by rigid/free isothermal boundaries was investigated by Kanchana et al. [19]. They demonstrate that alumina nanoparticles in water have the same effect as alumina and copper in water.

In this paper, the thermocapillary instability in a fluid-porous system is examined. The resulting eigenvalue problem is solved using a regular perturbation, and an expression for the thermal Marangoni number is obtained, and the results are dissipated graphically to determine the impact of solute Marangoni number Ms, the mechanical anisotropy parameter ξ, the depth ratio ζ, the Darcy number Da, thermal anisotropy parameter η, and the diffusivity ratios τ & τ_m along with other physical parameters.

2. Conceptual Model

We consider the horizontal two-layer system of an anisotropic porous bed of width d_m underlying a fluid layer of width d, the lower boundary of the porous layer is taken to be rigid(see Fig.1).

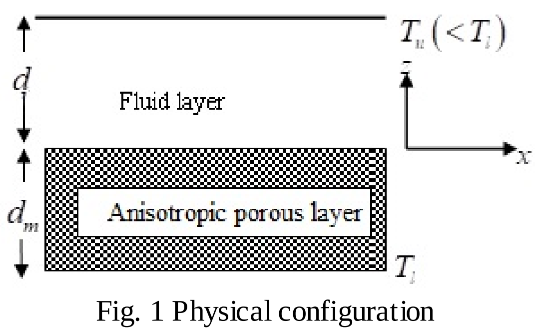

Fig. 1 Physical configuration

3. Mathematical Formulation

The mathematical governing relation for the above configuration are

Fluid zone:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\rho_0 \left(\frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \nabla \right) \vec{V} \right) = \mu \nabla^2 \vec{V} - \nabla p \tag{2}$$

$$\frac{\partial T}{\partial t} + \left(\vec{V} \cdot \nabla \right) T = \kappa \nabla^2 T \tag{3}$$

$$\frac{\partial C}{\partial t} + \left(\vec{V} \cdot \nabla \right) C = D \nabla^2 C \tag{4}$$

Porous zone:

$$\nabla_m \cdot \vec{V}_m = 0 \tag{5}$$

$$\frac{\rho_0}{\phi} \frac{\partial \vec{V}_m}{\partial t} = -\nabla_m p_m - \frac{\mu}{\underset{\sim}{K}} \cdot \vec{V}_m \tag{6}$$

$$A \frac{\partial T_m}{\partial t} + \left(\vec{V}_m \cdot \nabla_m \right) T_m = -\nabla_m \cdot \left(\underset{\sim}{\kappa} \cdot \nabla_m T_m \right) \tag{7}$$

$$\frac{\partial C_m}{\partial t} + \left(\vec{V}_m \cdot \nabla \right) C_m = D_m \nabla^2 C_m \tag{8}$$

Infinitesimal disturbances are implemented to measure the convective motion of the basic solution.

$$\vec{V} = \vec{V}', \quad T = T_b(z) + T' \; \&$$

$$C = C_b(z) + C', \quad p = p_b(z) + p' \tag{9}$$

$$\vec{V}_m = \vec{V}_m', \; T_m = T_{mb}(z) + T_m', \quad C_m = C_{mb}(z) + C_m', \; p_m = p_{mb}(z) + p_m', \tag{10}$$

The dimensional less disturbance equations are given by (after linearization)

$$\left(-\nabla^2 + \frac{1}{Pr} \frac{\partial}{\partial t} \right) \nabla^2 w = 0 \tag{11}$$

$$\left(-\nabla^2 + \frac{\partial}{\partial t} \right) T = w \tag{12}$$

$$\left(\frac{\partial}{\partial t} - \tau \nabla^2 \right) C = w \tag{13}$$

$$\left(\frac{Da}{Pr_m} \frac{\partial}{\partial t} + \xi \, \nabla_{mh}^2 + \frac{\partial^2}{\partial z_m^2} \right) w_m = 0 \tag{14}$$

$$\left(A\frac{\partial}{\partial t}-\eta\nabla_{mh}^2-\frac{\partial^2}{\partial z_m^2}\right)T_m=w_m \quad (15)$$

$$\left(\frac{\partial}{\partial t}-\tau_m\nabla^2\right)C=w_m \quad (16)$$

Normal mode analysis

$$(w,T,C)=\left[W(z),\Theta(z),S(z)\right]f(x,y) \quad (17)$$

$$(W_m,T_m,C_m)=\left[W_m(z_m),\Theta_m(z_m),S(z_m)\right]\times f_m(x_m,y_m) \quad (18)$$

where $f(x,y)$ and $f_m(x_m,y_m)$ are horizontal plan forms satisfying $\nabla_h^2 f=-a^2 f$ *and* $\nabla_{mh}^2 f_m=-a_m^2 f_m$.

Substituting Eqs. $(17)-(18)$ in Eqs. $(11)-(16)$, we obtain the following ordinary differential equations:

$$\left(D^2-a^2\right)^2W=0 \quad (19)$$

$$\left(D^2-a^2\right)\Theta=-W \quad (20)$$

$$\tau\left(D^2-a^2\right)S=-W \quad (21)$$

$$\left(D_m^2-\xi a_m^2\right)W_m=0 \quad (22)$$

$$\left(D_m^2-\eta a_m^2\right)\Theta_m=-W_m \quad (23)$$

$$\tau_m\left(D_m^2-a_m^2\right)S_m=-W_m \quad (24)$$

The boundary conditions are of the form

$$W=D\Theta=DS=0 \quad \text{at } z=1 \quad (25)$$

$$D^2W+M\,a^2\Theta+M_S\,a^2S=0 \ at\ z=1 \quad (26)$$

$$D_m\Theta_m=D_mS_m=W_m=0 \ at\ z_m=-1 \quad (27)$$

and $at\ z=0,$ are

$$W=\frac{\zeta}{\varepsilon_T}W_m \quad (28)$$

$$D\Theta=D_m\Theta_m \quad (29)$$

$$DS=D_mS_m \quad (30)$$

$$\Theta=\frac{\varepsilon_T}{\zeta}\Theta_m \quad (31)$$

$$S=\frac{\varepsilon_s}{\zeta}S_m \quad (32)$$

$$\left[D^2-3a^2\right]DW=\frac{-\zeta^4}{\varepsilon_T\sqrt{Da\xi}}D_mW_m \quad (33)$$

$$\left[D^2-\frac{\beta\zeta}{\sqrt{\xi Da}}D\right]W=\frac{-\beta\zeta^3}{\varepsilon_T\sqrt{\xi Da}}D_mW_m \quad (34)$$

4. Solution by regular perturbation technique

The dependent variables are now expanded in powers of a^2 in the form

$$(W,\Theta,S)=\sum_{i=0}^{N}\left(a^2\right)^i\left(W_i,\Theta_i,S_i\right) \quad (35)$$

$$(W_m,\Theta_m,S_m)=\sum_{i=0}^{N}\left(\frac{a^2}{\zeta^2}\right)^i\left(W_{mi},\Theta_{mi},S_{mi}\right) \quad (36)$$

Substituting these equations in to obtained eigen value problem and collecting the leading order in a^2 become,

$$D^4W_0=0 \quad (37)$$

$$D^2\Theta_0=-W_0 \quad (38)$$

$$\tau D^2S_0=-W_0 \quad (39)$$

$$D_m^2\,W_{m0}=0 \quad (40)$$

$$D_m^2\Theta_{m0}=-W_{m0} \quad (41)$$

$$\tau_mD_m^2S_{m0}=-W_{m0} \quad (42)$$

and the boundary conditions $(25)-(34)$ become

$$W_0=0,\ D\Theta_0=0,\ D^2W_0=0\ at\quad z=1 \quad (43)$$

$$W_{m0}=0,\ D_m\Theta_{m0}=0,\ at\quad z_m=-1 \quad (44)$$

and $at\ z=0,$ are

$$W_0=\frac{\zeta}{\varepsilon_T}W_{m0} \quad (45)$$

$$\Theta_0=\frac{\varepsilon_T}{\zeta}\Theta_{m0} \quad (46)$$

$$S_0=\frac{\varepsilon_s}{\zeta}S_{m0} \quad (47)$$

$$D\Theta_0=D_m\Theta_{m0} \quad (48)$$

$$DS_0=D_mS_{m0} \quad (49)$$

$$D^2W_0 - \frac{\beta\zeta}{\sqrt{\xi Da}} DW_0 = \frac{-\beta\zeta^3}{\varepsilon_T\sqrt{\xi Da}} D_m W_{m0} \quad (50)$$

$$D^3W_0 = \frac{-\zeta^4}{\varepsilon_T Da} D_m W_{m0} \quad (51)$$

The solution above equations is given by

$$W_0 = 0, \quad \Theta_0 = \frac{\varepsilon_T}{\zeta}, \ S_0 = \frac{\varepsilon_S}{\zeta} \quad (52)$$

$$W_{m0} = 0, \quad \Theta_{m0} = 1, \ S_{m0} = 1 \quad (53)$$

the first order in a^2, Eqs $(37)-(42)$ then reduce to

$$D^4W_1 = 0 \quad (54)$$

$$D^2\Theta_1 - \frac{\varepsilon_T}{\zeta} = -W_1 \quad (55)$$

$$\tau D^2S_1 - 1 = -W_1 \quad (56)$$

$$D_m^2 W_{m1} = 0 \quad (57)$$

$$D_m^2\Theta_{m1} - 1 = -W_{m1} \quad (58)$$

$$D_m^2 S_{m1} - 1 = -W_{m1} \quad (59)$$

and the boundary conditions $(25)-(34)$ become

$$W_{m1} = 0, D_m\Theta_{m1} = 0, \text{at} \quad z_m = -1 \quad (60)$$

$$W_1 = 0, D\Theta_1 = 0, \ \text{at} \quad z = 1 \quad (61)$$

$$D^2W_1 + M\frac{\varepsilon_T}{\varsigma} + M_S\frac{\varepsilon_s}{\varsigma} = 0 \ \text{ at } z = 1 \quad (62)$$

and *at* $z = 0$, are

$$W_1 = \frac{1}{\zeta\varepsilon_T} W_{m1} \quad (63)$$

$$\Theta_1 = \frac{\varepsilon_T}{\zeta^3}\Theta_{m1} \quad (64)$$

$$S_1 = \frac{\varepsilon_s}{\zeta^3} S_{m1} \quad (65)$$

$$D\Theta_1 = \frac{1}{\zeta^2} D_m\Theta_{m1} \quad (66)$$

$$DS_1 = \frac{1}{\zeta^2} D_m S_{m1} \quad (67)$$

$$D^2W_1 - \frac{\beta\zeta}{\sqrt{\xi Da}} DW_1 = \frac{-\beta\zeta}{\varepsilon_T\sqrt{\xi Da}} D_m W_{m1} \quad (68)$$

$$D^3W_1 = \frac{-\zeta^2}{\varepsilon_T \xi Da} D_m W_{m1}. \quad (69)$$

Then solvability condition is given by

$$\left\{ \begin{array}{c} \int_0^1 f(z) W_1\, dz + \frac{1}{\zeta^2}\int_{-1}^{0} W_{m1}\, dz \\ + \\ \frac{1}{\tau}\int_0^1 W_1\, dz + \frac{1}{\tau_m\ \zeta^2}\int_{-1}^{0} W_{m1}\, dz \end{array} \right\} = \left\{ \begin{array}{c} \frac{(\varepsilon_T + \varepsilon_s)}{\zeta} \\ + \\ \frac{(\eta + 1)}{\zeta^2} \end{array} \right\} \quad (70)$$

where $M_S = -\sigma_C\,\Delta C\, d/\mu D$ is the solute Marangoni number, $M = -\sigma_T\,\Delta T\, d/\mu\kappa$ is the thermal Marangoni number.

The general solution of Eqs. $(54)\&(57)$ are respectively given by

$$W_1 = c_1 + c_2 z + c_3 z^2 + c_4 z^3 \quad (71)$$

$$W_{m1} = c_5 + c_6 z_m \quad (72)$$

Where

$$c_1 = 4\mathrm{Da}\varepsilon_{\mathrm{T}}\ (2\sqrt{\mathrm{Da}} + \zeta\beta\ ),$$

$$c_2 = \left(-6\sqrt{\mathrm{Da}} - 3\zeta^2\beta + \varepsilon_s\,\zeta^2/\sqrt{\mathrm{Da}}\right)\Delta,$$

$$c_3 = \frac{7\varepsilon_{\mathrm{T}}\beta\eta\mathrm{Da}(\zeta^3\text{-}\xi\eta - 1)}{2\zeta\,\eta\ \Delta},$$

$$c_4 = \frac{\varepsilon_{\mathrm{T}}\zeta(\ 2\varepsilon_s\sqrt{\mathrm{Da}} + \varepsilon_{\mathrm{T}}\zeta\beta)}{2\xi\Delta},$$

$$c_5 = c_6 = \frac{-6\varepsilon_T^2(\ 2 + \zeta\varepsilon_S\beta/\sqrt{\mathrm{Da}})}{\zeta\ \Delta}$$

$$\Delta = 4\ \zeta^2\sqrt{\mathrm{Da}}\, M_T\ +\ (2\ \eta\varepsilon_T\text{-}\ 3\ Ms\xi)\zeta^3\beta$$

Substituting for W_1 and W_{m1} in Eq.(70), we obtain an expression for the thermal Marangoni number M_T in the form

$$M_T = \frac{120\eta\zeta\left(\begin{array}{c} 3\zeta^2\sqrt{\mathrm{Da}}\,(-Ms + \varepsilon_S\eta) + \\ 3Da\beta(\varepsilon_T - \zeta^2) + \beta\zeta^3(1 + \varepsilon_T) \end{array} \right)}{\Delta_1 + \Delta_2} \quad (73)$$

Where

$\Delta_1 = 7\varepsilon_T\ \zeta^2\sqrt{\text{Da}}\,Ms + \left(2\varepsilon_S\ \eta\varepsilon_T - 3\ Ms\xi\right)\zeta^3,$

$\Delta_2 = \left(2\ \eta^2\varepsilon_T - 3\ Ms\sqrt{\text{Da}}\ \xi^3\right)\zeta^3\beta + 6\zeta^4\xi Ms$

From (73), we note that in the absence of Ms , and as $\zeta \to \infty$, $M_c \to 48$. This is the exact value for a signal fluid layer that is defined (Pearson1958).

5.Results and Discussion

The onset of thermocapillary convective motion in a two layer system composed of a horizontal binary fluid with an anisotropic porous layer has been examined. The perturbation technique is used to solve the resulting eigenvalue problem.For the sake of comparison, the findings of Shivakumara et al. [20] are shown in Table 1 for various values ζ *and* Da with $M_S = 0$. Our findings are found to be in strong agreement.

The influence of the anisotropy effect on the convective motion of the composite system is presented in Fig.2. The graph depicts the impact of thermal Marangoni number M_T verses ξ for various values of solute Marangoni number M_S with $\varepsilon_s = 0.725, \beta = 1 = \zeta$, $Da = 0.003$ & $\varepsilon_T = 0.725$. It should be observed that for the above-mentioned values of M_S , the thermal Marangoni number reaches higher values at lower values of ξ. Decreases in ξ prolong the onset of surface-driven convection, in other words. On the contrary, decreasing the thermal anisotropy parameter η hastens the onset of thermocapillary convection, as shown in Fig.3.

In Figure4, we plot M_T versus ζ for various values of Da and M_S when $\beta = 1$, $\varepsilon_T = \varepsilon_s = 0.725$ are showed in a Fig 4. As expected, the impact of the decrease Da is to raise the value of M_T. And also noted that, the effect of Darcy number has a significant role on the system stability for $\zeta \le 0.5$, while the curves of various Darcy number merge into one when $\zeta > 0.5$ for both $M_S = 0$ and $M_S = 10$. Increasing M_S is delay the onset of thermocapillary convection.

The impact of the solute Marangoni number M_S on M_T is shown in Fig.5, for different values of τ & τ_m when $Da = 0.003$, $\varepsilon_T = 0.725 = \varepsilon_S$, $\eta = \xi = 0.5$ & $\zeta = 1$. It is clear from the figures that the thermal Marangoni number is reduced by increasing the value of M_S and thus has a non-stabilizing effect on the system. However, an raise in the values of the thermal diffusivity ratios τ & τ_m is to increase the thermal Marangoni number is delay the onset of thermocapillary convection.

The effect of the thermal diffusivity ratios τ *and* τ_m on M_T is shown in Figs6 and 7, respectively, for different values of $M_S = 0, 10, 20$ when $Da = 0.003$, $\varepsilon_T = 0.725 = \varepsilon_s$ $\eta = \xi = 0.5$ & $\zeta = 1$. It is clear from the figures that raising the value of M_S lowers the thermal Marangoni number, which has a non-stabilizing effect on the system. However, raise in the values of thermal diffusivity ratios τ *and* τ_m is to raise M_T , as a result, the start of convection is postponed.

Figure.8 shows the perturbed vertical velocity eigenfunctions W & W_m for various values of the thermal anisotropy parameter η for $\xi = 0.5$ $\zeta = 1$, $\varepsilon_T = 0.725 = \varepsilon_s$ and $Da = 0.003$. The effect of the thermal anisotropy parameter η has no noticeable influence on W_m but is to accelerate W for the higher values of the thermal anisotropy parameter η .

Table1 Comparison of M_T and ζ with Da when η = 0.5= ξ, ε_T = 0.725, β = 1 and $M_S = 0$

ζ	$Da = 0.001$		$Da = 0.003$		$Da = 0.005$	
	Present study	Shivakumara et al.[20]	Present study	Shivakumara et al.[20]	Present study	Shivakumara et al.[20]
0.1	5.178	5.178	3.198	3.198	2.631	2.631
0.5	68.934	68.934	42.717	42.717	31.999	31.999
1.0	72.414	72.414	64.118	64.118	58.314	58.314
1.5	66.136	66.136	62.651	62.651	60.069	60.069
2.0	62.091	62.091	60.058	60.058	58.567	58.567
2.5	59.465	59.465	58.055	58.055	57.038	57.038

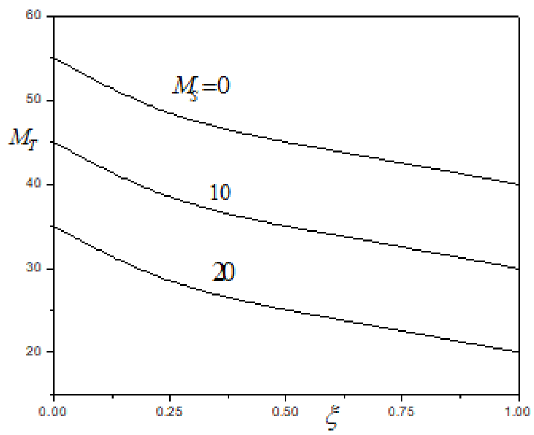

Fig. 2 M_T versus ξ for different values of Ms with $\tau_m = \eta = \tau = 0.5 \& \zeta = 1.$

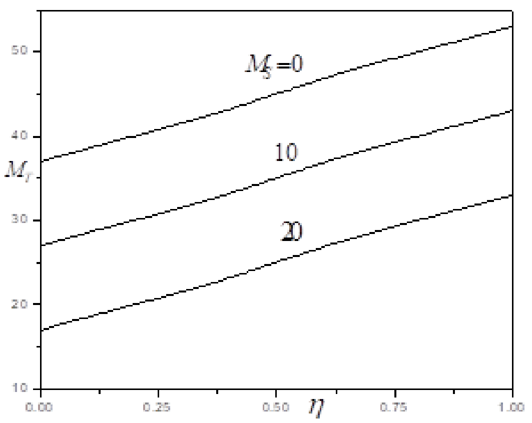

Fig. 3 M_T versus η for various values of Ms with $\tau_m = \xi = \tau = 0.5 \& \zeta = 1.$

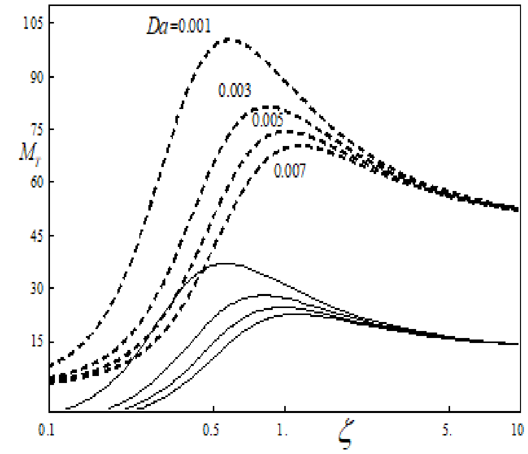

Fig. 4 M_T versus ζ for various values of Da for (a) *dashed line* $M_S = 0,\ \zeta = 1 \&$ $\eta = \xi = 0.5$
(b) *thick line* $M_S = 10, \eta = \xi = 0.5 \& \zeta = 1.$

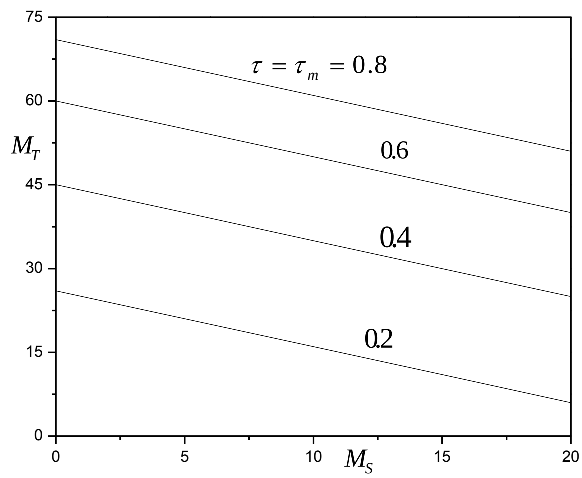

Fig. 5 M_T versus M_S for different values of τ & τ_m with $\eta = \xi = 0.5 \& \zeta = 1.$

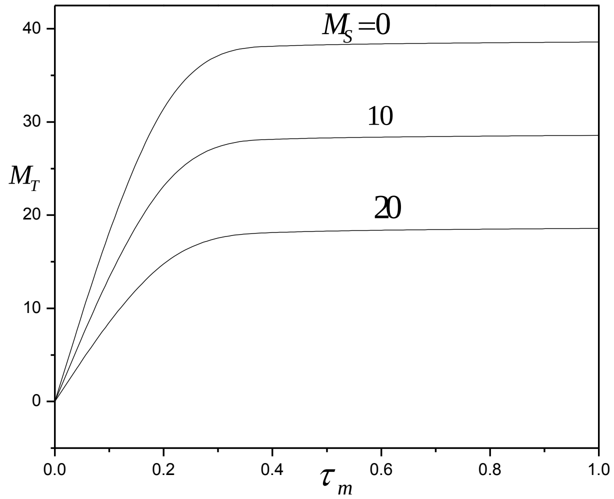

Fig. 6 M_T versus τ_m for different values of Ms with $\eta = \xi = \tau = 0.5 \& \zeta = 1$.

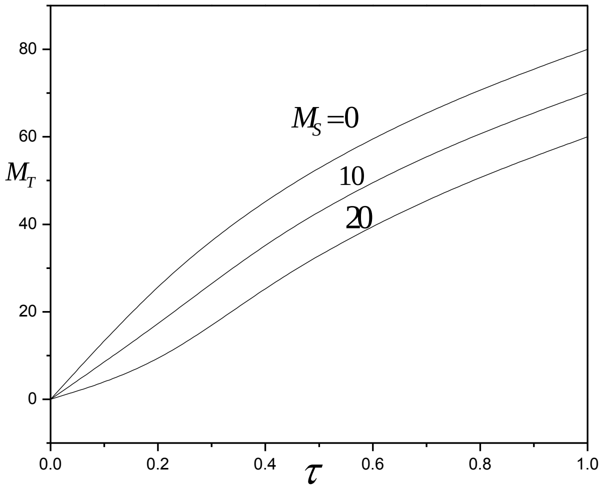

Fig. 7 M_T versus τ for different values of Ms with $\tau_m = \eta = \xi = 0.5 \quad \& \zeta = 1$.

6. Conclusions

Double-diffusive surface-driven convective motin in a system composed of a horizontal binary fluid with an anisotropic porous matrix has been investigated. The key outcomes of the study of linear stability are defined as follows:

- The vertical velocity flow has maximum as the effect of the thermal anisotropy parameter η increases.
- Stabilization of the system is achieved by decreasing the solute Marangoni number and the mechanical anisotropy parameter.
- The system stabilizes as the thermal anisotropy and diffusivity ratios parameters are increased.

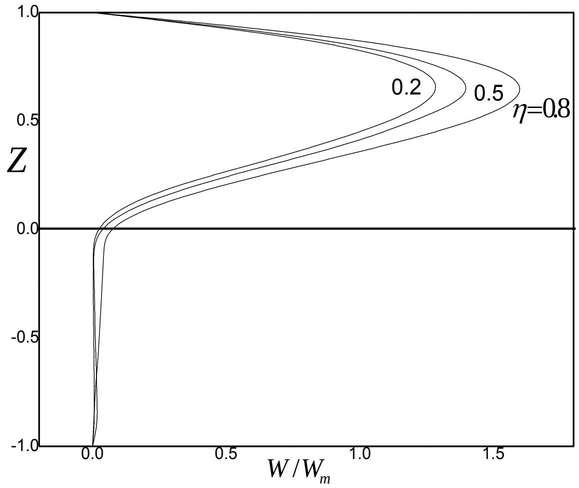

Fig. 8. Vertical velocity profile for different values of η with $\xi = 0.5$, $\zeta = 1$.

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