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Numerical simulation of unsteady natural convection flow inside a pattern of connected open square cavities

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ABSTRACT

Natural convection flow has several applications and is investigated extensively in the literature. The previous studies investigated the flow inside an isolated square cavity whether is closed or open. In the present study, flow simulations inside a pattern of connected open cavities for Ra from 10^3 to 10^6 are carried out using unsteady compressible Navier-Stokes solver. The flow inside the open cavity is circulated naturally. For Ra = 10^5 and 10^6, the results show that the flow structure is unsymmetrical, unstable, unsteady, and periodic. As a whole, the values of Nusselt number and velocities in the open cavity are much higher than those in the closed cavity.

1. Introduction

We face the applications of natural convection flows daily even if we do not notice it. The hot boiled egg loses heat and the cold water bottle acquires heat from the surrounding by natural convection flow. The double-glass windows and the cooling of the electronic equipment are applications of natural convection flow. The density is a function of temperature so that temperature gradient results in a density gradient. Under the effect of buoyancy force, the fluid flows naturally because of the density gradient.

The flow inside a differentially heated square cavity is a direct example of natural convection flow. El-Gendi and Aly [1] get rid of Boussinesq approximation by simulating the flow using compressible Navier-Stokes solver. They studied the effect of both temperature difference and the hot side temperature distribution at several Ra numbers on the flow inside the square and sinusoidal cavities. They found that the temperature difference has a remarkable effect on the velocity distribution and the thickness of the boundary layer inside the cavity at the same Ra. Varol et al. [2] investigated the effect of inclination angles and the length of corner heater at different Rayleigh and Prandtl numbers on the natural convection flow inside a closed square cavity. They found that the inclination angles and the length of corner heaters affect the maximum and minimum values of heat transfer. Also, Omranian et al. [3] investigated the effect of the inclination angle of both square and rectangle cavities on the natural convection flow. Ma and Xu [4] studied the effect of the fin location on the unsteady natural convection flow inside a rectangle cavity at different Rayleigh numbers. They classified the development of the flow into three phases: initial, transitional and fully developed. Khatamifar et al. [5] studied the effect of the partition thickness and position on the conjugate natural convection flow inside a square cavity at different Rayleigh numbers. They found that the average Nu increases by increasing Ra or decreasing the partition thickness, but the partition position has a negligible effect on it.

Many papers on mixed and forced convection in cavities with inlet and outlet ports were published. El-Gendi [6] found that the inlet flow velocities and angles have a significant effect on the isotherm contours of a square cavity. Schmeling et al. [7] investigated experimentally the effect of Reynolds and Archimedes numbers on the flow within a square cross-section, rectangular cavity. They found that at Archimedes number > 0.9, the buoyancy forces have a dominant effect on the heat flux than the inertia forces. Saeidi and Khodadadi [8] and Sourtiji et al. [9] found that the location of outlet port has a significant effect on the flow inside a square cavity. The effect of pulsating flow on mixed convection was investigated by Selimefendigil and Öztop [10]. They found that the Reynolds, Grashof, and Strouhal numbers have a remarkable effect on heat transfer enhancement. The effect of several parameters such as a discrete heat source [11], turbulence models [12], inlet and outlet ports in deferentially heated cavity [13–15], partition [16], cavity size [17], oscillation of incoming flow [18], and hot obstacles in inclined cavity [19] is also investigated.

In the previous studies, an isolated cavity was investigated and the flow enters the cavity steadily by means of external force. In addition, the condition of entering flow is not affected by the flow condition inside the cavity. Therefore, based on the Richardson number, the flow is categorized as natural, mixed, or forced convection flow. In the present study, a natural convection flow within a pattern of connected open cavities is investigated where the condition of entering flow

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Nomenclature

g	dimensionless gravitational acceleration
H	dimensionless height of the cavity
P	dimensionless pressure
Pr	Prandtl number, $Pr = \nu/\alpha$
R	dimensionless air gas constant
Ra	Rayleigh number, $Ra = g\beta\Delta TH^3Pr/\nu^2$
Re	Reynolds number $= u_{in}(2w)/\nu$
T_c	dimensionless temperature of the cold surface
T_h	dimensionless temperature of the hot surface
T_m	dimensionless reference temperature, $T_m = (T_h + T_c)/2$
u	dimensionless velocity component in x-direction
u^*	dimensionless velocity component in x-direction, $u^* = u/\sqrt{g\beta\Delta TH}$
v	dimensionless velocity component in y-direction
v^*	dimensionless velocity component in y-direction, $V^* = V/\sqrt{g\beta\Delta TH}$
W	dimensionless width of the cavity
W	dimensionless width of the inlet or exit port
x,y	dimensionless Cartesian coordinates
ΔT	dimensionless temperature difference, $\Delta T = T_h - T_c$

Greek symbols

β	dimensionless coefficient of thermal expansion, $\beta = 1/T_m$
ρ	dimensionless density
τ	dimensionless computational time
ϕ	dimensionless time for one period
μ	dimensionless total viscosity
ν	dimensionless kinematic viscosity
θ	dimensionless temperature, $\theta = (T - T_c)/(T_h - T_c)$

Subscript

c	cold
h	hot
in	inlet
‾	dimensional value

depends on the flow condition inside the cavity. A comparison between a closed and open cavity at $Ra = 10^5$ is carried out. Then, the effect of Ra ($10^3 \leq Ra \leq 10^6$) on the flow structure within the open cavity is investigated.

2. Numerical study

The numerical code was programmed using Fortran with double precision arithmetic and parallelized using Message Passing Interface (MPI). The calculations were carried out on a twelve-processor computer.

2.1. Physical model

Fig. 1 represents the pattern of connected open cavities. For investigating the current problem, some assumptions are considered as follows:

I The equation of state can be applied to the fluid within the cavity.
II The fluid within the cavity is air with Prandtl number of $Pr = 0.71$.
III The flow is laminar.
IV The investigated problem is two-dimensional.
V The no-slip condition is applied to the walls of the cavity.
VI Horizontal walls are treated as adiabatic surfaces and vertical walls as isothermal surfaces.
VII The initial temperature within the cavity is $T_m = (T_h + T_c)/2$
VIII The number of open cavities in the pattern is huge. Therefore, the periodic boundary condition can be applied to both openings.

The physical model is shown in Fig. 2. The dimensionless height and width of the square cavity are H and W, respectively. The top and bottom walls are adiabatic and the left and right sides are isothermal surfaces. The hot side is on the left and the cold side is on the right and the temperature difference between two sides is 20 K. There are two openings, one located on the top wall on the left and the other in the bottom wall on the right. The dimensionless width of both openings is W/5. The Periodic boundary condition is applied to both openings. In addition, their boundary conditions are updated every iteration. The results of the novel pattern of open connected cavities were compared with those of the common closed cavity at $Ra = 10^5$. In both the cases, the flow circulates due to the density gradient and buoyancy force only.

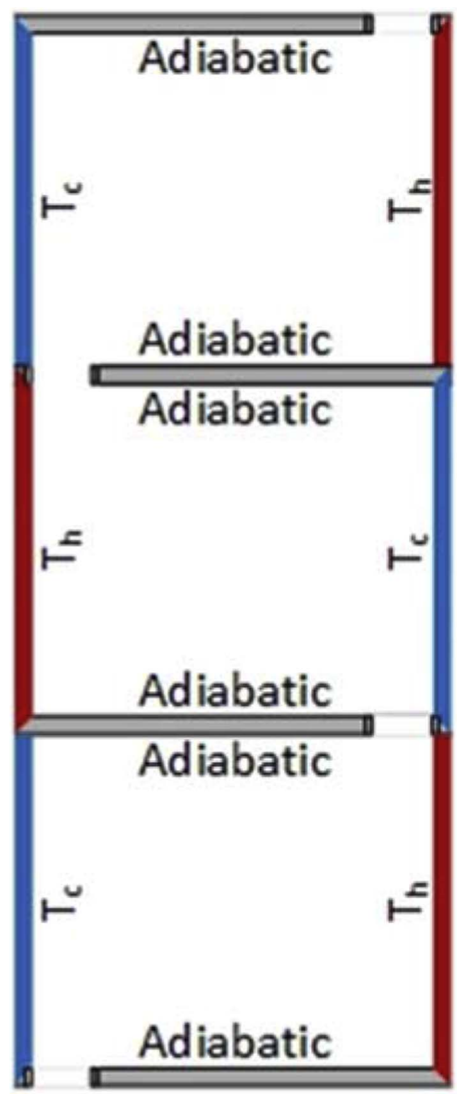

Fig. 1. Pattern of connected open square cavities.