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Proper orthogonal decomposition of thermally-induced flow structure in an enclosure with alternately active localized heat sources

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ABSTRACT

The paper presents the structure of buoyancy-driven flow occurring in an enclosure with two alternately active discrete heat sources. For the analysis of the mixing of the fluid layer and its effect on heat transfer process, the flow information has been presented both in time and spectral domain. The inherent dynamics is also studied using the proper orthogonal decomposition (POD). POD technique is used here to assess the energy content in the different modes and the related coherent structures of flow considering different Rayleigh numbers ($Ra = 10^3$–10^6), switching frequencies (Z^{-1} with $Z = 0.1$–0.8) and air as working fluid of Prandtl number (Pr) of 0.71. The results reveal nonlinear characteristics of hydrodynamics and heat transfer at higher Ra for low frequency. Here, POD helps understanding the flow dynamics from information about the coherent structures of different energy modes.

1. Introduction

Researchers have studied natural convection in enclosures for several decades due to its widespread applications, such as cooling of electronic equipment, thermal insulation, solar collector, etc. In contrast to steady-state study of heat transfer, relatively less work is available on pulsatile heating from the bottom wall of an enclosure. Unsteady heating with a sinusoidal or other form of temperature variation of walls was also studied earlier [1–9]. Although some work has been reported which deal with intermittent heating of enclosures and the consequent flow and thermal dynamics [8], the effect of periodic activation of multiple heat sources in an enclosure has only recently been investigated [10]. This configuration assumes significance in the context of thermally aware scheduling in multi-core processors of modern computers where jobs are allotted to different processors with an objective of minimizing hot spot formation. Although such scheduling is done primarily from considerations of ability of the system to dissipate the generated heat, our recent work [11] shows that alternate activation of two discrete heat sources in a cavity can alter the flow inside the enclosure itself leading to significant heat transfer augmentation. The pronounced effect of the switch-over frequency on heat transfer augmentation motivates a more detailed investigation of the underlying physics. The objective of the present work is to gain insight into the transport phenomena involved from an in-depth study of the fluid flow caused by the buoyancy effect.

The effect of alternately active heating from the bottom of an enclosure on the heat and fluid flow characteristics is assessed in this paper utilizing well-established methodologies. For the analysis of the mixing of the fluid layer and its effect on heat transfer process, the flow information has been presented both in time and spectral domain. The inherent dynamics is also studied using the proper orthogonal decomposition (POD). POD is a powerful decomposition technique for identifying the energetic modes that correlates the physical flow field. POD is extensively used in different thermo fluidic problems [12–15]. Ding et al. [16] used numerical data and highlighted the advantage of generating faster results through POD and used this concept to interpolate results at off-design parameters at a substantially less computational cost. Bleris and Kothare [17] analyzed the dynamics of thermal transience in a micro-system using POD. Data from finite element model (FEM) has been used as an input for this processing technique to test the performance of a controller. Khashehchi et al. [18] used POD on velocity fields generated by particle image velocimetry (PIV) to analyze the instabilities in flow past finned and foamed circular cylinder. The POD methodology was used by different researchers for a host of natural convection problems [19–22]. Podvin and Le Quéré [20] used low-dimensional models for representing chaotic

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flows in a differentially heated cavity. They observed that before the bifurcation point, the dynamics of the system could be reduced down to two energetic modes, although it is necessary to account for higher modes in the model beyond the bifurcation point. A ten-dimensional model successfully captured the chaotic flow dynamics far away from the bifurcation point. A turbulent Rayleigh––Bénard convection in a square domain was studied by Bailon-Cuba and Schumacher [21]. The low dimensional model based on POD of the velocity and temperature fields and the snapshot of direct numerical simulation (DNS) results were used to describe the temporal evolution of the large-scale mode amplitudes for a particular Rayleigh and Prandtl number. Podvin and Sergent [22] performed the large-eddy simulation (LES) of turbulent Rayleigh–Bénard convection of air in a parallelepiped cavity and used POD to describe the large-scale structures of the flow with their temporal evolution and found out their roles on the convective heat and momentum transfer.

Bae and Hyun [10] showed enhanced heat transfer by systematic changing of the state of the heaters (switching “on” and “off”) inside an enclosure. Detailed heat transfer analysis of a case of pulsatile heating using alternately active two heaters in an enclosure is reported in authors’ earlier work [11], which revealed the pronounced effect of the switch-over frequency on heat transfer augmentation. Since the transient results of various quantities presented in our earlier work [11] suggest superposition of several energetic modes, the effect of switching frequency on fluid flow pattern inside the enclosure is analyzed using POD technique. The objective of this present work is to extract spatial flow information in terms of coherent structures of different energy modes. In this work, POD snapshot method as has been discussed by Sirovich and Kirby [23] has been utilized and energy content in different modes along with contours of higher modes has been explicitly shown.

The paper is organized as follows: In Section 2, overview of the physical system and the CFD simulation are given. The details of POD analysis of the CFD generated flow structure is given in Section 3. In Section 4, the flow characteristics of the system are discussed with the help of different modal structures, FFT of the eigenmodes and streamfunctions. The POD modes for different pulsation frequencies are shown. Lastly, a conclusion is given in Section 5.

2. Description of physical system and cfd simulation

The schematic of the enclosure and heaters with their thermal conditions are shown in Fig. 1a, where two alternately active isothermal heaters (temperature T_H) are placed at the bottom wall of the enclosure. The assumption of constant temperature of the heat source is common in the context of electronic cooling e.g., [24]. Adiabatic boundary is assumed on the heater surface when the heater is switched “off”. Top wall and non-heated portion of bottom wall are adiabatic while a constant temperature T_C is maintained at the side walls ($T_H > T_C$). The switch-over time period (Z, dimensionless) is defined as the time interval between the consecutive switching “on” (or “off”) of a particular heater.

The motion of stagnant confined fluid inside the enclosure is initiated due to density difference when either of the heaters is switched on. The alternate activation of the heaters generates complex dynamics in the flow field. After the initial transience of flow establishment, periodic circulation patterns are evolved consisting of two circulating cells (vortices). The characteristics of evolved oscillatory flow pattern (as shown in Figs. 1b and c) with the interrupted heating is responsible for transporting heat in the enclosure and found strongly dependent on Z and Ra in our earlier study [11]. This is a buoyancy-driven flow and was simulated considering two-dimensional, laminar and incompressible flow within the framework of Boussinesq approximation and assuming rigid and impermeable walls, and no-slip boundary conditions. CFD simulations were carried out using an extremely validated in-house code based on the finite volume method (FVM) and SIMPLE algorithm [25], considering a set of dimensionless conservation equations for mass, momentum and energy as given below.

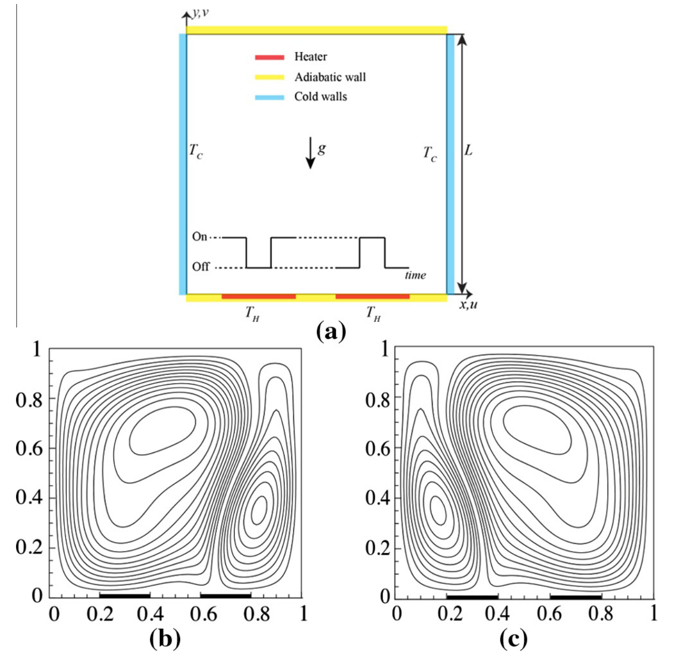

Fig. 1. (a) Schematic of the computational domain. The vortical structures formed inside the enclosure for $Z = 0.1$ and $Ra = 10^6$ at two different time instants (b) $\tau = 1$, 1.1 and (c) $\tau = 1.05$.

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

$$\frac{\partial \mathbf{V}}{\partial \tau} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\nabla P + Pr\nabla^2\mathbf{V} + RaPr\theta \boldsymbol{e_y} \tag{2}$$

$$\frac{\partial \theta}{\partial \tau} + (\mathbf{V} \cdot \nabla)\theta = \nabla^2\theta \tag{3}$$

The last term in Eq. (2) is the buoyancy force acting antiparallel to gravity (g), along the direction of vertical unit vector $\boldsymbol{e_y}$, and is coupled to dimensionless velocity ($\boldsymbol{V}$) and pressure (P) terms of Navier–Stokes momentum equation. In above equations, L is taken as domain length scale and $\frac{\alpha}{L}$ as the velocity scale where α is the thermal diffusivity of the working fluid. The temperature and physical time are non-dimensionalized by $\theta = (T - T_C)/(T_H - T_C)$ and $\tau = t/(L^2/\alpha)$ respectively.

The simulated stream function (ψ) inside the enclosure is utilized as “inputs” to the POD analysis that explores the underlying flow physics in terms of modal structure and power spectral density (PSD) function. The study is limited for the Rayleigh number ($Ra = Pr(g\beta(T_H - T_C)L^3)/\nu^2$) in the range of 10^3–10^6 and Prandtl number ($Pr = \nu/\alpha$) of 0.71, where β and ν are respectively volumetric thermal expansion coefficient and kinematic viscosity of the working fluid.

3. POD Procedure

POD executes a linear analysis in terms of optimal basis functions and a fluctuating entity, which can be any flow field data or image intensities from an experiment. In this work, the analysis has been performed on stream function data obtained numerically