6th Australasian Hydraulics and
Fluid Mechanics Conference
Adelaide, Australia, 5-9 December 1977

Liquid Jet Impact Studies with Plain Jets and Cavijets

K. S. JANAKIRAM
Research Scholar, Civil Engineering Department, Indian Institute of Sciences, Bangalore, India
B. C. SYAMALA RAO
Assistant Professor, Civil Engineering Department, Indian Institute of Science, Bangalore, India
and
S. R. SASIKANTH
Professor, Civil Engineering Department, National Institute of Engineering, Mysore, India

SUMMARY The characteristics of erosion due to the impingement of plain-and cavi-jets has been studied for four different nozzle sizes in each case with a rotating type impingement test rig. A dimensional analysis of the governing parameters is presented. The volume loss increases rapidly, attains a peak and decreases further with increase in stand-off distance for cavijets. The rate of increase in erosion with angle of impingement in case of cavijets is considerably higher than that with plain jets. The normalized volume loss rate for different sizes of jets indicate a unified trend with cavitation number K similar to that reported in cavitation erosion studies. The normalized volume loss rate indicate a unified variation with Strouhal number for constant velocity tests. The growth of area of erosion with test time is discussed.

1 INTRODUCTION

The erosion due to liquid impingement is a common type of damage observed in a variety of engineering equipments. Recent investigations have revealed that liquid impingement erosion and cavitation erosion have a number of similarities in their characteristics. Situations such as water turbines working under high heads and high speed steam turbines working under severe moisture conditions have been subjected to the action of jet or droplet impingement along with the cavitation action. This has resulted in serious problems of material damage, maintenance and reduction in efficiency. A similar situation arising due to the impact of rain drops on aircrafts moving at supersonic speeds has been realised. Apart from these detrimental effects, investigations are under way for the beneficial use of liquid jets in cutting, drilling and mining applications. The particular conditions which would improve the cutting efficiency have been the subject of many investigations in the recent years (1,2). The beneficial utilization of the cavitation characteristics in improving the jet cutting efficiency has led to the design of cavijets or cavitation-induced jets. The exploitation of the several characteristics of the ordinary and cavi-jets needs a more detailed and systematic investigation.

Several investigators on the erosion due to impingement have contributed to a better understanding of its dependence on different test conditions and parameters. Extensive reviews are now available on this subject (3,4,5). The formation of microjets in both the situations of cavitation and jet impingement has been reported by several investigators (6,7). The erosion behaviour characterised by the variations in weight or volume loss or mean depth of penetration rate has been studied by Heymann (4) and Schmitt et al (8).

Though the severity of impingement in liquid jets can be considered to a first approximation as directly proportional to the volume flux of impinging water, the introduction of cavitation into liquid jets results in several other factors playing significant roles in the erosion process. They are: the diameter ratio, the length of cavity formed and the size of jet impinging on the target. This paper reports comparative investigations on the characteristics of erosion due to plain- and cavi-jets. The variations of normalized volume loss and area of erosion with the following parameters viz., stand-off distance, angle of impingement frequency of impingement and test time are reported.

2 EXPERIMENTAL EQUIPMENT AND PROCEDURE

Fig. 1 shows a sketch of the plain nozzle and cavijet nozzle used in the experiments. Fig. 2 shows a schematic of the experimental set-up which has been designed and fabricated at the Hydraulics laboratory. The test rig consists of two liquid jets issuing from a pair of identical nozzles impinging onto four test specimens symmetrically mounted on the periphery of a rotating disc. The rotating disc is housed in a chamber which is provided with glass windows for visual observations. The disc is connected onto the shaft of a variable speed D.C.motor. A centrifugal pump of capacity 35 H.P. supplies water to the jets. Test specimens are cut from commercially pure aluminium sheets of 3 mm thickness. The important mechanical properties of the target material are: density = 2.7 mg/mm^3, yield strength = 645 kg/cm^2, tensile strength = 850 kg/cm^2, strain energy =73.2 kg-cm/cm^3 and ultimate resilience = 0.514 kg-cm/cm^3. The range of jet velocities was from 5m/sec to 40 m/sec. The test chamber was at the atmospheric pressure throughout the experiments. The average velocity of the jet was calculated from the discharge which was estimated by collecting a known volume of water in a calibrated measuring tank.

The damage data are obtained for 6, 8, 10 and 12 mm plain jet diameters and cavijets of diameter ratios (D/d) 2.66, 2.22, 1.81 and 1.53. The loss in weight of test specimens is obtained by using a Mettler balance of capacity 200 gm and a sensitivity of 0.1 mg. Before each weight measurement, the specimens are washed with soap and water dried by a hair drier, and placed in a desiccator for several hours. The equivalent diameter of the cavijet D_e, has been calculated using the relation

$$\frac{\pi D_e^2}{4} = \frac{\pi}{4}(D^2 - d^2) \quad (1)$$

where D = diameter of the nozzle and d = diameter of the inducer.

3 NON-DIMENSIONALISATION OF THE EROSION PARAMETERS

Several investigators (4,5) adopted different techniques for non-dimensionalising the erosion data, e.g., with reference to a highly resistant material. The dependance of erosion on other parameters can be interpreted better if they could be expressed as standard dimensionless numbers. The erosion due to jet impingement is dependant on the following parameters: 1) the jet velocity, U_o, 2) the tangential velocity, U_T, 3) the jet diameter, D 4) the jet diameter ratio, D/d (for cavijets) 5) the densities of the liquid ρ_l and the target material ρ_t 6) the acoustic velocities in the liquid, c_l and in the target material, c_t 7) the stand-off distance, L 8) the test time, t 9) the frequency of impingement, f 10) the angle of impingement, θ and 11) the mechanical properties of the material, M.

Expressing the parameters as a functional relationship

$$\varepsilon = F(U_o, U_T, D, D/d, \rho_L, \rho_t, c_l, c_t, L, t, f, \theta, M) \quad (2)$$

where is an erosion characteristics like volume loss rate V /t or area of erosion A_e. Three characteristic basic parameters (U_o, D, ρ), (U_o, t, ρ) and (U_o, f, ρ) were considered in the dimensional analysis of the parameters using the π theorem. The analysis with U_o, D, ρ as basic parameters yielded meaningful dimensionless relationship. These are:

$$\varepsilon = \left[\frac{V_l}{t U_R D^2}, \frac{A_e}{D^2}\right] = \phi\left(\frac{U_o}{c}, Re, \frac{fD}{U_o}, \frac{L}{D}, \frac{U_o t}{D}, \frac{\rho t}{c_l}, \frac{U_o}{c_t}, \frac{D}{d}, \frac{U_T}{U_o}, \frac{M}{\rho D}, \theta\right) \quad (3)$$

where $U_R = \sqrt{U_o^2 + U_T^2}$. The analysis of the experimental results is made considering these dimensionless parameters.

4 ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

4.1 Dependance of Erosion on Stand-off Distance

In the experiments the stand off distance was varied from 20 to 240 mm and its influence on erosion was studied for two jet diameter ratios of 1.81 and 1.53. The speed of the disc was kept constant at 1000 rpm. Fig. 3 shows a plot of the volume loss against the normalised stand-off distance, L/D_e. The stand-off distance is normalized with the equivalent diameter of the cavijet. The volume loss increases rapidly, attains a peak and then decreases as the stand-off distance is increased. The peak in erosion is observed in the range of 15 to 20 equivalent diameters of the cavijets. Compared to the influence of stand-off distance on erosion due to the plain jets, the peak in erosion with cavijets occurs at a larger stand-off distance. This shift in peak is evidently due to the effects of the disturbance.

The increase in erosion in the initial stages is more rapid compared to the same in the case of plain jets. This is due to the cavitation caused by the inducer in the nozzle. With further increase in the stand-off distance, the erosion decreases due to the cavitation bubbles collapsing before reaching the target. In addition, at large distances from the nozzle, the jet keeps spreading fast and hence the impact pressures are reduced.

4.2 Influence of Angle of Impingement on Erosion

The angle of impingement plays a significant role in the case of erosion of turbines and aircrafts. Pouchot et al (9) reported the dependance of erosion on the angle of impact of a droplet.

The study on dependance of area of erosion on the angle of impingement is important in the case of the jets used for cutting applications. The cutting performance of a jet of a given size and velocity is characterised by the surface area eroded. The present experiments are made by varying the jet velocity and the speed of the disc. The angle subtended by the resultant velocity with the test specimen varied from 15° to 65°. The area eroded for a test duration of 5 hours was measured. Fig. 4 shows plots of the normalized area of erosion Vs. the angle of impingement for four plain jets and four cavijets. From the figure it is seen that both the velocity components of the jet affect the erosion significantly. In the case of plain jets and cavijets the increase in the area of erosion with the angle of impingement is slightly faster compared to the same in the case of droplet impingement (8). The rate of increase in erosion is higher in the case of cavijets and it becomes approximately constant after a certain angle of impingement. In the case of plain jets the increase in the area of erosion is more or less uniform with increase in angle of impingement.

4.3 Influence of Normalized Volume Loss with Cavitation Number

In interpreting the erosion results from cavijets experiments it is desirable to have a parameter similar to the cavitation parameter

$$K = \frac{P_o - p_v}{\frac{1}{2} \varrho U_o^2} \quad (4)$$

where P_o = free stream pressure, p_v = the vapour pressure of the liquid and U_o = the free stream velocity.

In the present study, the pressure p_{min} at the point on the disturbance in the nozzle where the velocity is maximum is used in place of P_o. Hence the cavitation number for the present analysis is defined as

$$K = \frac{p_{min} - p_v}{\frac{1}{2} \varrho U_o^2} \quad (5)$$

Fig. 5 shows a plot of the normalized erosion rate Vs. cavitation number for two speeds of 1500 and 2500 rpm of the disc. The normalized volume loss rate is defined as a ratio of the volume loss to the product of test time, resultant velocity and square of the equivalent diameter of cavijet ($V_1 = V_l / t U_R D_e^2$). It may be observed that with increase in the jet velocity and the size of the cavitation inducer the normalized erosion rate increases. A similar trend has been reported with cavitation studies.

4.4 Influence of Frequency of Impingement

To study the influence of the frequency of impingement on erosion, tests were conducted with cavijets of diameter ratio 10/5.5 over a range of velocities from 5 to 35 m/s. The frequency of impingement was varied from 53 to 100 Hz. Fig. 6 shows a plot of the normalized volume loss rate with Strouhal number, fD_e/U_o where f is the frequency of impingement, D_e is the equivalent diameter of jet and U_o is jet velocity. No measurable volume loss was observed for impacts upto 53 Hz. The rate of increase of erosion is higher at larger frequencies of impingement. The threshold frequency of impingement i.e., the number of impacts necessary to initiate damage on the target can be obtained by extending the linear part of the plot to the x-axis. For the present case, where the jet diameter ratio is 10/5.5 the threshold frequency of impacts is 55 Hz.

4.5 Influence of Test Time on Area of erosion

Fig. 7 shows a plot of the growth of area of erosion with test time for 4 plain jets and 4 cavijets. It may be observed that in the initial stages, there is little difference in the area of erosion between plain and cavijets. In the later stages the area of erosion increases rapidly for the cavijets compared to the area for plain jets. This characteristic of cavijets can be used in cutting applications. For the cavijets, the area of erosion increases rapidly upto a certain time and thereafter the increase is very small. This is perhaps due to the cushioning effect provided by the water trapped in the eroded surface. Further, the impinging water might harden the surface of the target by work hardening. With plain jets, however the increase in the area of erosion with test time is less rapid and uniform.

5 CONCLUSIONS

a) The volume loss increases rapidly initially, attains a peak and decreases with increase in stand-off distance for cavijets. The peak occurs at a larger stand-off distance in the case of cavijets compared with the same for plain jets. b) The normalized volume loss rate increases as the angle of impingement is increased. This increase is more rapid in the case of cavijets than in the case of plain jets. c) The normalized volume loss rate increases rapidly with decrease in the cavitation number for cavijets which is in agreement with cavitation studies reported in literature. d) The frequency of impingement has a significant effect on erosion. The normalized volume loss rate indicated a unified variation with Strouhal number for constant velocity tests. e) The area of erosion is larger with cavijets than with plain jets at a given test time. The area of erosion increased uniformly with test time in case of plain jets while in case of cavijets the area increased rapidly upto a certain test time and thereafter the increase is mild.

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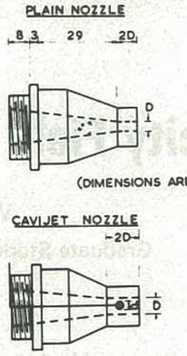

Figure 1 Nozzles

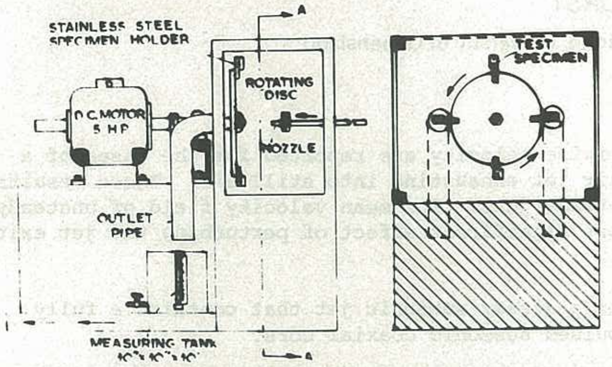

Figure 2 Side view and sectional elevation of the liquid jet impingement test rig

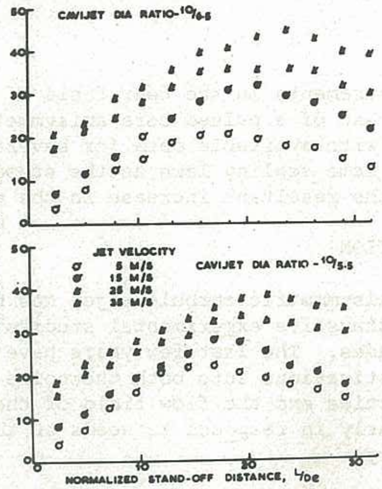

Figure 3 Influence of stand-off distance on volume loss

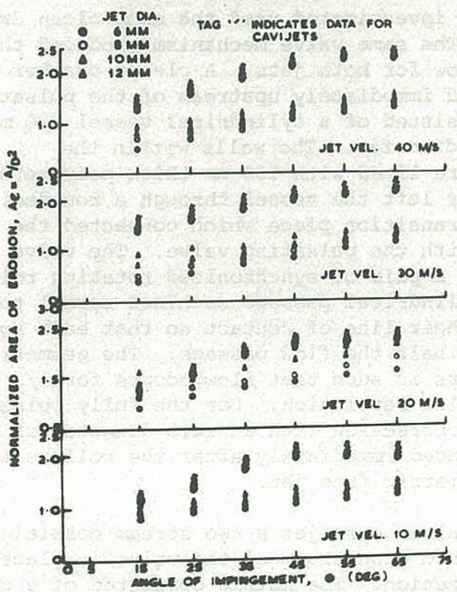

Figure 4 Influence of angle of impingement on area of erosion

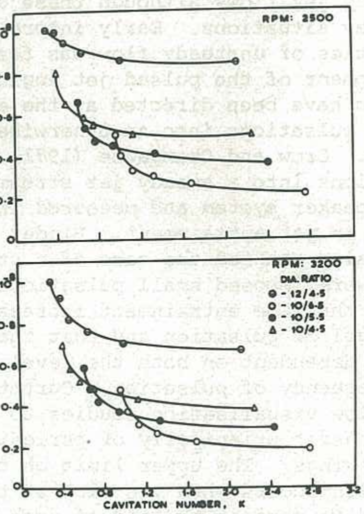

Figure 5 Variation of normalized volume loss rate with cavitation number

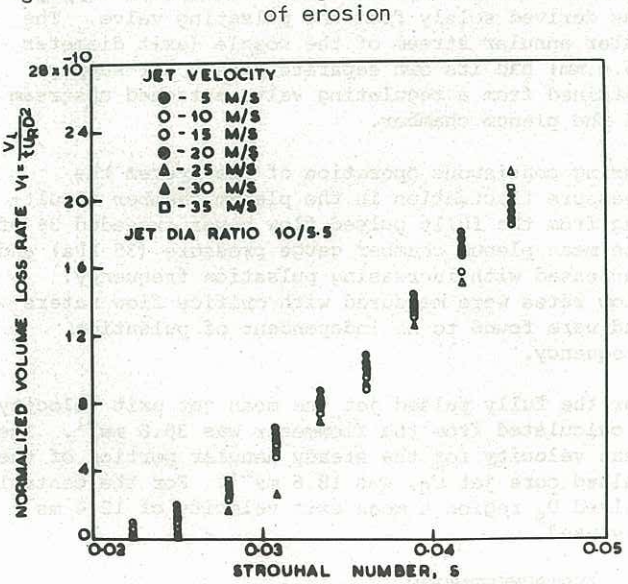

Figure 6 Influence of normalized volume loss on strouhal number

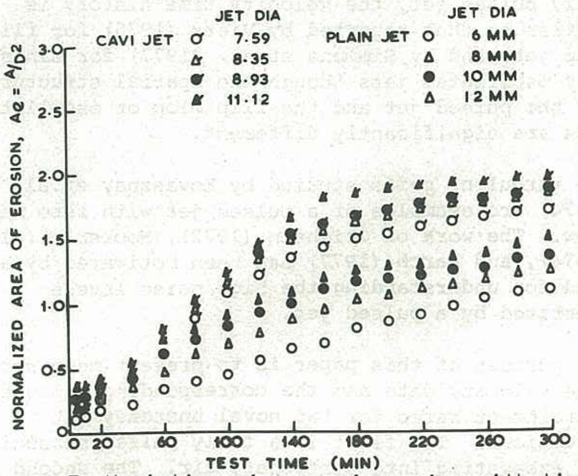

Figure 7 Variation of area of erosion with time