This is a study of strong precession-like oscillation produced by a triangular-jet flow through a short cylindrical chamber. In this flow, there is a strong swirl around the jet near the inlet end of the chamber and there is a strong sink focus on the cylindrical wall. A vortex rises from the sink focus. The vortex produced by the swirl and the vortex rising from the sink focus are connected to form a loop inside the chamber. If the loop breaks or more than about 35% of vortex circulation escapes from the chamber, oscillation stops.

INTRODUCTION

A nozzle consisting of only a cylindrical chamber with a concentric inlet orifice at one end and an exit lip at the other can produce a naturally oscillating deflected-jet flow [6]. The geometric constraints are that the inlet-diameter expansion ratio \((D/d_1)\) be larger than about 5.0, chamber length-to-diameter ratio \((L/D)\) be about 2.7, and the exit-diameter contraction ratio \((d_2/D)\) be not smaller than about 0.7. If the inlet orifice is an equilateral triangle, jet oscillation is sustained at equivalent inlet-diameter expansion ratios as low as 2.1 [5, 4]. Oscillation of the triangular jet is more complex than that of the circular jet, and for a chamber length of \(L=1.25D\), the jet is deflected but does not oscillate [4, 3]. Surface-flow visualisation of the non-oscillating jet captures the effect of jet deflection but not the turbulence motion. The “unwrapped” chamber surface in Figure 1 shows counter-rotating sink foci \(F_1\) and \(F_2\) upstream and on each side of the jet-reattachment node \(N\). A circumferential negative-bifurcation “ring” connects these foci. Reverse flow through the exit plane is attracted to the larger focus. A conditionally-averaged wall-pressure distribution of the oscillating jet has been constructed using data from a backward-facing “detector” pressure probe and simultaneous measurements on the chamber surface. The conditionally-averaged pressure distribution has the same features as the time-averaged static-pressure distribution of the stationary-deflected jet but it has greater asymmetry [2]. This and other evidence from flow visualisation suggests that the surface-flow topology of the oscillating jet has the same critical points and bifurcation lines (i.e. topology) as the stationary-deflected jet [2].

EXPERIMENTAL TECHNIQUE

Velocity distributions of the stationary \((L/D=1.25)\) and oscillating \((L/D=2.50)\) flows in the nozzle are measured using conditionally-sampled PIV. For both triangular-jet flows, the expansion ratio is \(D/d_1=3.5\), exit-lip diameter is \(d_2=0.9D\) and inlet-orifice Reynolds number is \(Re_1=70,000\). Seven cross-section planes normal to the chamber axis are illuminated by an Nd:YAG laser. A Perspex model of the nozzle is placed in a tank of water which is seeded with 20-\(\mu\)m-diameter Polyamide particles. A CCD camera located downstream of the nozzle records 720 PIV image pairs at each laser-sheet cross-section. Three backward-facing pressure probes are placed in the reattaching-flow region of the oscillating jet so that they detect a preferred azimuthal orientation of the deflected jet. Signals from these probes are processed by a circuit [1] which acts as a switch in the trigger line to the camera, and allows the camera to operate only when the precession is counter-clockwise. Only two detector probes are used in the stationary-deflected flow. PIV velocity vectors are calculated using the cross-correlation method with interrogation windows having a size of 32x32 pixels and 50% overlap.

Figure 2. Streamlines in cross-sections of triangular-jet flow; (a-g) stationary deflected \((L/D=1.25)\); (h-n) oscillating \((L/D=2.50)\).
VORTEX STRUCTURE

Figure 2 shows streamlines constructed from the ensemble-averaged PIV cross-sections of the stationary-deflected and oscillating flows. In Figure 2, jet reattachment is visible as saddle points. Foci $F_2$ and $F'_2$ are consistent with the surface-sink foci $F_a$ and $F_b$ shown in Figure 1. The vortex cores in both jet flows are reconstructed by tracking the foci in the streamlines of Figure 2 from one PIV cross-section plane to another. This tracking process includes the merging, joining and termination of vortex cores, and is consistent with the Helmholtz vortex law. The results are shown as vortex skeletons in Figure 3. In the interaction between jet flow near the inlet orifice and the surrounding swirl, vortex stretching in the jet shear-layer concentrates vorticity into the co-rotating vortex cores $F_{a1}$, $F_{b2}$, and $F_{b3}$. These merge into a single vortex core $F_{xm}$ as they are advected through the chamber by the jet flow. The vortex core rising from the weaker surface-sink focus $F_b$ also merges with $F_{xm}$. In the stationary-deflected flow (Figure 3(a,c)), the merged vortex $F_{xm}$ and the vortex $F_a$ rising from sink focus $F_a$ are advected out of the nozzle as a pair of counter-rotating vortices. In the oscillating flow (Figure 3(b,d)), the vortex $F_{xm}$ produced by the swirl and the vortex rising from the stronger sink focus $F_a$ are connected to form a loop which is contained within the chamber.

This model of the vortex structure is supported by Figure 4 which shows positive and negative contributions ($\Gamma^+$ and $\Gamma^-$ respectively) to circulation in the PIV cross-sections of each jet. About 35% of the swirl circulation in the stationary-deflected flow escapes from the chamber and 65% is captured by the nozzle. In the oscillating flow, the nozzle retains nearly all (92%) of the swirl circulation.

CONCLUSIONS

The extent to which vortex structure is contained within the nozzle distinguishes between the stationary-deflected and oscillating flows. In the oscillating flow, the vortex produced by the swirl and the sink-focus vortex rising from the wall at $F_a$ are connected to form a loop inside the chamber. If more than about 35% of vortex circulation escapes from the nozzle, oscillation stops.

References