# INVESTIGATION OF FORCED CONVECTIVE HEAT TRANSFER FROM A BLOCK LOCATED STAGGERED CAVITY WITH PARALLEL AND ANTI-PARALLEL WALL MOTION

by

***Meenakshi Sundar KANNAN[a*], Manikandan GURUNATHAN[a], Rajesh KANNA P.[b], Jan TALER[c], Dawid TALER[c], and Pawel OCLON[c]***

[a]Velammal College of Engineering and Technology, Madurai, India
[b]Al Ghurair University, Dubai, UAE
[c]Cracow University of Technology, Cracow, Poland

Original scientific paper
https://doi.org/10.2298/TSCI19S4281K

*The investigation reported in this paper is dealt about the steady-state laminar flow and heat transfer of a lid driven staggered cavity with the heated block. Based on the aspect ratio (AR = H/L = 0.5, H/L = 1, H/L = 2) three different block shapes are introduced for numerical experiments. The solid block with no slip and stationary wall condition is considered and it is located at the geometric center of the cavity. The simulations are carried out for Reynolds numbers 50, 100, 200, 300, 500, and 1000 and temperature of the block is 300 K. A clock-wise momentum is converged to the fluid, by the two driving lids on the top and bottom side of the cavity, lids are set into an anti-parallel wall motion. The upper lid moves to the right, while the lower one to the left, both are consider as same velocities. The results are found to be in good agreement with existing published results. It was found that the dynamics and the structure of the primary vortex and the corner vortices were strongly affected by the Reynolds number. The investigation clearly describes that increasing the Reynolds number values the overall drag coefficient decreases, similarly the value of average Nusselt number also increases with an increasing Reynolds number for all the values of different blocks under studied. The study reveals the important flow physics such as flow separation, boundary-layer and recirculation. The results will be beneficial for similar situation occur in many industrial problems.*

Keywords: *staggered cavity, drag, Nusselt number, Reynolds number*

## Introduction

Cavity flow problems with Lid-driven have been studied broadly for more than four decades and are one of the most popular fluid-flow problems in the CFD field. This ideal benchmark problem has attracted considerable research interests, as the hydrodynamics is relevant to numerous industrial applications [1-3]. The present study has been attempted to offer multiple benchmark solution on a lid-driven cavity flow [4-11]. Two-sided lid-driven staggered cavity looks to be a part of two benchmark problems: a lid-driven cavity and a backward facing step. Non-rectangular two-sided lid-driven cavities have been recently intro-

* Corresponding author, e-mail: meenakshisundark@gmail.com

duced and investigated as a important benchmark problem by Zhou *et al*. [12] and Nithiarasu and Liu [13]. Zhou *et al*. [12] have reported the results for different Reynolds numbers (50-3200) for two sided lid-driven cavity flow with lids moving in anti-parallel motion. Both symmetric and asymmetric flow patterns were obtained. Symmetric pattern was obtained for Reynolds number below 1000, asymmetric pattern was obtained at Re = 3200. Nithiarasu and Liu [13] have also got asymmetric flow patterns for Reynolds number more than 1000. Figure 1 indicates the schematic diagram of two-sided lid-driven staggered cavity with both top and bottom lids moving at same velocity, top wall move towards the forward parallel motion and bottom wall move towards the backward anti-parallel motion. Tekic *et al*. [14] have investigated parallel and anti-parallel motion using Lattice Boltzmann simulation. Staggered cavity is needed a diagonally symmetric cavity with two diagonal offsets of size 0.4 *L* and a wall of size *L*. For the given geometry, Zhou *et al*. [12] and Nithiarasu and Liu [13] have investigated only anti-parallel motion of lids. The present study targets the steady-state laminar flow forced convective heat transfer from a block located lid driven staggered cavity with both parallel and anti-parallel wall motion.

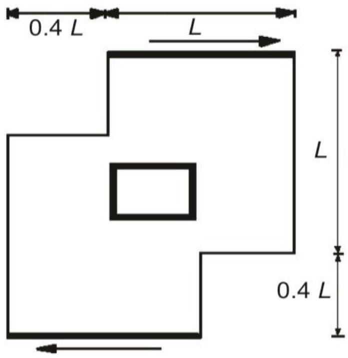


**Figure 1. Schematic diagram of block located two sided lid driven staggered cavity with parallel and anti-parallel wall motion**

## Numerical validation

In ordered to validate our solution, a similar benchmark of single side lid driven cavity is chosen and it is simulated for various different Reynolds numbers and compared with the results in the available literature. In fig. 2, *u* and *v* velocity profiles, through the geometrically centre of the cavity, are shown. The results are found to be in good agreement with existing published results.

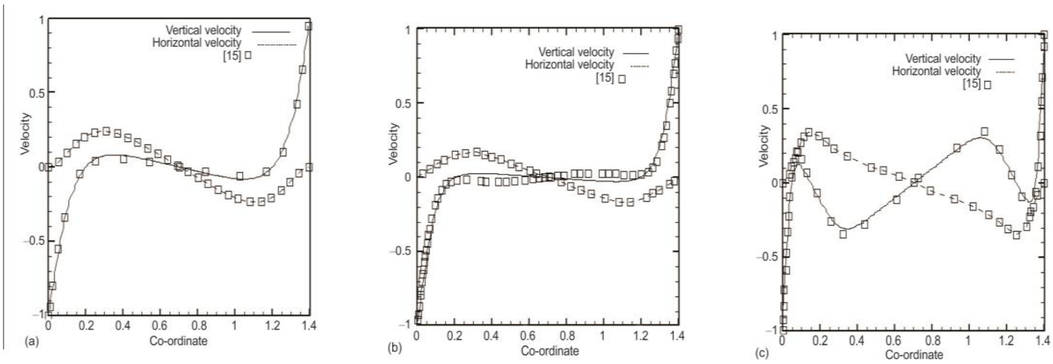


**Figure 2. Comparison of velocities for a double lid driven cavity both parallel and anti-parallel wall motion; horizontal and vertical velocity along mid width: (a) Re = 50, (b) Re = 100, and (c) Re = 1000**

### *Analysis and modelling*

The initial part of this study consists of numerical analysis of forced convection in a block located lid driven two dimensional staggered cavities in ANSYS FLUENT and post processing results were generated using Tecplot. The fluid-flow in a lid-driven cavity can be simulated by a set of momentum and mass conservation equations and so the governing equation for the problem is derived from the Navier-Stokes equation. For pressure velocity coupling Simple Scheme was used. In a partial discretization gradient was solved using Green Gause cell based scheme. Here pressure was assumed as standard pressure. Momentum and energy conditions are solved by second order upwind method. The left and right side walls of the cavities are adiabatic. The top lid is moved towards the parallel motion in a forward direction and the bottom lid is move towards the anti-parallel motion in a reverse direction. In fig. 3, Based on the aspect ratio ($AR = H/L = 0.5$, $H/L = 1$, $H/L = 2$) three different block shapes which are solid walled blocks with no slip and are in stationary wall condition were placed at the geometric centre of the cavity for the numerical experiments. Temperature of the block is set as 300 K. Different cases were simulated by varying the Reynolds number Re = 50, 100, 200, 500, and 1000. Simulations are carried out with grid resolution of 175 × 175.

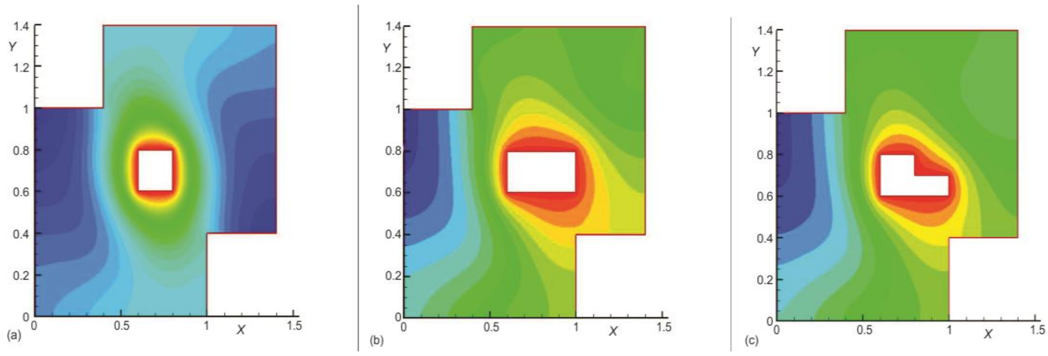


**Figure 3. Temperature contour of double lid driven staggered cavity both parallel and anti-parallel wall motion; horizontal and vertical velocity along mid width: Re = 50, (a) *H/L* = 1, (b) *H/L* = 0.5, and (c) *H/L* = 2**

### *Governing equation*

The fluid-flow in a lid-driven cavity can be simulated by a set of momentum and mass conservation equations. The equations used here are nothing but the Navier-Stokes equation as they obey the law of mechanics. This is nothing but the conservation of mass and conservation of momentum. Navier-Stokes equation was formulated from these two. The continuity equation also acts as a basic for the lid- driven cavity flow.

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

X- momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

Y- momentum equation:

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

The aforementioned equations were non-dimensionalized:

$$U = \frac{u}{U_\infty}, \quad V = \frac{v}{U_\infty}, \quad X = \frac{x}{L}, \quad Y = \frac{y}{L}, \quad P = \frac{P}{\rho U_\infty}, \quad \mathrm{Re} = \frac{U_\infty L}{\gamma}, \quad \gamma = \frac{\mu}{\rho} \tag{4}$$

Introducing the previous non-dimensional eq. (4) scales in the governing equations eqs. (1)-(3), we obtain the non-dimensional form of the equations:

Continuity equation:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{5}$$

X- momentum equation:

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{6}$$

Y- momentum equation:

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) \tag{7}$$

where $L$ is the reference length dimension (width of the cavity along the lower lid or wall), while $U_\infty$ – the velocity with which the top lid is driven from left to right in the $x$-direction. The fluid property $\gamma$ is the kinematic viscosity, $\mu$ – the dynamic viscosity, $\rho$ – the density of the fluid considered inside the cavity. The Reynold's number, is the ratio of inertial force to the viscous force, which influences the fluid-flow features in the cavity.

## Results discussion

A double lid driven cavity is different from the classic benchmark single lid-driven cavity, discussed in many previous researches due to the way the double lids are used as the name suggests. In a double driven cavity the lids are moved on both the top and bottom sides of the cavity. In this study, the flow in a non-rectangular cavity as shown in fig. 1 is investigated. As mentioned before, this problem was suggested as a benchmark by Nithiarasu and Liu [13], it is a diagonally symmetrical cavity with a longer side of size $L$ and a smaller side of size 0.4 $L$. The top lid is assumed to move at a prescribed positive horizontal velocity value and the bottom lid moves with a negative velocity with a magnitude equal to the velocity of the top lid. In fig. 4, streamlines were analysed in the mid width of the cavity along with parallel and anti-parallel wall motion for Re = 50. Two primary vortices were formed and also two secondary vortices were formed in left and right end of the cavity. The strength of the primary vortices was reduced when the Reynolds number was increased up to 400. Furthermore two secondary vortices were formed in all the four left and right corner of the cavities for a higher Reynolds number Re = 1000. In fig. 5, temperature contours were analysed in a same streamline condition. If the Reynolds number increases, decrease in temperature was observed in all the area ratios, $AR = H/L = 0.5$ (b) $H/L = 1$ (c) $H/L = 2$. Results clearly indicated that the temperature was decreased highly in $H/L = 2$ when Re was increased.

In figs. 5(A)-5(D), there is a decrease in temperature in the cavity and around the walls, when Reynolds number is increased, which is attributed to the formation of secondary vortices. The Primary vortices are reduced in size and offers secondary vortices around the corners.

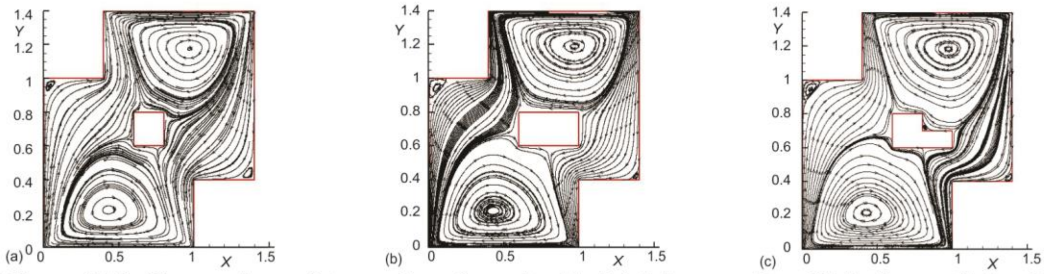

**Figure 4(A). Comparison of streamlines for a double lid driven cavity with both parallel and anti-parallel wall motion; horizontal and vertical velocities along mid width: Re = 50, (a) *AR* = *H/L* = 0.5, (b) *H/L* = 1, and (c) *H/L* = 2**

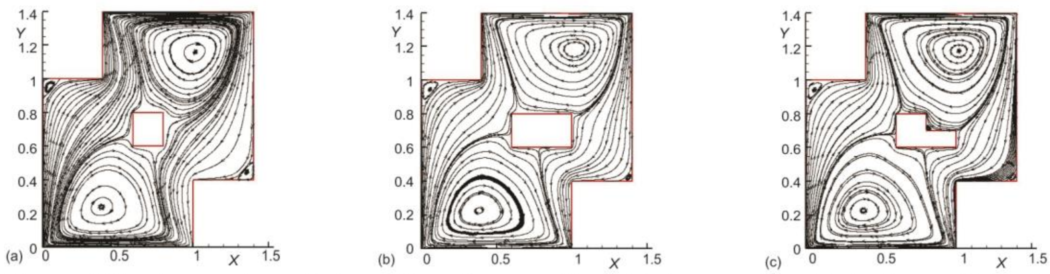

**Figure 4(B). Comparison of streamlines for a double lid driven cavity with both parallel and anti-parallel wall motion; horizontal and vertical velocities along mid width: Re = 100, (a) *AR* = *H/L*= 0.5. (b) *H/L* = 1, and (c) *H/L* = 2**

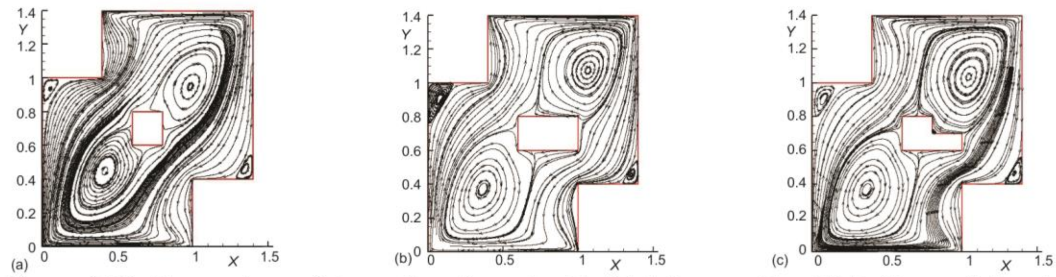

**Figure 4(C). Comparison of streamlines for a double lid driven cavity with both parallel and anti-parallel wall motion; horizontal and vertical velocities along mid width: Re = 400, (a) *AR* = *H/L* = 0.5, (b) *H/L* = 1, and (c) *H/L* = 2**

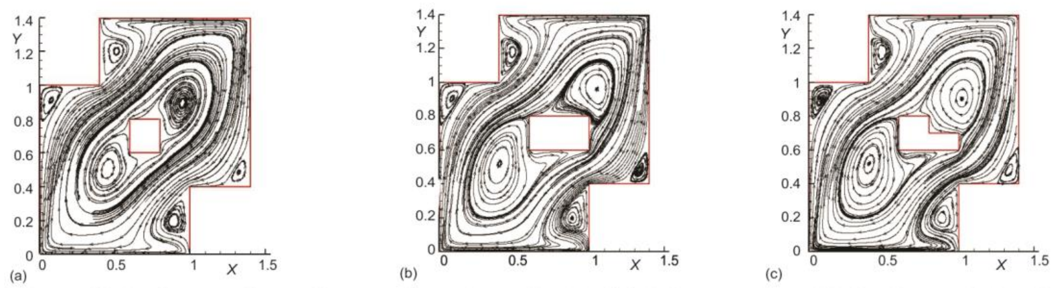

**Figure 4(D). Comparison of streamlines for a double lid driven cavity with both parallel and anti-parallel wallmotion; horizontal and vertical velocities along mid width: Re = 1000, (a) *AR* = *H/L* = 0.5, (b) *H/L* = 1, and (c) *H/L* = 2**

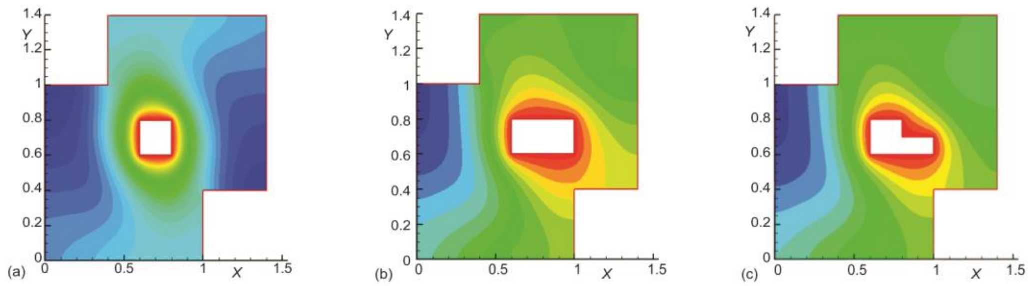

**Figure 5(A). Comparison of temperature Contour for a double lid driven cavity with both parallel and anti-parallel wallmotion; horizontal and vertical velocities along mid width: Re = 50, (a) *AR* = *H/L* = 0.5, (b) *H/L* = 1, and (c) *H/L* = 2**

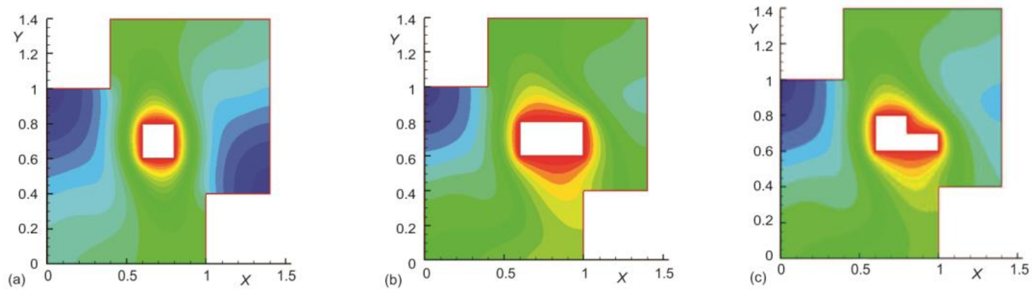

**Figure 5(B). Comparison of temperature Contour for a double lid driven cavity with both parallel and anti-parallel wallmotion; horizontal and vertical velocities along mid width: Re = 100, (a) *AR* = *H/L* = 0.5, (b) *H/L* = 1, and (c) *H/L* = 2**

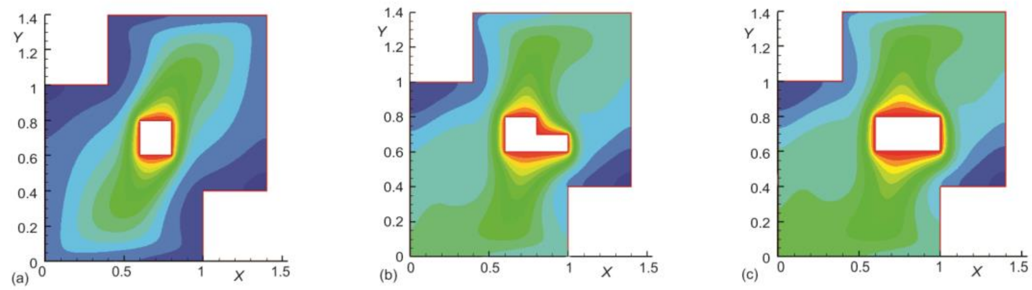

**Figure 5(C). Comparison of temperature Contour for a double lid driven cavity with both parallel and anti-parallel wallmotion; horizontal and vertical velocities along mid width: Re = 400, (a) *AR* = *H/L* = 0.5, (b) *H/L* = 1, and (c) *H/L* = 2**

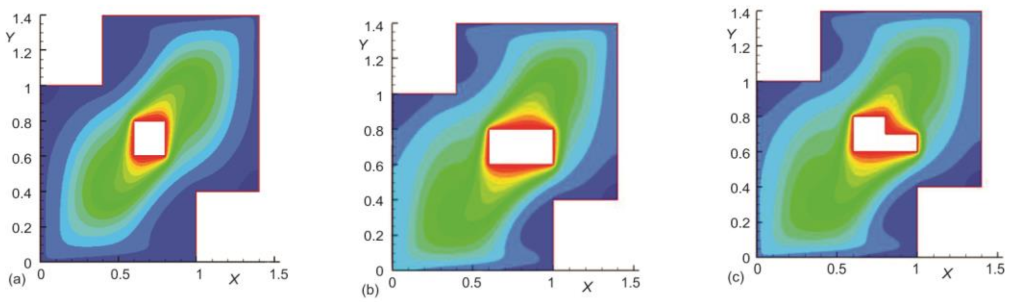

**Figure 5(D). Comparison of temperature Contour for a double lid driven cavity with both parallel and anti-parallel wallmotion; horizontal and vertical velocities along mid width: Re = 1000, (a) *AR* = *H/L* = 0.5, (b) *H/L* = 1, and (c) *H/L* = 2**

## Conclusion

Steady flow region was observed for Re = 50, 100, and 1000. The objective of this paper is to analyse the flow in connection with the effect of various geometric under different Reynolds numbers. When Re = 50 there are two major vortices are formed, two secondary small vortices are formed in left and right end corner of the cavities. If the Reynolds number increases secondary vortices strength are increased as show in fig 4. for higher Reynolds number furthermore two vortices are formed in all left and right end of the corners. Increasing Reynolds number more vortices are formed. In temperature contour the high heat is emitted in the rectangular block compare to the other two heated blocks. The flow is unstable with some form of chaotic motion in higher Reynolds number.

## Nomenclature

$D$ – diameter, [m]
$H$ – height, [m]
$k/L$ – heat transfer coefficient, [$WK^{-1}m^{-2}$]
$L$ – length, [m]
Nu – Nusselt Number, (= $hL/k$), [–]
$R$ – radius, [m]
Re – Reynolds Number, (= $uL/\nu$), [–]
$u$ – velocity, [$ms^{-1}$]
$u, v, w$ – components in Cartesian co-ordinates x, y, z, [m]
$W$ – width, [m]

*Greek symbols*

$\mu$ – dynamic viscosity (absolute), [$Nsm^{-2}$]
$\nu$ – kinematic viscosity, [$m^2s^{-1}$]

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Paper submitted: January 20, 2019
Paper revised: February 28, 2019
Paper accepted: April 15, 2019