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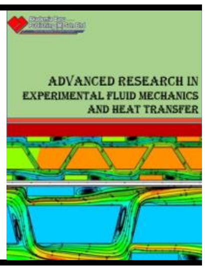

Temperature Condition Impact on The Onset of Rayleigh-Benard Convection in a Binary Fluid Saturated Anisotropic Porous Layer

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ABSTRACT

Rayleigh-Benard convection in a saturated anisotropic porous media is investigated numerically. The temperature-dependent viscosity effect was applied to the double-diffusive binary fluid, and the Galerkin method was used to determine the critical Rayleigh numbers for the free-free, rigid-free, and rigid-rigid representing the lower-upper boundaries. The lower and upper boundary was set to be either conducting or insulating to temperature. The purpose of this study is to study the stability of Rayleigh-Benard convection with different temperature conditions in a binary fluid saturated by an anisotropic porous layer. The obtained eigenvalue is numerically solved with respect to various temperatures and velocities using the single-term Galerkin technique. The results, presented graphically, indicate that the rigid-rigid boundaries are more stabilize compared to rigid-free and free-free boundaries. It is also shown that an increase of temperature-dependent viscosity tends to destabilize the onset of double-diffusive convection.

Keywords:
Temperature dependent viscosity; binary fluid; anisotropic porous

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1. Introduction

Rayleigh - Benard convection is the simplest system for turbulent convection where the layer of fluid is heated from below and cooled from above. In a double diffusive binary mixture, there are two effects which are Soret and Dufour [1-3]. It is first reported by Nield and Kuznetsov [4] where both stationary and oscillatory mode for thermosolutal convection binary fluid layer induced by thermal and solutal gradients is investigated. Abidin [5] investigated the linear stability characteristics of a porous layer with simultaneous temperature and solute concentration gradients for both strong and weak constant vertical flow and with also different temperature condition at the upper boundary.

A porous medium can be described as a solid or a series of solid materials (consists of pores or voids) with sufficient open space to allow fluid to move through or around the solids in or around

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them as described by Ramakrishna *et al.,* [6]. The physical characteristics of the fluid in the porous medium have countless applications with different surface geometries and boundary conditions such as nuclear waste management, the spread of pollutants, packed-bed reactors, petroleum reservoirs etc., which has attracted significant interest in recent decades.

The impact of temperature conditions on the onset of Rayleigh-Bénard convection in a binary fluid-saturated anisotropic porous layer is profoundly influenced by factors such as temperature-dependent viscosity and the Soret and Dufour effects. Griffiths [7] discusses the dynamics of thermals in extremely viscous fluids and highlights the significant role of temperature-dependent viscosity in altering convection patterns. Moorthy and Senthilvadivu [8] further explore how the Soret and Dufour effects influence natural convection flows in porous media, emphasizing the interplay between thermal and solutal gradients in such systems. Nanjundappa *et al.,* [9] examine Marangoni-Bénard ferroconvection, showing how temperature-dependent viscosity can impact the stability and onset of convection in fluid layers. Additionally, Pal and Mondal [10] investigate the effects of Soret and Dufour on magnetohydrodynamic (MHD) buoyancy-driven convection, which is relevant for understanding how temperature gradients influence convective stability in binary fluid systems.

The onset of Rayleigh-Bénard convection in a binary fluid-saturated anisotropic porous layer is significantly affected by temperature conditions, particularly due to variable viscosity and elastic effects. Ramirez and Saez [11] demonstrated that variable viscosity can alter boundary-layer heat transfer in porous media, highlighting the complexity of convective heat transfer under different temperature gradients. Sekhar and Jayalatha [12] further explored how elastic effects in liquids with temperature-dependent viscosity influence Rayleigh-Bénard convection, revealing that such variations can either stabilize or destabilize the convective patterns depending on the specific conditions. Trompert and Hansen [13] examined the Rayleigh number's dependence on convection with strongly temperature-dependent viscosity, showing that higher Rayleigh numbers can enhance convective activity, which is crucial for understanding the onset of convection in porous layers. These studies collectively emphasize that the temperature condition, particularly through its impact on viscosity, plays a pivotal role in initiating and modulating Rayleigh-Bénard convection in binary fluid systems.

According to Srinivasacharya *et al.,* [14] the Soret and Dufour effects are encountered in many practical applications such as in the areas of geosciences and chemical engineering. Shivakumara and Khalili [15] were studying convective instabilities in the presence of two opposing buoyancy driven components with different molecular diffusivities called double diffusive convection. The control of double-diffusive convection in porous media plays an important role. This can be achieved by different physical mechanisms such as rotation and or magnetic field or by non-uniform basic temperature gradients. The effect of vertical through flow on double diffusive convection in a porous medium is important due to its applications in engineering, geophysics, and seabed hydrodynamics.

Alam and Rahman [16] investigate the Dufour and Soret effects on mixed convection flow past a vertical porous flat plate embedded in a porous medium have been studied numerically. A similarity transformation was used to convert the governing nonlinear partial differential equations into a system of ordinary differential equations, which were then numerically solved using the Nachtsheim-Swigert shooting iteration technique and sixth order Runge-Kutta integration scheme. The local skin-friction coefficient, the local Nusselt number, and the local Sherwood number are a few examples of numerical values of physical quantities that are provided in tabular form.

Abidin *et al.,* [17] focused the effect of temperature dependent viscosity in a double diffusive binary fluid layer together with the coupled effects of Coriolis force and internal heat generation. The Soret and Dufour effects are taken into account as these effects were often being ignored in previous research problems due their small magnitude and the model aims to be beneficial for the problems in oceanography or in other geophysics areas. They set the upper boundary be free and insulating and the lower boundary is set as rigid. However, the temperature conditions were set to be insulating or conducting. They also assumed that the upper surface to be nondeformable and employed the stability analysis theory and the result were solved by using Galerkin method. They conclude that temperature dependent viscosity destabilize the system where the marginal shift downwards as they increase the effect.

Nagarathnamma *et al.,* [18] investigated the stability due to variable heat source and variable gravity field by applying the linear stability principle using the Galerkin method. In their research, they analyze the effect of variable internal heat source on instability in an anisotropic porous matrix that was analytically studied through a regular perturbation procedure. The boundaries are regarded as rigid-free and insulating with a linear stability assessment. Rusdi *et. al.,* [19] findings from 2024 are examined, showing how these forces affect heat transport and fluid dynamics in porous materials. This study offers thorough analysis and conclusions that greatly advance our knowledge of complex fluid dynamics under many physical circumstances. In addition, Senin *et. al.,*[20] delves deeper into the effects of fluctuating gravitational forces on ferrofluids in porous media, providing insights into the fluids' stability and convection patterns. This research contributes significantly to the field of fluid mechanics, especially with regard to ferrofluid behavior and applications under various gravitational conditions.

The research conducted by Lingenthiran *et al.,* [21] underscores the significant progress made in the application of nanofluids to augment wear resistance and lubrication efficiency in mechanical systems, stressing the crucial function of nanoscale particles in enhancing tribological characteristics. Furthermore, their research on green engineering investigates the ways in which nanofluids might improve sustainability and energy efficiency, offering an eco-friendly method of maximizing mechanical and thermal performance [22]. These developments are especially important when thinking about binary fluid systems, where the addition of nanofluids might further improve the special interactions between various fluid components. The activity of viscoelastic nanofluid films sprayed on a stretching cylinder was studied by Auwalu *et al.,* [23] showing the potential of such fluids in complicated dynamic systems and emphasizing the significance of stability and entropy generation in their performance.

Numerous advantages can be gained from this research. Convection is useful for a number of tasks, such as measuring mass flow rates through pipelines, forecasting weather patterns, and computing forces and moments in airplanes. More companies in the sector are processing their products through the use of Rayleigh-Bernard convection, which involves heat transfer. Additionally, this topic has not yet been examined or studied while considering various temperature conditions. In this work, we investigated analytically the impact of different temperature dependent viscosity on the threshold of stable thermal convection in a binary fluid saturated anisotropic porous media using linear stability analysis.

2. Methodology

A Boussinesq binary fluid saturated in a horizontal porous layer at a depth d is considered. The gravity force g acts in the plane, which has an infinite horizontal extension in both the x and y-direction. The binary fluid's density ρ and velocity, v = (u, v, w) are assumed to be linearly dependent on the solute concentration, S, and the temperature gradient, T.

For the Boussinesq approximation, we assumed that all of the fluid's physical properties were constant, with the exception of the kinematic viscosity and density. These two parameters depend on the temperature, T, and the solute concentration, S. The equations are given by

$$\mu = \mu_0 \exp\left|-\mu_t\left(T - T_0\right) + \mu_s\left(S - S_0\right)\right| \tag{1}$$

$$\rho = \rho_0\left[1 - \alpha_t\left(T - T_0\right) + \alpha_s\left(S - S_0\right)\right] \tag{2}$$

Here, μ_0 and ρ_0 are the reference values at the reference temperature, T_0 and the reference concentration, S_0. μ_t and $\alpha_t t$ are the rate of change of kinematic viscosity and density with temperature. μ_S and α_S are the rate of change of kinematic viscosity and rate of change of density with concentration. Following the analysis, the derivation will begin with the Rayleigh-Benard convection's four governing equations Eq. (3-6).

The governing equations used is the mass Eq. (3), momentum Eq. (4), energy equation Eq. (5) and solute Eq. (6).

$$\nabla \cdot v = 0, \tag{3}$$

$$\frac{\rho}{\xi}\left[\frac{\partial v}{\partial t}\right] + \left(v \cdot \nabla\right) v = -\nabla p + \mu K \cdot v + \rho g, \tag{4}$$

$$\rho c\left[\eta \frac{\partial T}{\partial t} + \left(v \cdot \nabla\right) T\right] = \rho c D_{TC} \nabla^2 C + \nabla \cdot \left(D \cdot \nabla T\right), \tag{5}$$

$$\xi \frac{\partial C}{\partial t} + \left(v \cdot \nabla\right) C = D_S \nabla^2 C + D_{CT} \nabla^2 T, \tag{6}$$

where ξ is the porosity, t is the dimensionless time, p is the pressure, μ is the kinematic viscosity, $K = K_x^{-1}\left(ii + jj\right) + K_x^{-1}\left(kk\right)$ is the inverse of the anisotropic permeability tensor, g is the gravity, c is the specific heat, η is the specific heat ratio, D_{TC} is the Dufour diffusivity, $D = D_x\left(ii + jj\right) + D_z\left(kk\right)$ is the anisotropic heat diffusion tensor, D_S is the solutal diffusivity and D_{CT} is the Soret diffusivity.

The setting brings about infinitesimal disturbances,

$$\left(x, y, z\right) = \frac{x, y, z}{d}, t = \frac{tK}{d^2}, \left(u, v, w\right) = \frac{d\left(u, v, w\right)}{\alpha_f},\ p = \frac{pd^2}{\mu \alpha_f}, T = \frac{\left(T - T_0\right)}{\Delta T}, C = \frac{\left(C - C_0\right)}{\Delta C},$$

where α_f represents the fluid's thermal diffusivity. The governing Eq. (3)-(6) and hence take the following form

$$\nabla \cdot v = 0, \tag{7}$$

$$\frac{1}{\xi \Pr}\left[\frac{\partial v}{\partial t} + v \cdot \nabla v\right] = -\nabla p + \nabla v^2 + RaT\hat{e}_z + RsC\hat{e}_z, \tag{8}$$

$$\eta \frac{\partial T}{\partial t} + v \cdot \nabla T = \nabla^2 T + Df \nabla^2 C, \tag{9}$$

$$\xi_n \frac{\partial C}{\partial t} + v \cdot \nabla C = \frac{1}{Le} \nabla^2 C + Sr \nabla^2 T, \tag{10}$$

where $\eta = \frac{D_x}{D_z}$ is the thermal anisotropy parameter, $\Pr = \frac{\xi v d^2}{\rho \alpha_f}$ is the Prandtl number, $\xi = \frac{K_x}{K_z}$ is the mechanical anisotropy parameter, $Ra = \frac{\alpha g d \Delta T K_Z}{\mu \alpha_f}$ is the Rayleigh number, $Rs = \frac{\alpha_c g d \Delta C K_z}{\mu D_S}$ is the Solutal Rayleigh number, $Df = \frac{D_{TC} \Delta C}{\alpha_f \Delta T}$ is the Dufour parameter, $Le = \frac{\alpha_f}{D_s}$ is the Lewis number and $Sr = \frac{D_{CT} \Delta T}{\alpha_f \Delta C}$ is the Soret parameter. Here, $\xi_n = \frac{\xi}{\eta}$ is the normalized porosity where in this problem $\xi = \eta = 1$ is used to limit the parameter space to the smallest possible value.

The basic state of quiescence is described as follows

$$(u, v, w) = (0,0,0), T = T_b(z), p = p_b(z), \rho = \rho_b(z), C = C_b(z) \tag{11}$$

Eq. (7)-(10) are reduced by using Eq. (11),

$$\frac{\partial p_b}{\partial z} = Ra T_b + Rs C_b \tag{12}$$

$$\frac{\partial^2 T_b}{\partial z^2} = -Df \frac{\partial^2 C_b}{\partial z^2} \tag{13}$$

$$\frac{1}{Le} \frac{\partial^2 C_b}{\partial z^2} = -Sr \frac{\partial^2 T_b}{\partial z^2} \tag{14}$$

Here, superimpose perturbations on the fundamental solution in the following manner

$$(u, v, w, T, p, \rho, C) = \begin{bmatrix} 0 + u', 0 + v', 0 + w' \\ T_b(z) + T', p_b(z) + p' \\ \rho_b(z) + \rho', C_b(z) + C' \end{bmatrix}, \tag{15}$$

is replaced in Eq. (7)-(10) and linearized by ignoring the prime quantity's products. The resulting equations are as follows

$$\nabla \cdot v' = 0, \tag{16}$$

$$\left[\frac{1}{\partial t \eta \Pr} + (\hat{e}_z + \frac{1}{\xi} \nabla^2) \right] v' = -\nabla p + \nabla v' + Ra T' \hat{e}_z + Rs C' \hat{e}_z, \tag{17}$$

$$\eta \frac{\partial T'}{\partial t} - w' = \nabla^2 T' + Df \nabla^2 C', \tag{18}$$

$$\xi_n \frac{\partial C'}{\partial t} - w' = \frac{1}{Le}\nabla^2 C' + Sf\nabla^2 T'. \quad (19)$$

Operating Eq. (17) by eliminating the pressure term by using curl identity together with Eq. (16) and Eq. (17) can be written as

$$\frac{1}{\Pr}\frac{\partial}{\partial t}\nabla^2 w' - \nabla^4 w' = RaT'\nabla^2{}_d + \frac{Rs}{Le}C'\nabla^2{}_d \quad (20)$$

The following is a normal mode representation

$$(w', T', C') = \left[W(z), \theta(z), \phi(z)\right]e^{st + i(a_x x + a_y y)} \quad (21)$$

By following a normal mode model in Eq. (21) and substitute into differential Eq. (18)-(20) to get

$$\bar{f}\left[\left(\frac{D^2}{\xi} - \alpha^2\right) + \frac{s}{P_r}(D^2 - \alpha^2)\right]W + \alpha Ra\theta - \alpha Rs\phi = 0 \quad (22)$$

$$\left(D^2 - \eta\alpha^2 - s\right)\theta + W + Df(D^2 - \alpha^2)\phi = 0, \quad (1)$$

$$\frac{1}{Le}\left(D^2 - \alpha^2 - s\right)\phi + W + Sr(D^2 - \alpha^2)\theta = 0, \quad (2)$$

where $\alpha = \left(\alpha_x^2 + \alpha_y^2\right)^{\frac{1}{2}}$, $D = \frac{d}{dz}$ and $\bar{f}(z) = e^{B\left(z - \frac{1}{2}\right)}$. α represented here is the dimensionless horizontal wavenumber and since in this research paper, only stationary mode been considered, we now set the growth parameter, s = 0. B is the dimensionless viscosity parameter. It is decided to be isosolutal and use the average viscosity and temperature between the upper and lower boundary as reference parameters

$$W = DW = \Phi = 0 \;\; at \;\; z = 0,$$

$$W = D^2W = \Phi = 0 \;\; at \;\; z = 1.$$

Meanwhile for the temperature conditions, it is set to be either conducting, $\theta = 0$ or insulating, $D\theta = 0$.

The three variables are written as a series of basis functions, and the system is approximated using the weighted residuals method of the Galerkin type

$$W = \sum_{n=1}^{N} A_n W_n \theta = \sum_{n=1}^{N} M_n \theta_n \phi = \sum_{n=1}^{N} E_n \phi_n \quad (25)$$

where A_n, M_n, E_n are unknown coefficients.

A system of three linear algebraic equations with three unknowns, A_n, M_n, E_n, n = 1, 2, 3, … , N, where N is the natural number, is obtained by using expressions for W, Θ and Φ in the linearized Eq.

(22)–(24), multiplying all equations with the base functions, respectively, and integrating the functions. When the determinant of the coefficient matrix disappears, the Rayleigh number, Ra, acts as the eigenvalue to produce a system with a non-trivial solution.

We obtain the system of linear homogeneous algebraic equations using the boundary condition

$$A_{ji}W_i + M_{ji}\theta_i + E_{ji}\phi_i = 0,$$

$$F_{ji}W_i + G_{ji}\theta_i + H_{ji}\phi_i = 0,$$

$$I_{ji}W_i + J_{ji}\theta_i + K_{ji}\phi_i = 0. \tag{26}$$

The matrix's determinant must be zero for the set above of homogeneous algebraic equations to have a nontrivial solution. The lower-upper boundary conditions, namely free-free, rigid-free, and rigid-rigid, are used to approximate the solutions to select W_n, Φ_n, Θ_n, in general.

$$W = \Phi = \sin\left(z\pi\right) \tag{27}$$

$$W = 3z^2 - 5z^3 + 2z^4, \Phi = z\left(1-z\right) \tag{28}$$

$$W = z^2 - 2z^3 + z^4, \Phi = z^2\left(1-z\right) \tag{29}$$

For the velocity conditions, the lower boundary was set to be conducted to the temperature, meanwhile the upper boundary was set to be conducting or insulating.

For conducting,

$$\Theta = z\left(1-z\right) \tag{30}$$

For insulating,

$$\Theta = z^2\left(1-z\right) \tag{31}$$

The eigenvalue for the lower upper free-free boundary conditions, which corresponds to the Rayleigh number Ra, is obtained as

$$Ra = \frac{-\left[C_1(C_5C_9 - C_6C_8) + C_3(C_4C_8 - C_5C_7\right]}{a^2\theta W(C_4C_9 - C_6C_7)}$$

$$C_1 = \frac{(DW)^2}{\xi} - a^2W^2 + 2B(D^2W)(DW) - 2Ba^2(DW)(W)$$
$$+B^2(DW)^2 + B^2a^2W^2$$
$$C_2 = -a^2 Ra\theta W$$
$$C_3 = -Lea^2 Rs\phi W$$
$$C_4 = W\theta$$
$$C_5 = (D\theta)^2 - \eta a^2\theta^2$$
$$C_6 = Df(D\phi)(D\theta) - Dfa^2\phi\theta$$
$$C_7 = W\phi$$
$$C_8 = Sr(D\theta)(D\phi) - Sra^2\theta\phi$$
$$C_9 = Le(D\phi)^2 - Lea^2\phi^2$$

3. Results

Using the Galerkin method, we present the marginal stability parameters, Ra and the corresponding critical wave number, a numerically. For a given set of parameters, the critical Rayleigh number for the onset of convection defined as the minimum of the global minima of marginal curve. According to Abidin *et al.,* [24], the effect of the solutal Rayleigh number stabilized the system under various boundary conditions. For free-free, rigid-free, and rigid-rigid boundary conditions, they achieve the same result as Malashetty and Swamy [10]. The critical Rayleigh number comparison values for various boundary conditions with Le = 5, Rs =10, 0.5, 0.3, Sr = 0, and Df = 0 are presented in Table 1. As the solutal Rayleigh number, Rs, rises, the marginal stability curves shift upward, and the critical Rayleigh number, Ra_c, rises as well. It also demonstrated that, regardless of the solute Rayleigh number, Rs, a rigid-free boundary has the highest critical Rayleigh number, followed by free-free and rigid-free boundaries.

Table 1
The comparison of critical values of Rayleigh number, Ra_c with various boundaries in the absence of temperature viscosity ($B = 0$)

Rs	Malashetty and Swamy [25]	Abidin *et al.,* [24]		
	Free- free	Free-free	Rigid-free	Rigid-rigid
10	54.53	54.54	58.18	324.14
25	86.60	86.60	90.24	394.73
50	136.20	136.20	140.00	477.92
100	229.18	229.18	233.33	629.81

In addition, Abidin *et al.,* [24], in a comparison with Nield and Kuznetsov [4] found that the temperature-dependent viscosity destabilized for every wavenumber as B increased. The comparisons of the critical Rayleigh number, Ra, with that of Neild and Kuznetsov [4] for various values of temperature-dependent viscosity, B, can be seen in Table 2 where it is also similar to Table 1, where the most stable system was the rigid-rigid boundary, followed by the rigid-free and free-free boundaries.

Table 2
The comparisons of critical values of Rayleigh number, Ra between Neild and Kuznetsov [1] and Abidin *et al.,* [24] for different values of temperature dependent viscosity, B

Lower-upper boundaries	Neild and Kuznetsov [4]	Abidin *et al.,* [24]			
	B = 0	B = 0	B = 1	B = 2	B = 3
Free-free	657.5	657.53	612.90	474.54	201.92
Rigid-free	1140	1138.71	1006.14	769.47	393.70
Rigid-rigid	1750	1749.98	1704.40	1567.16	1338.41

In this study, using the same validity comparison results, we extend the finding by setting the upper boundary to be either conducting or insulating to temperature. Figure 1 shows the comparison for different velocity conditions where the lower-upper boundaries were set to be free-free, rigid-free and rigid-rigid. It shows that rigid-rigid boundaries are more stable compared to the rigid-free and free-free boundaries for both conducting and insulating case.

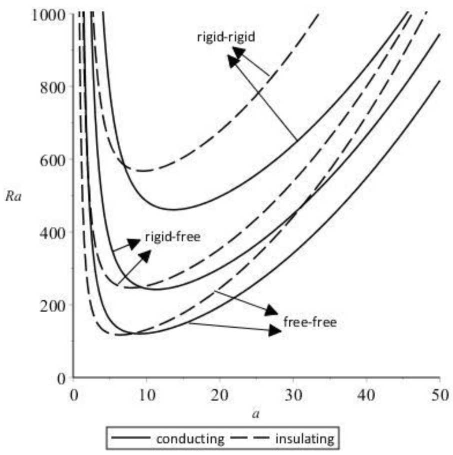

Fig. 1. Marginal stability curves for different upper boundary conditions

The stability of the Rayleigh-Benard convection in double-diffusive binary fluid with temperature-dependent viscosity, B is considered to analyze this effect in a double-diffusive binary fluid layer saturated in a porous layer. Figure 2 shows the result of marginal stability with different values of B on conducting case. It can be seen that the line stability curve shift to downward as the value of temperature dependent viscosity, *B* increase for free-free, rigid-free and rigid-rigid boundaries.

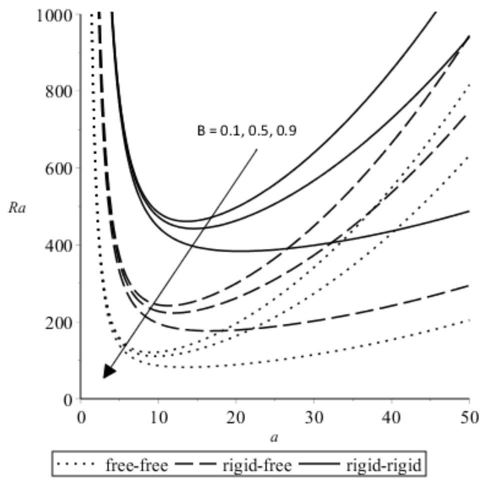

Fig. 2. Marginal stability curves for Conducting case with different B

The insulating case shown in Figure 3, shows a similar result where the marginal stability curves shifts downward as B is increases and the rigid-rigid boundary is the most stable system compared to the free-free boundary, as shown by the increasing critical Rayleigh number. The critical Rayleigh number, Ra_c obtained is shown clearly in Table 3. Here, the values are set ξ = 0.5, η = 0.3, Le = 5, Rs =10, Sr = 0.005, and Df = 0.005. The table also convey that conducting cases are more stable compared to insulating cases as the value in conducting cases exhibit a lower critical Rayleigh number, Ra_c.

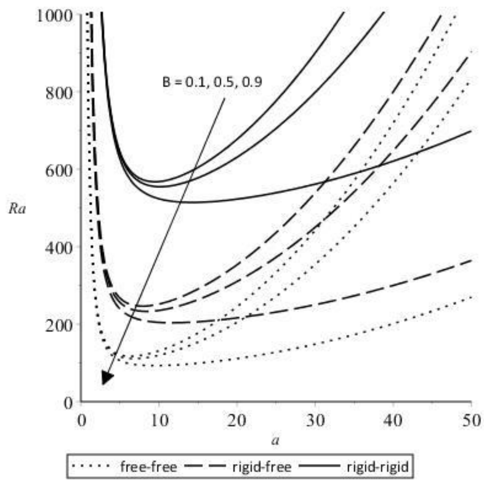

Fig. 3. Marginal stability curves for Insulating case with different B

Table 3
The comparisons of critical values of Rayleigh number, Ra_c for different values of temperature dependent viscosity, B

Lower-upper	Conducting			Insulating		
boundaries	B = 0.1	B = 0.5	B = 0.9	B = 0.1	B = 0.5	B = 0.9
Free-free	120.43	112.06	82.12	117.17	111.07	93.06
Rigid-free	242.11	223.16	176.55	246.84	234.62	203.78
Rigid-rigid	461.28	442.95	383.72	572.07	554.95	514.37

4. Conclusions

A comprehensive study of the temperature dependence of Rayleigh-Benard convection in a binary fluid-saturated anisotropic porous layer has been conducted. The present of double-diffusive convection is greatly influenced by the existence of temperature-dependent viscosity, or B where an increase of B will progress the onset of double-diffusive convection. From the analysis, it can be seen that the rigid-rigid system is the most stable boundary condition when compared to the free-free and rigid-free borders. This result emphasizes how important viscosity variations and boundary conditions are in controlling the stability and behavior of convective patterns in these kinds of systems.

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