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Physical Modelling of Self-Aeration in a Cavitating Sudden PIPE Expansion Flow

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ABSTRACT

Sudden pipe expansions have been known as efficient hydraulic energy dissipaters for a long time. The complex phenomenon of flow separation and velocity discontinuity at the interface of incoming jet and the recirculation flow, results in intensive shear and tensile rupture of the fluid and the associated destructive phenomenon of cavitation. This paper focuses on aeration in sudden pipe expansion as a remedy to recover the effects of cavitation. The experimental setup consists of a sudden pipe expansion with an expansion to inflow diameter ratio of 3.675. Variation of air content ratio with respect to the Reynolds number and effect of air entrainment on time averaged velocity and pressure distribution is investigated. Finally a combination of sudden pipe expansion and aeration is recommended for energy dissipation at bottom outlets and tunnel spillways.

Keywords

Cavitation; PIPE expansion; Pressure; Aaeration

1. Introduction

As the workability of expansion in energy dissipation is well understood for some hence, but pressure fluctuation and resulting phenomena of cavitation have strictly limited the application of sudden pipe expansion as an energy dissipater. When the local pressure at a point in a flowing mass drops to the vapour pressure of the liquid, cavitation begins by formation of small microscopic cavities. Vapour cavities travel in the flow to the downstream region where they eventually collapse as a result of increased static pressure. When bubble implosions occur near solid boundaries, the generated transient pressure waves and micro jets which form as a result of cavity collapse are responsible for fatigue failure and subsequent pitting of the surface. It has been known for several decades that the destructive effects of cavitation could be mitigated in the presence of air bubbles. This principle has led to the design of aerators. The air entrainment techniques appear to be particularly appropriate when flow velocities exceed about 25 m/s for which cavity prevention techniques are not applicable. Warnock (1947) was the first person who introduced the advantages of air entrainment for preventing cavitation damage downstream of sluice way controls works. Peterka (1953), on account of experiments, proved the benefits of aeration. Peterka's work might be considered as classic in the study of the benefits of air entrainment for prevention of cavitation damage. In his

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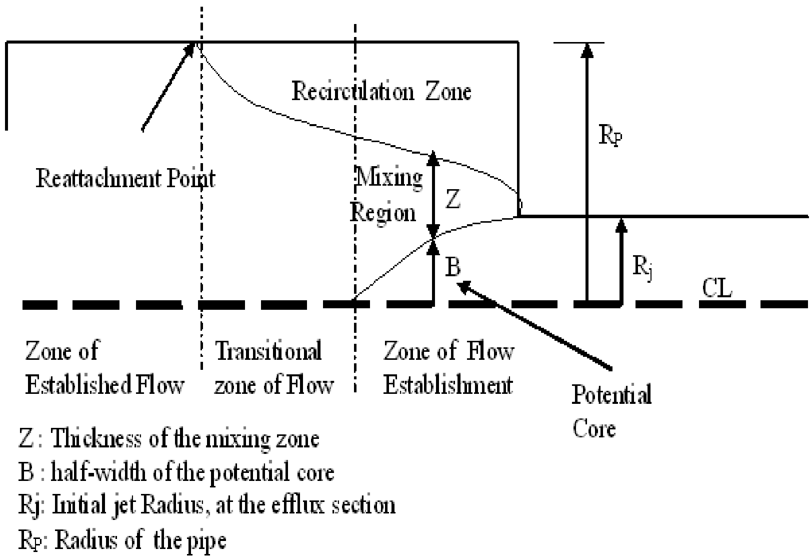
first set of tests, Peterka induced cavitation on polished brass disks using a vibratory technique and was able to show that entrainment would reduce the intensity caused by cavitation. In his second set of tests Peterka mounted smooth faced concrete test specimens just downstream of the throat of a venture like device in which he could induce cavitation by steadily increasing the flow rate velocities in excess of 30 m/s were achieved. For each test, the weight loss resulting from cavitation was measured. Then for a number of tests, he induced varying amount of air into the flow. The results clarified the effect of aeration on reducing the cavitation damage. Peterka concluded that with 6-8% entrained air, the damage due to cavitation would be eliminated significantly. Clyde and Tullis (1983) suggested that the injection of air, suppressed the formation of vapour bubbles. Oskolkov and Semenkov (1979), Quineta (1980) and Vischer et.al (1982), have stated that the aeration changes the compressibility of flow. Wood (1984) believed that the increase in fluid compressibility, after aeration, would cause the ability of absorbing the impact of the collapsing cavitation bubbles. Han et al. (2010) tested the behaviour of aeration in cavitation region of high speed velocity flows using advanced experimental features. They also presented the relations between smallest air concentration without cavitation erosion and the flow velocity. In addition they compared the cavitation numbers in cavitation region with and without aeration. Xu et al. (2010) studied the semi-cylindrical irregularity of cavitation structure by means of high speed photography and then showed the cavitation structure and its interaction between aeration and cavitation bubbles. Zhang et al. (2011) worked on the relation of cavitation in sudden expansion pipe and they found that the incipient cavitation number increased with the scale and velocity. And the incipient cavitation number increased linearly with the enlargement ratio for an enlarged geometry. In addition they revealed that once the velocity exceeds 12.7 ms^{-1} the suggested value of reference velocity by Keller, which is 12.7 ms^{-1} does not reflect the scale effect of the velocity properly. Zhanng et al. (2011) presented a three-dimensional numerical simulation model of aerated flows and used it to analyse the characteristics of hydraulic aeration flows by two turbulent models (VOF model and Mixture model).

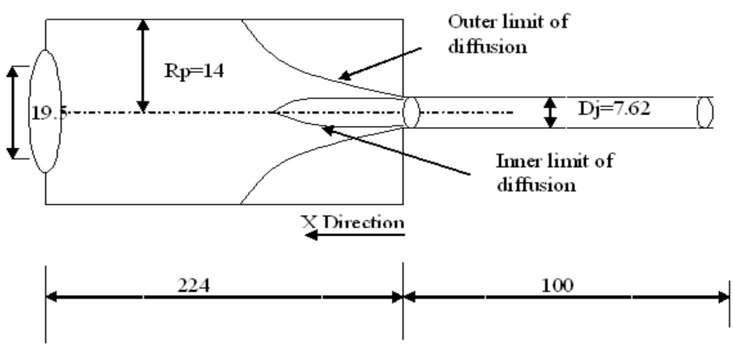
2. Physical Model and Instrumentation

The expansion used here was located 2.5 m from the inlet of the test section and was preceded by a short smooth contraction converting upstream pipe diameter of 300 mm to downstream diameter of 76.2 mm. The pipe diameter at the inlet to the expansion was Dj = 76.2 mm and its length was 100cm, which ensures formation of the fully developed flow at the jet inlet. Downstream pipe diameter was 280 mm. These dimensions produce an expansion radius of Rp/Rj=3.675. These parameters and schematic setup of the rig is illustrated in fig1-a and b.The main body of the sudden expansion was made of Perspex. The smooth contraction was fabricated from stainless steel. Measurements of pressure and velocity distributions were possible from 10 axial holes of 2cm-diameters corresponding to x values of -6, 6, 12,24,30,42,54,66,78 and 114 cm. Figure 1 shows the origin of the coordinates from which longitudinal x-distances were measured. These measuring points were located on the side wall of the pipes and were covered by caps to prevent from water leakage. Also, pressure tapings of 1 mm diameter were provided along the bottom of the pipe to allow wall pressure distribution to be measured. The tapings were connected to differential pressure transducer and the measurements were carried out using a data logger. The pressure transducers used, were able to measure gage pressures between -1 and +1 bar with a natural frequency of 1 kHz.

The measurements of static and total pressure were done by pitot tube. To adjust the pitot tube on the side wall of the pipe, a 2cm diameter screw was designed which sealed the side wall holes during measurements. The screw had a longitudinal narrow hole from which it was possible to protrude the pitot tube. The stem of the pitot tube was 20 cm so it was possible to measure total and static pressures at different radial locations by altering the protrusion length. The pitot tube was connected to the pressure transducers and data logger.



(a)



(b)

Fig. 1. (a) Definition of different flow zones in submerged jet
(b). Schematic illustration of flow geometry (the units are in centimeters)

Fig. 2. Picture of sudden pipe expansion

Also a vertical aerating shaft with a bell mouth inlet was designed and connected to 21 aeration vents provided at equal circumferential distances on the sudden expansion inlet section. Figure 2 shows the distribution of aerator vents on the side wall of the enlargement. The air velocity was measured by simply applying the Bernoulli's equation to the top of the bell mouth where the pressure and velocity are zero and a control section on the shaft. The air pressure at the control section was measured by a calibrated inclined manometer available to measure gage pressures as low as 5 mm of water. After obtaining the air velocity, the volumetric air discharge was calculated. Figures 3 and 4 illustrate the distribution of air water discharge ratio (Qa/Qw) and air water velocity ratio (Va/Vw) versus the incoming jet's logarithmic Reynolds numbers, respectively. As it is shown in this figure, the variation of air -water discharge ratio is between 6% for low Reynolds flows and 8.5% for high Reynolds flows. These limits match well with the entrainment amount required to eliminate cavitation effects on dam spillways, proposed by Peterka. The measured air velocities as indicated in figure 4 are between 2.5 to 3.5 times the incoming jet velocity.

Figure 5 shows the variation of non dimensional inlet air pressure with respect to the Reynolds number. As it was expected, the air pressure decreases by increasing the Reynolds number.

Figure 6 shows the distribution of mean axial velocity of the flow at three different sections. It is found that the velocity at regions near the centre of fast moving eddies due to the concentrations of the air bubbles, increases. Also, for the zones near the efflux section aeration results in an increase in centre line axial velocity of the flow, while at far distances from the inlet, due to the reduction of air concentration, the dissipation rate increases and the velocity dissipates faster than no aeration flow case.

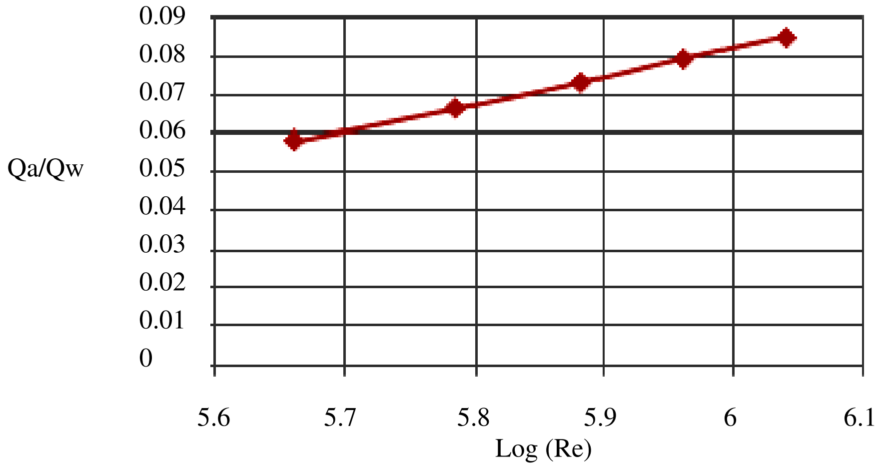


Fig. 3. Variation of air-water discharge ratio

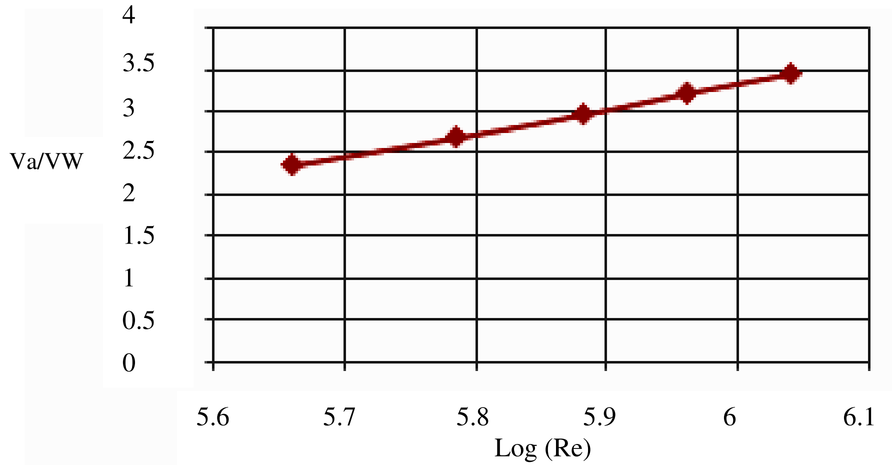


Fig. 4. Variation of air velocity ratio

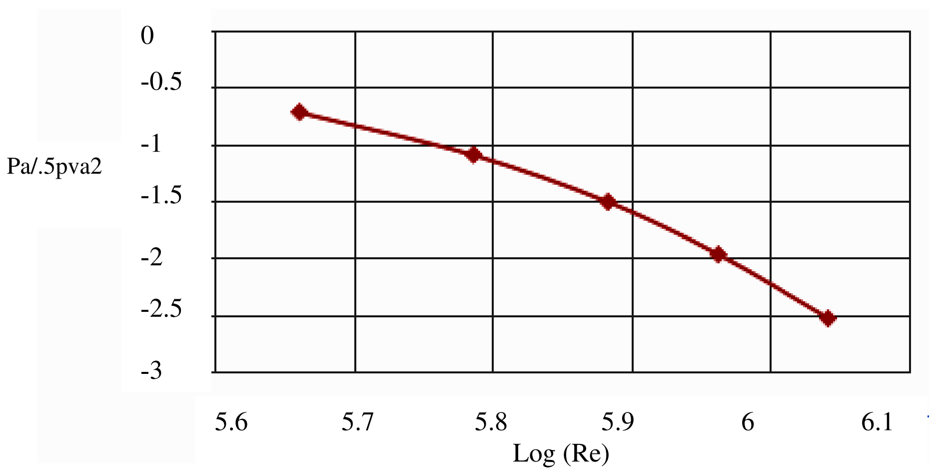


Fig. 5. Variation of inlet air pressure versus the Reynolds number

Figure 7 shows the variation of air pressure in the aeration shaft versus the jets Reynolds number. It is obvious that increasing the jet inlet velocity decreases the static pressure and increases the cavitation potential.

In Figure 7, distribution of static pressure on the centre line of the jet is demonstrated. As it is expected after aeration the minimum negative pressure increases remarkably so that the effect of cavitation with 7-8 % aeration discharge ratio vanishes completely. Finally, the distribution of maximum axial velocity of the jet is presented in Figure 8. The most interesting point in this figure is the velocity increase, as much as, 28 %, at the inlet.

3. Conclusion

As it was observed the aeration technique is a simple and applicable solution to the problem of cavitation. The self-aeration method in sudden pipe expansion is quite enough to prevent the structure from cavitation damage. The amount of entrained air was measured between 6-8% of water volume, which increased the mean negative pressure considerably, so that no trend of cavitation was sensed after aerating. The location of aeration vents should be as close as possible to the centre of fast moving eddies, because the mean negative pressures

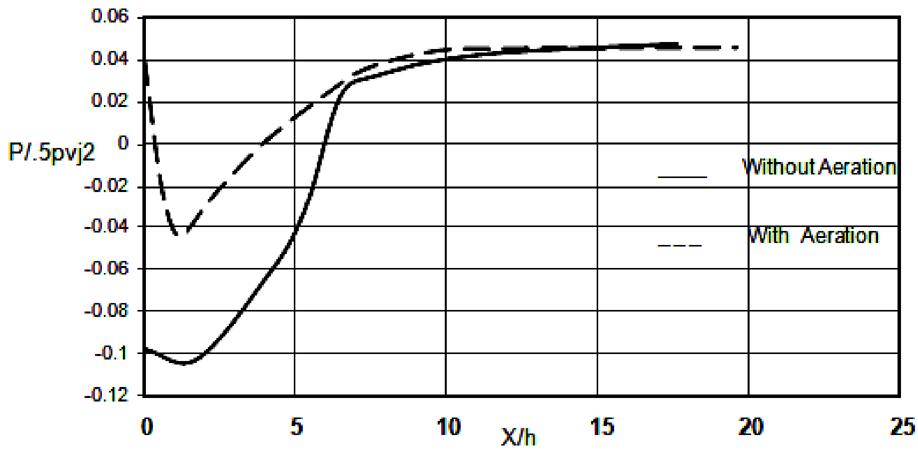


Fig. 7. Mean static pressure distribution on the centre line of the jet

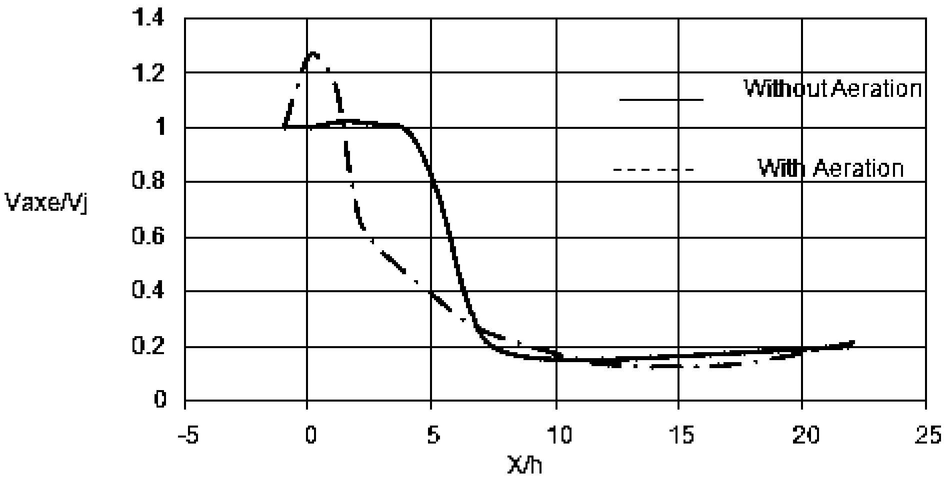


Fig. 8. Distribution of maximum velocity

are generated at the centre of eddies, so the air bubbles, due to the pressure gradient, mitigate towards the centre of the eddies (locus of cavitation nuclei). Figure 6, confirms this conclusion. As it was noted, the flow velocity at the edge of the mixing zone and near the recirculation zone, increases. The author believes that by varying the circumferential distances of the aeration vents, the pressure and velocity distribution will change. Investigation on the relation of the location of aeration vents to flow parameters, cavitation number and dissipation rate with respect to the expansion ratio will be work of the author in the near future.

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