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Effects of phase shift on the heat transfer characteristics in pulsating mixed convection flow in a multiple vented cavity

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ABSTRACT

In the current study, numerical investigation of pulsating mixed convection in a multiple vented cavity with phase shift is carried out for the range of parameters; Richardson number ($0.25 \leqslant Ri \leqslant 4$), phase shift ($0 \leqslant \phi \leqslant \pi$) and Strouhal number is fixed at 1. The governing equations are solved with a general purpose finite volume based solver. The effects of Ri number and phase shift parameters on the fluid flow and heat transfer characteristics are numerically studied. It is observed that the flow field and heat transfer enhancement are influenced by the variation of these parameters. Furthermore, recurrence plot analysis is applied for the analysis of the time series (spatial averaged Nusselt number along the vertical wall of the cavity) and for a combination of different parameters, the systems are identified using recurrence quantification analysis parameters including recurrence rate, laminarity, determinism, trapping time and entropy.

1. Introduction

Convection in enclosures is of vital importance in many engineering applications such as heat exchangers, food processing units, MEMs and many others. A vast amount of literature is dedicated to the numerical study of natural or mixed convection in cavities [1–11]. The instability mechanism and unsteadiness of the flow inside vented cavities have attracted much attention due to the need for efficient design of these systems with maximum heat transfer and minimum power requirements. Shi and Khodadadi [8] have numerically studied the periodic laminar flow and heat transfer in a lid-driven square cavity due to an oscillating thin fin for Reynolds number of 100 and 1000. They examined the dynamical system for periodic flow and thermal fields for a range of Strouhal numbers between 0.005 and 5. Nishimura and Kunitsugu [11] have numerically studied the fluid mixing in cavity with time periodic lid velocity using finite element method. They showed that for the best mixing an optimum frequency exists and oscillation amplitude and the geometric aspect ratio have also influence on the mixing. Velazquez et al. [12] have investigated the pulsating flow of 2D laminar flow in a heated rectangle for Reynolds number of 100 and Strouhal numbers between 0 and 0.4. They showed that the prescribed pulsation enhances heat transfer in the cavity due to the periodic change in the recirculation flow pattern generated by the pulsation. Unsteady flow and thermal field around a thin fin on a sidewall of a differentially heated cavity is studied experimentally by Xu et al. [13]. Laminar transient mixed convection in a vertical cylindrical cavity is studied numerically by Bouhdjar et al. [14]. They studied the dynamic field for different Richardson numbers and different geometrical parameters such as the inlet and outlet

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positions of the fluid. They showed that for the cylindrical cavity, the most efficient configuration with respect to thermal storage efficiency is achieved. They have observed the transition to the quasi-steady state, separation and oscillations of the thermal flow above the fin and these oscillations trigger instability of the downstream thermal boundary layer flow which enhances the convection. Saeidi and Khodadadi [15] have studied the unsteady laminar flow with an square enclosure with two ventilation ports. They showed that for Strouhal number of 0.1, the mean Nusselt numbers on the four walls exhibit large amplitudes of oscillation, but at Strouhal number of 10, the amplitudes of oscillation on various walls are generally degraded. They also showed that, heat transfer enhancement is observed for the range of considered Strouhal numbers. Noor et al. [16] have studied the flow and heat transfer in a cavity with double sided oscillating lids. They studied the effects of oscillating frequency of the lid motion and Reynolds number. They observed that the oscillating frequency change the flow pattern at very low Reynolds number significantly. Zhao et al. [17] have studied the characteristic of mixed convection in a multiple ventilated cavity and its transition from laminar to chaotic state for the Reynolds numbers between 1000 and 2500. They have observed that as Ri increases the solution may exhibit a change from steady-state to periodic oscillation, and then to non-periodic oscillatory state. They used nonlinear time series analysis tools to compute the correlation dimension, Kolmogorov entropy and Lyapunov exponents in order to detect chaos.

In this article, we have studied the problem of pulsating flow in a multiple vented cavity with phase shift for a range of Richardson numbers and phase shift parameters. The effects of these parameters on the flow and heat transfer are investigated. The addition of the phase shift parameter for this type of problem is the originality of this study. Furthermore, time series data obtained from spatial averaged Nusselt number along the walls of the cavity is analyzed using recurrence plots. Recurrence quantification analysis parameters including recurrence rate, laminarity, determinism, trapping time and entropy are also provided to quantify the nonlinear time series of Nusselt numbers for different combinations of Richardson numbers and phase shift parameters.

2. Numerical simulation

A schematic sketch of the physical problem is shown in Fig. 1. A square cavity (height H) with multiple ventilation ports is considered. At the inlet ports which are located at left and right vertical walls of the cavity, a uniform velocity with a sinusoidal time dependent part ($u = u_0 + 0.75u_0 \sin(2\pi ft)$) and a uniform temperature (T_c) are imposed. At the right inlet port, the sinusoidal velocity is imposed with a phase shift ϕ ($u = u_0 + 0.75u_0 \sin(2\pi ft + \phi)$). The width of each inlet and outlet ports is $0.1H$. The vertical walls are kept at constant temperature T_h while the top and bottom walls are assumed to be adiabatic. Working fluid is air with a Prandtl number of Pr = 0.71. It is assumed that thermo-physical properties of the fluid is temperature independent. The flow is assumed to be two dimensional, Newtonian, incompressible and in the laminar flow regime.

By using the dimensionless parameters,

$$(U,V) = \frac{(u,v)}{u_0}, \quad (X,Y) = \frac{(x,y)}{H}, \quad \tau = \frac{tH}{u_0}, \quad P = \frac{\bar{p}}{\rho u_0^2}, \quad \theta = \frac{T - T_c}{T_h - T_c} \tag{1}$$

for a two dimensional, incompressible, laminar and unsteady case, the continuity, momentum and energy equations can be expressed in the nondimensional form as in the following:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0, \tag{2}$$

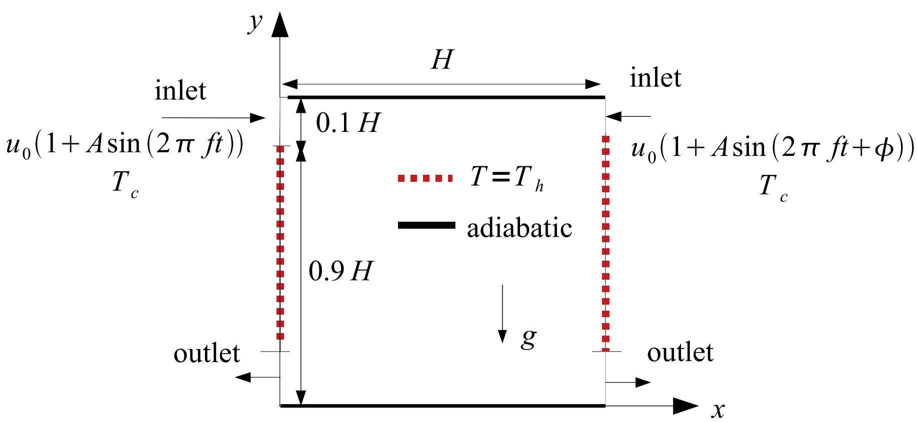

Fig. 1. Geometry with boundary conditions.