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Research Paper Engineering



Stream Function Formulation of Lid Driven Cavity

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ABSTRACT

In the present work the two-dimensional lid driven cavity incompressible flow problem is presented. First order upwind scheme (FOU) for the stream function-vorticity formulation is used. Iterations are solved using the C++ program with second convergence criteria (CON2). The work concentrates to study the effect of Reynolds number (100,200…600), aspect ratio (1, 1.2, 1.4 …2.0) of the cavity, and the velocity (1, 2, 3…6) of the lid on the stream function. To validate the simulation, the results are compared with other solutions in the literature.

Keywords : FOU, AR, CON2, Lid, Stream Function

I. INTRODUCTION

Cavity flows, in general, have been a common experimental approach used to check or improve numerical or theoretical schemes. Weiss and Florsheim [5] were one of the first to study Stokes flow in rectangular cavities without a moving boundary. Using two different aspect ratios, they obtained approximate experimental solutions for flows over cavities and confirmed these results with their theoretical predictions. Pan and Acrivos [6] were among the first to develop numerical techniques that predicted solutions for steady flows in rectangular cavities with a moving top wall and perform experiments for a variety of Reynolds numbers. Improvements to the numerical techniques have been a continual effort, but with Schreiber and Keller's work [7], they improved not only the reliability, but also the efficiency and accuracy. The lid-driven cavity flow is one of the most studied fluid problems in the field of computational fluid dynamics. The simplicity of the geometry of the cavity flow makes the problem easy to code and apply boundary conditions quite easily. Driven cavity flow serve as a benchmark problem for numerical methods in terms of accuracy, numerical efficiency etc. Owing to their broad range of natural, industrial and biomedical applications, cavity flows have been studied for years by both experimental and numerical investigation.

Lid driven cavity flow studies are useful to improve many practical application prototypes such as short dwell coaters and melt-spinning processes in forming continuous metal ribbons, processing foods, polymers used to produce high-grade paper and photographic film etc. In addition, this knowledge could be applied to fundamental closed-streamline flow, improving manufacturing systems efficiency, and the study complex flow physics of constituting an ideal vehicle. In the past, understanding of the re-circulating flow within the cavity has been treated as one of the fundamental challenges for fluid dynamics researchers. Therefore, a number of studies have been performed extensively and the solutions for flow behaviors are carried out.

II. GOVERNING EQUATIONS

Governing equations: incompressible 2-D flow vorticity, velocity and stream function

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad Where\ u = \frac{\partial \psi}{\partial y}\ ,\ v = -\frac{\partial \psi}{\partial x} \qquad (1)$$

$$\omega = -\left(\frac{\partial^2 \psi}{\partial x} + \frac{\partial^2 \psi}{\partial y}\right) \qquad (2)$$

Where ψ is the stream function, ω is vorticity, x and y are the Cartesian coordinates

Therefore, equation for stream function is,

∇^2 ψ=-ω Poisson's Equation

Vorticity transport equation

uω_x+ vω_y=v∇^2 ω, Where,u =ψ,;v= -ψ (3)

(A)Finite Difference Discretization of Boundary Conditions

Stream function

ψ_(1,j)=0 & ψ_(imax,j)=0 for 1≤j≤j_(max) (4)

ψ_(i,1)=0 & ψ_(i,jmax)=0 for 1≤j≤i_(max) (5)

Vorticity

$$\omega_{1,j} = -\frac{2\psi_{2,j}}{\Delta x^2}\ for\ 1 \le j \le j_{max} \qquad \text{Left surface}$$

$$\omega_{imax,j} = -\frac{2\psi_{imax-1,j}}{\Delta x^2}\ for\ 1 \le j \le j_{max} \qquad \text{Right surface}$$

$$\omega_{i,1} = -\frac{2\psi_{i,2}}{\Delta y^2}\ for\ 1 \le i \le j_{max} \qquad \text{Bottom surface}$$

$$\omega_{i,jmax} = -\frac{(2\psi_{i,jmax-1} + 2u_0\Delta y)}{\Delta y^2}\ for\ 1 \le i \le j_{max} \rightarrow \text{Top surface}$$

(B) Accuracy and Convergence

As a measure of convergence to the steady state, during the simulation we found two residual parameters. The first residual parameter, CON1, is defined as the maximum absolute residual of the finite difference equations of steady stream function and vorticity equations. These are respectively given as

$$CON1_{\psi} = \max\left|\frac{\psi^{n+1}_{i-1,j} - 2\psi^{n+1}_{i,j} + \psi^{n+1}_{i+1,j}}{\Delta x^2} + \frac{\psi^{n+1}_{i,j-1} - 2\psi^{n+1}_{i,j} + \psi^{n+1}_{i,j+1}}{\Delta x^2} + \omega^{n+1}_{i,j}\right| \qquad (6)$$

$$CON1_{\omega} = \max\left(\left|\begin{array}{l} \frac{1}{\mathrm{Re}}\frac{\omega_{i-1,j}^{n+1}-2\omega_{i,j}^{n+1}+\omega_{i+1,j}^{n+1}}{\Delta h^2}+ \\ \frac{1}{\mathrm{Re}}\frac{\omega_{i,j-1}^{n+1}-2\omega_{i,j}^{n+1}+\omega_{i,j+1}^{n+1}}{\Delta h^2}- \\ \frac{\psi_{i,j+1}^{n+1}-\psi_{i,j-1}^{n+1}}{2\Delta h}\frac{\omega_{i+1,j}^{n+1}-\omega_{i-1,j}^{n+1}}{2\Delta h}+ \\ \frac{\psi_{i+1,j}^{n+1}-\psi_{i-1,j}^{n+1}}{2\Delta h}\frac{\omega_{i+1,j}^{n+1}-\omega_{i,j-1}^{n+1}}{2\Delta h} \end{array}\right|\right) \quad \ldots\ldots(7)$$

The magnitude of CON1 is an indication of the degree to which the solution has converged to steady state. In the limit CON1 would be zero.

The second residual parameter, CON2, is defined as the maximum absolute difference between two iteration steps in the stream function and vorticity variables. These are respectively given as

$$CON2_{\psi} = \max\left(\left|\psi_{i,j}^{n+1}-\psi_{i,j}^{n}\right|\right) \quad \ldots\ldots(8)$$

$$CON2_{\omega} = \max\left(\left|\omega_{i,j}^{n+1}-\omega_{i,j}^{n}\right|\right) \quad \ldots\ldots(9)$$

CON2 gives an indication of the significant digit on which the code is iterating.

For all Reynolds numbers we considered that convergence was achieved when CON1ψ ≤ 10-5 was achieved. Such a low value was chosen to ensure the accuracy of the solution. At these convergence levels the second residual parameters were in the order of CON2ψ ≤ 10-3 that means the stream function variables are accurate to 3 digit accuracy respectively at a grid point and even more accurate at the rest of the grids.

(C) Description of the geometry

In this work, we have considered a two-dimensional lid-driven cavity flow in a square domain with height = 1 m (Figure 1). The top wall is moving with a constant velocity of 1 unit in X direction, while bottom and side walls are stationary. The flow is considered at Re = 100. Since the flow is viscous, the moving lid will cause a motion in the fluid.

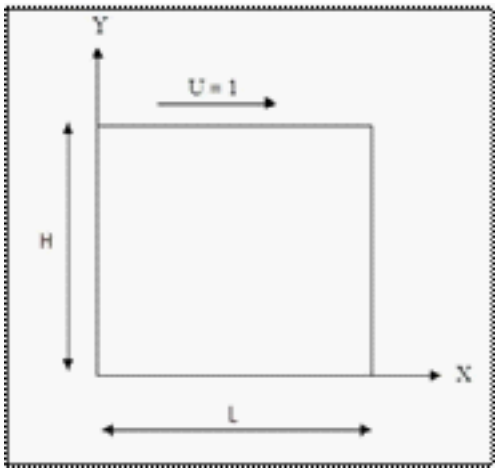


Figure 1 A Square cavity

VALIDATION

Here we have compared the simulated results with the available references in the literature as shown in the Table 1. The values of minimum stream function are compared and the obtained values are closer to the reference values. Reynolds number is kept constant and results are generated at various grid sizes. Stream function contours are shown in figure 2. Primary vortex in the grid size 32×32 is slightly different, otherwise in grid size 65×65, 81×81, 120×120 it is almost same. Table 2 shows that at various grid sizes and constant Reynolds number the value of stream function (ψ_min) remain unchanged.

Table 1 – Stream function values for different grid sizes at Re = 100

Re	References	Grid size	ψ_min
100	[1]	32×32	-0.103
	Present		-0.102
	[2]	65×65	-0.103
	Present		-0.105
	[3]	81×81	-0.103
	Present		-0.106
	[4]	120×120	-0.103
	Present		-0.105

Table 2 – Stream function values at various grid sizes and Re = 80

Grid size	Re	ψ_min
65×65	80	-0.105
70×70	80	-0.105
81×81	80	-0.105

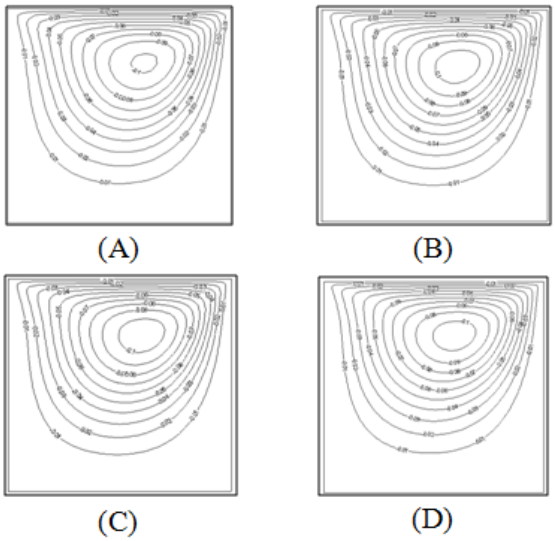


Figure 2 Stream function contours for different grid sizes, A (32×32),

B (65×65), C (81×81), D (120×120) for constant Re = 100, U=1.

Results and Discussions

The effect of Aspect Ratio, Reynolds Number and Velocity on the stream function (ψ_min) are investigated by simulation.

Table 3 Values of stream function (ψ_min) for varying Aspect ratio and velocity (U) at Re 100.

A.R	U1	U2	U3	U4	U5	U6
1	-0.106	-0.2171	-0.3238	-0.4272	-0.5272	-0.6239
1.2	-0.1063	-0.2181	-0.3242	-0.4264	-0.5255	-0.621
1.4	-0.1063	-0.2182	-0.324	-0.4258	-0.5245	-0.6199
1.6	-0.1063	-0.2182	-0.324	-0.4258	-0.5244	-0.6199
1.8	-0.1063	-0.2182	-0.324	-0.4258	-0.5244	-0.6198
2	-0.1063	-0.2182	-0.324	-0.4258	-0.5244	-0.6198

Table 4 Values of stream function for varying Aspect ratio and Reynolds number (Re).

Re	U1	U2	U3	U4	U5	U6
100	-0.1063	-0.2182	-0.3204	-0.4258	-0.5244	-0.6198
200	-0.1098	-0.2139	-0.3099	-0.4	-0.4841	-0.5628
300	-0.1095	-0.2064	-0.2946	-0.3744	-0.4468	-0.5125
400	-0.1076	-0.1993	-0.2802	-0.3513	-0.4134	-0.4665
500	-0.1053	-0.1922	-0.2668	-0.3297	-0.3785	-0.359
600	-0.103	-0.1857	-0.2541	-0.3052	-0.2776	-0.3165

The figures (3, 4) show the graphical representation of the above tabulated values. In figure 3 it is observed that for particular lid velocity the change in A.R does not affect the stream function. But the stream function is varying inversely with lid velocity. At low lid velocity there is no effect of variation of Reynolds number on stream function as shown in fig 4. If we work with high lid velocity, the stream function value is directly proportional with Reynolds number. Also at high Reynolds number and high velocity the secondary vortices are developed in the cavity.

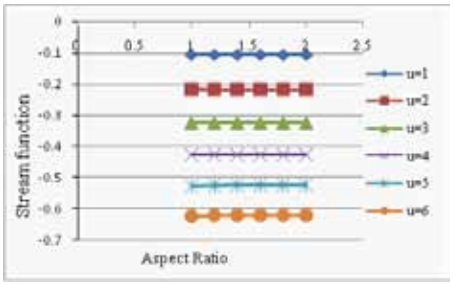


Figure 3 Graphical representation of stream function v/s aspect ratio for varying velocities at Re = 100

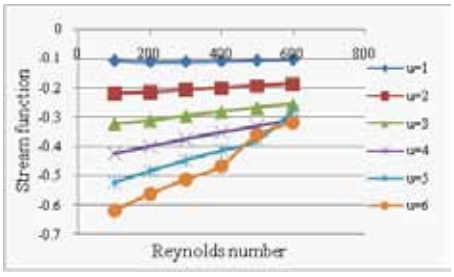


Figure 4 Graphical representation of stream function v/s Reynolds number for varying velocities A.R = 2.

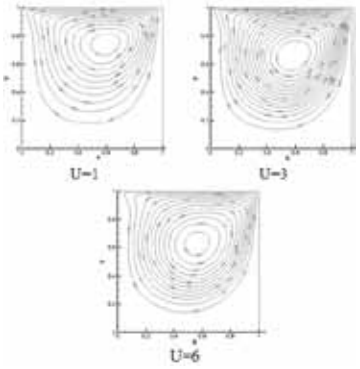


Figure 5 Stream function contours for square cavity for Re =100.

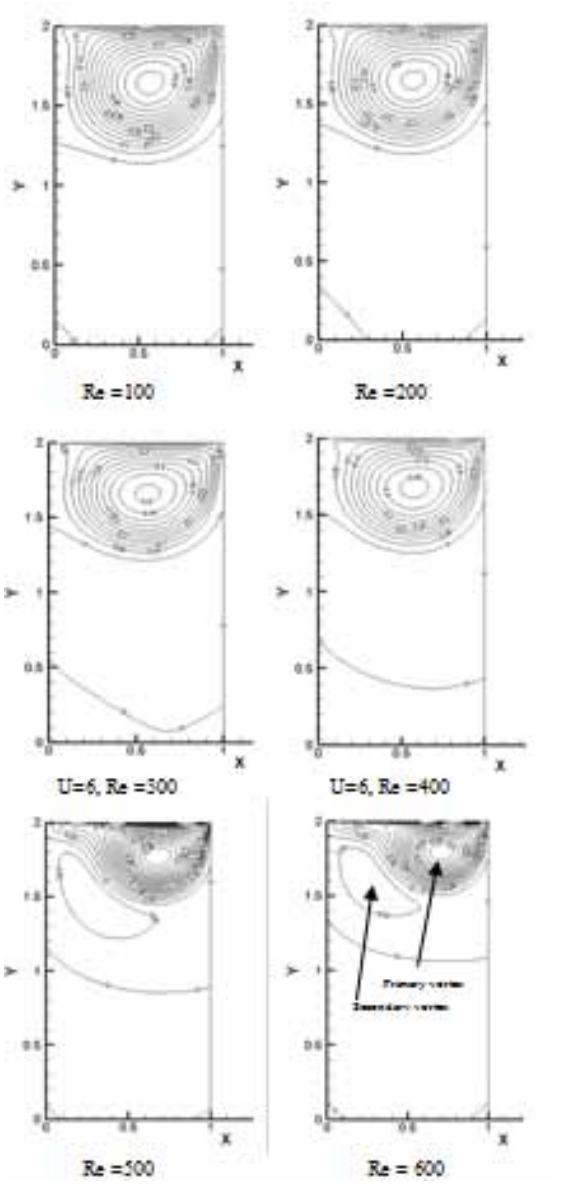


Figure 6 Stream function contours for velocity U = 6 units and Aspect ratio 2.

IV. CONCLUSIONS

The present computations not only confirms the flow features of the problem, but also reveals the effects of Reynolds number and the aspect ratio on the type of flow in the lid-driven cavity in a systematic way. We conclude the followings,

1. For square cavity as shown in figure 5 for different velocities the secondary vortices are not getting developed.
2. In high aspect ratio cavity, secondary vortices are developed for Reynolds number 500 and above as shown in the Fig. 6.
3. Variation in minimum stream function value with Reynolds number is negligible at low lid velocity; whereas it is significant at high lid-velocity.

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