During the test programme that was followed (Section 4.2.4), the configuration of the valves downstream of the test section was modified so as to allow the use of as wide a flow and pressure range as possible.

4.2.2 MEASUREMENTS

All flow, pressure and vibration measurements taken during the tests were displayed on the instrument panel (as described in Section 4.2.1, (Figure 4.9).

The pressure measurements were taken by three separate means :

i) Pressure gauges (Bourdon type)
ii) Pressure transducer (electrical)
iii) Differential pressure transmitter

The incipient cavitation point was determined from the characteristic curves, following the method outlined in Section 4.1.2. Also, the aural measurement of incipient cavitation was recorded, as given by a 'frying bacon' noise (Tullis J.P. & Marschner B.W. 1968; Ball J.W. et al, 1975).

During the experimental tests it was found that cavitation occurred at the bluff body of the vortex flow meter above a flow of 50 l/s, creating a need for the back-up method of flow measurement to be employed. This was an orifice plate located downstream of the last lateral tee in the original drain line. Furthermore, the vibration created through cavitation resulted in some electrical component failures in the vortex flow meter, thus necessitating occasional repair. Also, a problem was experienced with the 'U' tube manometer used with the downstream orifice plate; difficulties were experienced in obtaining suitable fluids commercially for use with the manometer. Hence it was decided to examine the use of the test orifice as a flow measuring device. In the work of Numachi F. et al (1960) it was shown that cavitation did not modify the expected flow pressure drop relationship, thus indicating that a cavitating orifice can be used to measure flow. For the 0,377 diameter ratio orifice the measured flow rates were compared to the theoretical ones; for the same pressure drops, the data are shown in Figure 4.10, the derived and theoretical equations being

Derived $P = 1,55\ Q^{1,82}$ 4.1

Theory $P = 0,82\ Q^{2}$ 4.2

The root mean square deviation for the experimental data was calculated to be ± 10,7%, with cavitation not appearing to affect flow rates and pressure drops. This confirmed that provided adequate data are available to determine the equation for the orifice, and the pressure taps are outside the cavitation zone, cavitating orifices can be used to measure flow rates. The derived equations for the other test orifices and the percentage root mean square deviations are given below in Table 4.1.

d/D	± % ROOT MEAN SQUARE DEVIATION	EQUATION	
0,276	± 2,8%	$P = 1,53\ Q^{2,3}$	4.3
0,330	± 3,9%	$P = Q^{2,15}$	4.4
0,377	± 10,7%	$P = 1,55\ Q^{1,87}$	4.1
0,444	± 8,7%	$P = 0,45\ Q^{1,94}$	4.5

TABLE 4.1 TEST ORIFICE FLOW EQUATIONS

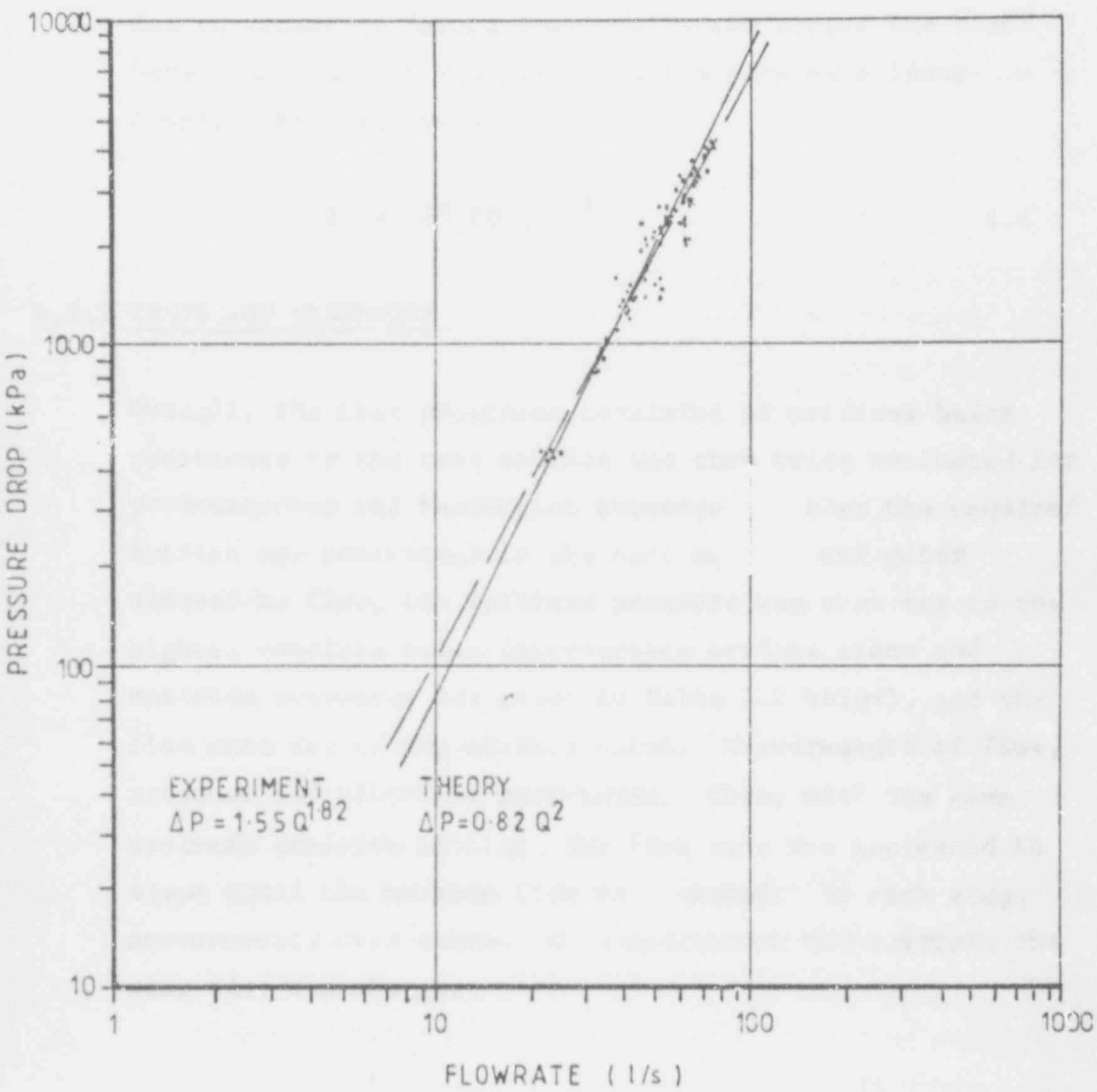


FIGURE 4.10 FLOWRATE vs PRESSURE DROP FOR 0.377 RATIO ORIFICE - EAST DRIEFONTEIN GOLD MINE

In view of the above situation, it was decided to utilise the test orifices as flow measuring devices, calibration equations having first been established using the vortex flow meter and the downstream orifice plate. For the 0,206 diameter ratio orifice, the results from the downstream orifice were used. The vortex flowmeter being in-operable due to vibration damage from cavitation across its bluff body. An equation was fitted to the data at a later stage; this was found to be

$$P = 80{,}28\, Q^{1{,}44} \qquad 4.6$$

4.2.3 TESTS AND PROCEDURE

Overall, the test programme consisted of orifices being positioned in the test section and then being evaluated for pressure drop and cavitation behaviour. After the required orifice was positioned in the test section and water allowed to flow, the upstream pressure was then set to the highest required value (appropriate orifice sizes and upstream pressures are given in Table 4.2 below), and the flow rate set to the minimum value. Measurements of flow, pressure and vibration were taken. Then, with the same upstream pressure setting, the flow rate was increased in steps until the maximum flow was reached. At each step, measurements were taken. Once cavitation had started, the step size was changed.

Orifice sizes (mm)	20,0	26,8	32,1	36,7	43,2
d/D	0,206	0,276	0,330	0,337	0,444
(d/D)	0,042	0,076	0,109	0,142	0,198

Available upstream pressures (kPa) : 2000, 3000, 4000, 5000, 6000, 7000

TABLE 4.2 ORIFICE SIZES AND UPSTREAM PRESSURES

After the maximum flow rate had been reached, the flow was then reduced to the minimum value and the upstream pressure adjusted to the next value. The same procedure as given above was then followed.

The object of conducting the tests in this manner was to collect data on flow, vibration, and pressure drop, in order to draw a characteristic cavitation curve for each orifice/upstream pressure combination.

The predicted velocities for incipient cavitation (Equations 2.16 and 2.17) are shown in Figure 4.11, and are used later for calculating theoretical pressure drops (for incipient cavitation) for comparison with the experimental data.

The results for the tests are to be found in Section 5.2.

To operate the test facility the following sequence of operations was carried out (refer to Figure 4.7) :

i) The two isolating valves (Nos. 1 & 5) and the pump column drain valves (PCD valves) were closed and the drain valve (No. 3) opened.

ii) The test section was removed and the correct size orifice fitted (to fit the orifice, all instrument connections were first released). The test section middle flange was then uncoupled and the correct orifice located in the test section, the flanges were rejoined and the test section was then replaced in the test facility.

iii) All instrument connections were re-attached to the test section.

iv) The drain valve (No. 3) was closed and the globe valves (Nos. 5 & 6) opened one-quarter of full travel.

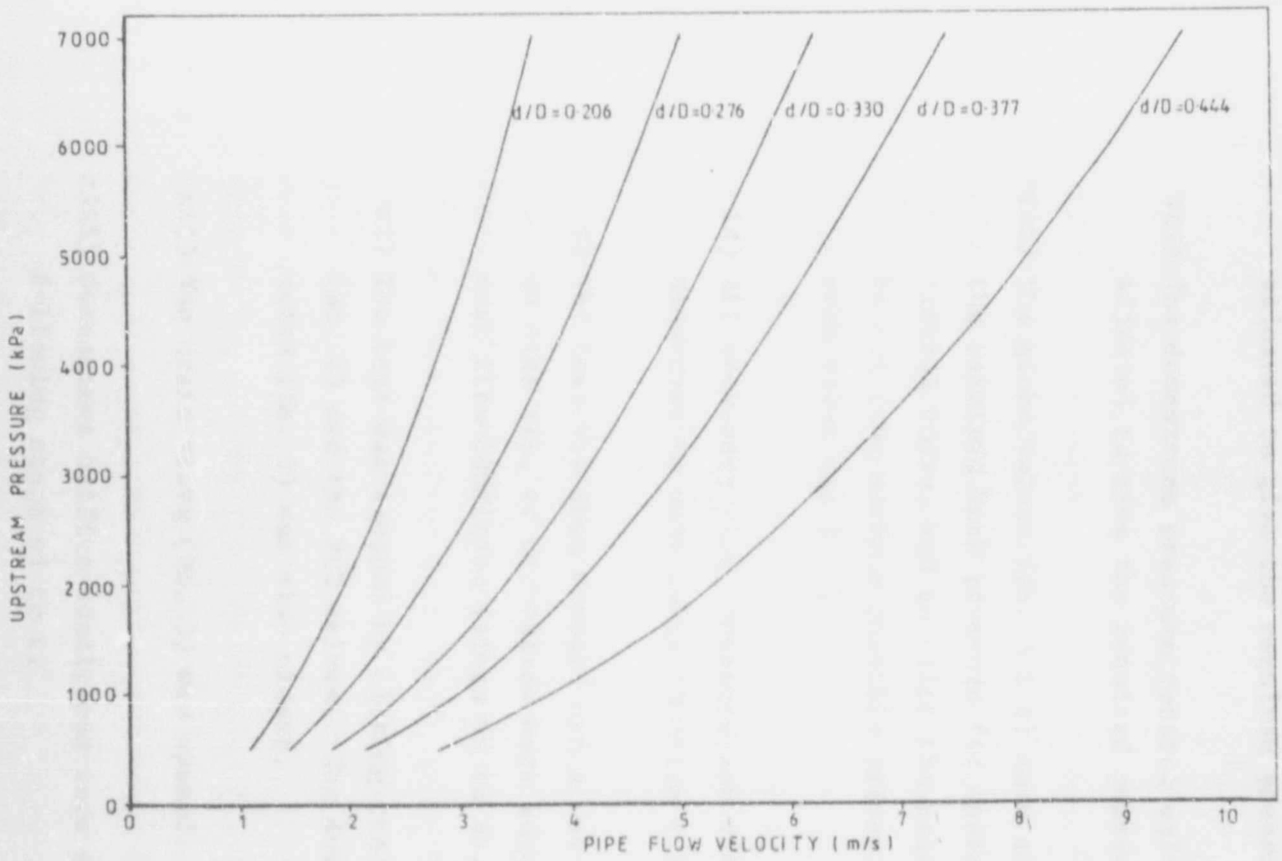


FIGURE 4.11 PREDICTED INCIPIENT CAVITATION FLOW VELOCITIES FOR EAST DRIEFONTEIN GOLD MINE TESTS

v) The PCD valves connecting the test facility to the pump column were opened, followed by the isolating valve (No. 1), allowing water to enter the test rig.

vi) The upstream pressure control valve (No. 2) was adjusted to give the required pressure setting.

vii) The downstream pressure control valve (No. 4) was adjusted to give the required pressure setting.

viii) The globe valves (No. 5 & 6) were adjusted to give the required back pressure for operation of the control valve, and to allow the required flow rate to be set (the maximum possible pressure ratio across each valve was 3 : 1).

ix) All necessary flow, pressure and vibration measurements were taken (Section 4.2.2).

x) The test was then stopped and a new orifice used (go to step xi), or the valves were adjusted to give the next flow condition (steps vi to x).

xi) The test was stopped by closing the isolating valve (No. 1) and the PCD valves. The downstream isolating valve (No. 5) was also closed.

xii) The drain valve (No. 3) was opened.

xiii) Subsequent orifice conditions were set up by following steps vi to x.

5. RESULTS, DISCUSSION AND ANALYSIS OF RESULTS

The results of the experiments carried out at the University of the Witwatersrand and at East Driefontein Gold Mine are presented in the following two sub-sections, 5.1 and 5.2. The analysis applied to the results is given in the third sub-section, 5.3.

5.1 UNIVERSITY OF THE WITWATERSRAND

The results of the orifice pressure drop tests are given in Tables 5.1 & 5.2. To assist in interpretation, the cavitation indices used by workers at the Colorado State University and Reynolds number based on pipe and orifice flow velocites were calculated, and are included in the tables. The flow and pressure drop data are shown in Figure 5.1 and for comparison the theoretical pressure drop values are also shown, a discussion being given in Section 5.1.3.

Of the orifices tested only two (d/D = 0,43 and 0,61) demonstrated no cavitation to full cavitation, and photographs of these are given in Figures 5.4 to 5.10. The 0,24 and 0,79 diameter ratio orifices exhibited light cavitation, photographs for the 0,79 orifice ratio being given in Figure 5.2. The experimental incipient cavitation points were also determined, and correspond to visual observation of very light cavitation around the circumference of the orifice; these are listed in Table 5.3 below. As noise measurements were taken for the 0,43 and 0,61 d/D orifice only, the characteristic cavitation graphs have been drawn for these orifices (Figure 5.3) and the incipient points marked. In place of the cavitation index σ_1 (Figure 4.5a), the measured pressure drop was used as the horizontal axis; this was to give a better understanding of the characteristic curve, and to use one measurement (pressure drop) only, so reducing potential error. Along with the experimental data (Table 5.3) are the predicted incipient cavitation points from Ball J.W. et al, (1975).

d (mm)	d/D	$(d/D)^2$	Pu (kPa)	ΔP (kPa)	Q (l/s)	V (m/s)	Re_v	U (m/s)	Re_u	σ_1	σ_2	Noise (dBA)
8,1	0,24	0,058	360	359,3	0,89	1,01	50 760	17,53	129 100	0,23	82,7	-
-	0,24	0,058	260	239,5	0,72	0,82	24 970	14,18	104 400	0,43	100,6	-
14,3	0,43	0,185	350	178	2,11	2,39	72 790	12,95	168 300	1,44	44,6	77
-	0,43	0,185	345	174	2,2	2,5	76 140	13,5	175 500	1,46	40,8	77
-	0,43	0,185	345	214	2,29	2,6	79 180	14,05	182 600	1,0	31,8	82
-	0,43	0,185	337	241	2,56	2,9	83 320	15,71	204 200	0,75	21,3	84
-	0,43	0,185	340	274	2,6	2,95	89 840	15,95	207 300	0,54	17,2	88
-	0,43	0,185	335	290	2,66	3,02	91 970	16,32	212 100	0,44	14,1	91
-	0,43	0,185	335	312	2,7	3,06	93 190	16,56	215 200	0,34	11,4	93
-	0,43	0,185	335	320	2,74	3,11	94 710	16,81	218 500	0,34	11	96
-	0,43	0,185	335	325	2,8	3,18	96 850	17,18	223 300	0,32	10	97
-	0,43	0,185	332	327	2,9	3,2	97 450	17,3	224 900	0,28	8,9	98
-	0,43	0,185	335	330	2,82	3,29	100 190	17,8	231 400	0,28	8,9	98

TABLE 5.1 UNIVERSITY OF THE WITWATERSRAND RESULTS

d (mm)	d/D	$(d/D)^2$	Pu (kPa)	ΔP (kPa)	Q (l/s)	V (m/s)	Re_v	U (m/s)	Re_u	σ_1	σ_2	Noise (dBA)
20,3	0,61	0,368	300	136	4,1	4,65	141 600	12,5	230 700	1,82	11,45	78
-	0,61	0,368	290	99	4,13	4,69	142 800	12,59	232 300	2,78	12,5	78
-	0,61	0,368	285	67	4,4	2,05	162 430	13,4	247 300	2,05	9,9	78
-	0,61	0,368	276	136	5	5,67	172 700	15,24	281 500	1,64	6,95	79
-	0,61	0,368	265	192	5,2	5,9	179 700	15,85	292 200	0,81	4,49	84
-	0,61	0,368	260	234	5,17	5,86	178 500	15,76	290 800	0,47	3,19	90
-	0,61	0,368	250	225	5,46	6,19	188 500	16,65	307 300	0,48	2,83	97
-	0,61	0,368	245	221	5,38	6,1	185 800	16,4	302 700	0,48	2,88	102
-	0,61	0,368	245	222	5,5	6,24	190 000	16,77	309 500	0,48	2,75	97
-	0,61	0,368	240	217	5,49	6,23	189 700	16,74	308 900	0,49	2,76	98
26,5	0,79	0,628	195	35	6,29	7,14	217 400	11,43	275 300	6,94	4,78	-
-	0,79	0,628	200	15	6,34	7,19	218 900	11,52	277 500	18,3	5,2	-
-	0,79	0,628	120	115	7,25	8,22	250 300	13,18	317 500	4,17	2,37	-
-	0,79	0,628	120	80	7,5	8,51	259 200	13,65	328 800	1,71	1,71	-

TABLE 5.2 UNIVERSITY OF THE WITWATERSRAND RESULTS

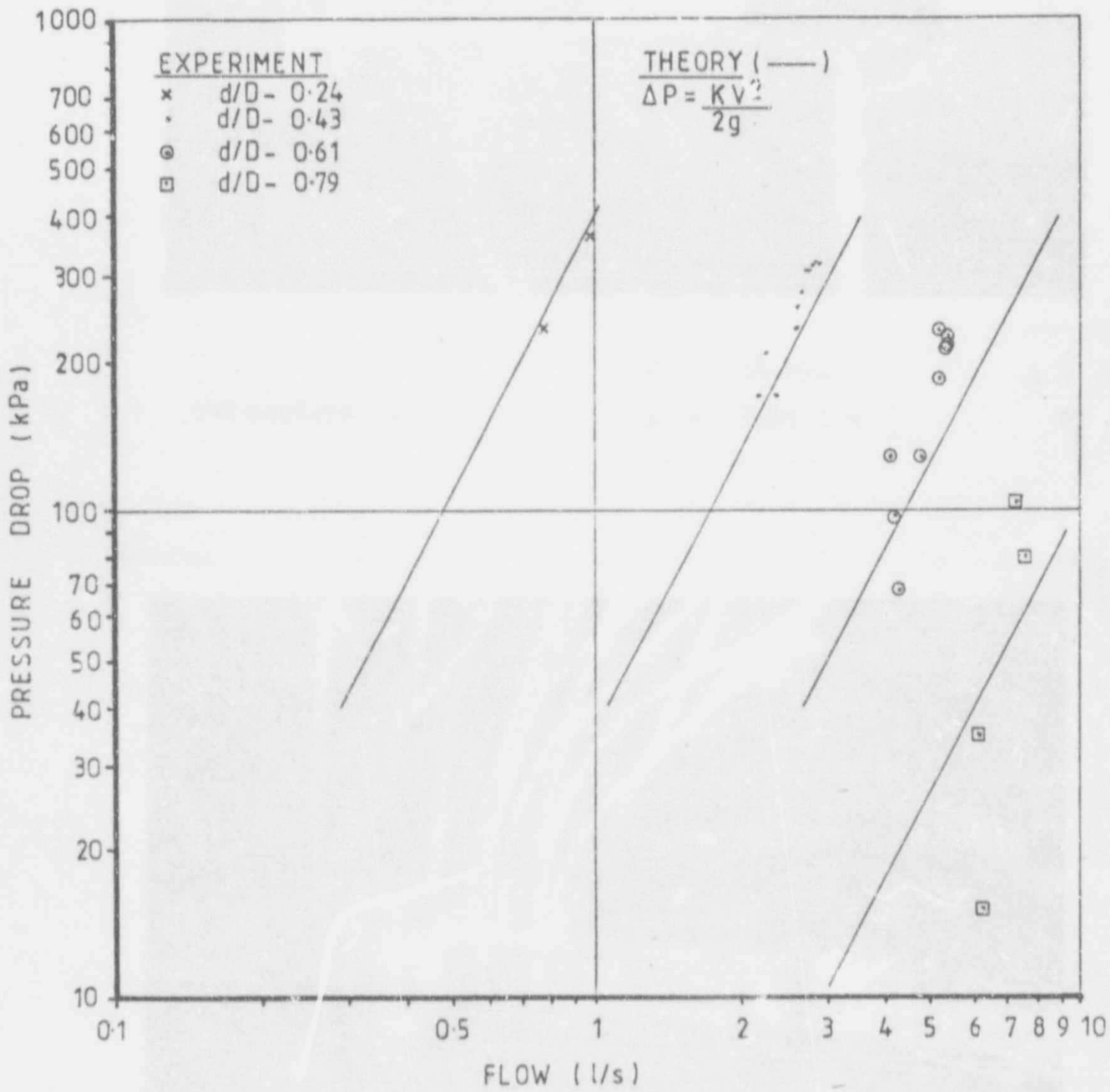
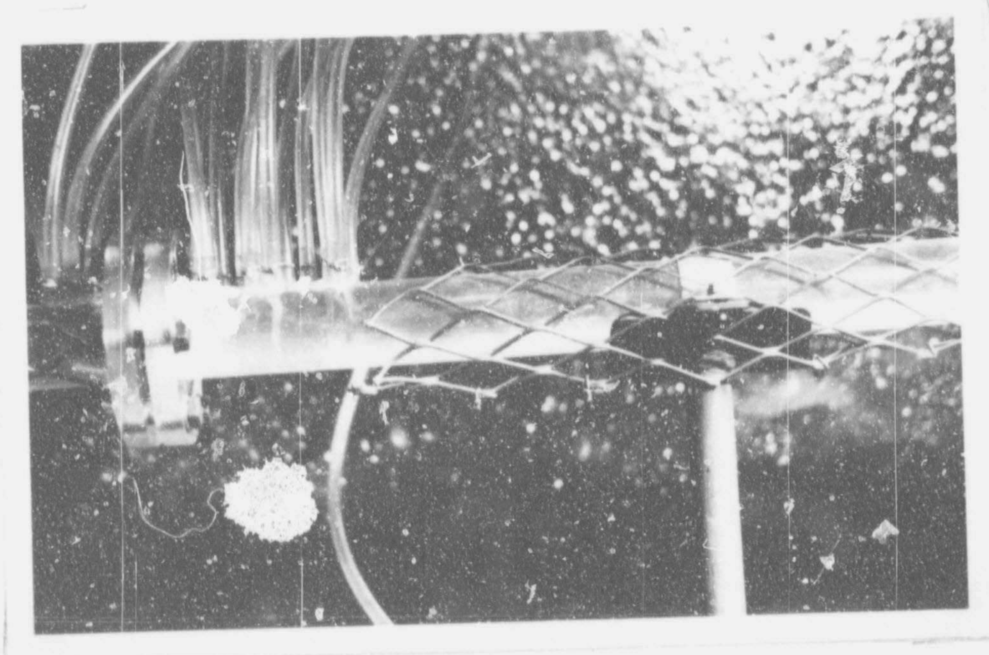


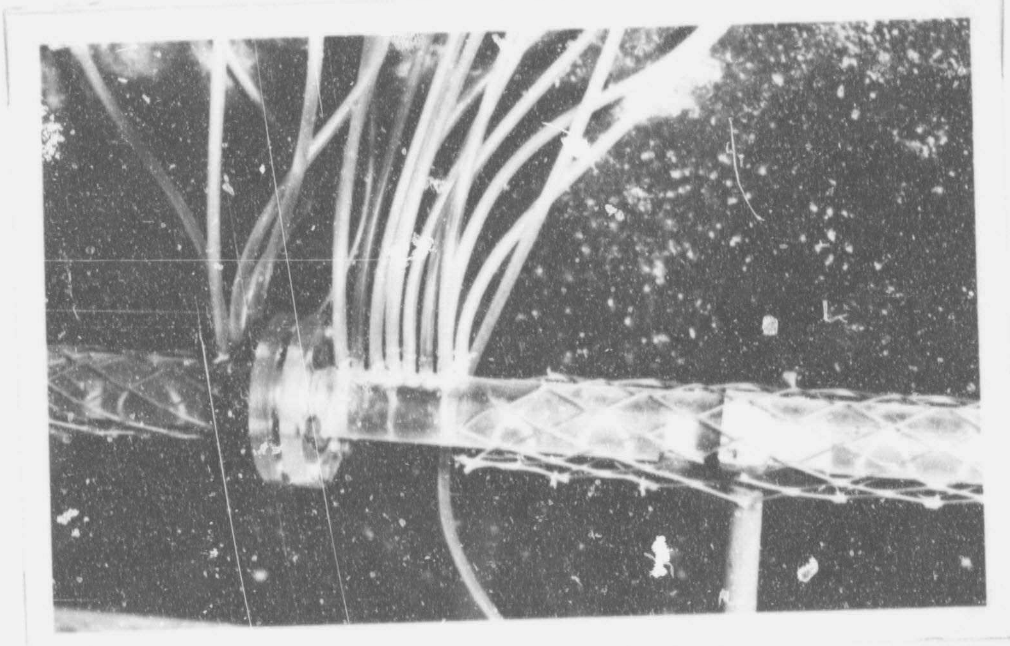
FIGURE 5.1 ORIFICE FLOW AND PRESSURE DROP RESULTS - UNIVERSITY OF THE WITWATERSRAND



PHOTOGRAPH 14

P = 120 kPa
Q = 7,25 l/s

ΔP = 115 kPa
σ_1 = 4,17

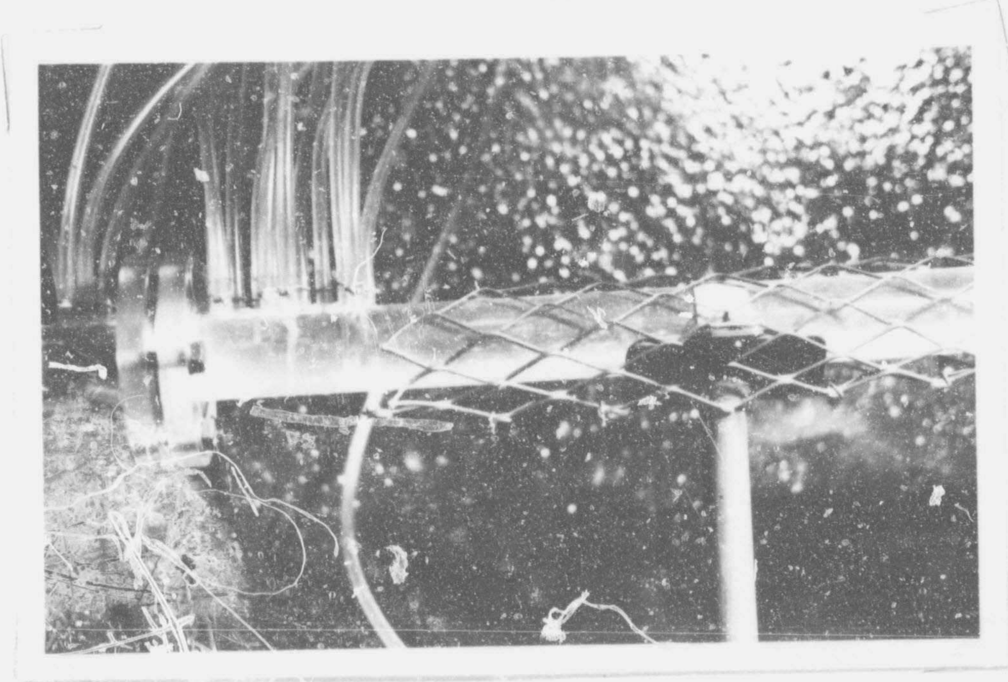


PHOTOGRAPH 15

P = 120 kPa
Q = 7,5 l/s

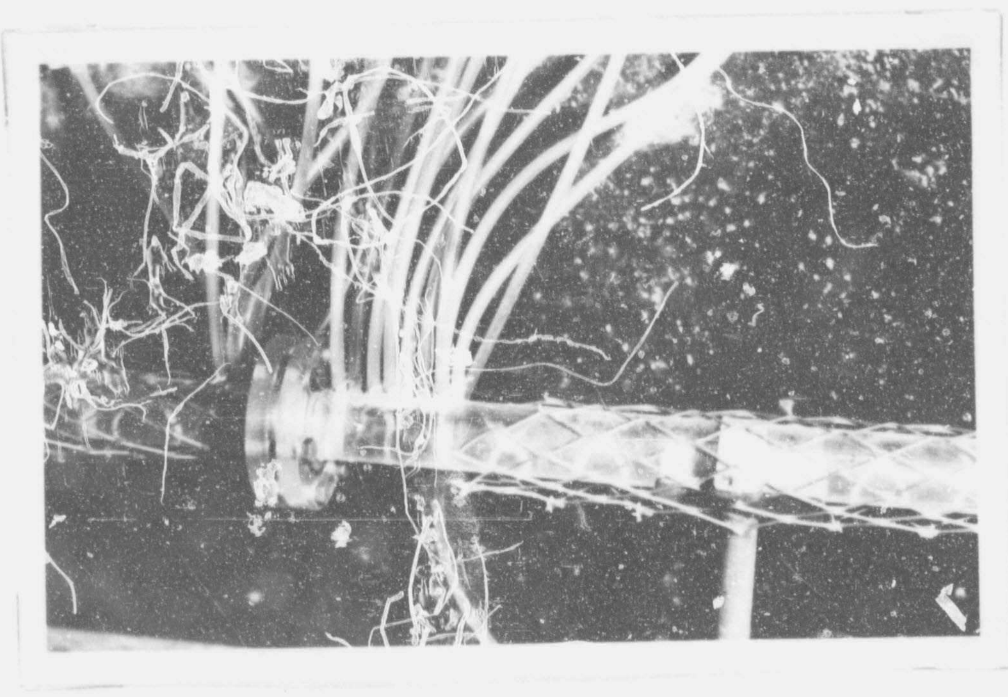
ΔP = 80 kPa
σ_1 = 1,71

FIGURE 5.2 CAVITATION PHOTOGRAPHS d/D = 0,79



PHOTOGRAPH 14

P = 120 kPa   Q = 7,25 l/s ΔP = 115 kPa σ_1 = 4,17



PHOTOGRAPH 15

P = 120 kPa   Q = 7,5 l/s ΔP = 80 kPa σ_1 = 1,71

FIGURE 5.2 CAVITATION PHOTOGRAPHS d/D = 0,79

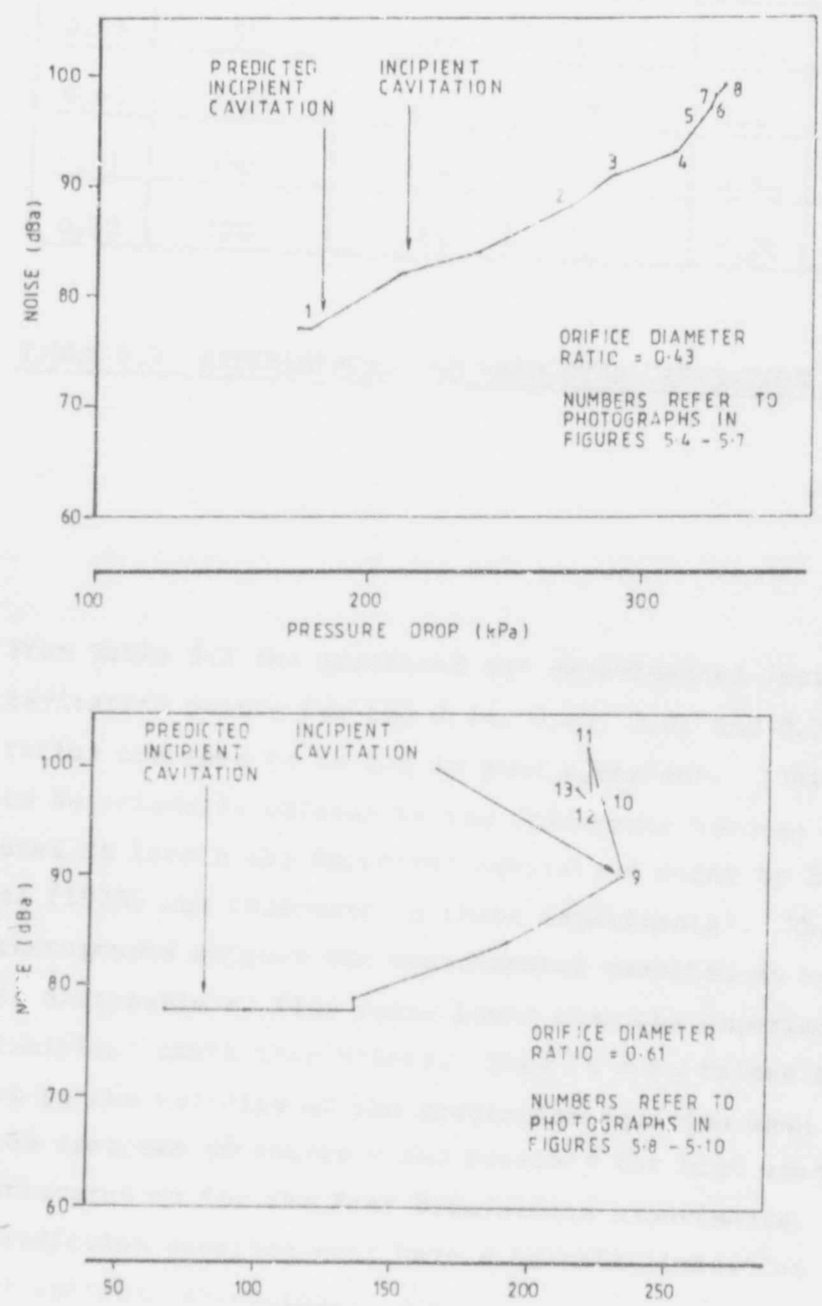


FIGURE 5.3 CAVITATION CURVES - UNIVERSITY OF THE WITWATERSRAND

d/D	Pu (kPa)	Exp ΔP (kPa)	Pred ΔP (kPa)	Exp σ_1	Pred σ_2
0,24	360	359	485	0,28	-
0,43	345	214	182	1,1	1,4
0,61	260	234	81	0,54	3,4
0,79	120	115	29	0,91	6,6

TABLE 5.3 EXPERIMENTAL AND PREDICTED CAVITATION LIMITS

From Table 5.3 the predicted and experimental incipient cavitation points for the 0,24, 0,43, 0,61 and 0,79 orifice ratios are seen to be not in good agreement. (This is thought to be primarily related to the difference between the method used to locate the incipient cavitation point by Ball J.W. et al (1975) and that used in these experiments). The photographs support the experimental results, as no cavitation is noticeable at flow rates lower than the experimental incipient cavitation points. This in turn raises some doubt as to the validity of the prediction equation when used for low upstream pressures - and possibly for high upstream pressures as for the East Driefontein experiments. Hence, the prediction equation must have a certain limitation in respect of upstream pressures.

To quantify the prediction method for the incipient cavitation point, equations were fitted to the date for the 0,43 and 0,61 d/D orifices in the incipient cavitation area in line with the method given in Section 4.1.2, the average errors for the equations being given below :

d/D	± % ERROR		
	POWER	LOG	EXP
0,43	2,0	1,7	1,7
0,61	4,9	5,1	4,7

The equation of best fit was an exponential curve of the form

$$y = a e^{bx} \quad 5.1$$

which in terms of the cavitation curve is

$$\text{Noise} = a e^{b(\text{pressure drop})} \quad 5.2$$

For a curve, the tangent at the incipient cavitation point can be located by means of an angle between the pressure drop axis and the tangent. This is given by Pedoe J. (1971) :

$$\cos \theta = \frac{1}{\left(1 + \left[\frac{dN}{dP}\right]^2\right)^{0,5}} \quad 5.3$$

where dN/dΔP is the first derivative of the curve fitted to the data points. If the angle θ is known, or can be ascertained, then the equation can be made explicit for the incipient cavitation pressure drop (provided the derivative permits algebraic manipulation).

The equations for the two cavitation curves are

$$d/D = 0{,}43 \qquad N = 60{,}83\ e^{1{,}35 \times 0^{-3} \Delta P} \qquad 5.4$$

$$d/D = 0{,}61 \qquad N = 67{,}23\ e^{1{,}45 \times 0^{-3} \Delta P} \qquad 5.5$$

and the calculated tangent angles are

$d/D = 0{,}43$ $\theta = 6{,}2°$ for $\Delta P = 214$ kPa

$d/D = 0{,}61$ $\theta = 7{,}8°$ for $\Delta P = 234$ kPa

For the predicted results from Ball J.W. et al (1975) the angles are :

for $d/D = 0{,}43$ $\theta = 5{,}9°$ $\Delta P = 182$ kPa

for $d/D = 0{,}61$ $\theta = 6{,}2°$ $\Delta P = 81$ kPa

As mentioned earlier the term, incipient cavitation, is not well defined, hence it would appear incorrect to base the angle for the above study solely on the angles from the predicted or experimental results. An average has therefore been taken, i.e. 6,5°, and this will be used in assessing the East Driefontein results.

5.1.1 OBSERVATIONS

Flow cavitation tests

Observations made during the flow cavitation tests are as follows :-

i) For both cavitating orifices (d/D = 0,43 and 0,61) the flow downstream of the cavitation zone appeared aerated.

ii) For all orifices tested, the incipient cavitation appeared to emanate from the leading edge/trailing edge area of the orifice.

iii) The cavitation bubbles did not appear spherical when viewed using a stroboscope.

Vapour pressure tests

Vapour pressure tests carried out on disturbed and undisturbed water from the same source yielded the following observations :

i) The disturbed water produced visible bubbles at a higher absolute pressure than the undisturbed water.

ii) Both samples began to cavitate vigorously at pressures higher than the vapour pressure.

iii) The lowest pressure attained for each sample was 2,4 kPa (abs) at 20°C (the theoretical vapour pressure at 20°C is 2,34 kPa), which, in view of the purpose of the tests, can be taken as broad agreement between experiment and theory. The variation is believed to be due to air in solution which is in excess of the air at the vapour pressure.

5.1.2 ERROR ANALYSIS

The following section shows the error analysis for the measurements and calculated values, for the experiments conducted at the University of the Witwatersrand. In all cases the root mean sqaure (RMS) error has been calculated, and three assumptions made. These are : (i) the gravitation constant 'g' is 9,81 m/s^2, (ii) the density of water is 1000 kg/m^3, and (iii) the vapour pressure of the water used is as determined from temperature measurements.

Flowrate

The flowrate was measured ... ically by measuring the level change in a tank and measuring the time period for this to occur. The volume change is given by the product of the level change and the tank area :-

$$V = \Delta h \times A \qquad 5.6$$

Level change was measured using a sight glass which had a millimetre scale positioned behind it (error of ± 2 mm per reading). The Δh values ranged from 500 m to 700 m.

The tank diameter was measured using a millimetre rule (diameter = 560 mm), with an estimated error of ± 1 mm.

Time periods for flow measurements ranged from 24 to 171 s; the stopwatch measured to ± 0,1 s. However, due to the method of switching water to and from the tank, an error of ± 2 s is estimated.

Flowrate is given by the following equation :

$$Q = \frac{\Delta h \times A}{t} \qquad 5.7$$

and the error of flow measurements by

$$Q \text{ error } \% = \pm\left((\% \Delta h)^2 + (\% A)^2 + (\% t)^2\right)^{0,5} \qquad 5.8$$

Q(1/s)	+ %
0,72	1,3
2,0	2,3
4,0	4,7
6,0	6,9
7,5	8,4

Pressure :

The pressures were measured using a pressure gauge (standard industrial quality, ± 0,5% FSD) which had been precalibrated using a dead weight (± 0,1% accuracy). The readability of the gauge was 2,5 kPa; this has been taken as the accuracy of measurement. Thus the error of measuremet is given by

$$P \text{ error } \% = \frac{2,5 \times 100}{\text{Pressure (kPa)}} \qquad 5.9$$

and the errors are :-

P (kPa)	± %
5	50
25	10
50	5
100	2,5
150	1,7
200	1,3
250	1,0
300	0,8
350	0,7
400	0,6

Noise :

Cavitation noise was measured using a sound level meter. As the measurements are used only to describe the cavitation levels, the accuracy of measurements has not been considered.

Differential Pressure :

This was calculated by subtracting the upstream and downstream pressure measurements. The accuracy of measurement is given by

$$\Delta P \text{ error } (\%) = \frac{2 \times \text{Pressure Gauge Error (kPa)} \times 100}{\Delta P \text{ (kPa)}} \qquad 5.10$$

ΔP (kPa)	$\pm$ %
5	100
30	16,7
80	6,3
100	5,0
150	3,3
200	2,5
250	2,0
300	1,7
360	1,4

Flow Velocity :

The flow velocity is calculated from the measured flow and the pipe area

$$V = \frac{Q}{A} \quad 5.11$$

Therefore the error is given by

$$V \text{ error } \% = \pm \left((\%Q)^2 + (\%A)^2 \right)^{0,5} \quad 5.12$$

V (m/s)	$\pm$ %
0,82	1,4
2	1,8
4	3,5
6	5,3
8,51	8,4

Cavitation Number σ_1 :

The cavitation number σ_1 is calculated from the ratio of the downstream pressure (minus the vapour pressure) to the pressure drop :

$$\sigma_1 = \frac{P_D - P_V}{P_U - P_D} \qquad 5.13$$

the error is given by

$$\sigma_1 \text{ error } = \pm\left((\% P_D)^2 + (\% P_V)^2 + (\% P_U)^2 + (\% P_D)^2\right)^{0,5} \qquad 5.14$$

In the experiments the cavitation index ranged between 0.23 and 18.3, the calculated errors for the indices being

d/D	σ_1	± %
0,24	0,23	2,5
	0,43	2,2
0,43	0,28	2,8
	0,75	2,5
	1,46	1,9
0,61	0,47	1,1
	1,64	2,8
	2,78	5,1
0,79	1.71	7,9
	18,3	222,0

Cavitation number σ_2 :

The cavitation number σ_2 is calculated from the ratio, downstream pressure minus the vapour pressure to the velocity head.

$$\sigma_2 = \frac{P_D - P_V}{\rho V^2} \qquad 5.15$$

the error is given by

$$\sigma_2 \text{ error } \% = \pm \left((\% P_D)^2 + 2(\% V)^2 + (\% P_V)^2 \right)^{0,5} \qquad 5.16$$

d/D	σ_2	± %
0,24	82,7	3,3
	100,6	2,9
0,43	8,46	4,7
	21,3	4,7
	40,8	3,3
0,61	3,19	7,6
	6,95	7,1
	12,5	5,9
0,79	5,2	9,5
	1,71	12,0

The aforegoing calculated errors for the University of the Witwatersrand work are used in the following section - 5.1.2 Discussion of Results - for discussion related to the experimental and calculated results. Generally the calculated errors show the accuracy of measurement to be satisfactory, except where low pressure, low pressure drops and short time

Author Greenfield Paul Somerford
Name of thesis Investigation Of Incipient Cavitation Limits For Square-edged Orifice Plate Pressure Dissipators In High Pressure Water Reticulation Systems. 1985

PUBLISHER:
University of the Witwatersrand, Johannesburg
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