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Double-diffusive convection in two-layer viscoelastic fluid systems

Zhiman Luan[1], Chen Yin[2,3*], Stuart Norris[4] and Ye Zhang[1,5]

[1]School of Mathematics and Statistics, Beijing Institute of Technology, Beijing, 100081, China

[2]School of Mathematics, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, 211106, China

[3]Key Laboratory of Mathematical Modelling and High Performance Computing of Air Vehicles (NUAA), MIIT, Nanjing, Jiangsu, 211106, China

[4]Department of Mechanical and Mechatronics Engineering, The University of Auckland, Auckland 1010, New Zealand

[5]MSU-BIT-SMBU Joint Research Center of Applied Mathematics, Shenzhen MSU-BIT University, Shenzhen, 518172, China

*yinchen@nuaa.edu.cn

1. INTRODUCTION

Double-diffusive convection, driven by combined thermal and solutal gradients, occurs in many natural and industrial processes, such as oceanography, geophysics, and chemical engineering. When the fluid is viscoelastic, elastic stresses interact with viscous effects, altering the onset and patterns of convection.

While double-diffusive convection in Newtonian fluids has been widely studied, the effects of viscoelasticity in multi-layer systems remain less explored. This study investigates a two-layer system saturated with a viscoelastic fluid, modeled using a linear viscoelastic constitutive relation that incorporates stress relaxation and strain retardation times.

The governing equations are nondimensionalized, yielding key parameters including the Biot number, layer thickness ratio, strain retardation time, stress relaxation time, solutal Rayleigh number, and Sherwood number. Linear stability analysis, solved numerically via the spectral method, is used to examine the onset of convection. This study provides insights into how these parameters influence the onset and characteristics of double-diffusive convection in layered viscoelastic systems, relevant to both theoretical and practical applications.

2. APPROACH

The system under consideration consists of two horizontal layers, one saturated with a viscoelastic fluid and the other representing a porous layer. The governing equations for momentum, heat, and mass transfer are formulated for a linear viscoelastic fluid, incorporating both stress relaxation and strain retardation effects.

The equations are nondimensionalized using characteristic scales for length, time, temperature, and solute concentration, resulting in key nondimensional parameters such as the Biot number (Bi), thickness ratio, solutal Rayleigh number (Ra_S), Sherwood number (Sh), stress relaxation time (λ), and strain retardation time (ε).

Linear stability analysis is applied by perturbing the quiescent conduction solution and linearizing the governing equations. The resulting eigenvalue problem is discretized and solved using the Chebyshev Tau spectral method, which provides high accuracy and computational efficiency for determining the critical Rayleigh numbers and corresponding instability modes.

3. RESULTS

- Thickness ratio effects: Greater thickness ratio increases the Rayleigh stability. This implies that increasing the thickness of the fluid layer or decreasing the thickness of the porous layer tends to stabilize the system, thereby delaying the onset of convection.
- Solutal effects: Greater solutal Rayleigh numbers Ra_S delay instability onset. Variation in Ra_S leads to changes in the modal structure of the system. Depending on Ra_S, the convection may exhibit either a single-mode or a double-mode instability.
- Surface heat and mass transfer effects: Greater Biot numbers increase the convective stability. Besides, the system reaches a saturation of instability when $Bi = 1$. Greater Sherwood number increase stabilities as well. However, the system is still not saturated in terms of instability when $Sh = 1$.
- Viscoelastic effects: Great stress ralaxation time λ and strain retardation time ε palys different role in convective instability. The former accelerates the onset of convection while the latter delays it.

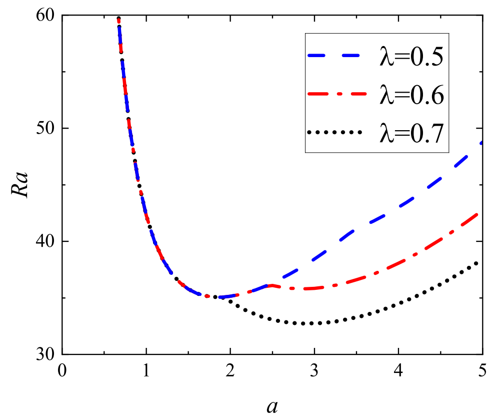

Figure 1. Neutral curves of Rayleigh flow for a set of stress retardation times λ.

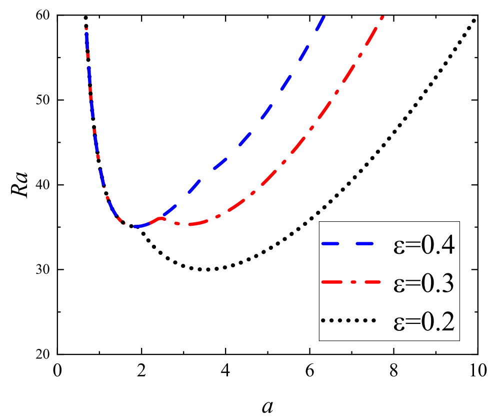

Figure 2. Neutral curves of Rayleigh flow for a set of stress retardation times ε.

4. CONCLUSIONS

This study examined double-diffusive convection in a two-layer viscoelastic system. Results show that increasing the layer thickness ratio, solutal Rayleigh number, Biot number, and Sherwood number enhances convective stability, while viscoelastic parameters have opposite effects. Variations in solutal Rayleigh number can lead to a transition between different dominant instability modes. These findings highlight the combined influence of geometric, thermal, solutal, and viscoelastic effects on the onset and nature of convection in layered fluid systems.

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