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DECELERATION AS ONSET OF ASYMMETRY IN SYMMETRICALLY CONFINED FLOWS

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Abstract

The present study investigates the effect of deceleration on the threshold of transition from asymmetry to symmetry with respect to the flow through a symmetric 1:3 sudden expansion. A finite volume computational fluid dynamics code is utilised for simulating the unsteady decelerating flow for various deceleration rates in order to define the critical Reynolds number at which the onset takes place for each case. Results show that higher deceleration rates lead to lower critical Reynolds numbers and furthermore that this, in conjunction with existing studies that show that for steady symmetrically-expanding flows, higher expansion ratios lead to lower critical Reynolds numbers, underlines the flow deceleration effect as the key factor to the onset of asymmetry.

1. Introduction

Symmetry-breaking flows and the relative aspects thereof are being studied for many years. The phenomenon consists of a symmetric flow,

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which becomes asymmetric when specific conditions are met. This phenomenon is exemplary depicted in – but not limited to – planar symmetric sudden-expansion flows where the flow field is dominated by two equally sized recirculation zones that become uneven when the Reynolds number exceeds a critical value.

The specification of the critical value of the Reynolds number of such flows has been the focus for many studies. Durst et al. [4] and Cherdron et al. [3] performed laser-anemometer experiments in 1:2 and 1:3 planar expansions in order to obtain the critical Reynolds number for symmetry breaking. Their method is to investigate the flow at gradually higher Reynolds numbers and thus specify the critical value at which one recirculation region starts growing at the expense of the other. Later measurements by Fearn et al. [6] on a 1:3 expansion include the bifurcation diagram which shows the vertical component of velocity at the symmetry axis of the geometry 25.5mm from the expansion versus the Reynolds number. This provided a full range view of the symmetry breaking phenomenon together with the critical Reynolds number at the onset namely the occurrence of non-zero values of the aforementioned velocity. Subsequent experimental study by Durst et al. [5] provided the bifurcation diagram for a 1:2 expansion.

In addition to the experimental studies, different approaches have been carried out to investigate this phenomenon. Hawa and Rusak [7] used asymptotic analysis to study the effect of slight asymmetry in a channel with a 1:3 expansion and investigated the resulting change in the bifurcation diagram. Similarly, Shapira et al. [15] performed linear stability analysis in conjunction with perturbed flow parameters in order to specify the critical Reynolds number for a symmetric expansion with a slope of 100 to 900 and ratios of up to 1:3. Purely numerical studies include the work by Schreck and Schäfer [14] and Battaglia and Papadopoulos [1] that exploited computational fluid dynamics and performed 3D flow simulations for the expansion flow. Both the groups aimed at examining the three dimensionality effects on the symmetry breaking phenomenon. The first group provided results for 1:3 expansion and various aspect ratios and confirmed their agreement with experimental results whereas the second group provided results for 1:2 expansion and 1:6 aspect ratio and showed that overall, side-wall proximity enhances flow stability, thus sustaining laminar flow symmetry to higher Reynolds numbers.

The investigation of the symmetry-breaking phenomenon in symmetric sudden expansions is also extended in non-Newtonian flows where numerical studies were carried out and critical values of the flow parameters at the onset of asymmetry are provided (Neofytou and Drikakis [9] and Oliveira [11]).

In addition to the symmetric sudden expansion case, baffled channel flow is another example of deceleration-induced symmetry breaking flows. Roberts [12] investigated both numerically and experimentally the flow instability in a baffled channel where thin baffles are mounted on both channel walls periodically in the direction of the main flow. The results show that the flow is governed by recirculation zones in between the baffles that are symmetric as regards to the centreline of the geometry for low Reynolds number whereas they become asymmetric and time dependent above a critical value of the Reynolds number. Kang and Yang [8] confirmed this phenomenon in their numerical study that aimed at understanding how baffle interval and Reynolds number influence the flow instability.

Another case of symmetry-breaking flow is the flow about a circular cylinder between parallel walls. Chen et al. [2] performed numerical experiments to ascertain how the steady flow past a circular cylinder loses stability as the Reynolds number is increased. A set of numerical experiments has been made and it was revealed that, for a given blockage ratio, the flow remains steady at small Reynolds numbers whereas, above a critical Reynolds number, the flow would eventually settle down to a new state comprising a time-periodic motion. Sahin and Owens [13] solved the flow field around a confined circular cylinder in a channel and provided results with respect to lateral wall proximity effects on stability and wake structure behind the cylinder. These results include the critical Reynolds number at the onset of asymmetry for a wide range of blockage ratios.

Finally, Tsui and Lu [16] performed a study of the recirculating flow in planar, symmetrical branching channels including channels of Y and Tee shapes. Results show that when a slight pressure difference is imposed at the outlets, the flow patterns are essentially not affected for the Tee branch, whereas they change significantly in the Y branch. In the latter, the second vortex in the upper branch is eliminated and the vortices in the lower branch are greatly shortened and widened, thus revealing a breaking of symmetry.

All the aforementioned studies are based on geometrical setups where the flow decelerates at the area where the symmetry-breaking phenomenon occurs, that is, the velocity is higher upstream than downstream. Increasing of the Reynolds number in order to specify the critical value essentially means a more prominent difference between the upstream and downstream velocities and thus a more abrupt deceleration. Hence deceleration seems to play a critical role on the onset of asymmetry whereas up to the author's knowledge, this phenomenon does not occur in cases of accelerating flow. This issue, in conjunction with the fact that there seem to be no studies that look into symmetry-breaking flow aspects in unsteady flows, leads to the two-fold purpose of the current study, which is (i) to establish the importance of deceleration as the onset of asymmetry and (ii) to give quantitative results on the deceleration rate as catalytic effect on the occurrence of this phenomenon.

2. Method

2.1. Geometry setup and parameters

The geometry of the problem consists of a channel with a sudden expansion (Figure 1) with an expansion ratio of 1:3. The length of the channel is 40 times the downstream height. This was found to be adequate in terms of restoring the fully developed flow at the outlet (Neofytou and Drikakis [9]). The boundary conditions are as follows: at the wall boundary, the pressure values are derived by extrapolation from the inner nodes, whereas the velocity boundary value is set equal to zero following the no-slip condition. At the outflow boundary, the velocity values are set equal to the values of the inner nodes, whereas the pressure is set equal to the reference value of 1. At the inflow boundary, the pressure value is derived by extrapolation whereas the velocity values are set as the fully-developed profile of a Poiseuille flow. The Reynolds number is defined as

$$Re = \frac{\overline{u}h}{\nu}, \tag{1}$$

where h is the height of the inlet section and $\overline{u}$ is the mean inlet velocity.

With respect to studying the deceleration effects, unsteady flow is imposed at the inlet and several cases with varying deceleration rates are examined. Simulation is initiated by imposing a mean inlet velocity that corresponds to $Re_{ini} = 150$ that is a value well above the critical value, proceeds by steadily decreasing the velocity at a specific rate and terminates when the mean inlet velocity corresponds to $Re_{term} = 10$ that is a value well below the critical value. The deceleration rate is defined as

$$a = \frac{Re_{ini} - Re_{term}}{\Delta T}, \tag{2}$$

where ΔT is the dimensionless duration of the transition from Re_{ini} to Re_{term}.

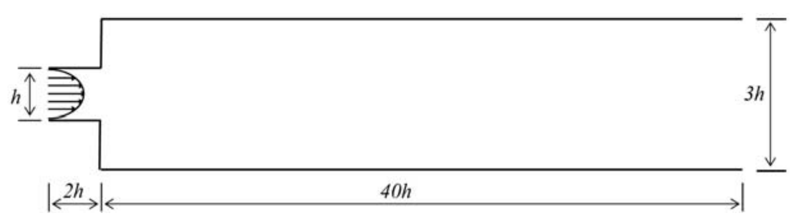

Figure 1. Geometry details of the computational domain.

2.2. Numerical model

The computational method employed is based on the finite volume scheme in conjunction with the pressure-correction method for a colocated arrangement of variables and it is used for the solution of flows in multi-block domains (Neofytou and Tsangaris [10]). In particular, the convection terms are discretised using the QUICK scheme, which is third-order accurate and therefore reduces the problem of numerical diffusion compared to lower order schemes. In addition, the diffusion terms are calculated using a second-order central differencing scheme where deferred correction is also used in order to enhance convergence by ensuring diagonal dominance of the matrix of system of equations. Finally, the discretised equations are required to satisfy the momentum and mass balance at every control volume via an iterative solution algorithm, which in the present case, is the semi implicit method for pressure-linked equations (SIMPLE). The computational domain is discretised using a two-block grid where the first block (B1) includes the inlet section whereas the second block (B2) includes the expanded section.

3. Results and Discussion

3.1. Numerical independence and validation

3.1.1. Space-discretisation independence

In order to assure a converged solution with respect to the grid refinement, a grid independence study is carried out using three grid $x \times y$ resolutions, namely grid 0 with 109×57 control volumes (CVs), grid 1 with $199 \times 117\,\mathrm{CVs}$ and grid 2 with $309 \times 177\,\mathrm{CVs}$. The test is carried out for $Re = 70$ by comparing the non-dimensionalised with the mean inlet velocity v-velocity profile at the symmetry plane along x-axis. It can be seen that the results for grids 1 and 2 are very close (Figure 2) and therefore grid 1 is used for all further computations of this study.

3.1.2. Time-discretisation independence

Time discretisation is required in this case, that is, ΔT should be divided in a number of equally spaced time steps dt. In order to ensure that the results are independent of the dt value, two simulation cases of different dt for a deceleration of $a = 1/2$ are carried out. Results are shown in Figure 3 where the two sets of plots are shown, namely the velocity v at the point on the centreline where the symmetry-breaking onset occurs (x_c) against the Reynolds number and the velocity profile at the centreline at the critical Reynolds number against the length of the channel. It can be seen that there is essentially no difference between the $dt = 0.1$ and the $dt = 0.01$ cases, therefore $dt = 0.1$ is used in all subsequent simulations.

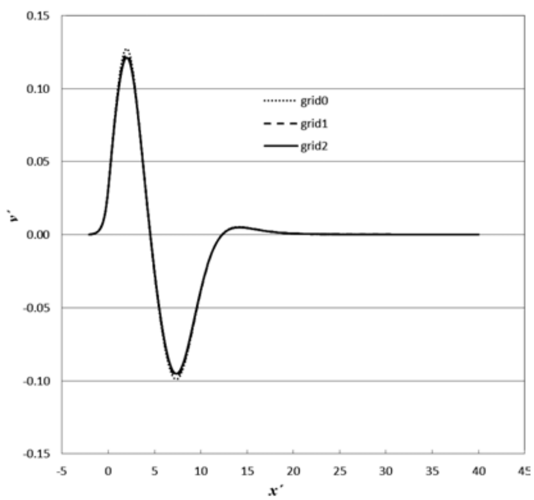

Figure 2. Space-discretisation independence.

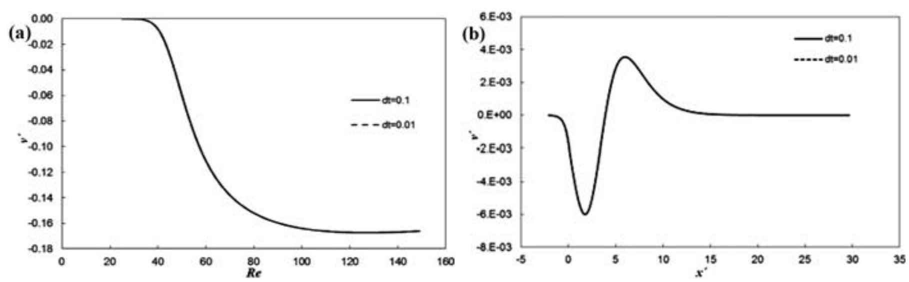

Figure 3. Time-discretisation independence for $a = 1/2$ and (a) $v' = f(Re)$ at the centreline and at x_c; and (b) $v' = f(x')$ at the centreline and at Re_c.

3.1.3. Validation

The validation of the numerical method is carried out by comparing current results with available benchmark results in the literature. The steady flow in a 1:3 sudden expansion is selected and steady flow simulations for various Reynolds numbers at increments of 0.5 are carried out so as to determine the critical value. The onset of the asymmetry is assumed when the value of the vertical velocity at any point of the centreline exceeds 5% of the value of the mean inlet velocity and this seems to occur at $Re = 53.5$ (Figure 4). This result is in close agreement with previously reported results (Fearn et al. [6]).

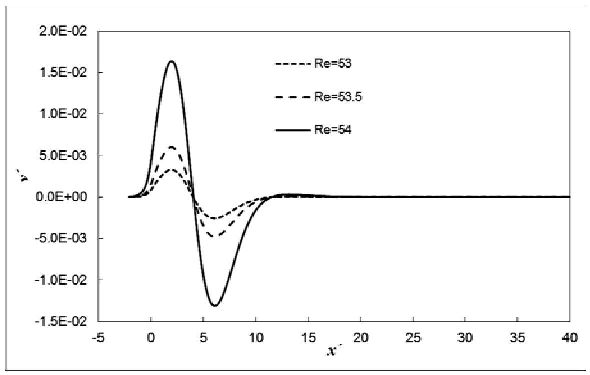

Figure 4. Diagram $v' = f(x')$ for various Reynolds-number steady-state flow cases.

3.2. Deceleration rate effects

For assessing the deceleration rate effects, eight cases of different deceleration rates ranging from $1/2$ to $1/72$ were studied. The simulation of the flow fields is divided in three phases: (i) it begins at high Reynolds numbers where the flow field is markedly asymmetric as expected and continues to be so as the inlet velocity steadily decrease being however well beyond the critical value. (ii) As the inlet velocity keeps decreasing, the flow tends to a symmetric state. This is the most important phase as therein the inlet velocity or in other words the Reynolds equivalent reaches the critical value and the flow becomes symmetric. (iii) As the inlet velocity keeps decreasing, the flow is dominated by two symmetric eddies at the expansion that are reducing in size with deceleration.

At the instant, at which the flow becomes symmetric according to the criterion mentioned in Subsection 3.1.3, there is a peak in the *v* velocity right after the expansion followed by another peak at the opposite direction owing to the remaining asymmetric flow features. This pattern is similar in all flow cases as seen in Figure 5 where the *x*-wise profile of *v* velocity normalised with the inlet velocity is depicted for the critical Reynolds number of each case.

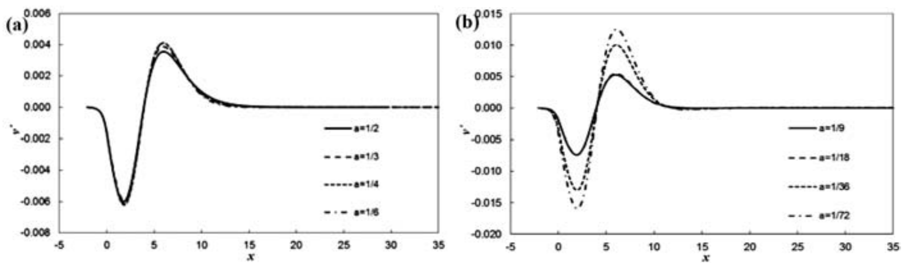

Figure 5. Diagrams $v' = f(x')$ at the centreline and at Re_c for (a) $a = 1/2\text{-}1/6$; and (b) $a = 1/9 - 1/72$.

At intense deceleration rates, the pattern seems to be identical with the peak rising slightly – in absolute values – above the symmetry criterion. As the deceleration rates become moderate, the difference in the patterns becomes evident with peak that is rising significantly over the symmetry criterion for lower deceleration rates. This owes to the more abrupt transition to symmetry for milder deceleration rates as shown in Figure 6 where the peak value at the geometry centreline of *v* velocity normalised with the mean inlet velocity is depicted against the Reynolds number corresponding to the mean inlet velocity for each deceleration rate case. The diagrams in Figure 6 bare a strong resemblance to the bifurcation diagram that is constructed in past studies following many steady flow cases for different Reynolds number in order to specify the critical Reynolds number. It can be seen that for intense deceleration, e.g., $a = 1/2$ (Figure 6(a)), the slope of decreasing *v*-velocity is smoother meaning that deceleration due to unsteady flow is prominent as the onset factor whereas at milder deceleration rates the slope is abrupt meaning that deceleration due to steady flow, namely flow passing from the inlet section to the expansion, is dominant, e.g., $a = 1/72$ (Figure 6(b)). This could also be explained with the fact that the milder the deceleration the more the diagram tends to the aforementioned steady flow bifurcation diagram. In addition, the peak of the v-velocity in Figure 5 is moved slightly downstream as the deceleration rates become milder.

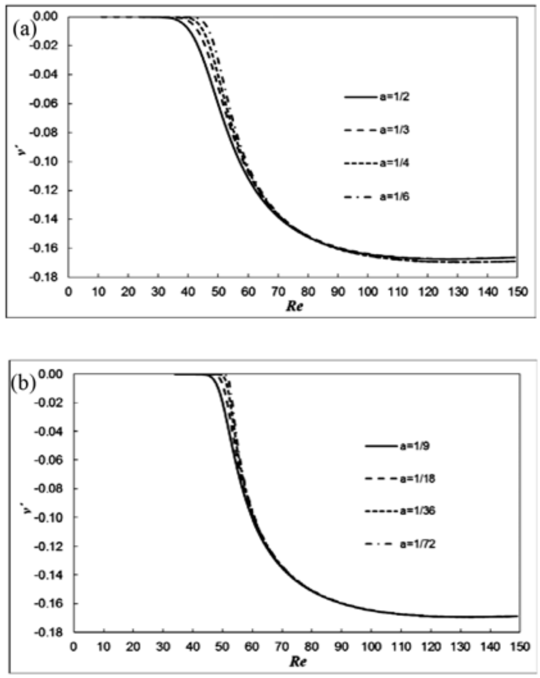

Figure 6. Bifurcation diagrams $v' = f(Re)$ at x_c for (a) $a = 1/2 - 1/6$; and (b) $a = 1/9 - 1/72$.

The critical Reynolds numbers for all cases are shown in Table 1 and illustrated in Figure 7, where it can be clearly seen that deceleration rate markedly affects the onset of asymmetry. Indeed as deceleration rate becomes more intense, the critical value of the Reynolds number lowers. This tendency seems more of curved behaviour rather than linear that is the change of the critical Reynolds number values is rather more marked for low deceleration rates whereas it seems smoother as the deceleration rate becomes more intense.

The latter result renders the hypothesis that deceleration is the inducing factor of asymmetry phenomena in symmetrically confined flows as true.

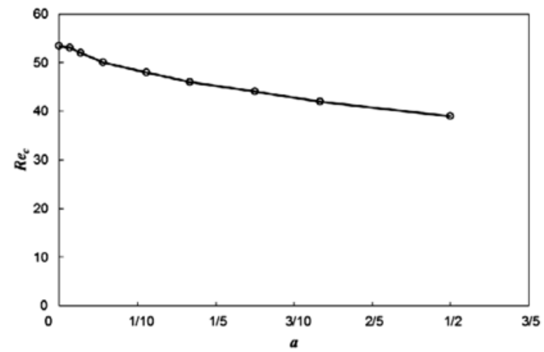

Figure 7. Diagram $Re_c = f(a)$.

Table 1. Values of critical Re numbers and points of onset of asymmetry (x_c) for various deceleration rates

a	1/2	1/3	1/4	1/6	1/9	1/18	1/36	1/72
Re_c	39	42	44	46	48	50	52	53

4. Conclusions

A numerical study on the flow transition from symmetry to asymmetry for unsteady decelerating fluid flows in a suddenly expanding 1:3 channel is carried out. The critical Reynolds number for which this phenomenon occurs has been derived for various values of deceleration rate. From the results, the following conclusions are drawn:

- The flow is changed from symmetric to asymmetric as the corresponding Reynolds number due to unsteady deceleration, drops below a critical value.

- Abrupt transition from asymmetry to symmetry is induced for mild deceleration rates whereas the transition becomes smoother for more intense deceleration rates.

- As unsteady deceleration rate becomes more intense, the value of the critical Reynolds number becomes lower. Previous studies on steady sudden expanding flows conclude that higher expansion rates lead to lower critical Reynolds numbers. Therefore, the issue of deceleration is again evident as prominent factor in the onset of asymmetry due to the fact that higher expansion ratios translate to more intense deceleration as the flow passes through the expansion. Therefore, deceleration proves to be indeed the onset of asymmetry in symmetrically confined flows.

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