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Effect of a Downstream Sudden Contraction on Flow Instability Behind a Sudden Pipe Expansion

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Abstract

In this paper, turbulent flow behind a sudden pipe expansion followed by a sudden contraction is numerically simulated, in order to investigate the effect of the downstream contraction on the flow instability in non-swirling flows, as well as in weakly swirling flows. Calculations are carried out using CFX4.3, in which the transient RANS approach and the standard k-ε model are implemented. The diameter ratio for both the expansion and the contraction is five. The length of the large pipe (normalised by its diameter D) is varied in the range from 1.0 to 4.0, and the results are compared with those for the case without a contraction. The current results show that a sudden contraction tends to stabilise the non-swirling flow when the large pipe length is reduced. However this stabilising effect does not apply to swirling flow, although the precessing direction and frequency are affected significantly.

Introduction

Many flow devices, such as burners and spray dryers, can be represented by an axisymmetric sudden expansion with regard to their flow fields. When the expansion ratio is sufficiently large, the flow is unstable and self-sustained oscillations may develop. The unsteady behaviours have been observed experimentally (Nathan *et al*. [6]) and predicted numerically (Guo *et al*. [2]). For the expansion ratio of about five, the simulated oscillation pattern can be described, in terms of the jet motion, as a combination of a precession and a flapping motion in a rotating frame of reference. The predicted large flow structures (Guo *et al*. [4]) are similar to those observed experimentally for a precessing jet flow (Nathan *et al*. [6]). The extension to weak swirl flows showed that the unsteady behaviour caused by a precessing vortex core (PVC) (Dellenback *et al*. [1]) can also be simulated using this CFD approach (Guo *et al*. [5]). The expansion flow with an expansion ratio of five is unstable over a range of swirl numbers from zero up to 0.48, even when vortex breakdown occurs (Guo *et al*. [3]). These results have demonstrated that both the asymmetry and self-sustained oscillations are intrinsic features of this flow in spite of the axisymmetric geometry, and simulation results based on the assumption of axisymmetric and/or steady state flow would make little sense in such situations.

Previous simulations assumed that the large pipe following a sudden expansion was infinitely long. However, in many applications, such as spray dryers, the chamber length is limited and the downstream contraction is likely to affect the flow behaviour. In the current paper, the influence of the sudden contraction for the case of an expansion ratio of five has been investigated numerically for non-swirling flow, as well as for weakly swirling flows. The length of the large pipe (normalised by its diameter D) was varied in the range from 1.0 to 4.0.

Geometrical Model

Figure 1 gives the dimension notation for the simulated domain and the co-ordinate system. The inlet and outlet have the same diameter. The expansion ratio is E=5, the length of the inlet pipe is $l_1 = 5d$ and the length of the exit pipe is $l_2 = 2.5d$. The exit pipe is shorter than the entry pipe because the downstream flow has less effect on the upstream flow. The Reynolds number used is 10^5 based on the average inflow velocity and inlet diameter. The inlet and the outlet are specified as fully developed pipe flow. The length of the large pipe section varies from 1 to 4 diameters (D).

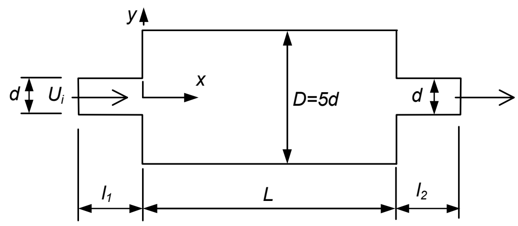

Figure 1. Schematic diagram of the geometry used in the simulation.

A typical grid used in the simulation is shown in Figure 2. The grid distribution in the cross-section is virtually uniform because we need to be able to track the central jet (or vortex core) as it moves about inside the chamber due to the transient nature of the flow. Meanwhile, a smoothly refined grid density in the axial direction is applied respectively in the vicinity of both the expansion and the contraction, where high gradients of flow quantities are expected.

The total number of cells is in the range from 90,000 to 150,000, which is large enough to accurately predict the lowest frequency of interest. The grid size and cell distribution used here are similar to those in our former papers [3,4], where grid sensitivity was checked carefully in the case of an infinitely long chamber for both the low-frequency precession and the higher-frequency flapping oscillation. In the present paper, the predicted precession frequency gives a consistent trend with the variation of the pipe length, although different grid sizes are used, which further shows reasonable grid independence of the results.

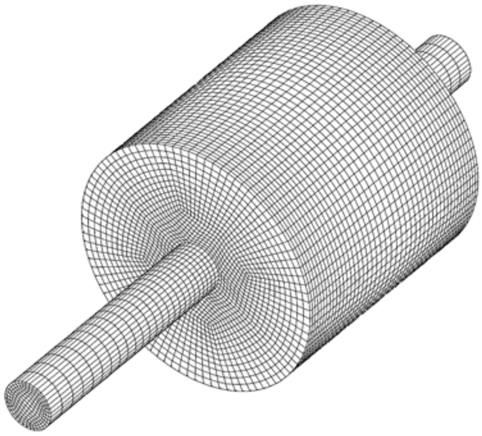

Figure 2. Typical grid used in the simulations (E=5, L/D=1.0).

Simulation Procedure

Calculations have been carried out using the CFD package CFX4.3, which uses the finite volume formulation on a block-structured mesh. The transient Reynolds-Averaged Navier Stokes (TRANS) equation approach, together with the standard k-ε turbulence model, has been used. This approach could be classified as a Very Large Eddy Simulation (VLES, as described by Speziale [7]). In effect, the k-ε model performs like a subgrid model, to handle small-scale turbulence, while leaving the largest scales to be resolved by the transient treatment in the averaged equation. In practice, all the important energy-carrying eddies can be resolved, so that grid independence of the resolved flow structures has been achieved in terms of the scope of the recirculation zone and the oscillation frequency.

Flow equations for velocities and turbulent quantities are discretised using second order schemes. The quadratic backward scheme is used for time stepping. PISO was used for pressure correction. For the current flow, it is found that convergence is extremely difficult in a steady simulation. However, convergence can be easily achieved in a transient calculation for each time step as long as the time step is sufficiently small. (A typical time step is two orders of magnitude smaller than the oscillation period for unsteady flow.) Velocity components and pressure are recorded at several fixed points for every time step. A transient simulation is able to distinguish between a stable flow and an unstable one. Figure 3 is an example of a flow oscillation induced by an initial disturbance being damped out as time proceeds, approaching a steady flow-field. On the other hand, starting from a symmetric initial flowfield, a self-sustained unsteady flow can develop for some geometrical configurations (as shown in Figure 4). Therefore the initial conditions used are not critical for predicting the state of the flow. This feature also excludes the possibility that the oscillation is an artifact of the numerical schemes.

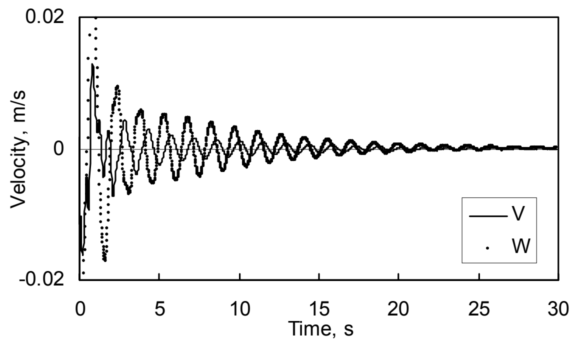

Figure 3. A time sequence for cross-stream velocities at a centreline point 0.2D from the expansion (d=0.1 m, Ui=10 m/s, E=5, L/D=1.0, no swirl).

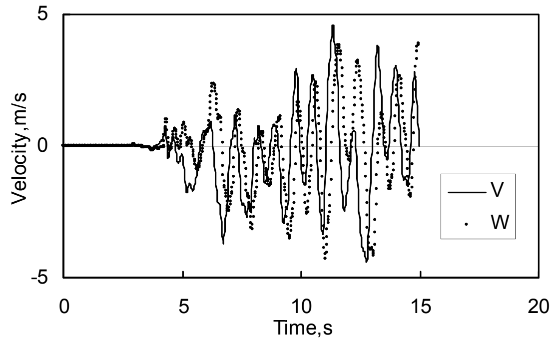

Figure 4. A time sequence for cross-stream velocities at a centreline point 0.2D from the expansion (d=0.1 m, E=5, Ui=10 m/s, L/D=1.0, S=0.4).

Results

L/D=∞

Simulation results have been presented for the expansion ratio of five for both non-swirling flow (Guo *et al*. [4]) and weakly swirling flow (Guo *et al*. [3]). In these cases, the simulation domain was taken as L/D=~20, and the outlet was treated as fully developed pipe flow. Consequently, the flow structures, such as the recirculation zone, are relatively unconstrained due to the absence of downstream confinement. An essentially periodic oscillation of the flowfield has been predicted in terms of the jet motion or the location of the vortex core with time. The larger pipe could be regarded as infinitely long, since the oscillation frequencies are insensitive to further pipe extensions.

Non Swirling Flow

- **L/D=4.0**

A pattern (called a limit cycle) can be formed for the case of a regular flow oscillation by plotting the time-varying cross-stream velocities (W against V) at a centreline point. The limit cycle for the case of L/D=4.0 is identical to the case of the long pipe, i.e., a combination of precession and flapping in the rotating frame of reference. This shows that the flow instability is dominated by the near field (close to the expansion plane) flow structures, and the contraction has little effect on the flow instability if L/D is above four. This is comparable with the case of an infinitely long pipe.

- **L/D=3.0**

A self-sustained oscillation pattern has been obtained. The frequencies decrease by 10-20% compared with the case of an infinitely long pipe. The flow structure shown by the streaklines (Figure 5) does not differ significantly from the case of an infinitely long pipe except in the near region of the contraction. The jet exiting the inlet tube hits the wall at an angle to the centreline on one side of the chamber, and a strong reverse flow is created on the other side. Thus a ring-like recirculation zone is formed, which tends to enhance the large-scale mixing in the streamwise direction. In the vicinity of the contraction, the recirculation ring is flattened by the forward facing step. A swirling flow is observed just behind the expansion step. These flow structures differ considerably from the toroidal recirculation zone surrounding a central jet that characterises an axisymmetric flow.

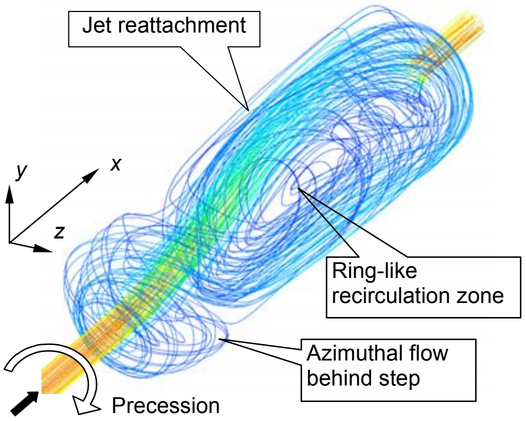

Figure 5. Instantaneous streaklines for precessing flow (E=5, L/D=3, no swirl).

For the above cases where flow instability occurs, self-sustained oscillation of the flow field normally results. The flow quantities at fixed points are periodic or semi-periodic in time. In most cases, the jet emanating from the inlet pipe precesses about the centreline.

- **L/D=2.0**

This case seems to be close to a transitional region. The oscillation pattern becomes more irregular, and the presence of a precession is not obvious since no clear limit cycle can be seen. The oscillation frequency decreases about threefold relative to the case of infinite length. It appears that this geometrical configuration (L/D) is close to the transition point between steady and unsteady flow, where hysteresis and uncertainty are possible.

- **L/D=1.0 and 1.5**

A further reduced length of the large pipe has considerably restricted the recirculation zone (about 12 step heights or 4.8 D for L/D=∞), thus the effect of the forward facing step became significant. Oscillations in a transient calculation damped out gradually and approached a steady-state symmetric solution. Then a subsequent steady calculation converged more easily. However, any direct steady simulation starting from scratch is difficult to converge. Figure 6 shows vectors in a slice through the centreline. Recirculation occurs over the whole length of the large pipe, but the centre of the vortex is close to the contraction plane. This causes a relatively high radial velocity at the surface of the forward facing step.

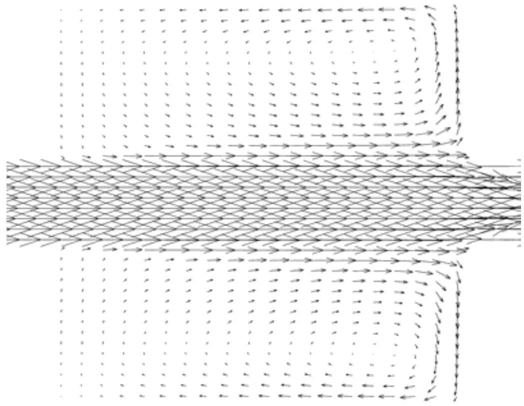

Figure 6. Vectors for steady flows showing a symmetric pattern (E=5, L/D=1.5, no swirl).

Figure 7 shows the precession frequency for non-swirling flows, normalised by D and the inlet velocity (or Strouhal number), varying with L/D. The precession frequency is zero for steady-state flows below L/D=1.5, and increases gradually until approaching a constant value above L/D=4.0.

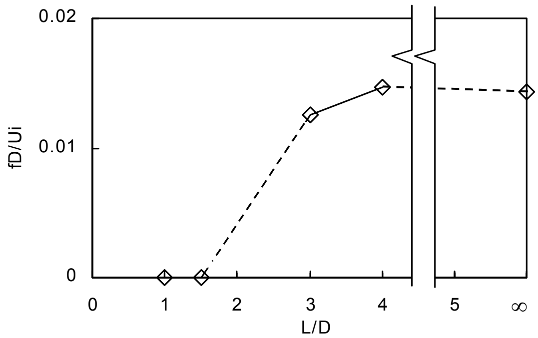

Figure 7. Variation of the precession frequency with pipe length (E=5, no swirl).

Swirling flow

Swirl is introduced from the inlet in the form of solid body rotation for the tangential velocity profile, while the axial velocity at the inlet is set to be uniform. The swirl intensity is calculated in terms of a swirl number, defined as the ratio of the axial flux of tangential momentum to the axial flux of axial momentum divided by the inlet radius. Two swirl numbers have been considered, i.e., 0.1 and 0.4 (calculated at the inlet). For L/D=1.0 and 1.5, unlike the cases without inlet swirl, the swirling flow is still unstable. The vortex core is found to depart from the centreline within the chamber and precesses about the centreline in a direction coincident with the swirl. Therefore, unlike the case of no swirl, the introduction of inlet swirl makes the precession direction predictable.

Figure 8 gives such limit cycles at two points, which characterise the fluid motion in a cross-stream plane. A precession of low frequency can be seen, although more complex oscillations of higher frequency have been superimposed.

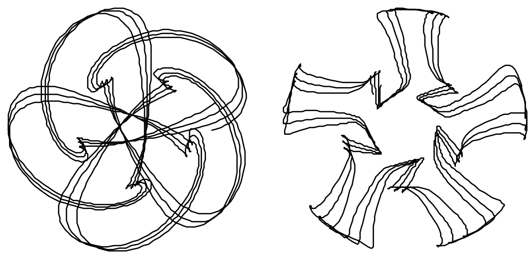

Figure 8. Limit cycle at different distances from the expansion (S=0.1, L/D=2.0).

Figure 9 shows a streakline image for precessing swirl flow to compare with the non-swirled case. The flow pattern appears more complex as a swirl velocity component is added to the whole field. The enhanced mixing causes the jet, although still pointing towards the wall, to disperse quickly and the jet reattachment point to move upstream.

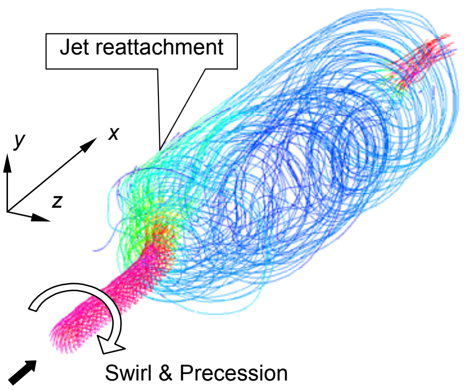

Figure 9. Instantaneous streaklines for precessing flow (E=5, L/D=3, S=0.4).

Figure 10 shows the variation of the normalised precession frequency with L/D. While the precessing direction for the non-swirling case is arbitrary without any preference, introduction of swirl makes it predictable. For L/D in the range of 1.0 and 1.5, the precession occurs in the same direction as the swirl. For the case of S=0.1, this direction is different from the case of an infinitely long pipe, therefore a processing direction reversal is expected as L/D varies in the range from 1.5 to 2.0. For L/D above 2.0, the precession is against the mean swirl direction. However, for a higher swirl number of 0.4, the large-scale precession has always been found to be in the same direction as the swirl.

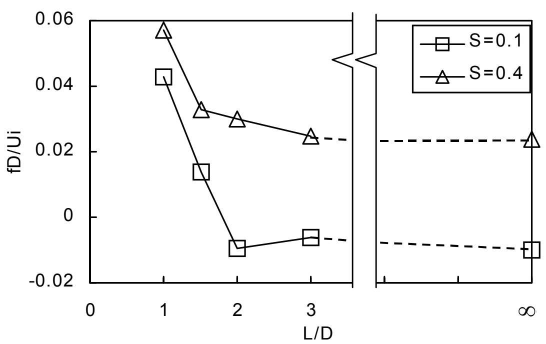

Figure 10. Variation of the precession frequency with the larger pipe length and inlet swirl number. (A negative value indicates that the precessing direction is opposite to the swirl.)

Self-sustained oscillations and their frequencies are the most important characteristic of the flow instability considered here. Table 1 gives the normalised precession frequencies (Strouhal number defined as fD/U_i) for both swirling flow and non-swirling flow. A negative value indicates that the precessing direction is opposite to the mean swirl direction.

L/D	S=0	S=0.1	S=0.4
1.0	Steady	0.043	0.057
1.5	Steady	~0.014	0.033
2.0	Irregular	−0.0094	0.029
3.0	0.0122	−0.0060	0.025
4.0	0.0147		
∞	0.0143	−0.01	0.024

Table 1. Strouhal number (fD/U_i) associated with precession.

Conclusions

Turbulent flows in a sudden pipe expansion followed by a sudden contraction have been simulated using CFD. The length of larger pipe was varied from 1.0-4.0D, while the diameter ratio remained constant (E=5.0). It is found that a downstream sudden contraction tends to stabilise the non-swirling flow. When L/D is below about 2.0, steady symmetric flow may be achieved, although this steady solution is difficult to achieve. When the ratio of length to diameter (L/D) is above 4.0, no significant effect is seen on the large flow structure and oscillation frequencies.

The contraction has a weak stabilising effect on the oscillation when swirl is introduced at the inlet, that is, no steady solutions have been obtained with swirling flow. Decreasing the large pipe length has increased the precession frequency.

References

[1] Dellenback, P.S., Metzger, D.E., and Neitzel, G.P., Measurement in Turbulent Swirling Flow Through an Abrupt Axisymmetric Expansion, *AIAA Journal*, **26**, 1988, 669-681.

[2] Guo, B., Langrish, T.A.G., and Fletcher, D.F., Time-Dependent Simulation of Turbulent Flows in Axisymmetric Sudden Expansions," *Proc. 13th Australasian Fluid Mechanics Conference*, Thompson, M.C., and Hourigan, K., Eds., Melbourne, Australia, December 13-18, 1998, 283-286.

[3] Guo, B., Langrish, T.A.G., and Fletcher, D.F., CFD Simulation of Precession in Sudden Pipe Expansion Flows With Low Inlet Swirl, *Applied Mathematical Modelling*, 2001, accepted.

[4] Guo, B., Langrish, T.A.G., and Fletcher, D.F., Numerical Simulation of Unsteady Turbulent Flow in Axisymmetric Sudden Expansions, *Journal of Fluids Engineering*, **123**, 2001, 574-587.

[5] Guo, B., Langrish, T.A.G., and Fletcher, D.F., Simulation of Turbulent Swirl Flow in an Axisymmetric Sudden Expansion, *AIAA Journal*, **39**, 2001, 96-102.

[6] Nathan, G.J., Hill, S.J., and Luxton, R.E., An Axisymmetric 'Fluidic' Nozzle to Generate Jet Precession, *Journal of Fluid Mechanics*, **370**, 1998, 347-380.

[7] Speziale, C.G., Turbulence Modeling for Time-Dependent RANS and VLES: A Review," *AIAA Journal*, **36**, 1998, 173-184.