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A PRECESSING ASYMMETRIC FLOW FIELD IN AN ABRUPTLY EXPANDING AXI-SYMMETRIC DUCT

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Abstract

Recent investigations by Hallet and Gunther (1984) and Dellenback et. al. (1988) have revealed a precessing asymmetric flow field downstream of an abrupt, axi-symmetric expansion when the upstream flow is weakly swirled. The direction of the precession was found to be the opposite of that of the swirl, its frequency was measured as a function of swirl number, and its existence was attributed to the presence of the swirl.

Related research conducted at the University of Adelaide on an Enhanced Mixing, EM, nozzle is presented here. The essential element of the nozzle is an abrupt axi-symmetric expansion into a "short" cavity. The jet from the throat does not expand symmetrically into the cavity but attaches asymmetrically to the wall. This condition is inherently unstable, causing the attached jet to precess around the inside of the downstream duct. When a small lip is placed at the exit plane, the exiting asymmetric jet is deflected at a large angle from the nozzle axis and precesses. The resulting flowfield is a highly mixed jet with rates of entrainment some five times that of a simple jet.

It has been found that the onset of the described asymmetric phenomenon is a function of the expansion ratio and Reynolds Number, and that upstream swirl is not an essential pre-requisite for its occurrence. The Strouhal Number of the non-swirled precession is found to be constant when based upon the mean velocity in the upstream pipe and the step height, ie. $St_h = f_p h/u_1 \approx 5 \times 10^{-3}$.

The influence of expansion ratio has been investigated elsewhere in flow through plane, two-dimensional abrupt expansions. Those results also indicate that expansion ratio and Reynolds Number control the onset of asymmetric flow patterns. However the investigations of the flow through orifice plates and abrupt axi-symmetric expansions has nearly all been conducted with diameter ratios typical of flow measuring devices, ie. less than three. The present investigation has found that an expansion ratio based on diameter of about five is required to generate asymmetric flow in the axi-symmetric geometry, unless swirl is introduced as reported by Hallett and Gunther.

The paper briefly discusses the asymmetric flow field which occurs in non-swirling axi-symmetric geometries in relation to the results of swirling flows in axi-symmetric geometries and in relation to plane two-dimensional flows.

1 Introduction

Whilst much effort has been expended in investigating the flow through orifice plates and abrupt axi-symmetric expansions, it has nearly all been conducted at diameter ratios typical of orifice plate flow meters, ie. less than three (see for example Bull and Agarwal 1983). However when the diameter of the upstream pipe, d_1, is typically one fifth of that of the downstream pipe, D, the jet from the throat does not expand symmetrically into the cavity but attaches asymmetrically to the wall. This condition is inherently unstable, causing the attached jet to precess around the inside of the downstream duct. The frequency of the precession is governed by the step height and the velocity through the upstream pipe, such that $St_h = f_p h/u_1 \approx 5 \times 10^{-3}$.

The precessing asymmetric flow phenomenon can be generated at much lower expansion ratios if swirl is imparted to the flow. Thus Hallet and Gunther (1984), H&G, who are credited with first observing this asymmetric flow, used an expansion ratio of only 2.2. Dallenback et. al. (1988), DM&N, examined the flow in more detail and found the dependence of the precession frequency (for one expansion ratio only) as a function of Swirl Number. They found that the direction of precession was the opposite of that of the swirl and that, near a critical zone, the precession becomes weaker as the swirl intensity is increased, and ceases when the swirl reaches the critical level that causes the onset of a central recirculation zone.

This paper introduces the dominant parameters which control the transition from symmetric to asymmetric flow in axi-symmetric abrupt expansions and briefly discusses them in relation to other research in both plane, two-dimensional and axi-symmetric flow.

2 The effect of Expansion Ratio

Whilst a detailed investigation of the effect of expansion ratio on the transition between symmetric and asymmetric flows in axi-symmetric ducts has not been made to the best knowledge of the authors, a lot can be inferred from two-dimensional investigations.

There are three primary classes of flow patterns through plane, two-dimensional abruptly expanding ducts, depending predominantly on the expansion ratio, E, and the Reynolds number.

Abbot and Kline (1962) found that when E ≤ 1.5 the two shear layers on either side of the expansion are sufficiently far removed to be independent of each other as shown in Figure 1. Consequently, in the first category, the flow on each side is similar to that behind an equivalent backward facing step where Eaton and Johnston (1981) found that the reattachment length, x_r, scales on step height with a dependence on velocity which decreases with increasing Reynolds number.

In the second class of flow, described by Cherdron et. al. (1978) and shown in Figure 2, the two shear layers interact with one another causing the reattachment length on one side of the expansion to be be longer than that of the backward facing step, and that on the other to be shorter.

The third class of flow, illustrated in Figure 3, occurs when either the expansion ratio or the Reynolds number is increased still further, causing a third and then a fourth recirculation zone to form downstream from the two primary recirculation zones. Ouwa et. al. (1981) and Armaly et. al. (1983) found that for this case, the flow behaves like that in a narrow jet expanding asymmetrically and attaching itself to one wall and then the other, before eventually expanding to fill the section.

Whilst the influence of expansion ratio upon flow symmetry in two-dimensional ducts provides a useful analogy to three dimensional ducts, any direct comparison must be made with caution. An asymmetric expansion of a plane jet is bi-stable and steady in the sense that while there is no initial preference for the wall to which the jet will attach, once attached it will remain in that position. However in an axi-symmetric expansion an asymmetric reattachment is inherently unstable as an infinity of reattachment points are equally probable. Furthermore the pressure imbalance on either side of a reattaching plane jet, which sustains the streamline curvature, cannot be sustained by an axi-symmetric jet because the spaces "above" and "below" the jet are connected and so the jet cannot separate the high and low pressure "zones". Such a condition is perpetually unstable and so is consistant with the observed precession of the jet and its reattachment point around the inside of the duct.

Nevertheless, it is interesting that Ouwa et. al. (1981) found that for a plane, two-dimesional geometry, the critical value of expansion ratio required to generate a reattachment of sufficient asymmetry that a third (downstream) recirculation zone is formed is $E_c = 5$ when $Re_h = 30$. This is approximately the same Expansion Ratio that is found in the present investigation to generate asymmetric flow in an axi-symmetric configuration if E is based on diameter.

3 The Strouhal Number of the Precession

Detailed hot wire anemometry experiments conducted in air and quantitative flow visualisation experiments conducted in water indicate that the Strouhal Number of the precession motion based upon mean flow velocity in the upstream pipe, u_1 and the step height, h, is independant of the upstream Reynolds Number Re_1 and the nozzle scale; ie. $St_h = f_p h/u_1 \approx 5 \times 10^{-3}$

3.1 Experimental Arrangements

To understand the experimental techniques used to measure St_h, it is necessary to give a brief description of the flow patterns. Inversely, the experimental techniques themselves themselves powerful evidence of the precessing jet phenomenon. A more detailed description of the flow patterns within the nozzle is given by Nathan (1988).

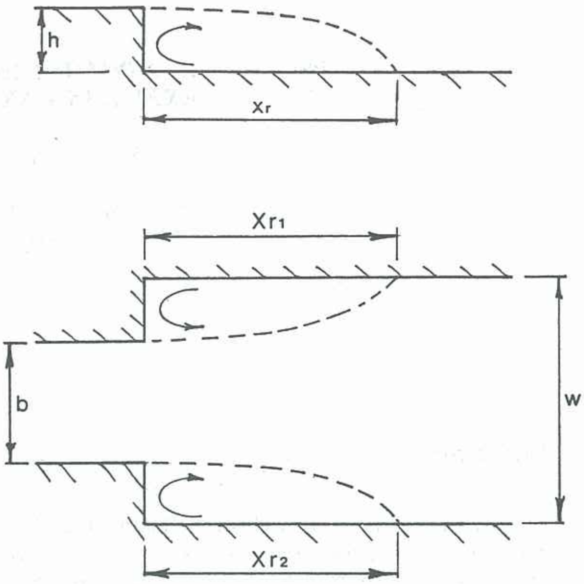

Figure 1: Abruptly expanding duct with both shear layers independant, compared with a backward facing step; Note: $x_{r1} = x_{r2} = x_r$ for $w/b \leq 1.5$

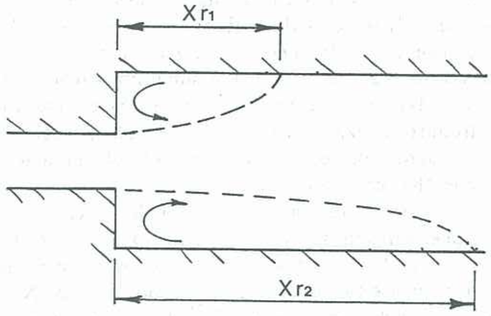

Figure 2: Abruptly expanding duct with shear layers interacting; Note: $x_{r2} > x_r > x_{r1}$ for $w/b > 1.5$

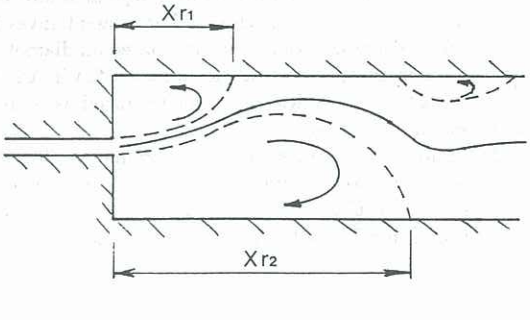

Figure 3: Abruptly expanding duct with shear layers strongly interacting; Note the presence of a third recirculation zone and strong flow asymmetry.

The jet expands asymmetrically into the downstream duct so that at any instant it is attached to one azimuthal station of the duct. The duct is sufficiently short relative to its diameter to ensure that the asymmetric jet does not fill the exit plane of the duct. Now the entrainment of surrounding fluid by the jet within the duct causes the static pressure within the duct to be less than ambient. Consequently a reverse flow of ambient fluid is induced into the duct through that part of the exit plane which is unoccupied by the asymmetric jet. Since the asymmetric jet is continually processing, it can be seen that at a fixed point near the boundary within the exit plane the flow must alternate between a positive and a negative direction as the jet sweeps past it.

Using water as the working fluid through a nozzle submerged in a large water flume, dynamic observation of the flow phenomena is allowed. A dye trace placed in the exit plane of the nozzle is observed to "flip" into and out from the nozzle with a frequency whose magnitude is suitable for direct measurement using a stop watch.

When the same nozzle is operated at the same Reynolds Number in air, the precession frequency is much higher although it is still very low in relation to other fluid mechanical time scales. For example, using a nozzle with a downstream duct, D, of 90mm and a Reynolds Number Re_1 of 10^5, the precession frequency is of the order of ten Hertz. This frequency can also be measured using a hot wire anemometer positioned in the exit plane of the nozzle.

3.2 Results

The results of the frequency measurements obtained using dye traces in water are shown in Figure 4. The precession frequency f_p is directly proportional to both $\overline{u_1}$ and Re_1. The Strouhal No. of the precession is constant with a value $St_h = f_p h/\overline{u_1} \approx 5 \times 10^{-3}$, which is approximately the same as that measured by hot wire anemometry in air.

Each data point plotted in Figure 4 is averaged over at least 120 real time measurements. That is, the time taken for ten "flips" was measured at least twelve times, and the average of these results is plotted in Figure 4. The results of the hot wire anemometry experiments are in excellent agreement with the results obtained using dye. They are the subject of another paper in preparation

3.3 Discussion

The present observations of jet precession compare well with the results of H&G and DM&N, who found that St decreases toward zero as the swirl number S decreases toward a low value which they assumed to be zero. Measurement was found not to be possible within this region due to the highly unsteady nature of the flow. The present investigation suggests that this unsteadiness occurs when E is less than a critical value, E_c as indicated below. H&G and DM&N presented their results in terms of a Strouhal number appropriate for symmetric flow in cyclone separators, $St_D = fD^3/Q$. When recalculated in terms of St_h, we find that its value at the lowest swirl number for which data was measurable, corresponding to the peak below which St begins its descent, is an order of magnitude greater than the value obtained by the present investigators with zero swirl, $S = 0$, depending upon the Reynolds number.

It is postulated that the precession frequency scales upon the fluid-mechanical "reattachment length", ie. the distance to the three dimensional positive bifurcation. The reattachment length scales on the step height for both orifice plates, investigated by Agarwal (1986), and plane steps, reviewed by Eaton and Johnston (1981). In the present nozzle, the more complex geometry imposes a secondary influence on f_p.

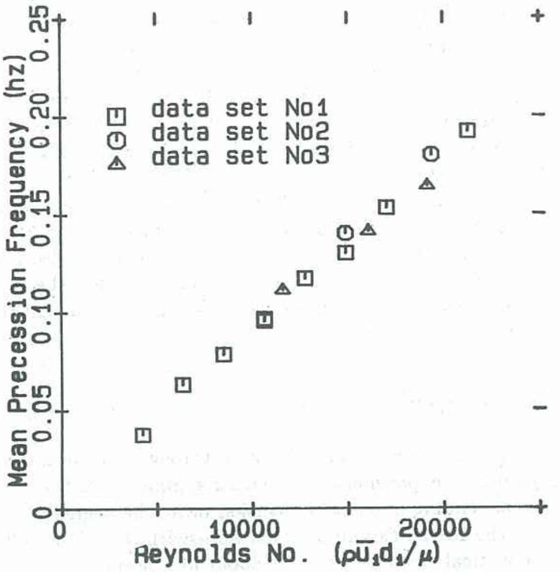

Figure 4: The Precession Frequency of the MLC nozzle as determined using a dye trace in water, with each data point averaged over at least 120 cycles.

The Strouhal Numbers associated with acoustic excitation have been well investigated, and are typically within the range 0.1 (Welsh and Gibson (1979)) to 0.6 (Parekh et. al. (1987)). These values are two orders of magnitude greater than those associated with the present jet precession which is clear evidence that the two phenomena are distinct. Furthermore, the same mechanism and Strouhal number occur in both air and water at the same Reynolds Number, which would not be possible with acoustic excitation since the flows in the two fluids have a Mach number ratio of about seventy.

4 The Effect of Swirl

H&G and DM&N investigated flow through an axi-symmetric sudden expansion with expansion ratios based on diameter of $E = 2.2$ and $E = 1.94$ respectively. They observed, H&G using flow visualisation and DM&N using Laser Doppler Anemometry, a precessing asymmetric flow field when the Swirl Number, S, was less than the value S_c required for the onset of vortex breakdown. (Up to six classes of vortex breakdown have been identified but all are characterised by a free stagnation point and a reverse flow zone; Leibovich 1978, 1984). DM&N found that for $S < S_c$, the asymmetric flow field precesses in the opposite direction to that of the mean swirl. They calculated the Strouhal Number of the precession, based on upstream pipe diameter and velocity, and found that it was a strong function of S and a weaker function of Reynolds Number.

The present investigation has been conducted using both swirling and non-swirling flows. It has been found that the onset of the precessing asymmetric flow-field is dependant upon the Expansion Ratio for a wide range of Reynolds Numbers when the flow entering the duct is not swirled. However, the critical expansion ratio is difficult to determine unambiguously because the flow switches intermittently between the symmetric and asymmetric patterns near $E = E_c$

Nevertheless, for the geometric configurations tested in the present experiments, ie. $1 < l/D < 4$, it has been found that $E_c \approx 5$ when the flow is not initially swirled.

Although it was not within the scope of the present investigtation to investigate swirled flow within expansions where $E < 5$, it is apparent from the results of H&G and DM&N that E_c is a function of S. It is also anticipated that the value of S_c will depend upon E. However the addition of upstream swirl has been found to reduce the occurrence of intermittency of the asymmetric flow field. It also leads to an increase in the precession frequency within the range of swirl used, as may be deduced from the requirement that angular momentum be conserved.

5 Conclusions

It has been found that the flow through an abrupt axisymmetric expansion can be either symmetric or asymmetric, depending upon the expansion ratio, the degree of swirl and the Reynolds number. For non-swirling turbulent flow the critical expansion ratio is about five based on diameter, although exact values are difficult to determine definitively due to an intermittent transition between the two flow types.

A Strouhal number to characterise the precession has been proposed, based upon step height and velocity in the upstream duct. Further research is needed to quantify the relationship between swirl, expansion ratio and Strouhal number.

6 Acknowledgements

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7 Notation

d_1 : diameter of upstream pipe
d_2 : diameter at the exit plane of the EM nozzle
D : diameter of downstream pipe
E : Expansion Ratio; $E = D/d_1$
E_c : Critical Expansion Ratio, for asymmetric flow
f_p : frequency of jet precession
h : step height at sudden expansion
l : length of cavity in EM nozzle
P_d : Driving Pressure, upstream of the nozzle
Re_1 : Reynolds number in the upstream pipe
St_h : Strouhal Number based on h; $St_h = fh/u_1$
u_1 : velocity in upstream pipe

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