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BRIEF COMMUNICATION

EROSION IN CONICAL DIFFUSERS IN PARTICULATE-LADEN CAVITATING FLOW

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Abstract—This paper highlights the serious damage that can occur in diffusing sections of pipework in which a cavitating particulate-laden fluid is flowing. The combined effects of particle erosion and cavitation are shown to remove considerably more material than would be expected from summing the effects of the individual mechanisms. It is demonstrated that, to be sure of avoiding this accelerated surface erosion, the transition from a smaller flow section to a larger one needs to be an abrupt expansion. If pressure recovery is important, a possible design solution is proposed. In the case of swirling flow, the expansion again needs to be abrupt. Evidence was also obtained which showed that, by allowing air to be entrained into the low pressure region in the flow, the cavitation and the erosion can be substantially reduced.

Key Words: erosion, particles, cavitation, diffusers, pressure recovery

1. INTRODUCTION

The recovery of kinetic energy, or dynamic pressure, from a high speed internal flow is normally achieved using a diffuser. For circular section ducting this involves a conical transition between the smaller diameter duct and the larger diameter duct in which the flowing fluid will slow down. The dynamic pressure in the flow is recovered as the fluid slows and this results in an increase in the static pressure of the flow. If the angle of the diffuser is too large there is a separation of the flow and losses increase; if the angle is too small the diffuser is unnecessarily long and the frictional losses at the wall become excessive. The optimum total angle for a conical diffuser is commonly taken to be 7° (E.S.D.U. 1976), although this is influenced by the inlet flow conditions. Recent work by the authors (Owen & Abdul-Ghani 1991) has been concerned with developing fluidic non-moving-part flow control valves for use with multiphase flows such as those from oil wells where there can be a mixture of oil, gas, water and sand. As part of this work a study was made of the performance of diffusers in two-phase gas/liquid flow where it was shown how diffuser performance fell with increasing void fraction (Owen *et al.* 1992). Also included in that study was some limited data showing how cavitation in the diffuser throat affected the pressure recovery.

Following the testing of fluidic valves and diffusers in gas/liquid two-phase flow, further investigations were carried out to assess the erosive effects of sand by subjecting the fluidic valve to a flow of sand-laden water. It was found early on in these tests that the abrasive action of the sand was very significantly affected by the presence of cavitation. The erosion tests and the results are considered in some detail elsewhere (Madadnia & Owen 1993) and only a brief description will be included here. An experimental facility was built in which water was recirculated through 75 mm steel pipework. Sand, with a particle size range 0.5–0.7 mm, was injected into the flow to provide an abrasive medium; the initial sand/water concentration was 10% by mass, although as time progressed the sand was degraded. Two identical fluidic valves were assembled in series so that each was exposed to the same flow. Before entering the internal passages of each fluidic valve, the flow passes through a plenum chamber so that, although the two valves were close-coupled, the flow development for each will be the same. The upstream valve, however, was at a higher pressure than the downstream and was therefore exposed only to particle erosion, whilst the downstream valve was exposed to the combined effects of cavitation and particle erosion. The valves were

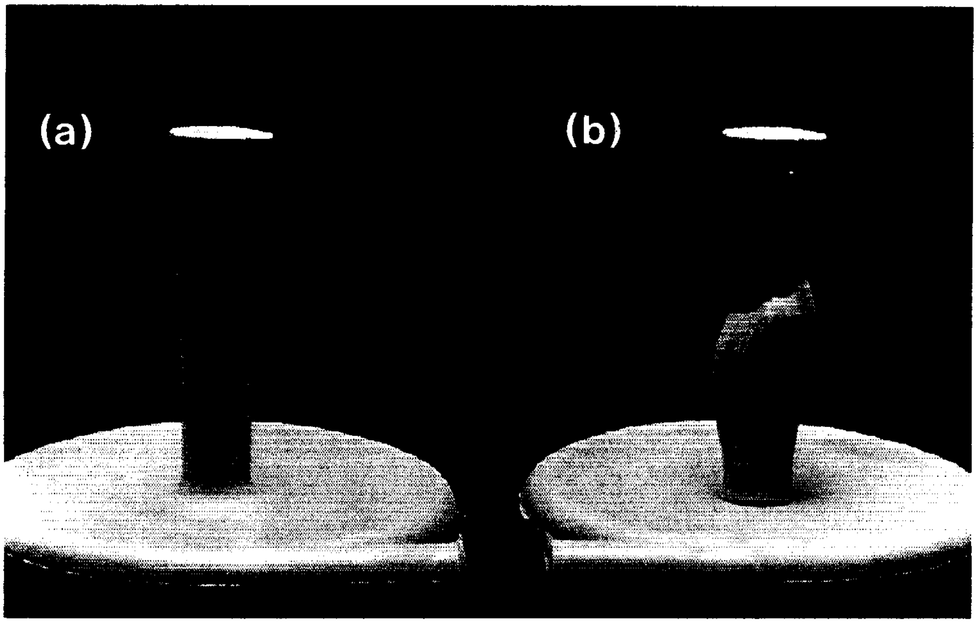

Figure 1. Erosion of the conical diffuser showing (a) the case of particle erosion alone and (b) particle erosion accompanied by cavitation.

manufactured from aluminium so that they would not be too resistant to erosion and after about 30 min of running they were removed from the rig and examined. To illustrate the extent of the erosion, a flexible casting was made of the internal passages of the two valves. Figure 1 shows the two castings and of interest to this paper is the long conical portion of the castings which represent the first 150 mm or so of the diffuser.

Figure 1(a) is the non-cavitating case, which shows no apparent evidence of erosion. Inspection of the metal surface showed some scouring, but no appreciable metal removal. Figure 1(b) is the case when the flow was cavitating. The erosion is self-evident and is most severe where the cavitation was collapsing. It can be seen that the material removal is concentrated; the contour where the eroded zone meets the unaffected diffuser wall does not show a gentle blending, but shows a clear sharp edge. Cavitation was seen to begin where the flow entered the parallel section and collapsed over a region as shown in figure 2. The erosion coincided with the area of cavitation collapse.

If we consider the three processes of erosion: cavitation alone, particulate erosion alone and the combined effects of cavitation and particulate erosion: the visual evidence of the experiments showed that the first mechanism did no more than discolour the surface; the second mechanism

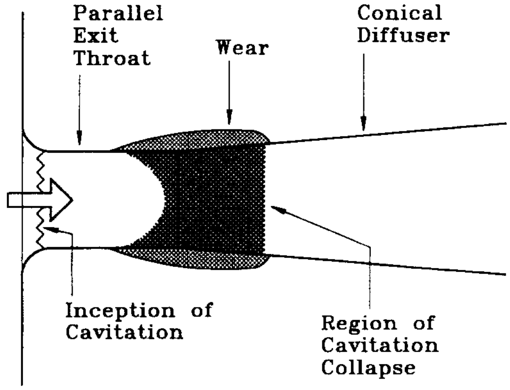

Figure 2. Regions of cavitation and wear in diffuser.

caused some material removal by a scouring action; the third mechanism caused considerable material removal. The erosion due to the combined effects of cavitation and particle abrasion was considerably greater than the sum of the individual effects. It is not clear why this should be so, but similar effects are observed in cavitation-corrosion and the phenomenon has been termed "synergism". This is discussed in more detail by Madadnia & Owen (1993).

The use of a diffuser in particulate-laden flows is therefore likely to lead to erosion problems if the flow cavitates. Thus, if a flow component, such as the outlet section of a throttle valve, is being designed for use in particulate-laden flows where cavitation may be present, care must be taken. The simplest design would be to have a sudden expansion and to sacrifice any pressure recovery. Before resorting to this, however, consideration was given to producing a design of diffuser which would allow the cavitation to collapse within the flow away from the wall, whilst still allowing some controlled expansion and hence some pressure recovery.

2. DIFFUSER EXPERIMENTS

Consider the three designs of diffuser shown in figure 3. Figure 3(a) is the standard conical diffuser, figure 3(b) is a sudden enlargement and figure 3(c) is a carefully selected combination of the two. The aim of the design in figure 3(c) is to force the flow to separate from the wall using a sudden enlargement. The sudden rise in the pressure will cause the cavitation to collapse, but it will do so away from the wall and will therefore prevent abrasion/cavitation erosion from occurring. With the cavitation having collapsed, pressure recovery can be obtained in the following conical section.

An important criterion for the diffusing section to be effective is that the flow must re-attach to the wall in the parallel section before entering the conical expansion. Pressure recovery can still be effected in sudden expansions and it is shown by Miller (1978) that the maximum pressure recovery coefficient is about 0.5 and that this happens for an expansion ratio of about 2. The sudden expansion in figure 3(c) was therefore chosen to be about 2. Ramamurthy *et al.* (1991) showed that the flow over a backward facing step has a re-attachment length of about 7 times the step height. The design of figure 3(c) has a wall length to step height ratio of about 16. It was suspected that the effect of the cavitation voidage on the separation bubble might be to increase the re-attachment length and therefore the ratio of 16 was considered beneficial; it would also allow some boundary layer redevelopment before the flow enters the conical section. The combination of an optimum sudden enlargement and an adequate parallel section for re-attachment was therefore the basis for the design shown in figure 3(c).

The diffusers shown in figure 3 were tested for pressure recovery in water and for erosion in a sand/water mixture. For the flows used in the present work, the Reynolds number at the inlet to the diffuser (based on the throat diameter and velocity) was always greater than 10^5 thus ensuring the pressure recovery was independent of flow rate (E.S.D.U. 1976). The flow was non-swirling. To measure the pressure recovery, the diffusers, manufactured from Perspex, were installed one at a time into pipe work and the flow through them was increased by opening a downstream valve. The flow rate was measured, together with the pressures upstream and downstream of the diffuser and at the diffuser throat. The pressure tapping for the downstream pressure was located a short distance after the diffuser at a position where the pressure recovery was complete, whilst the throat pressure was measured half way along the parallel section shown in figure 3. As the downstream pressure was decreased, so the flow through the diffuser increased and the throat pressure decreased causing the flow in the diffuser throat to cavitate and eventually to become choked. If the pressures in the throat and downstream of the diffuser are P_t and P_d respectively, the vapour pressure and density of the liquid are P_v and ρ respectively and the liquid velocity in the throat of the diffuser is V_t, then the pressure recovery coefficient and the cavitation number can be defined as follows:

$$\text{Pressure recovery coefficient} = \frac{P_d - P_t}{1/2\rho V_t^2}, \qquad [1]$$

$$\text{Cavitation number} = \frac{P_t - P_v}{1/2\rho V_t^2}. \qquad [2]$$

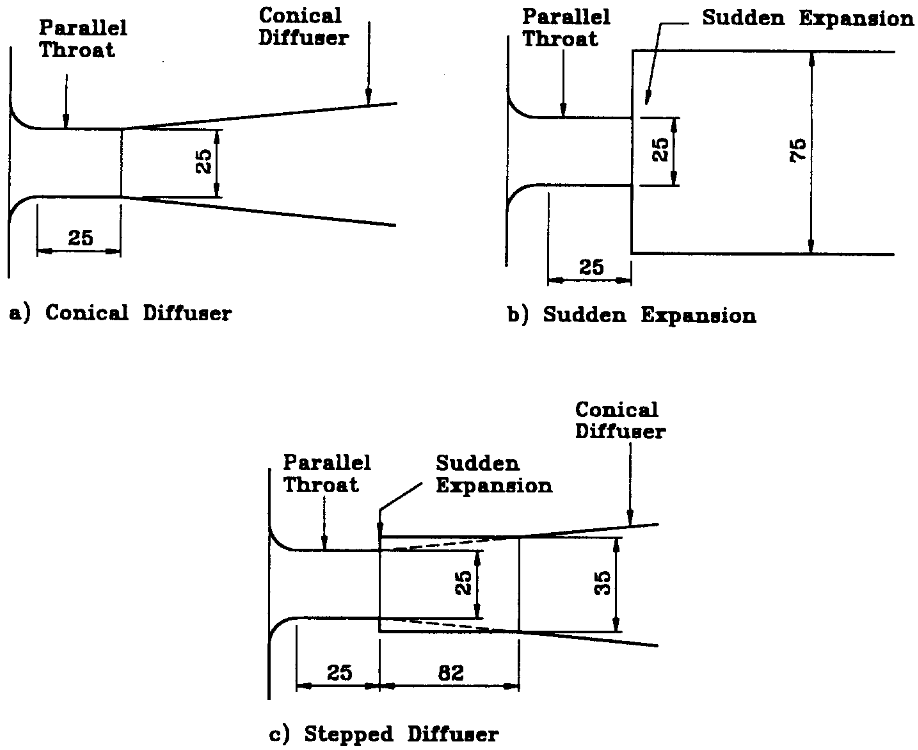

Figure 3. Diffuser geometries.

Figure 4 shows how the pressure recovery coefficient varies with the cavitation number for each of the diffusers. Cavitation increases as the cavitation number decreases; therefore, at a cavitation number of 2, say, the flow is non-cavitating. Under these conditions the conical diffuser has a pressure recovery of about 85% whilst the abrupt expansion has a pressure recovery of about 35%. The design of figure 3(c), however, is still capable of recovering about 70% of the dynamic pressure. It was observed that the flow in the stepped diffuser of figure 3(c) was able to re-attach to the parallel section before the conical expansion. As the level of cavitation increases (i.e. the cavitation number reduces) so the performance of the conical diffuser falls until at a cavitation number of about 0.3 the flow becomes choked. It can be seen that the other two designs of diffuser maintain

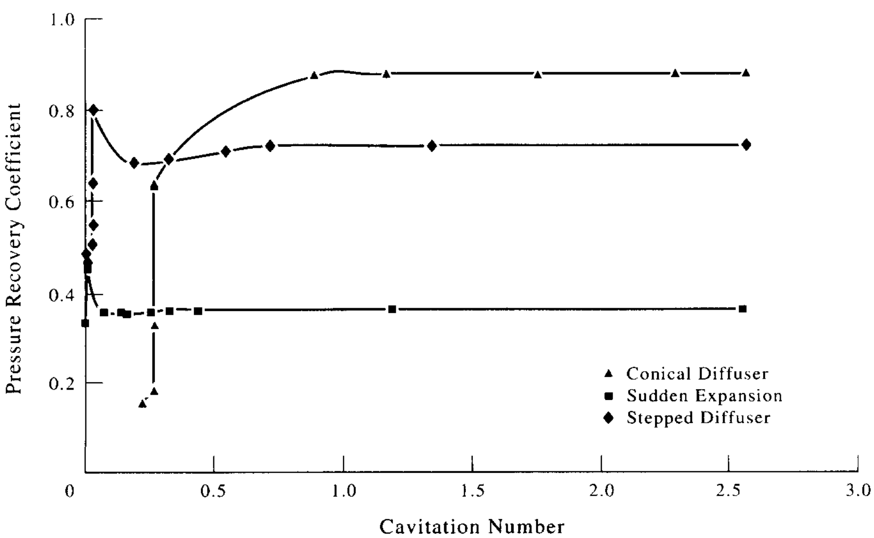

Figure 4. Diffuser pressure recovery.

their performance for higher levels of cavitation, i.e. the flow through the sudden expansion does not choke. Other studies on cavitating or flashing liquids discharged through a sudden expansion, such as Burnett (1947), have also shown that under these conditions the flow does not choke.

The three designs of diffuser, this time manufactured from aluminium, were then each installed in turn into the erosion rig and sand-laden water was passed through them. The conical diffuser was exposed to the flow for about 30 min and again a substantial amount of erosion was observed. The other two designs of diffuser were exposed for about 6 h and no intense erosion was found, although with aluminium being a relatively soft material there was some abrasive erosion in the throat of each. The tests just described were with non-swirling flow. Abrasion tests were also carried out on the diffusers with swirling flow and this time the stepped diffuser of figure 3(c) did suffer from erosion. For swirling flow therefore, only a large abrupt expansion can prevent the combined effects of abrasive and cavitation erosion damaging the duct wall.

A final test was carried out in which air was allowed to be entrained from the atmosphere into the low pressure region in the flow. This is the basis for the non-cavitating valve design of Baumann (1985). The entrained air suppresses the cavitation by allowing a small increase in pressure and also has a cushioning effect on the collapsing cavitation. It was found that the introduction of sufficient air to produce a volumetric quality of about 4% prevented severe erosion.

3. CONCLUDING REMARKS

Expanding sections in pipework and in pipe components are very common. The purpose of this paper has been to highlight the danger of excessive erosion in cavitating particulate-laden flows. To be sure of avoiding the excessive erosion that has been shown to occur when the two effects combine, the expansion should be an abrupt one. If pressure recovery is an important consideration, the stepped diffuser design offers a possible solution. If the flow is swirling, which it may be as it flows from, for example, a valve, the expansion again needs to be an abrupt one. Another solution to the erosion problem that can be considered is to allow air to be entrained into the low pressure region.

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