Proceedings of the Institution of Mechanical Engineers

I MECH E

Cavitation

International Conference

9–11 December 1992
Robinson College, Cambridge

Sponsored by
Power Industries Division of the
Institution of Mechanical Engineers

In association with
Japan Society of Mechanical Engineers
Royal Institution of Naval Architects

IMechE 1992–11

Published for IMechE by
Mechanical Engineering Publications Limited

The effects of air injection upon cavitation erosion

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SYNOPSIS Cavitation experiments on aluminium specimens in a small water tunnel at a constant fluid velocity of 14.3 m/s and at maximum erosion rate have shown that injecting air bubbles greatly reduces the mass loss rate. For instance an injected air flow rate of only 0.03% (by volume) halved the erosion rate, 0.1% reduced the erosion rate almost to zero. The bubbles ranged in size from 8 to 80 μm with a mean size of 20 μm.

1 INTRODUCTION

It had long been known from the literature that the amount of air in water has a significant effect upon cavitation. In the incipient stage air-content governs just when cavitation begins and how it grows thereafter. In the more developed stages of cavitation air influences both noise and erosion rate. Moreover it had been demonstrated that erosion rate could be decreased by injecting air bubbles into the flow.

Nevertheless because of the widely differing ways in which the published experiments had been carried out, they did not form a consistent group. For the engineer who might wish to use air injection for reducing erosion there was little quantitative information available to guide the choice of air to water ratio and what bubble size distribution to use.

2 OBJECTIVES

It was decided therefore to make some systematic experiments to investigate the effects of air content and of bubble size distribution upon cavitation erosion.

3 LITERATURE SURVEY

Publications up to 1971 had been comprehensively reviewed by Hammitt (1) who outlined considerable evidence for the reduction of cavitation erosion rate with increasing air-content. Nevertheless at that time he considered that it was too early to develop any general theoretical model capable of giving reliable quantitative predictions.

Later Stinebring (2) in water tunnel tests on a cylindrical body, showed that increasing the air content from 10 to 20 ppm halved the measured erosion rate.

In the field of ship propellers Huse (3) found that injecting air at the top of propeller ducts reduced cavitation erosion. Lövik and Wassenden (4) verified theoretically and by model tests that increasing the total air content reduced both high frequency noise and vibration. They also found that the free air/water ratio increased as the total air content was increased. Dahmer and Miller (5) demonstrated the reduction of erosion rate on a model propeller by injecting air bubbles upstream.

There had been considerable confusion in the meaning of the term air-content because it had been used by different authors to apply variously to dissolved, free, and total (i.e. free plus dissolved) air-content. Which was the most relevant parameter? Several authors had suggested, and finally Le Coffre et al (6) clearly proved experimentally, that dissolved air, per se, can only have a second order effect upon cavitation erosion rate.

The most appropriate parameter therefore seems to be the free air-content, in the form of nuclei and bubbles, but this is not so easy to measure directly.

4 APPARATUS

A small water tunnel as shown in Fig 1 was designed to meet the specified objectives. The components numbered in Fig 1 are listed in Table 1, and the more important are now described and referred to by their numbers in square brackets.

Special features were:-

The provision for injecting air-bubbles of various sizes upstream of the test section [14] and a bubble eliminator downstream [5]. The bubble size distribution at inlet to the test section was measured by a commercial laser diffraction particle sizer [27, 28]. The water passed through a heat exchanger [2] so as to maintain the water temperature betwen 20 and 22°C.

There was also a relatively large stilling vessel [7] pressurised by the pump [3] giving a residence time of more than three minutes at pressures up to 9 bar. This ensured that most of the remaining air had gone back into solution before the water left the vessel, to be recharged with air bubbles [at 14] before re-entering the working section [26]. Optical measurements for the case when no air was being injected, showed that very few bubbles were in the water. The water, because of its history, was always near to being saturated with air initially. Thus most of the air subsequently injected would be expected to persist as free air in the flow as it passed through the working section.

4.1 Working section

The working section [26] provided a flow duct which was rectangular, 6x12 mm in cross section. Its perspex side walls were transparent to reveal the cavitating flow. The top wall was removable and carried the pure aluminium test specimen, and the bottom wall was made of nylon (Delrin) to minimise erosion. To cause rapid erosion a 60° wedge cavitation source was used which spanned the flow upstream of the test section, blocking half its area at the throat where the maximum velocity was adjusted to be 14.3 m/s.

The specimen holder was designed so that the specimen's face would be flush with the surface of the the section and directly exposed to collapsing bubbles from the wedge.

5 OPTICAL SYSTEM AND BUBBLES

Directly upstream of the working section was a stainless steel cell [24] providing the same sized rectangular section for the flow (6x12 mm) but having in its side walls, parallel optical-quality circular glass windows giving a field of view 12 mm in diameter. The laser beam of the particle sizer shone through these, permitting the size/number distribution of the air-bubbles in the water to be measured.

5.1 Removal of solid particles

To keep the circuit as free as possible from solid particles the interior of the stilling vessel [7] was cleaned and coated with nylon, the heat exchanger tubes thoroughly scrubbed, and all pipes and fittings made in stainless steel. In addition the water in the circuit was filtered at three points as follows.

Water entering from the mains to fill the rig was filtered by a 6-micron (μm) coarse filter [1]. The float controlled head tank [4] to the air-eliminator was supplied through a 2μm filter by the transfer pump [12] mounted in the sump [11].

Further fine filtration was provided, in series or parallel with the working section, by a 1 μm filter [6].

5.2 Bubble size distribution

Flowing water, even in laboratory rigs, usually contains both air bubbles and solid particles but nobody had yet produced an ideal method of discriminating between bubbles and solid particles.

A detailed study was therefore made of various commercial and research instruments available for making particle and/or bubble size distribution measurements. After reviewing these it was decided to buy a Malvern 2600D laser diffraction instrument originally designed for droplet and spray particle-sizing and to develop it for bubble sizing in liquids. It could cover a size range from 0.5 to 564 μm but, like many optical techniques, could not discriminate between solids and bubbles.

To overcome this difficulty it was decided to incorporate a fine filter (already mentioned) in the flow approaching the working section of the water tunnel to remove all solid particles bigger than about 2 m. Any diffraction signals measured in the flow were then likely to be caused by bubbles.

The Malvern particle sizer does not normally require calibration but to confirm its reliability a few check tests were made using graded solid nylon spheres ranging from 15 to 30 μm, and polypropelene of 150 μm diameter. As the agreement in size was satisfactory further tests were made to show that the instrument responded to clouds of random sized bubbles in the same size range as the solid particles.

5.3 Measurement of bubble size distribution

The Malvern 2600D particle sizer comprises a laser transmitter, a detector system, and a data processor.

The transmitter [27] uses a 2mW He-Ne laser and beam expander. The detector system [28] includes a Fourier Transform lens at the focal point of which is placed a solid state detector consisting of 31 concentric photosensitive rings each of which is related to a certain size of bubble and particle.

The data processor includes a microcomputer with VDU and integral disc drive together with a hard-copying printer. It is provided with a software package and, for the present experiment, two lenses of focal lengths 6.3 and 10 cm, covering the particle size diameters of 0.5 - 188 μm, and 1.9 to 188 μm, respectively.

The operating principle is that the beam of laser light passes through the working section and is brought to a focus on the axis provided there are no particles or bubbles in the small field of view. The presence of particles or bubbles of different sizes causes the light from the laser beam to be diffracted through different angles. The result is a series of concentric light rings of various radii each related to a particular size of particle. The electrical output from the rings is scanned, amplified and fed into the computer for analysis.

6 AIR INJECTION

A special air injection section was made as shown in Fig 2a comprising a perspex body sandwiched between stainless steel flanges which were connected to the 9.5 mm (3/8") stainless steel piping of the circuit. The annular flow passage round the central injection nozzle decreased in area downstream by a factor of 16:1 (1 " to 3/8" bore).

The nozzles were conical and machined from sintered bronze varying only in pore size as follows

GRADE	NOMINAL PORE SIZE - μm
B	9 - 12
C	15 - 20
E	55 - 65

The injected airflow was controlled by means of a pressure-regulator and set by a fine needle-valve. The flowrate was measured by a float type "Gapmeter".

Because of anomalies experienced with bubble size distribution, an alternative injector was made to fit in the 9.5 mm bore tube as shown in Fig 2b. It consisted of an L-shaped hypodermic stainless steel tube injecting on the pipe axis and pointing downstream.

7 AIR ELIMINATOR

If the continually injected air were allowed to remain in the tunnel circuit the background level would become excessive. It was therefore necessary to remove the injected bubbles after they had passed through the test section. An air-eliminator [5 in Fig 1] was specially developed for this purpose which allowed the more buoyant air bubbles to rise and escape to atmosphere through a vertical tube (5 cm bore, 1 m long) in the lid.

As shown in Fig 3 obtained by Karayiannis (7), it took about thirty minutes running at fixed water and air flowrates before the free air content measured by the Malvern bubble-sizer reached a reasonably steady value. After this the measured free air content remained within about 2.5% of the mean value. However this mean value obtained from integrating the bubble count, was usually about 17% higher than the free air/water ratio computed from the measured air injection rate and the water flowrate. However it should be noted that initially when air injection began, the free air/water injection rate was about 19% less than that obtained from the air injection rate and the water flow. Only after about 12 minutes from the commencement of air injection did the two values agree. Beyond 12 minutes it seems that some bubbles may have been trapped in the circuit and never got out.

Lövik and Rasmussen in Fig 7 (4) had found that as the total air content was increased from about 30% of saturated, the corresponding increase in the free air content was relatively small. However with water initially 60% saturated, the free gas content increased very rapidly as more air was added. So perhaps in our tests the circuit was initially 19% undersaturated (see Fig 3) and as further air was added it tended to go into solution for the first 12 minutes until saturation was reached. Thereafter the only place it could go was as free bubbles, thus forming the 17% excess between free air measured by the bubble size and that injected. After 30 minutes injection this free air content became constant and remained in the system.

8 AIR-CONTENT MEASUREMENT

Because of its greater speed and convenience compared with the Van Slyke apparatus a simplified form of apparatus originally developed by Brand (8) was used to measure total air-content. The actual apparatus was an improved version developed by the authors at Southampton and described in Reference 9.

The dissolved air-content was computed from measurements of dissolved oxygen using a commercial electrode type meter and a method of calculation evolved by Fry (12). Free air content could be obtained from the difference between these or directly from integrating the bubble size distribution

9 RESULTS

9.1. Erosion tests

Mass loss measurements were made on pure aluminium specimens mounted flush with the upper wall of the working section in a zone of collapsing bubbles generated by the 60° wedge upstream.

All tests were run at a throat velocity near to 14.3 m/s and pressures were adjusted to give predetermined cavitation conditions corresponding to maximum erosion rate (5.7 Bar and a flowrate of 62.2 l/m. The nine hour tests were interrupted and the specimens removed and weighed at 2, 5, 7 and 9 hours after commencement.

To investigate the influence of air content, systematic erosion tests were made at various preset ratios of air injection corresponding to air/water ratios by volume (at the pressure upstream of the working station) of zero, 0.03, 0.05 and 0.11%.

To study the effect of bubble size distribution a corresponding group of tests was made at the same air/water ratios but injecting the air through similar injector cones made of three grades of sintered bronze. They ranged in nominal pore size from 9 to 65 μm.

9.2 Air and erosion rates

Typical examples of damage patterns are shown in Fig 4. They are similar to those previously encountered in larger but geometrically similar rigs at Southampton (11) operating at the same cavitation conditions. The second damage zone, along the axis downstream, is similar to that recorded by Yokomizo, downstream of a cavitating cylinder. He showed this to be caused by bubbles collapsing in the upstream zones and rebounding to grow and collapse again as they travel downstream (12).

Fig 5 shows that once erosion had begun, the mass loss rate was constant and thus the cumulative mass loss versus time curves were linear for all conditions.

It is also clear from Fig 5 that injecting relatively small quantities of air markedly reduced the erosion rate. Only 0.03% by volume of the water flow halved the mass loss rate, and

0.11% reduced erosion to almost zero for the nine hour duration of the tests.

9.3 Bubble size distribution

However, similar tests made with three pore sizes of injector at corresponding air flowrates, showed almost no effect of pore size. Moreover bubble size distributions measured optically showed little difference in shape or in magnitude. Typical distributions are shown in Fig 6. The size range of bubbles in all tests was between 8 and 80 microns, the mean size was 20 µm and in all cases there were peak numbers of bubbles per cubic mm at about 10, 30 and 50 µm.

This surprising result was explored further by removing the sintered bronze injector cone and allowing the air to enter through a relatively large 6.35 mm hole in the centre body pointing downstream. As this gave exactly the same results as before, the centre body was swivelled round 180° to inject upstream, but there was still no change in the measured bubble size distribution.

Finally the whole injection section was replaced by a length of 9.5 mm bore pipe, the same as in the rest of the circuit, containing a single L-shaped hypodermic tube (0.125 mm bore) injecting downstream (Fig 2b). Once again it gave identical results.

So it seems that however the air was injected the bubble distribution just upstream of the test section remained the same. It was therefore independent of

- pore size of the injector
- size of the single orifice through which it was injected
- the direction of injection - upstream, downstream or radial
- the size and cross-sectional area of the injector station

A possible explanation is that the bubble size distribution measured at inlet to the working section is determined by the shear and turbulent stress distributions along the intervening 125 diameters of 9.5 mm bore pipe between the injecting and measuring stations.

This seems to be plausible based on findings from investigations into the break up of droplets and bubbles in shear flows (13). It shows the difficulty of maintaining "unnatural" bubble size distributions for long after the injection point. In pipeflow it is the velocity and turbulence distributions which govern the bubble size distribution.

10 CONCLUSIONS

Our results have confirmed the trends already described in the literature, that cavitation erosion rate decreases with increased free-air content of the water. However the amounts of air required to produce a significant reduction are comparatively small. Experiments described by Hammitt (1) involved air quantities ranging from 1 to 10% of the water flowrate compared with 0.1% in our case. One reason for this may be that the amount of air needed to suppress cavitation erosion increases with water velocity and in our case the test velocity was 14.3m/s compared with 60m/s in some of the published experiments. Also in some cases air was added to undersaturated water so that not all of the injected air remained in free bubble form.

In our tests the bubble size distribution was always very similar irrespective of the method of air injection. The mean size was 20 µm, bubbles ranging from about 8 to 80 µm. It remains to be demonstrated what effect other mean bubble sizes may have upon similar erosion tests.

11 ACKNOWLEDGEMENTS

This research was financed partly by Mechanical Engineering Department, Southampton University and partly by a grant from the Science and Engineering Research Council. Thanks are also due to the Workshop Staff who made the rig and to Dr T.G. Karayiannis who completed the studies of bubble size distribution.

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TABLE 1 List of Components for Figure 1

Item No	Description	Item No	Description
1	6 micron element filter	20	Solenoid valve
2	Heat Exchanger	21	Pressure regulator
3	24-stage, 6Kw pump	22	Air bottle
4	Head Tank	23	Pressure transducer
5	Air eliminator tank	24	Optical cell
6	1 micron element main filter	25	Reducer nozzle
7	Stilling tank	26	Working section
8	Stainless steel manifold	27	Laser beam transmitter
9	Safety valve	28	Laser beam receiver
10	Turbine meter	29	Data processor and computer
11	Sump tank	30	Printer
12	Centrifugal pump	31	Support
13	2 micron element filter	32	Voltmeter
14	Air injector	33	Counter
15	Window	34	Electronic thermometer
16	Check valve	35	Bourdon gauge
17	Air flow meter	36	Emergency stop
18	Pressure gauge	37	Steel frame
19	Pressure regulator/valve		

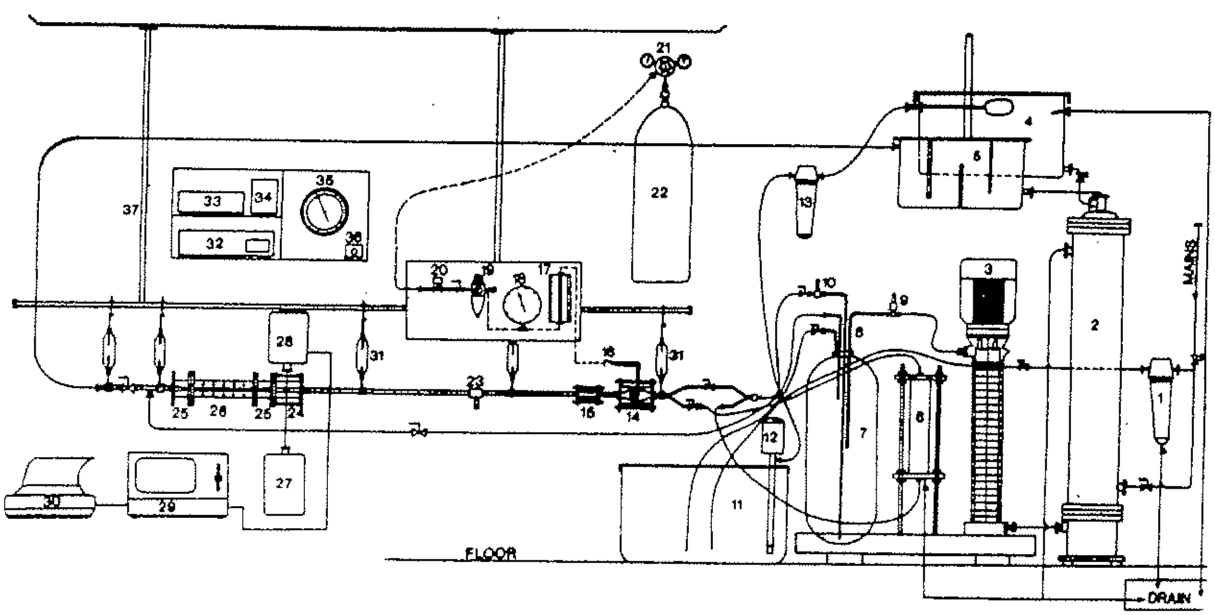


Fig 1 General layout of rig

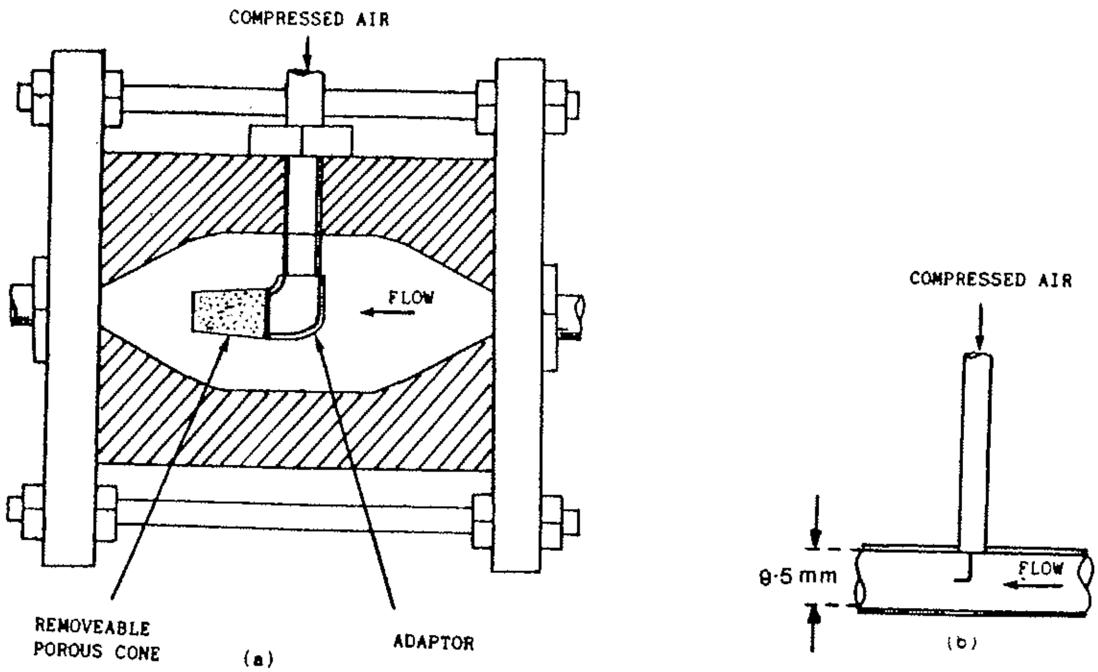


Fig 2 Air injection systems used

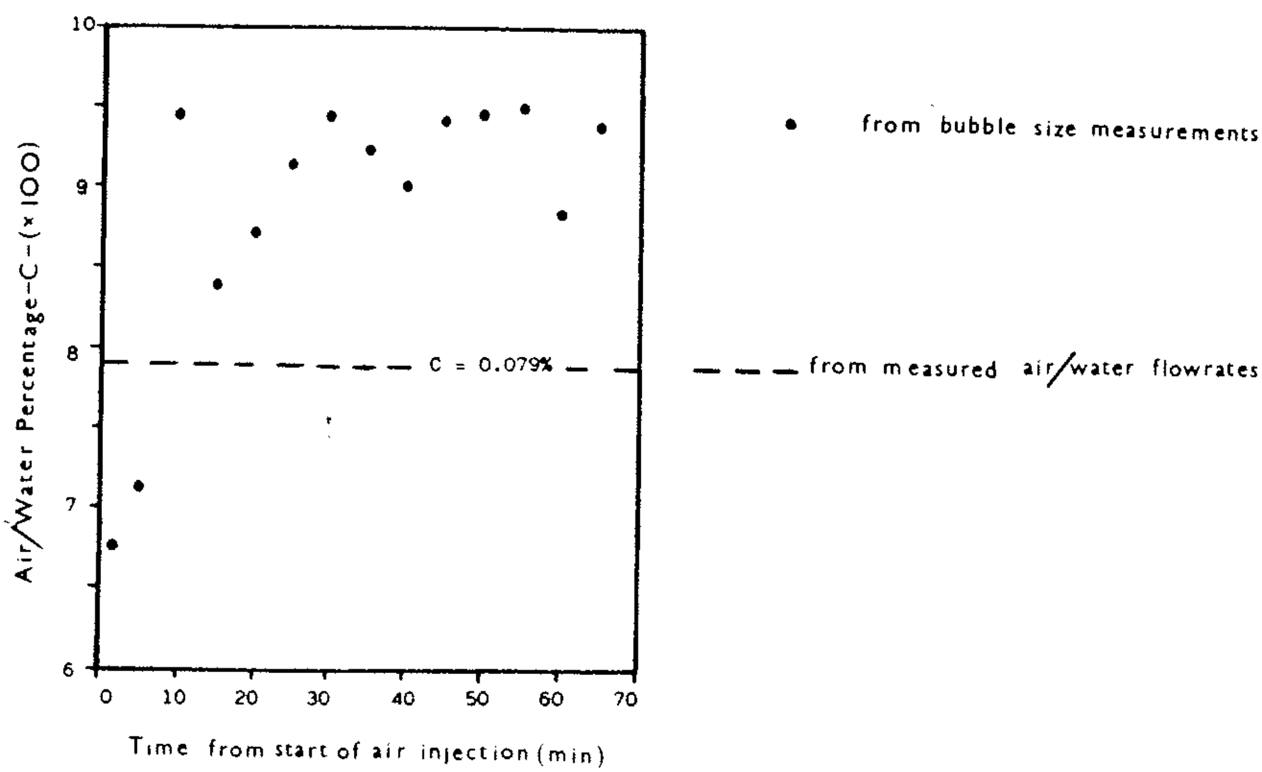


Fig 3 Variation of air/water percentage C with time

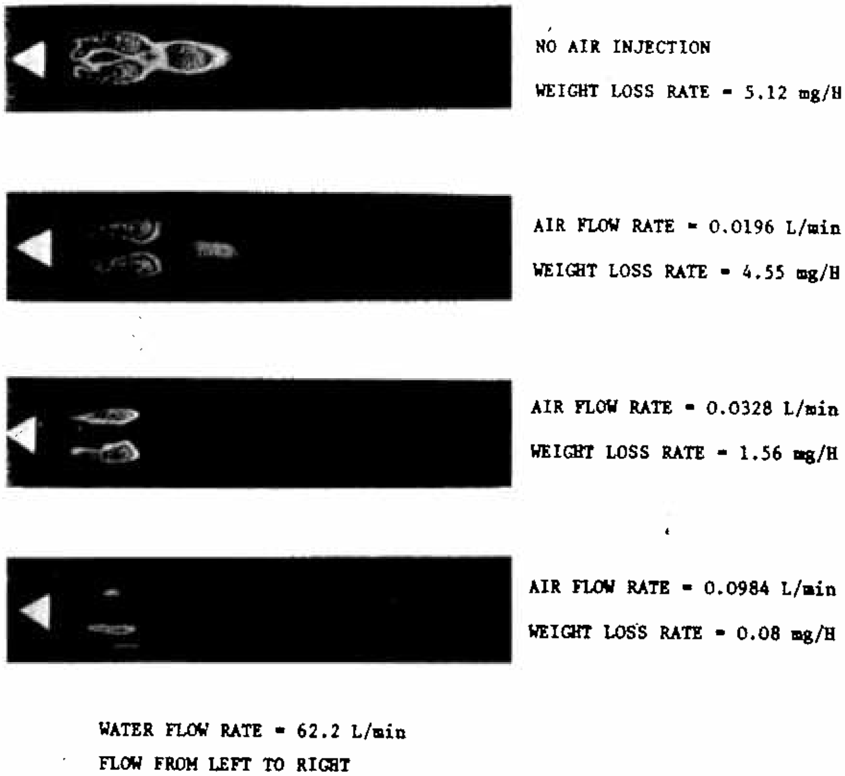


Fig 4 Visible effect of air injection upon cavitation erosion

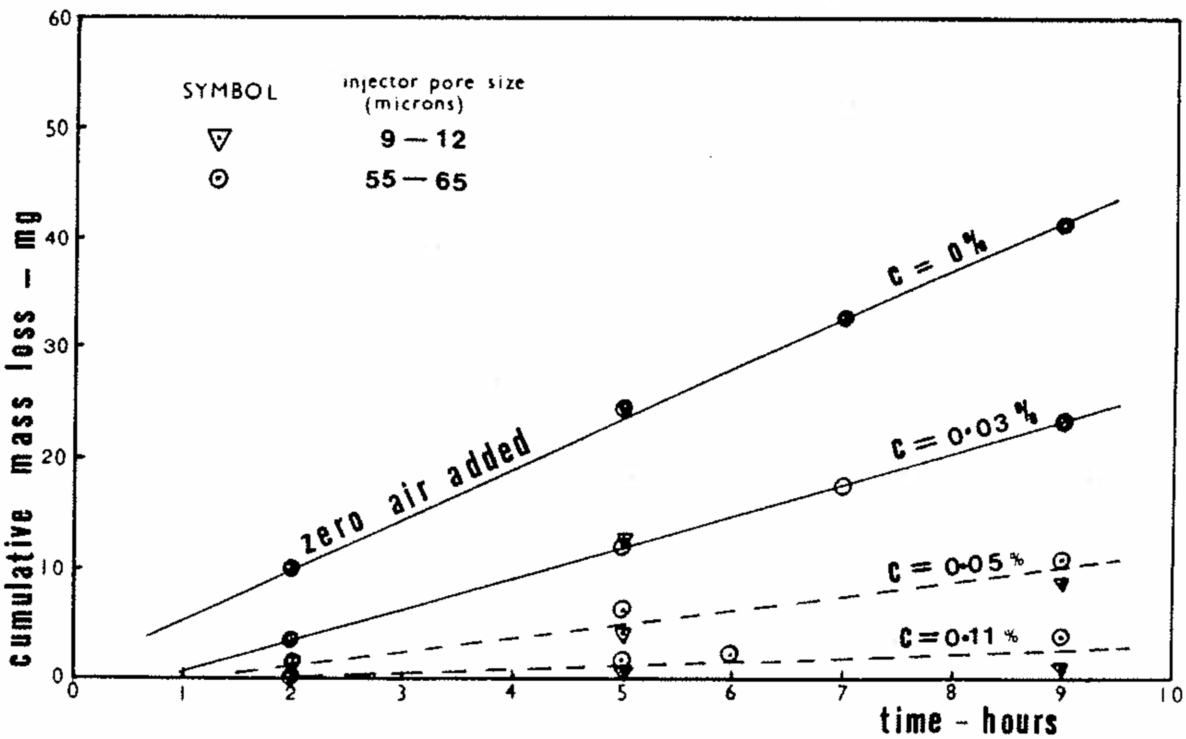
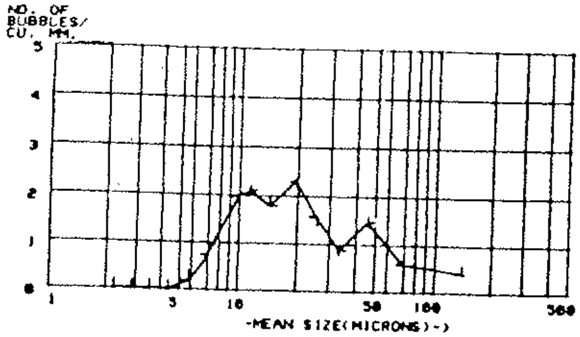
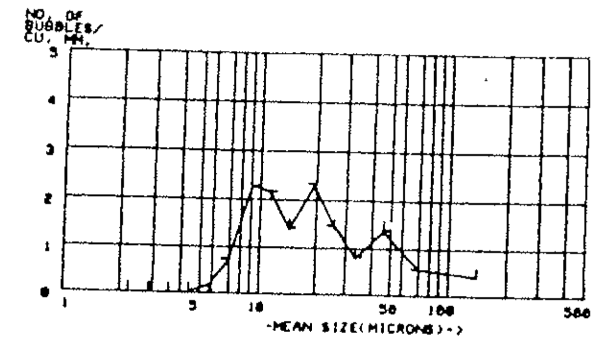


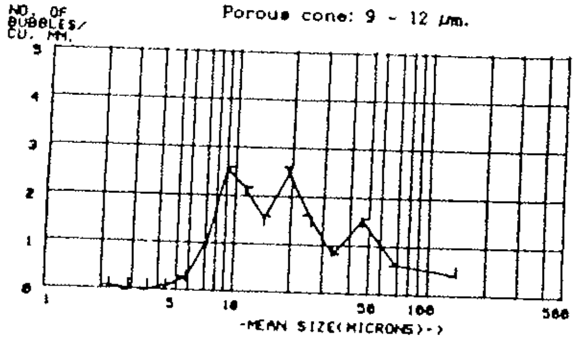
Fig 5 Effect of air injection upon mass loss rate C = air/water %



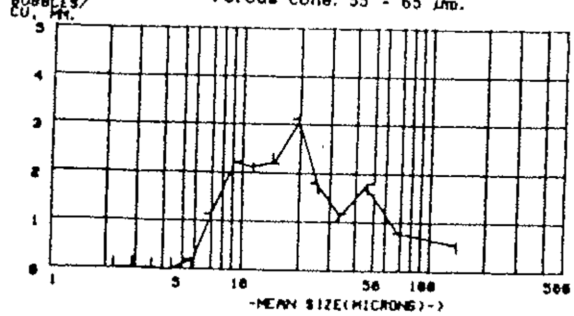
Porous cone: 9 - 12 µm.



Porous cone: 55 - 65 µm.



Porous cone removed.



0.125 mm tube(see Fig 2b)

P=5.76 bar, V=14.3 m/s, and C=0.81 - 0.95 %

Fig 6 Bubble size distribution for various air injection methods