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Numerical Investigation of Unsteady Laminar in Oscillated Lid-Driven Cavity Flow

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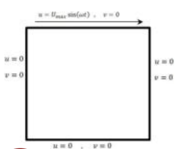
Graphical abstract



Abstract

This article reports the flow characteristics in an oscillated lid-driven cavity. The mesoscale numerical scheme of the multiple relaxation time lattice Boltzmann method is applied to solve for the fluid flow equation. Our predicted results revealed that the flow behavior is critically dependent on the dimensionless Reynolds number and frequency of the oscillated top lid of the cavity.

Keywords: Cavity flow, Reynolds number, lid frequency, lattice Boltzmann

1.0 INTRODUCTION

Flow in shear driven cavity is one of the most attractive research fields of fluid mechanics. It arises in many engineering problems such as short-dwell and flexible blade coaters. This type of flow configuration has also been used as a benchmark problem for many numerical methods due to its simple geometry and complicated flow behaviours. It is usually very difficult to capture the flow phenomena near the singular points at the corners of the cavity.

1.1 Literature Review

The shear driven cavity flow has become a topic of research since early 1960s [1]. At that time, their interest was to understand the three dimensionality effect and aspect ratio on the flow characteristics in the cavity. Due to the limitation of computational resources at the earliest stage of research, the experimental method was the only way to investigate the flow structure. Koseff and Street [2] conducted a comprehensive study on the subject. Other experimental workers are Migeon *et al.* [3], Ilegbusi and Mat [4], Vogel *et al.* [5] and many more.

As mentioned, many of the researchers considered the shear driven cavity flow for validating their numerical schemes. Nor Azwadi and Mohammad Reza [6] considered the cubic interpolated pseudo particle method and validate their results with the shear driven flow in shallow cavities. Li *et al.* [7] applied the new version of multiple relaxation time lattice Boltzmann method to investigate the fluid flow in deep cavity.

There have been some works devoted to the issue of heat transfer in the shear driven cavity. The effect of differentially heated walls of cavity on the flow structure has been the main research topic by Aydin and his co-workers [8]. The presence of temperature gradient in the cavity leads to a more complex structure of flow. The temperature gradient introduces buoyancy force to the fluid which its strength affects the mode of heat transfer mechanism in the cavity.

1.2 Present Study

In the present study, we will consider a square shear driven cavity with an oscillated top lid. There are very few reports on this case even it has many industrial applications such as food processing technology, particulate mixing process, heat removal, etc. The computations are conducted on a two-dimensional plane. This two dimensional approximation was undertaken based on a physical assumption that the behaviour of the lid driven vortex is relatively unaffected by the three dimensionality of the flow. Figure 1 shows the geometry case study and the boundary conditions.

2.0 THE GOVERNING EQUATIONS AND SOLUTION METHOD

Among the three numerical scales, the mesoscale of lattice Boltzman method (LBM) has shown it capabilities in predicting wide range of fluid flow problem. LBM foundation adopts the kinetic theory of gases which considers the evolution of fluid based on the behaviour at molecular level [9]. Accordingly, LBM resolves the macroscale of fluid flow indirectly by solving the evolution equation of particle distribution function and models the propagation and collision of particle distribution which are believed to be the fundamental behaviours at molecular level.

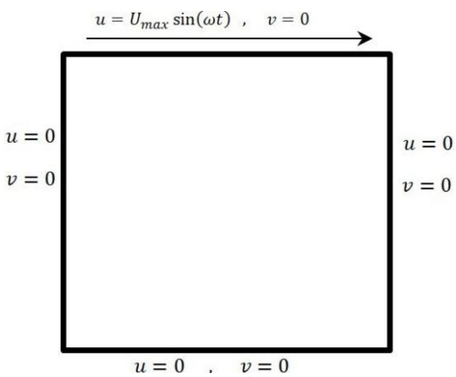


Figure 1 Geometry of the present case.

The starting point for lattice Boltzmann simulations are the evolution equation of particle distribution function *f* which can be written as

$$f_i\left(\mathbf{x}+\mathbf{c}\Delta t, t+\Delta t\right) = f_i\left(\mathbf{x}, t\right) - M^{-1}S\left[m - m^{eq}\right] \quad (1)$$

Where *M* is a matrix that transform the distribution function *f* to the velocity moment $m = Mf$, and *S* is the relaxation matrix. The *M* matrix and its inverse for two dimensional and nine velocity model are

$$M = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -4 & -1 & -1 & -1 & -1 & 2 & 2 & 2 & 2 \\ 4 & -2 & -2 & -2 & -2 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 \\ 0 & -2 & 0 & 2 & 0 & 1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1 \\ 0 & 0 & -2 & 0 & 2 & 1 & 1 & -1 & -1 \\ 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \end{bmatrix} \quad (2)$$

$$M = \beta\begin{bmatrix} 4 & -4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & -1 & -2 & 6 & -6 & 0 & 0 & 9 & 0 \\ 4 & -1 & -2 & 0 & 0 & 6 & -6 & -9 & 0 \\ 4 & -1 & -2 & -6 & 6 & 0 & 0 & 9 & 0 \\ 4 & -1 & -2 & 0 & 0 & -6 & 6 & -9 & 0 \\ 4 & 2 & 1 & 6 & 3 & 6 & 3 & 0 & 9 \\ 4 & 2 & 1 & -6 & -3 & 6 & 3 & 0 & -9 \\ 4 & 2 & 1 & -6 & -3 & -6 & -3 & 0 & 9 \\ 4 & 2 & 1 & 6 & 3 & -6 & -3 & 0 & -9 \end{bmatrix} \quad (3)$$

where $\beta = 1/36$ the moment vector m is $m = (\rho, e, \epsilon, j_x, q_x, j_y, q_y, p_{xx}, p_{xy})^T$. The equilibrium of themoment m^{eq} is $m_0^{eq} = \rho$, $m_1^{eq} = -2\rho + 3(j_x^2+j_y^2)$, $m_2^{eq} = \rho - 3(j_x^2 + j_y^2)$, $m_3^{eq} = j_x$, $m_4^{eq} = -j_x$, $m_5^{eq} = j_y$, $m_6^{eq} = -j_y$, $m_7^{eq} = (j_x^2 - j_y^2)$, $m_8^{eq} = j_x j_y$, where $j_x = \rho u_x = \sum_i f_i^{eq} c_{ix}$ and $j_y = \rho u_y = \sum_i f_i^{eq} c_{iy}$ (4)

The diagonal matrix *S* is expressed as follow

$$M = \begin{bmatrix} S_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & S_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & S_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & S_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & S_5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & S_6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_8 \end{bmatrix} \quad (5)$$

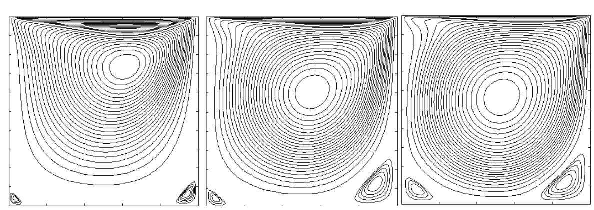
In compact notation S can be written as $S = \text{diag}(1, 1.4, 1.4, S_3, 1.2, S_5, 1.2, S_7, S_8)$ where $S_7 = S_8 = 2/(1+6\nu)$ and S_3 and S_5 are arbitrary which can be set as 1. Finally the macroscopic variables such as the density and fluid velocity can be computed in terms of the particle distribution functions as

, (6)

■3.0 RESULTS AND DISCUSSION

3.1 Code Validation

We begin with the validation of computer program code written in MATLAB language by predicting the behaviour of fluid flow in a lid-driven cavity flow. For this purpose, the top is constantly slide to the right at constant velocity. The computed streamline for three different Reynolds number is shown in Fig. 2. Apparently, as the Reynolds Number increases the secondary vortices at the lower right and lower left corner grow as well. The center of the primary vortices seems to move toward the center of the cavity. These findings are in good agreement with the previous researchers [10]. The comparison of horizontal and vertical velocity profiles at the mid width and mid height of the cavity for Re = 1000 are demonstrated in Fig. 4. Again good agreements were obtained with the benchmark results [10].

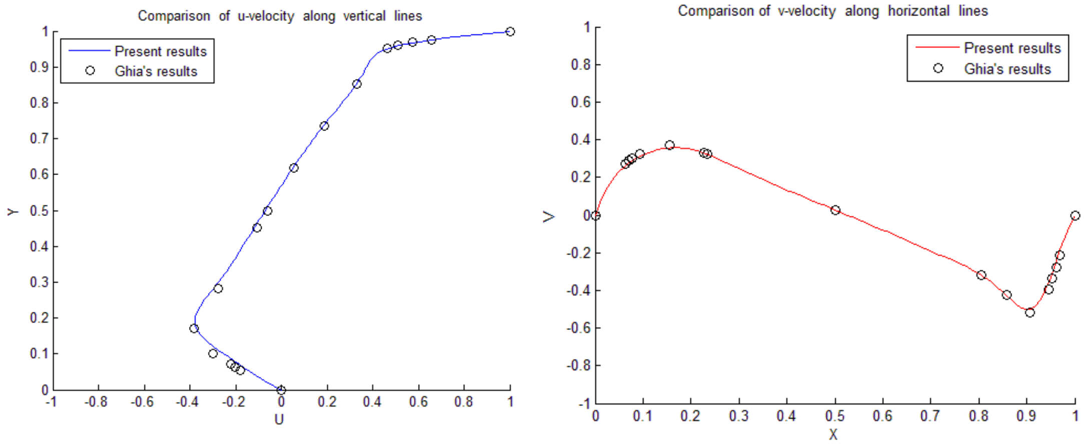


(a) Re = 100 (b) Re = 400 (c) Re = 1000

Figure 2 Streamline plot using multiple relaxation time lattice Boltzmann method

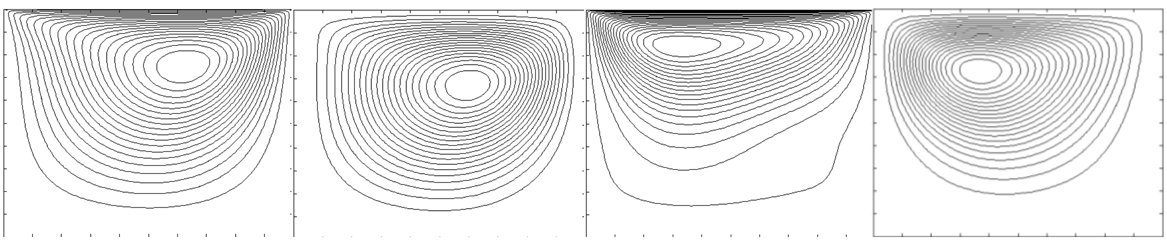
3.2 Effect of Reynolds Number on the Streamlines

First, the effect of Reynolds number is investigated while the dimensionless lid frequency was fixed at 1. Figures 4 and 5 demonstrate the predicted streamline for Re = 100 and 1000 respectively. At low value of Reynolds number, the center of vortex was formed at the right area of the cavity due to the positive horizontal direction of the top lid. When the lid moved to negative direction, it drags the flow together with center of the vortex to the left region. At high value of Reynolds number, strong shear force drags the flow and cause the vortex to break into two smaller vortices.



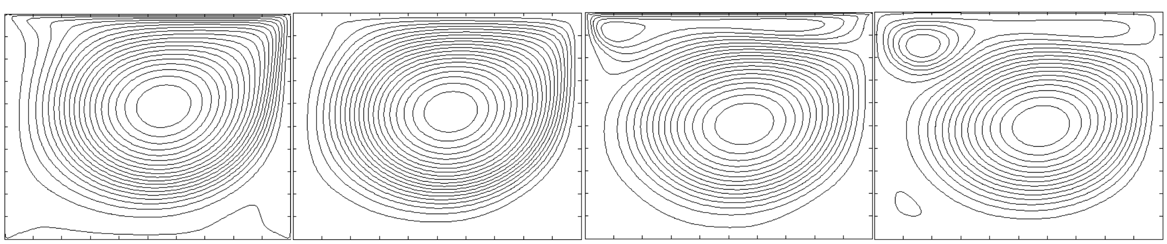
(a) (b)

Figure 3 Plots of dimensionless vertical velocity profiles at mid height (a) and horizontal velocity profiles at mid width (b) of the cavity while Re = 1000



(a) (b) (c) (d)

Figure 4 Snapshots of streamline for Re = 100 and lid frequency = 1 at time (a) π/2 (b) π (c) 3π/2 (d) 2π



(a) (b) (c) (d)

Figure 5 Snapshots of streamline for Re = 1000 and lid frequency = 1 at time (a) π/2 (b) π (c) 3π/2 (d) 2π

3.3 Effect of Reynolds Number on the Velocity Profile

The effect of Reynolds number of the velocity profiles are shown in Figs. 6 and 7 for Reynolds number 100 and 1000 respectively. They demonstrate the positive and negative values according to the values of moving lid.

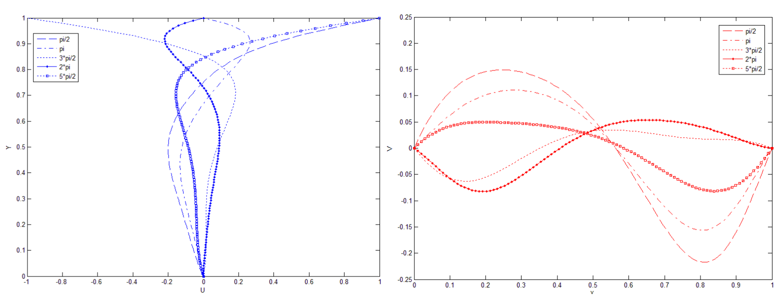


Figure 6 effect of oscillated wall on the horizontal velocity profile at x=0.5 (left) and vertical velocity profile at y=0.5 (right) for Re = 100

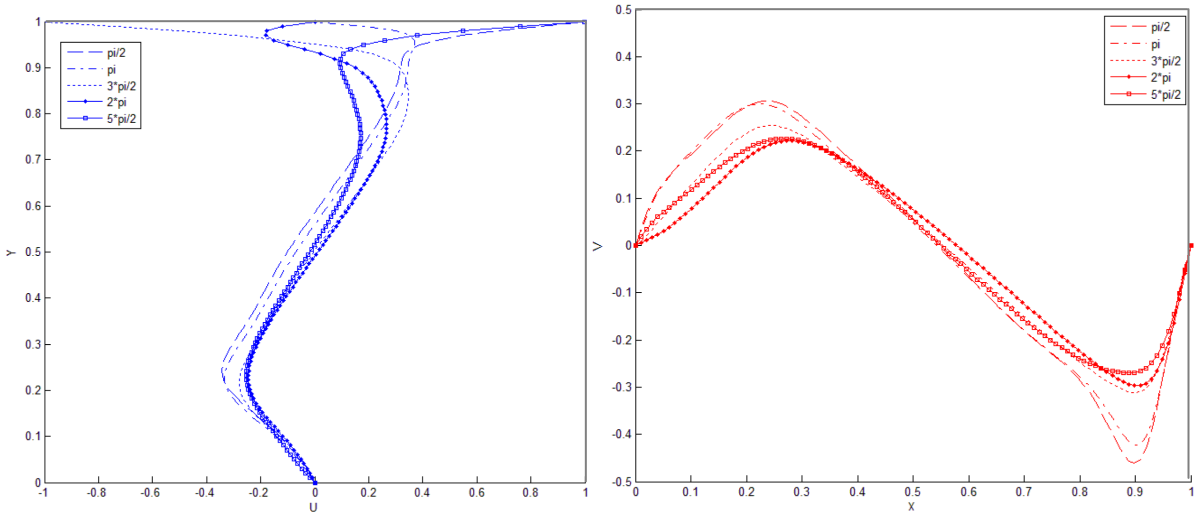
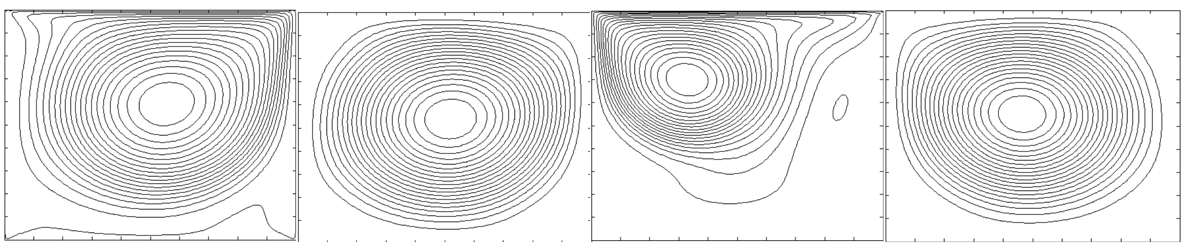


Figure 7 Effect of oscillated wall on the horizontal velocity profile at x=0.5 (left) and vertical velocity profile at y=0.5 (right) for Re = 1000

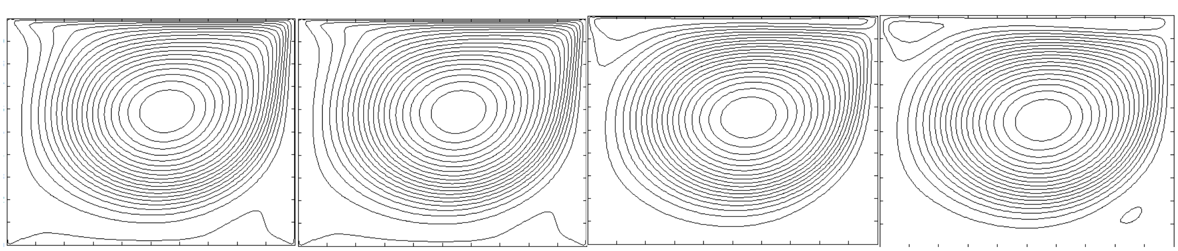
3.4 Effect of Lid Frequency on the Streamlines

Finally the effect lid frequency on the streamline is demonstrated in Figs. 8 and 9. The Reynolds number was set at 1000 and the lid frequency is set at 0.1 and 5. At a lower value of lid frequency, deeper penetration of fluid into the cavity compared to the frequency at a higher value. This causes the fluid at almost motionless at the lower region in the cavity for the later case.



(a) (b) (c) (d)

Figure 8 Snapshots of streamline for Re = 1000 and lid frequency = 0.1 at time (a) π/2 (b) π (c) 3π/2 (d) 2π



(a) (b) (c) (d)

Figure 9 Snapshots of streamline for Re = 1000 and lid frequency = 5 at time (a) π/2 (b) π (c) 3π/2 (d) 2π

■4.0 CONCLUSIONS

The flow in a shear cavity with oscillated top lid was investigated using the mesoscale numerical technique of multiple relaxation time lattice Boltzmann method. All the physical structures of fluid flow have been re captured and reproduced. This indicate the capability of the present numerical scheme in predicting wide range of fluid flow problem

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