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# Numerical investigation and dynamical analysis of mixed convection in a vented cavity with pulsating flow

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ABSTRACT

In the present study, numerical investigation of pulsating mixed convection in a multiple vented cavity is carried out for the range of parameters; Reynolds number ($500 \leqslant Re \leqslant 2000$), Grashof number ($10^4 \leqslant Gr \leqslant 10^6$), Strouhal number ($0 \leqslant St \leqslant 2$). The governing equations are solved with a general purpose finite volume based solver. The effects of various parameters on the fluid flow and heat transfer characteristics are numerically studied. It is observed that the flow field and heat transfer rate are influenced by the variations of Reynolds, Grashof and Strouhal numbers. 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

Mixed convection has various engineering application areas such as design of heat exchangers, nuclear reactors, solar collectors, cooling of electronic equipments and modern buildings. A vast amount of literature is dedicated to the mixed convection in cavities [1–7]. The unsteadiness of flow and instability mechanism 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. Laminar transient mixed convection in a vertical cylindrical cavity is studied numerically by [1]. They studied the dynamic field for different Richardson numbers and different geometrical parameters such as the inlet and outlet positions of the fluid. They showed that the most efficient configuration with respect to thermal storage efficiency is obtained for the cylindrical cavity. [2] 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. Unsteady flow and thermal field around a thin fin on a sidewall of a differentially heated cavity is studied experimentally by [8]. 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. [9] 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. [10] have numerically studied the laminar pulsating flow in a backward facing step with an upper wall mounted adiabatic thin fin. They have investigated the effects of Reynolds number, pulsating amplitude and frequency on the fluid flow and heat transfer. They have reported that compared to steady flow with no-fin case, adding a fin is not advantageous for heat transfer enhancement in pulsating flow. [3] 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. [6] 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. [4] 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

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**Nomenclature**

| | |
|---|---|
| Gr | Grashof number, $\frac{g\beta\Delta T H^3}{\nu^2}$ |
| $H$ | cavity length |
| $h$ | local heat transfer coefficient |
| $k$ | thermal conductivity |
| $n$ | unit normal vector |
| Nu | local Nusselt number, $hH/k$ |
| $p$ | pressure |
| Pr | Prandtl number, $\frac{\nu}{\alpha}$ |
| Re | Reynolds number, $\frac{u_0 H}{\nu}$ |
| Ri | Richardson number, $\frac{\mathrm{Gr}}{\mathrm{Re}^2}$ |
| St | Strouhal number, $fH/u_0$ |
| $T$ | temperature |
| $u,\ v$ | $x$–$y$ velocity components |
| $x,\ y$ | Cartesian coordinates |
| *Greek symbols* | |
| $\alpha$ | thermal diffusivity |
| $\beta$ | thermal expansion coefficient |
| $\theta$ | non-dimensional temperature, $\frac{T-T_c}{T_h-T_c}$ |
| $\nu$ | kinematic viscosity |
| $\rho$ | density of the fluid |
| $\tau$ | non-dimensional time, $u_0 t/H$ |
| *Subscripts* | |
| $c$ | cold |
| $h$ | hot |
| $m$ | mean |

Strouhal numbers. [11] have investigated the flow field and heat transfer characteristics in a square cavity with two ventilation ports for the mixed convection case. At the inlet port, pulsating velocities for a range of Strouhal numbers and Reynolds numbers are imposed. They reported that optimum Strouhal number is between 0.5 and 1 for the best thermal performance and minimum pressure drop. [12] 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 non-linear 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 pulsating flow in a multiple vented cavity for a range of Reynolds, Grashof and Strouhal numbers. The effects of these parameters on the flow field and heat transfer are numerically investigated. 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 non-linear time series of Nusselt numbers for different combinations of Reynolds, Grashof and Strouhal numbers.

## 2. Numerical simulation

A schematic diagram of the physical problem considered in this study 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, uniform velocity with a sinusoidal time dependent part $(u = u_0(1 + 0.75\sin(2\pi f t)))$ and

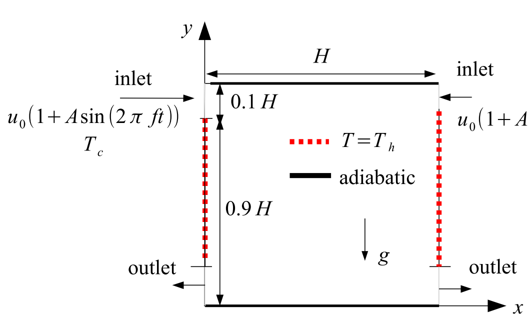


**Fig. 1.** Geometry with boundary conditions.

uniform temperature ($T_c$) are imposed. The widths of each inlet and outlet ports are set to 0.1$H$. 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,

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

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

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0, \qquad (2)$$

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right), \qquad (3)$$

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \frac{\mathrm{Gr}}{\mathrm{Re}^2}\Theta, \qquad (4)$$

$$\frac{\partial \theta}{\partial \tau} + U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{\mathrm{RePr}}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right), \qquad (5)$$

where the relevant physical non-dimensional numbers are Reynolds number (Re), Grashof number (Gr) and Strouhal number (St) are defined as

$$\mathrm{Re} = \frac{u_0 H}{\nu}, \quad \mathrm{Gr} = \frac{g\beta(T_h - T_c)H^3}{\nu^2}, \quad \mathrm{St} = \frac{fH}{u_0} \qquad (6)$$

The boundary conditions for the considered problem in non-dimensional form can be expressed as:

- At the inlet ports, velocity is unidirectional sinusoidal, temperature and velocity are uniform, $(U = 1 + A\sin(2\pi \mathrm{St}\tau),\ V = 0,\ \theta = 0)$
- At the bottom wall, downstream of the step, temperature is constant, $(\theta = 1)$
- At the exit ports, gradients of all variables in the x-direction are set to zero, $\left(\frac{\partial U}{\partial X} = 0,\ \frac{\partial V}{\partial X} = 0,\ \frac{\partial \theta}{\partial X} = 0\right)$
- On the top and bottom walls, adiabatic wall with no-slip boundary conditions are assumed, $(U = 0,\ V = 0,\ \frac{\partial \theta}{\partial n} = 0)$
- On the left and right vertical walls, constant temperature with no-slip boundary conditions are assumed, $(U = 0,\ V = 0,\ \theta = 1)$

Local Nusselt number is defined as