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Flow and heat transfer in a driven square cavity with double-sided oscillating lids in anti-phase

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ABSTRACT

Flow and heat transfer inside a square cavity with double-sided oscillating lids have been studied numerically. The oscillating angular frequency of lid motion, ϖ, and Reynolds number, Re, are two important parameters in this study. In terms of primary vortices, simulations at Re and ϖ up to 1000 and 5, respectively, showed that the flow patterns can be categorized into four modes: (i) a pair of vertical vortices, (ii) a pair of swing vortices, (iii) diagonal-dominated vortices and (iv) two pairs of swing vortices. The flow patterns change at different frequencies for Reynolds numbers greater than 300. Nevertheless, the oscillating frequency did not offer significant effect to change flow pattern at very low Reynolds number such as at Re $\leqslant$ 10. Heat transfer, represented by average Nusselt number (Nu) along the lids is increased at higher Re whereas it is decreased as ϖ increases.

1. Introduction

Lid-driven cavity flow is found in many engineering applications, for example, within mixing, coating and drying technologies. There are many numerical studies in classical single lid-driven cavity flow conducted by researchers and some of them can be found from Refs. [1–8]. Some studies of cavity flow with an oscillating lid have been done by few researchers [9–13]. Soh and Goodrich [9] introduced a new time-accurate finite difference method to solve unsteady incompressible Navier–Stokes equations in primitive variables. They solved flows inside a cavity with an impulsively starting lid and an oscillating lid at Re = 400 by using solution of lid-driven cavity flow with constant lid speed as an initial condition. Their results give a basic information of cavity flow with an oscillating lid. Iwatsu et al. [10] performed a numerical investigation to study the effect of external excitation on the flow structure in a square cavity. They found less variation of flow structures in low frequency values. Nishimura and Kunitsugu [11] studied fluid mixing and mass transfer in two-dimensional cavities with an oscillating lid. They used the Galerkin finite element method to solve cavity flow problems for different amplitudes of the oscillating wall velocity, Strouhal number and aspect ratio. The simulations have been performed at low Reynolds number equal to 50. It was shown that the mixing depends on an optimum oscillatory frequency, oscillating amplitude and aspect ratio. Sriram et al. [12] made analysis of variations and flow structures in a periodically lid-driven cavity at different frequencies, amplitudes and Reynolds numbers. It was found that at very low Re, the flow throughout the periodic driven cavity qualitatively resembles the classical steady lid-driven cavity flow. On the contrary, at high Re, the entire cavity is occupied with multiple vortices. Recently, Khanafer et al. [13] have performed numerical simulations to investigate the effects of a number of pertinent dimensionless parameters, namely the Reynolds number, Grashof number and the dimensionless oscillation frequency of the sliding lid on unsteady mixed convection in a driven cavity using an externally excited sliding lid.

The single lid-driven cavity flow problems were extended to the case of two-sided lid-driven cavity flow by some researchers [14–17]. Kuhlmann et al. [14] performed experimental and theoretical investigations for the two- and three-dimensional flows driven by anti-parallel motion of two facing walls. Their results indicated that the existence of non-unique two-dimensional steady flows depends upon the cavity aspect ratio and the Reynolds number. Albensoeder and Kuhlmann [15] studied the three-dimensional instability of two counter-rotating vortices in the cavity flow driven by two parallel moving walls with the same speed. They made numerical investigation about the type of instability and the dependence of the critical Reynolds and wave number on the aspect ratio. Furthermore Albensoeder and Kuhlmann [16] investigated the stability balloon for the double-lid-driven cavity flow. The flow is driven by the parallel or anti-parallel motion of two facing walls. When the cavity is infinitely extended in the spanwise directional variety of different three-dimensional flow instabilities can arise.

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Nomenclature

Re	Reynolds number, u_0H/υ
Gr	Grashof number, $g\beta(T_H - T_C)H_3/\upsilon^3$
Pr	Prandtl number, υ/α
Nu	average Nusselt number
C_f	friction coefficient
H	cavity height (m)
u_0	constant lid speed (m s^{-1})
T_H	temperature of the bottom lid (K)
T_C	temperature of the top lid (K)
g	gravitational acceleration (m s^{-2})
t	non-dimensional time
f	non-dimensional frequency
p	non-dimensional pressure
u	non-dimensional velocity component in the x-direction
v	non-dimensional velocity component in the y-direction
x, y	non-dimensional Cartesian coordinates

Greek symbols

ϖ	non-dimensional oscillation angular frequency, $\omega H/u_0$
ω	oscillation angular frequency
θ	non-dimensional temperature
υ	kinematic viscosity of fluid (m^2 s^{-1})
α	thermal diffusivity (m^2 s^{-1})
β	coefficient of thermal expansion (K^{-1})

Luo and Yang [17] observed fluid flow and heat transfer in a two-sided lid-driven cavity with an aspect ratio of 1.96 numerically. The top and bottom lids of the cavity have different temperatures and move in opposite directions to generate a temperature gradient and thermal transport. The Reynolds number and the Grashof number are used as main parameters for the isothermal and the non-isothermal flow cases, respectively.

Among the studies of square cavity flows, we believe that there is no available manuscript about oscillatory double-sided lid-driven cavity flow. The present study is performed to observe this type of flow numerically. The dimensionless lid oscillating angular frequency, ϖ, together with Reynolds number are considered as two important parameters in this present study. The numerical scheme was validated with the cavity flow with oscillating lid of Khanafer et al. [13].

2. Problem description and numerical procedure

2.1. Problem description

A two-dimensional square cavity is considered for the present study as shown in Fig. 1. The top and bottom walls are considered as oscillating lids following the cosine function $u = u_0 \cos\omega t$ and $u = -u_0 \cos\omega t$, respectively, while the no-slip condition is imposed on the solid walls. The bottom wall is sustained at a higher temperature and the vertical walls are assumed to be adiabatic. The working fluid is air with constant Pr = 0.71. There are two important parameters in this study, i.e., Reynolds number, Re, and dimensionless oscillating angular frequency of lid motion, ϖ, defined as $\varpi = \omega H/u_0$ where ϖ, u_0 and H are lid oscillation frequency, maximum lid speed and cavity height, respectively. Re and ϖ vary from 10 to 1000 and from 1 to 5, respectively. Buoyancy effect was not considered except for validation.

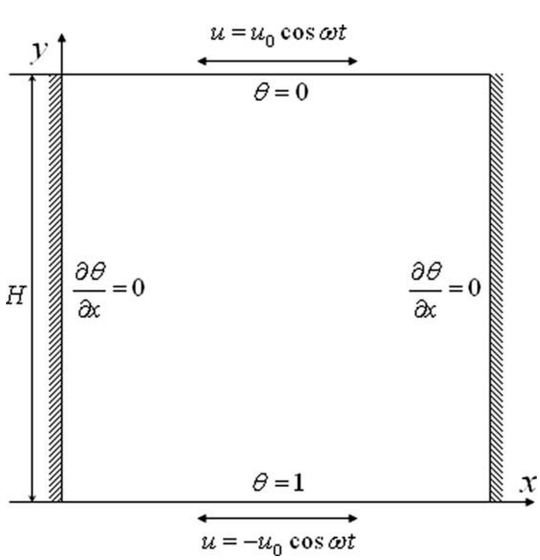

Fig. 1. Problem description and geometry of the square cavity.

2.2. The governing equations

The two-dimensional Navier–Stokes, continuity and energy equations in primitive variables for an unsteady incompressible laminar viscous flow with the Boussinesq assumption are denoted in dimensionless forms using the following dimensionless variables

$$x = \frac{x^*}{H} \quad y = \frac{y^*}{H} \quad u = \frac{u^*}{u_0} \quad v = \frac{v^*}{u_0} \quad \theta = \frac{T - T_C}{T_H - T_C}$$
$$p = \frac{p^*}{\rho u_0^2} \quad \mathrm{Re} = \frac{uH}{\upsilon} \quad \mathrm{Pr} = \frac{\upsilon}{\alpha} \quad \mathrm{Gr} = \frac{g\beta(T - T_C)H^3}{\upsilon^2} \tag{1}$$

Hence, the non-dimensional governing equations are continuity equation,

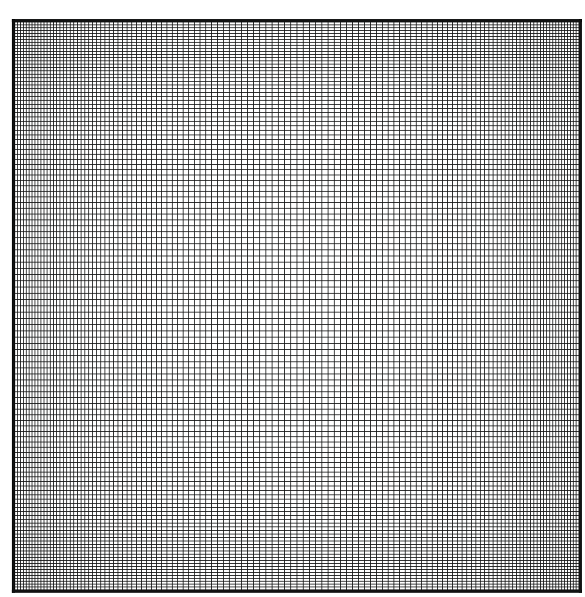

Fig. 2. The typical grid arrangement, 125 × 125 grid size.