Constraining Parallel Flow in a Domain with Corrugated Surfaces

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Abstract

Natural convection occurs in many natural and industrial systems, which explains the growing interest it receives from the scientific community. Understanding the thermal behavior of such systems is essential for accurately predicting fluid flow and heat transfer in increasingly complex geometries. Engineers often face challenges due to the diversity in domain size, geometry, fluid properties, and boundary conditions.

Many theoretical and experimental studies have focused on natural convection in enclosures. These studies are relevant to various applications, such as cooling of electronic components, building thermal regulation, and gas separation.

This numerical study aims to model laminar, two-dimensional natural convection in a horizontal rectangular cavity filled with air. The cavity is heated differentially: the left wall is maintained at a hot temperature Th, and the right wall at a cold temperature Tc. The top and bottom walls are assumed to be adiabatic and impermeable. Under these conditions, the geometry promotes the development of a parallel flow within the cavity.

The mathematical formulation of the problem begins with the definition of the domain geometry, the simplifying assumptions, and the boundary conditions associated with the Navier-Stokes equations. Through a judicious choice of non-dimensional variables, the system of equations is expressed in dimensionless form, introducing key dimensionless numbers that serve as control parameters for the studied phenomenon.

The governing equations are discretized using the finite volume method. Due to the geometric complexity, a coordinate transformation is applied to simplify the numerical treatment of the control volumes. The velocity-pressure coupling is handled using the SIMPLER algorithm.

The main objective of this study is to investigate the influence of the deformation amplitude, combined with the intensity of thermal forcing (characterized by the Rayleigh number), on the limitation of the primary parallel flow within an elongated cavity. Initially, the cavity base is considered flat. In a second stage, a wavy bottom wall is introduced, where the amplitude of the undulations varies, while the number of waves is fixed at four.

Numerical simulations are carried out for different amplitudes (0, 0.02, 0.05, 0.1, 0.25), and for Rayleigh numbers in the range $10^{+3} < Ra < 10^{+6}$.

The key findings of this study are summarized as follows:

- At low Rayleigh numbers and small waviness amplitudes (0 to 0.05), the convective flow establishes a single-cell parallel regime occupying the entire cavity.
- The development of a sinuous parallel flow is possible under conditions of low waviness amplitude and strong thermal forcing, without causing flow discontinuities.
- Increasing the Rayleigh number intensifies the flow, facilitating the onset of a secondary convective regime even at small deformation amplitudes. In contrast, large deformations disrupt the parallel flow, subdividing the cavity into multiple counter-rotating cells.
- A high thermal forcing (Ra = 10+6) combined with a significant deformation amplitude (0.25) leads to the detachment of the thermal boundary layer.
- The heat transfer coefficient, both average and local Nusselt numbers, confirms that the enhancement of heat transfer correlates with the increase of the Rayleigh number.
- A notable reduction in heat transfer is observed as the waviness amplitude increases, across all Rayleigh numbers considered.

Future work may focus on extending this analysis to include transient effects to capture the flow's temporal evolution, or investigating the influence of incorporating a porous matrix on thermosolutal natural convection. Furthermore, exploring the problem in three-dimensional geometries represents a promising direction for further research.

Keywords

Corrugated Surface, CFD, Natural convection.