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NATURAL CONVECTION OF DIFFERENTIAL HEATED CAVITY WITH POLYMER ADDITIVES

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1. ABSTRACT

This study aims to investigate viscoelastic natural convection flow using the general pressure equation, considering Rayleigh (Ra) numbers ranging from 10^4 to 10^7, Weissenberg (Wi) numbers ranging from 1 to 100, and a maximum elongation length (L^2_{max}) equal to 10 and 500. The results indicate that at low elasticity effects (Wi=10), there is a slight increase in both maximum horizontal and vertical velocities, resulting in higher heat transfer. Conversely, high elasticity effects (Wi=100, L^2_{max}=500) led to a decrease in heat transfer compared to its Newtonian counterpart. The presence of polymer generated opposing stress near the wall, resulting in a decrease in vertical velocity and, consequently, heat transfer.

2. INTRODUCTION

Flows with polymer additives exhibit distinct characteristics that distinguish them from Newtonian fluids. One particularly intriguing phenomenon in this realm is polymer-induced turbulent drag reduction, which remains evident even with minute quantities of additives in turbulent flow. Since drag is closely tied to near-wall flow structures, it's natural to explore how polymer additives affect heat transport. However, it's important to note that the study of heat transport in polymer-additive flows hasn't received as much attention as their dynamic aspects.

In recent years, there's been a growing interest in understanding the heat transfer characteristics of viscoelastic polymer solutions in natural convection scenarios driven by temperature gradients. Specifically, research has focused on Rayleigh-Benard convection, where both heat transfer enhancement (THE) and heat transfer reduction (HTR) compared to Newtonian flows are observed for FENE-P fluid[1]. However, studying natural convection in cavities with differentially heated side walls is uncommon. Therefore, due to the limited exploration in this specific context, further investigations are warranted to determine if phenomena like heat transfer enhancement (THE) and heat transfer reduction (HTR) can occur in natural convection scenarios with differentially heated side walls for polymer-added fluids.

3. METHDOLOGY

The governing equations for simulating the thermal viscous-elastic fluid are,

$$\frac{\partial \mathrm{p}}{\partial \mathrm{t}}+\frac{1}{Ma^2}\frac{\partial u_i}{\partial x_i}=\frac{\gamma}{RePr}\frac{\partial^2 p}{\partial x_j \partial x_j} \qquad (1)$$

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$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{b}{Re}\frac{\partial^2 u_i}{\partial x_j\partial x_j}+\frac{Gr}{Re^2}\cdot T\ +\frac{1-b}{Wi\cdot Re}\frac{\partial\tau_{ij}^p}{\partial x_j} \quad (2)$$

$$\frac{\partial T}{\partial t}+\mathrm{u_j}\frac{\partial T}{\partial x_j}=\frac{\beta}{Gr^{1/2}Pr}\frac{\partial^2 T}{\partial x_j\partial x_j} \quad (3)$$

where b is the solvent to total viscosity ratio, and τ^p is the polymer stress. The Weissenberg number (Wi) defined as $Wi=\frac{\lambda_p u_o}{L}$. Here, $\gamma=\mathrm{Pr}$ and $\mathrm{Ma}=0.1$ are adopted in the present work, as Toutant [2] suggested.

The polymer-addition stress τ^p is obtained by solving the conformation tensor equation. This study adopts the finitely extensible non-linear elastic dumbbell model with the Peterlin's approximation (FENE-P) [1,3]. An elastic spring connects a pair of spherical beads polymer molecules. The polymer stress and the conformation tensor are expressed as,

$$\tau_{ij}^p=\frac{\mu_p}{\lambda_p}\left[\frac{1}{1-tr(C_{ij})/L_{max}^2}C_{ij}-\delta_{ij}\right] \quad (5)$$

$$\frac{\partial C_{ij}}{\partial t}+\frac{\partial u_k C_{ij}}{\partial x_k}=C_{ik}\frac{\partial u_j}{\partial x_k}+C_{jk}\frac{\partial u_i}{\partial x_k}-\frac{1}{Wi}\left[\frac{1}{1-tr(C_{ij})/L_{max}^2}C_{ij}-\delta_{ij}\right] \quad (6)$$

The numerical procedure is based on the finite volume approach with a staggered grid arrangement[4], where governing equations' spatial and temporal terms are discretized using the second-order central difference scheme and the third-order TVD Runge-Kutta scheme [5]. Besides, the third-order TVD MUSCL scheme is used on convection terms of conformation tensor to improve the numerical stability. One-dimensional decomposition using GPU-Direct is adopted for the multi-GPU computation.

4. RESULTS

This study considers the natural convection within a cubic cavity with two differentially heated opposing vertical walls (x=0 and 1). The rest of the walls are adiabatic. Fig. 1 shows the Predicted Nusselt number variations. The visco-elastic results of Chauhan et al. and the Newtionian flow of Turan et al. are also included for comparisons. For Newtonian flow, i.e., b=1, the three results show slight difference results, but is within the acceptable range. For the visco-elastic flows, the present results show heat transfer enhancement and reduction, respectively for the short and long polymer lengths. While, Chauhan et al.'s results indicate heat transfer enhancement regardless of the polymer lengths adopted.

Additionally, the effect of elasticity on the flow was also studied as shown in Fig. 2. With low elasticity (Wi=10, L^2_{max}=100,500), the maximum horizontal and vertical velocity increase slightly. On the other hand, with high elasticity Wi=100, L^2_{max}==500), the decreasing magnitude of maximum U and W indicates a weakening of convective transport with increasing elasticity.

5. CONCLUSIONS

In conclusion, a two-dimensional viscoelastic natural convection flow was studied using the general pressure equation with varying parameters: Ra values ranging from 10^4 to 10^7, Wi values from 1 to 100, and L^2_{max} values of 10 and 500. The findings indicated that with low elasticity effects (Wi = 10, L^2_{max}=10), there was a slight increase in both maximum horizontal and vertical velocities, leading to higher heat transfer rates. However, with high elasticity effects (Wi = 100, L^2_{max}=500), a decrease in horizontal and vertical velocities was observed, resulting in reduced heat transfer. The presence of polymer generated opposing stress near the wall, resulting in a decrease in vertical velocity and, consequently, heat transfer.

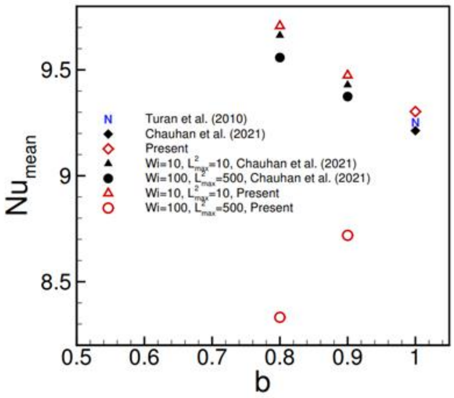

Fig. 1 Predicted Nusselt numbers at different solvent-to-viscosity ratios at Pr=7 and Ra=10^6.

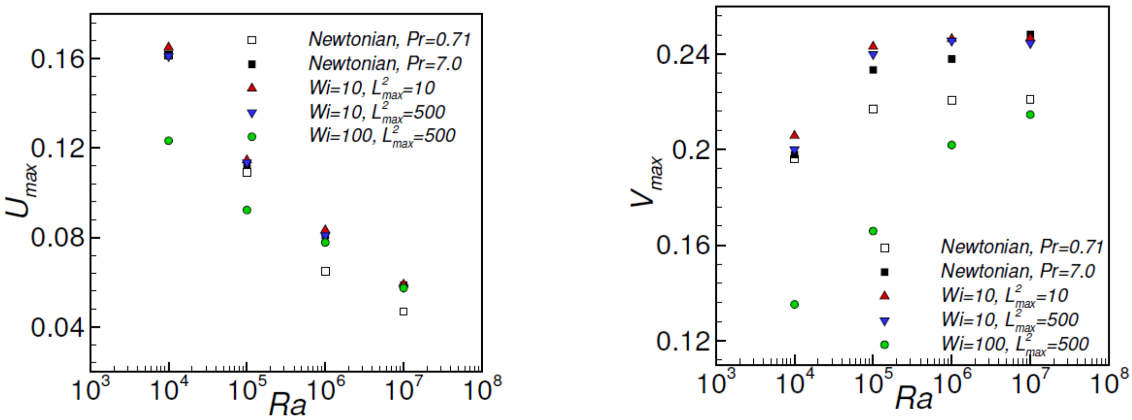

Fig. 2. The maximum horizontal U and vertical V velocities at Ra = $10^4 \sim 10^7$.

REFERENCES

[1] R.B. Bird, P.J. Dotson, & N.L. Johnson, Polymer solution rheology based on a finitely extensible bead-spring chain model, J. Non-Newtonian Fluid Mech., 7(1980) 213-235.

[2] A. Toutant, General and exact pressure evolution equation, Physics Letters A, 301(2017) 3739–3742.

[3] A. Peterlin, Gradient dependence of intrinsic viscosity of freely flexible linear macromolecules, Journal of Chemical Physics, 33(1960) 1799-1802.

[4] X. Shi, X. & C.A. Lin, Simulations of wall bounded turbulent flows using general pressure equation, Flow Turbulence and Combustion, 105(2020) 67–82.

[5] S. Gottlieb & C.W. Shu, Total variation diminishing Runge-Kutta schemes, Mathematics of computation, 67(1998) 73-85.