Bifurcation phenomenon in Newtonian Fluid Flows through a Symmetric Sudden Expansion

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ABSTRACT—***The aim of the present study is to numerically investigate the bifurcation phenomenon in two dimensional sudden channel expansions. The numerical work is carried out using FLUENT, a commercial Computational Fluid Dynamics package. It uses the finite-volume method to solve the governing equations for a fluid. Geometry and grid is created using GAMBIT which is the preprocessor bundled with FLUENT. The working fluid used is di-ethylene glycol for steady, incompressible and laminar flow region. The present study shows that the re-attachment length and the size of re-circulation zones depend on the expansion ratio and Reynolds number.***

Keywords—Sudden expansion, recirculation, flow separation, reattachment and bifurcation.

1. INTRODUCTION

When a Newtonian fluid flows at low to moderate Reynolds number in a 2D channel and encounters a sudden expansion, flow separation occurs resulting in the formation of vortices. A bifurcation phenomenon, consisting of a transition from symmetric to asymmetric flow, occurs above a critical Reynolds number that depends on the expansion ratio of the channel and the rheology of the fluid. Flow through sudden expansion passages find numerous applications such as in the oil transportation industry, various manufacturing processes like extrusion, injection molding, polymer processing etc. Review of previous works on this field reveals the requirement of research work specially focused on the laminar region for expansion geometry.

The laminar flow of inelastic Non-Newtonian fluids, obeying the power-law model, through a planar sudden expansion with a 1:3 expansion ratio was investigated numerically by M.S.N. Oliveira et al. [1] Flow bifurcation is delayed for shear-thinning fluids when compared to the Newtonian fluids while this phenomenon occurs earlier in the case of shear-thickening fluids. The recirculating eddies along the walls become more stretched as the shear-thickening behaviour is enhanced, while they become more curved when the shear-thinning behaviour is enhanced. The flow reattachment length was determined experimentally by Hammad et al. [2]. They extracted the velocity vectors and streamlines in the flow field for an expansion ratio of 2with Reynolds Number between 20.6and 211.1. The flow of viscoelastic liquids with constant shear viscosity through symmetric sudden expansion geometries is studied numerically by Paulo J. Oliveira [3]. For Newtonian liquids in a 1:3 expansion geometry the flow becomes asymmetric for a Reynolds number of about 54. For the non-Newtonian case the transition depends on both the concentration and the extensibility parameters of the model and the size of vortices are smaller for the viscoelastic liquid compared with the Newtonian fluid. The investigation of viscoelastic flow in a planar sudden expansion with an expansion ratio D/d = 4 is studied numerically by Gerardo N. Rocha et al. [4]. A symmetry-breaking bifurcation was found for both Newtonian and viscoelastic fluids, at different Reynolds numbers in each case and represents the transition from a symmetric to an asymmetric flow. The critical Reynolds number at the bifurcation was 36 and 46 for the Newtonian and viscoelastic fluids and found that the critical Reynolds number decreases with increasing expansion ratio. At higher Reynolds number, Rehigher than 64 or 73.5 for the Newtonian and viscoelastic liquid, a second bifurcation point is observed and a further recirculation regions on the upper wall. The effect of elasticity tends to delay the onset of the bifurcation, and the vortex length and intensity are always lower for the viscoelastic fluid when compared with the Newtonian fluid. Bifurcation phenomena in three-dimensional sudden channel expansions are studied numerically by Badekas et al. [5]. At low Reynolds number the recirculation zones are fully symmetric and increase in size with increasing Reynolds number. After crossing the bifurcation point there exists a small and a large recirculation zone. With further increasing Reynolds number, the small zone first becomes smaller and finally remains constant in size, while the large zone continuously becomes larger. The various aspects of flow in the laminar and the critical zone have been studied extensively in the past few decades, but they are still in need of more study.

2. PHYSICAL DESCRIPTION

The geometric configuration of the problem is shown in Figure1. Fluid flows axially through an inlet channel of height d and length l, followed by another channel of length L. The Expansion Ratio (ER) is defined by ER = D/d, where D is the downstream channel height. The Reynolds number (Re) is defined using the upstream channel height and flow velocity at the inlet. The working fluid used is di-ethylene glycol having density of 1118.2 kg/m^3 and viscosity of 0.038 Pa-s. The boundary conditions considered for the numerical solution are uniform velocity at inlet, strong one-directional flow situation has been considered at outlet, thereby specifying the outflow boundary condition. No-slip boundary condition has been taken on walls. The conservative form of governing equations for continuity and momentum for the steady flow field are Refer to (1), (2) & (3).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}=-\frac{\partial P}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right] \qquad (2)$$

$$\rho u\frac{\partial v}{\partial x}+\rho v\frac{\partial v}{\partial y}=-\frac{\partial P}{\partial y}+\mu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right] \qquad (3$$

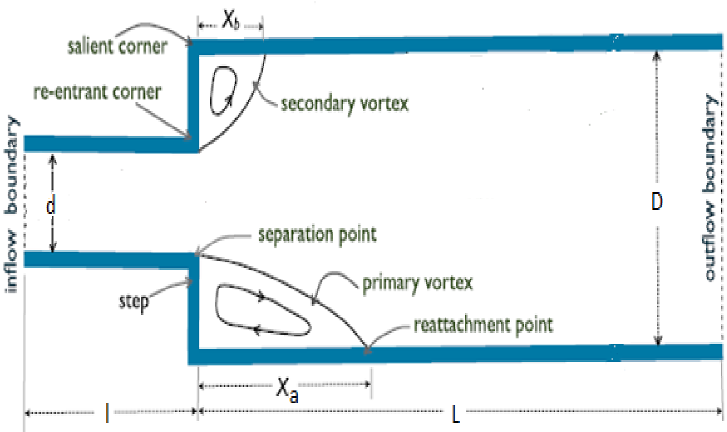

Figure 1: Physical domain of the problem

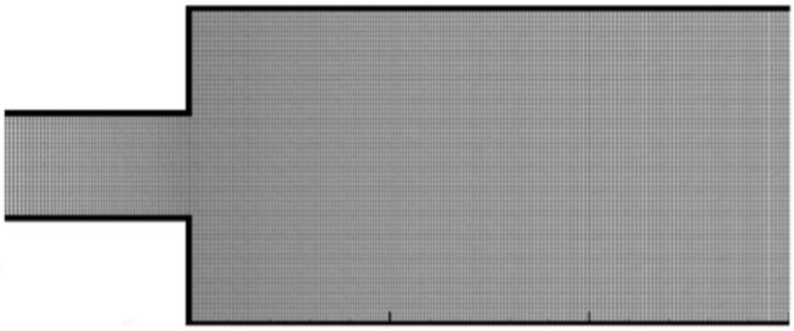

Figure 2: Mesh distribution of the geometry

3. GRID INDEPENDENCE STUDY

The 2D problem geometry is created by using Gambit 2.2 software. Then the geometry is meshed into smaller cells. Higher the number of cells the greater is the accuracy with more rigorous calculations and lower convergence limit. This is then exported as a 2D mesh file to be solved in solver Fluent 6.3. Grid independence study is conducted by using successively smaller cell sizes.

Table 1: Project selection matrix rules

Mesh	Block	N_x X N_y	CPU time
Mesh A	I II III IV	50 X 15 125 X 10 125 X 15 125 X 10	0.45 – 1 Hour
Mesh B	I II III IV	100 X 30 250 X 20 250 X 30 250 X 20	2.46 Hours
Mesh C	I II III IV	200 X 60 500 X 40 500 X 60 500 X 40	4.30 Hours
Mesh D	I II III IV	400 X 120 1000 X 80 1000 X 120 1000 X 80	10 Hours

The mesh distribution of the flow geometry is shown in Figure 2. The grid independence study has been performed to study the effect of mesh size. As the number of the cells increases the result of the numerical simulation will attain the perfect result. Also when the number of the cells increases the time required to converge the solution is also increases. The number of cells can be increased according to the size of the computational domain. The number of cells could be increased to get a much precise result for a much bigger computational domain. The computational domain is mapped by block-structured meshes and is partitioned into four blocks as shown in Figure 3. Grids are finer near the step of the expansion while they are coarser near the inlet and outlet. In order to check the grid dependence on the results, four different grids were used, namely meshes A, B, C and D, as detailed in Table 1 which summarizes the number of cells ($N_x.N_y$). The mesh C with 82000 cells is chosen for this study. The reason for choosing this number of cells is because the simulation will be quiet efficient, quantitative and consumes less time to produce the numerical results.

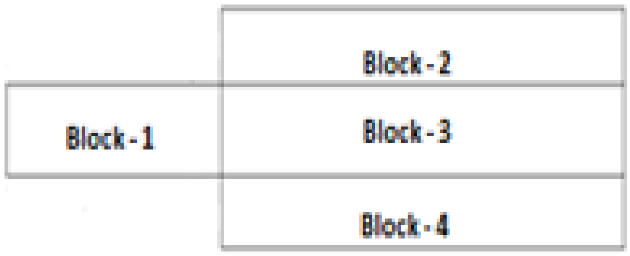

Figure 3: Blocks used in the sudden expansion geometry

4. VALIDATION

The experimental configuration of Hammad et al. [2] has been considered for experimental validation of the present numerical study. The physical configurations of the geometry are l = 16d and L = 20D. Figure 7 represents the streamlines plot for the region of separation at Re=77.6 and ER=2. The flow reattachment length, X_r/d = 3 for the experimental work and 2.8 for the present numerical work shown in Figure 8. Hence, these results represent the good agreement of present numerical simulations with the experimental results as reported by Hammad et al. [2].

5. RESULT AND DISCUSSION

The effects of expansion ratio on the flow field in a sudden expansion channel are analyzed to understand the flow characteristics. A set of streamlines are plotted using different ERs with a fixed Re=133. From the streamlines plotted using the Re=133 it is observed that the reattachment length obtained for different ERs are different. For an ER of 1.5, it is observed that the velocity of the fluid have reduced when it is entered to the sudden expansion region. The center region of the flow at the sudden expansion will have a higher velocity than the regions which are closer to the walls. No vortices are formed in this case.

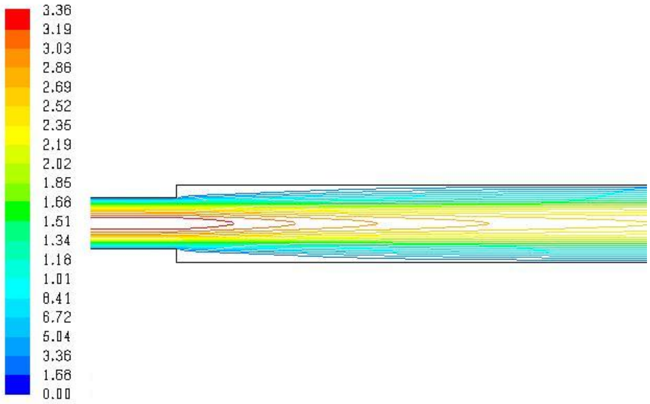

Figure 4: Stream wise velocity contours for ER=1.5

Figure 5.represents the streamwise velocity contours for an ER 2. It is observed that, one flow vortex rotate (in counter clockwise direction) near upper wall andanother flow vortex rotate (in clockwise direction) near lower wall around the inlet region of the sudden enlarged channel. It is also observed that there is symmetry on the flow field with respect to the horizontal axis of the geometry.

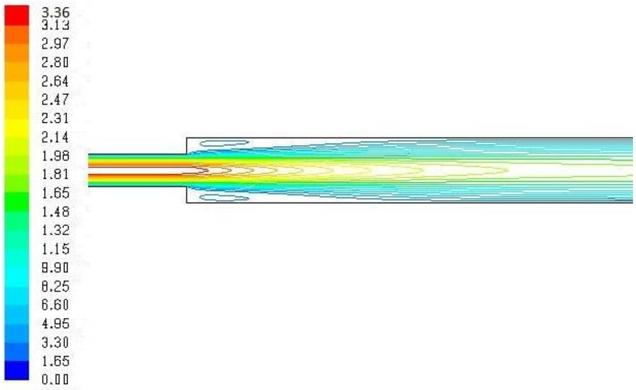

Figure 5: Streamwise velocity contours for ER=2

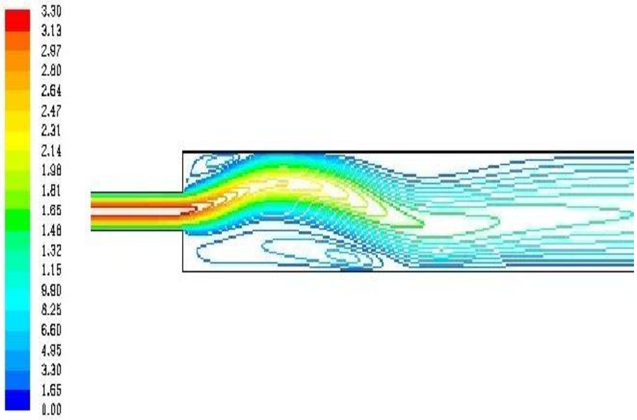

Figure 6: Streamwise velocity contours for ER=3

This flow symmetry suggests that the flow field remains stable at Re = 133 for an ER of 2. This point of stability is called as bifurcation point. After this upper point of stability, the symmetric flow pattern is destroyed and the flow tends to become unstable with the increase in ER.

The Fig.6 represents the streamwise velocity contours for an ER 3. The size of the vortices formed on the upper wall and the lower wall are entirely different. A weaker secondary vortex is formed in the upper wall and a primary separation bubble is formed in the lower wall. The flow becomes asymmetry and entered into the unstable regime.For unstable flow field, the flow reattachment length at upper wall differs with respect to the flow reattachment length atlower wall and flow structure takes wavy shape.

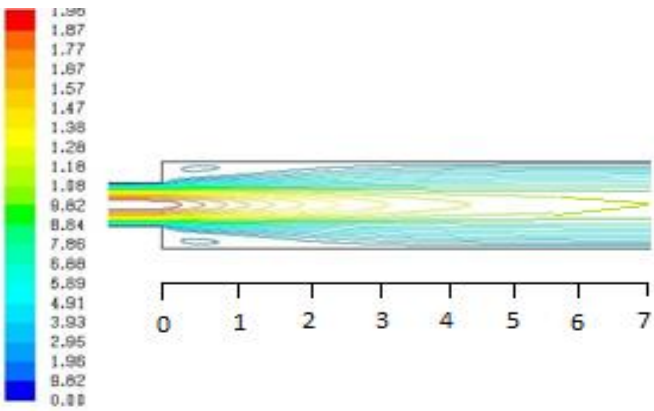

Figure 7: Streamlines plot for ER=2 at Re = 77.6

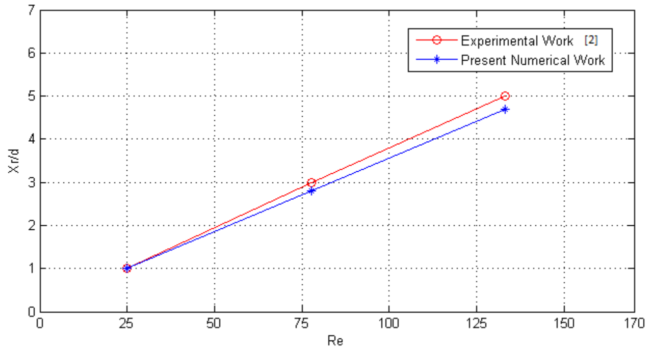

Figure 8: Comparison of reattachment length as obtainedfrom present Numerical Work and experimental Work [2]

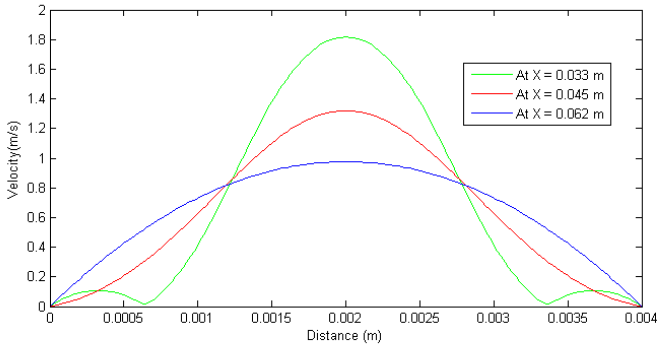

Figure 9: Variation of axial velocity with the radial direction at X = 0.033m, 0.045m ,0.062m

Figure 9 is the axial velocity profile towards the radial direction at different axial locations for ER = 2, Re = 77.6. The magnitude of the axial velocity is maximum at the center of the channel and decreases towards the radial direction of the channel. At X=0.062 m, the axial velocity is parabolic in nature and the fluid is reattached to the wall and the reattachment length is obtained.

6. CONCLUSION

In the present work, the analysis of sudden expansion flow geometry has been carried out numerically for the purpose ofunderstanding the flow characteristics and also the physical aspects of the flow separation phenomenon at the downstream, such as the reattachment and redevelopment of the flow. A good agreement has been observed between the present numerical results and experimental results which show that the reattachment length increases with the increase in Reynolds number.

From the numerical results it is observed that no vortices are formed for an ER = 1.5. The magnitude of axial velocity is maximum at the center of the channel and it diminishes towards the radial direction. For ER = 2, vortices are formed in the upper and lower wall of the channel and flow field becomes stable. This point of stability is called bifurcation point and Re = 133 becomes Critical for ER = 2. Any further increase in Re or ER results in the formation of asymmetry flow field about the horizontal axis of the channel. For ER = 3, the flow becomes asymmetry and enters into the unstable flow regime. Vortices of different size are formed at the upper and lower wall of the channel. The flow structure takes wavy shape, the reattachment length at the lower wall increases and it decreases at the upper wall of the channel. So it is found that the formation of recirculation zones depends on Re and ER of the channel.

7. NOMENCLATURE

ER	Expansion ratio
l	Length of the computational domain of contractionregion (m)
L	length of the computational domain of expansionregion (m)
μ	Viscosity of fluid flow (Pa-s)

ρ	Density of the fluid (Kg/m^3)
Re	Reynolds Number
X_r	Reattachment length (m)

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