High speed cine observations of cavitating flow in a duct

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The dynamics of cavities produced in cavitating flow confined in a duct was studied. The ultimate purpose of the work is to develop models of the flow to assist in predicting cavitation erosion and noise. Observations of the cavitating flow using high speed cine photography allowed confirmation to be made of the shedding mechanism originally described by Knapp, and measurements of the cavity dimensions to be determined as a function of time. It was found that the time for a cavity to collapse was about three times greater than expected from Rayleigh's classical theory.

Keywords: *cavitation, duct flow, cine photography*

Introduction

The purpose of this work was to observe, using high speed cine photography, the cavitating flow produced by constrictions in a duct. These observations can assist in developing models of cavitating flow which will be useful in predicting the onset and severity of cavitation erosion and the characteristics of cavitation noise. In experimental studies the cavitating flow in, for example, pump impellers and valves may be simulated by the venturi-type channel formed by a convergent–divergent (con–div) wedge. Another use of the venturi-type channel is for generating standard cavitation conditions in order to test the erosion resistance of different materials under more realistic conditions than vibratory cavitation; but one disadvantage of this method is the comparatively lengthy time required for testing. Considerably higher erosion rates may be obtained by using either a cylinder or a symmetrical 60° wedge as a cavitation inducer[1].

High speed cine films, when viewed at normal speed to produce 'slow motion' can be used to obtain a qualitative picture of the development of cavities in a cavitating flow, but the interpretation of such films is subjective and perhaps of limited use in the further development of flow models. Most of the effort reported in this paper has been to produce a few quantitative details of the cavitating flow by analysing the films frame by frame. The main features of interest are the mean length of the attached cavity, the maximum size of the detached cavity, the time required for its collapse, and the shedding frequency. The relationship between mean cavity length and throat cavitations number is well established but little if anything is known about relationships between the other quantities. Some knowledge of these would be useful in developing models of cavity dynamics which can be used to predict the severity of cavitation erosion and the characteristics of cavitation noise.

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This paper is essentially an updated version of a previous paper[2] which dealt with the cavitating flow produced by a con–div wedge inducer. For the new work a further inducer, namely the summetrical wedge inducer, was studied, and the technique for examining the cine films was improved. The latter resulted in a larger number of cavity detachments being analysed, and some significant differences were found.

Experimental work

Experimental apparatus

The cavitating flow was filmed in a cavitation tunnel specially designed for the demonstration of the phenomenon of cavitation. The tunnel consists of an 11 kW centrifugal pump drawing water from a large reservoir, open to atmosphere. The water is discharged from the pump through 50 mm nominal bore piepwork to a parallel-sided working section 400 mm in length and 40 mm × 20 mm in cross-section, which has transparent windows on both of the 40 mm sides. In the pipe upstream of the working section there is a diaphragm valve follwed by a flow straightener and a smooth contraction immediately upstream of the working section. Downstream of the working section, there is a small angle diffuser and a second diaphragm valve. The two valves are used to obtain independent control of the flow rate and cavitation number in the working section. Finally the water is returned to the reservoir by way of a submerged discharge pipe, thus minimizing the entrainment of air bubbles. It is assumed that the air content of the water remains constant at or near the saturation value.

The cavitation is produced by two different ypes of insert: one is a convergent–divergent wedge-shaped liner and the other is a symmetrical wedge with a 60° included angle (see Fig 1). The size of the con–div wedge liner gives an actual flow blockage of nearly 50 percent at choking, ie indefinitely long cavity, and the size of the symmetrical wedge gives a slightly larger blockage at choking of nearly 56 per cent. The fluid velocity obtained in the throat is between 20 and 25 m/s in each case.

The state of the cavitation is defined in terms of a cavitation number σ_0 measured upstream of the liner or insert but within the parallel-sided working section, as follows:

$$\sigma_0=\frac{p_0-p_v}{\frac{1}{2}\rho U_0^2} \tag{1}$$

Since the choking or blocking value of σ_0 varies with the amount of blockage and only slightly with velocity, ie Reynolds number, it is convenient to define an effective throat cavitation number σ as follows:

$$\sigma=\frac{\sigma_0-\sigma_{0b}}{1+\sigma_{0b}} \tag{2}$$

where σ_{0b} corresponds to the value of σ_0 at choking or blocking.

It can also be deduced that the throat velocity U is given by

$$U=U_0(1+\sigma_{0b})^{1/2} \tag{3}$$

It is implicitly assumed that the blockage does not change much with cavitation number or Reynolds number. It can be seen from Eq (2) that choking corresponds to a throat cavitation number of zero.

The cavitation was filmed using a Hycam rotating prism cine camera with Ilford HP5 16 mm film at 3000 frames per second. Since the working section had transparent windows on both sides, it was possible to illuminate the cavitation from the rear. The most successful arrangement consisted of four 500 W floodlights, positioned to give oblique illumination of the rear of the working section. Screens were fitted to shield the camera from the direct light. For accurate measurement of the time, a Gordon timing light generator attached to the camera marked the film at 10 ms intervals. It was found that only the last 12 m of the film was suitable for analysis, since the first 18 m or so was required for acceleration to a steady speed. The films were developed in a Hadland 16 mm negative processor and were analysed using at first a film editor and subsequently an enlarger with a 50 mm focal length lens.

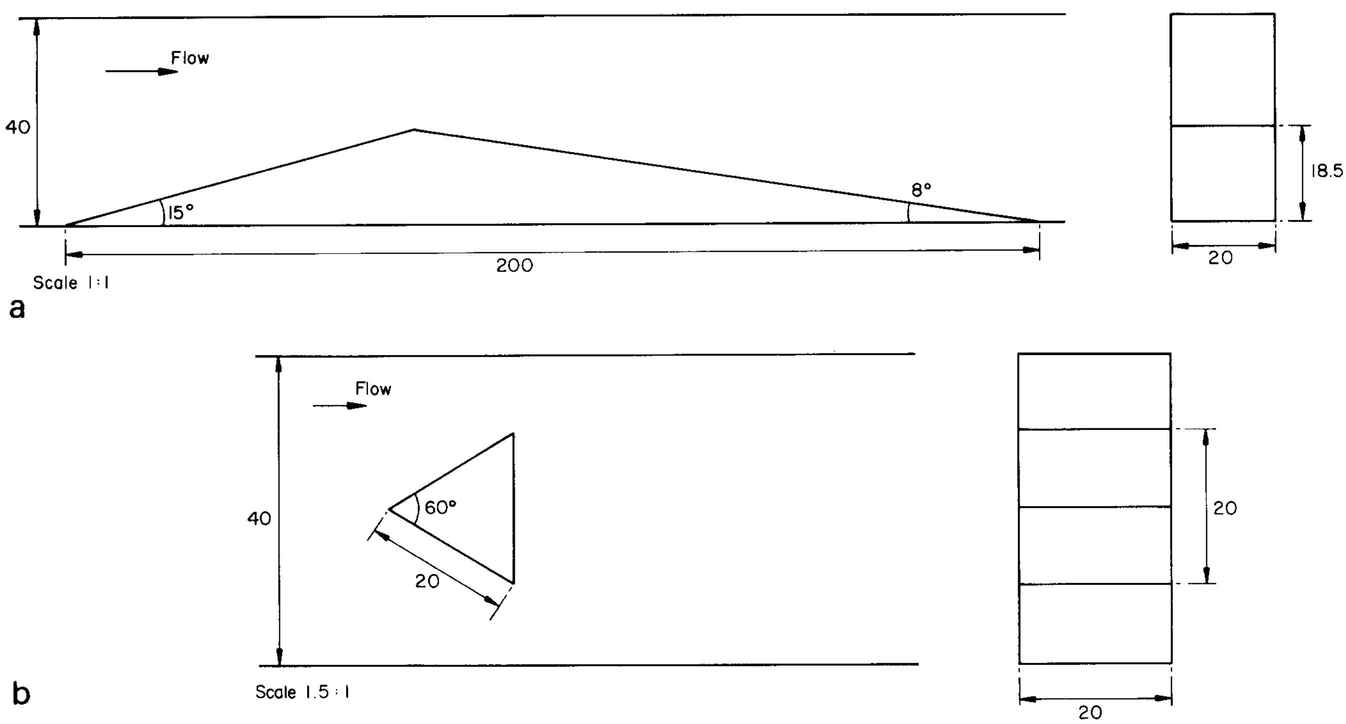

Fig 1 Sketch of cavitation inducers and location in tunnel working section for (a) convergent–divergent wedge and (b) symmetrical wedge. Dimensions: mm

Notation

A_1	Throat cross-sectional area
A_2	Upstream or downstream duct cross-sectional area
p_0	Static pressure in working section of tunnel
p_v	Saturated vapour pressure at bulk liquid temperature
Δp	Pressure difference producing cavity collapse
R_m	Maximum cavity radius, ie at break-off
t	Throat width
t_c	Cavity collapse time
U	Mean velocity in throat
U_0	Mean velocity in working section of tunnel
V_{av}	Average volumetric rate of collapse
λ	Mean attached cavity length
ν	Mean cavity shedding frequency
ρ	Fluid density
σ	Throat cavitation number
σ_0	Cavitation number in working section of tunnel
σ_{0b}	Choked value of σ_0

Experimental results

Two series of experiments were done: the first on the con–div wedge and the second on the symmetrical wedge with one repeat run for the con–div wedge. For the first series, films were exposed for six cavitation conditions, consisting of cavitation number σ equal to 0.067, 0.035, 0.019 and 0.013 for a throat velocity U of 25.3 m/s and velocity equal to 23.0 and 27.4 m/s at a cavitation number of 0.019. All the films were obtained on the same day to eliminate any variation due to change in reservoir air content, temperature and atmospheric pressure. The above cavitation numbers gave a cavity which was not less than about 30 mm long and not greater than the length of the divergent portion, ie approximately 130 mm.

In the second series, the single run for the con–div wedge was made at a value of 0.0033 and a velocity of 24.5 m/s; for the symmetrical wedge the velocity was kept constant at 21.7 m/s and cavitation number set equal to 0.36, 0.2, 0.117, 0.05 and 0.025.

The first set of films was analysed using a film editor fitted with a graticule so that various streamwise and transverse dimensions of cavities could be obtained. These results, which are fully detailed in Ref 2, are less reliable than the present set because the technique used for analysis was cruder, and generally a much smaller number of samples was used.

The second set of data, including one representative case from the first set, namely $\sigma = 0.013$, $U = 25.3$ m/s, was analysed using an enlarger which produced an image approximately 0.275 of the true size of the object. The cavity shapes were transferred to paper by simply drawing round the projected images, and these drawings were used subsequently to obtain the various dimensions.

The main features of interest were the average shedding frequency, the average length of the attached cavity, the average radius of the detached cavity at break-off, and the time required for the detached cavity to collapse completely. The quantities were determined by averaging over a large number of cycles, generally 30 to 50. The average radius at break-off was estimated by measuring two mutually perpendicular cavity dimensions in the frame where the detached cavity was first visible and then finding the geometric mean, which was then averaged over the number of sequences studied. The time required for the cavity to collapse was found from the time elapsed between break-offs, which was reckoned to be half a frame before the frame in which the separated cavity was first visible, and complete collapse, which again was reckoned to be half a frame after the one in which it was last visible. This quantity was also averaged over the number of sequences studied.

The variation of the mean radius of the detached cavity as determined from two mutually perpendicular dimensions as before, and the position of the detached cavity with respect to the inducer throat, were also determined as a function of time. The number of sequences studied in this respect for each cavitation condition was generally between 8 and 10.

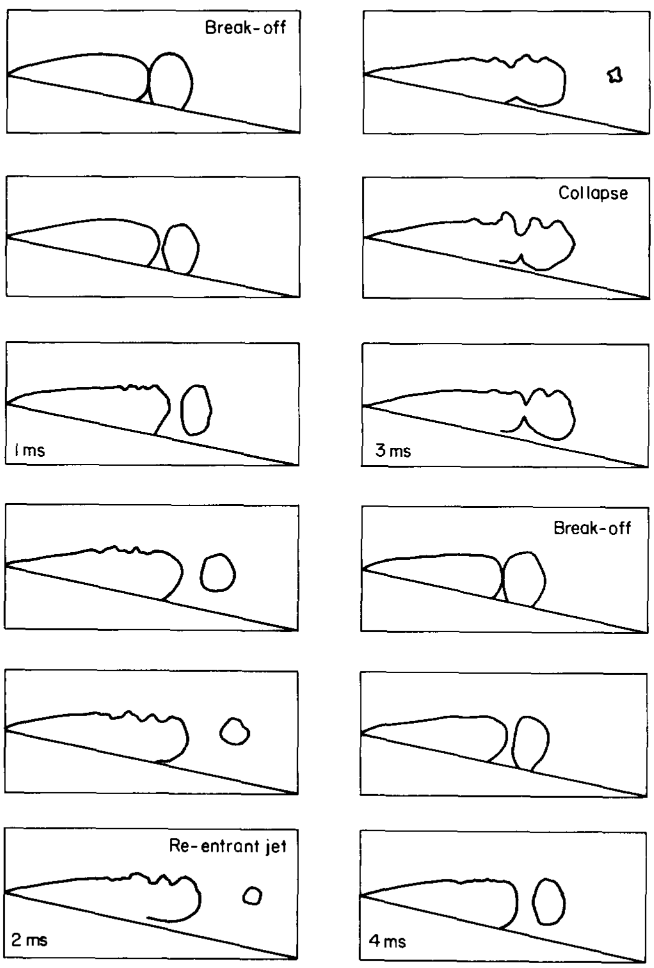

Fig 2 Idealized cavity break-off and collapse sequence for convergent–divergent wedge inducer

Discussion of results

Observed cavity cycling

Qualitative examination of the films revealed a flow pattern of cavity growth, shedding and collapse very similar to that first described by Knapp[3] for 'fixed' cavities on two-dimensional bluff bodies and also by Furness[4] for the con–div wedge configuration. Briefly, Knapp's machanism is as follows. A jet is formed at the trailing edge of the cavity and is directed upstream within the cavity. When the jet penetrates to the point of flow separation, or throat, the cavitation is momentarily interrupted and the whole cavity is detached and convected downstream where it ultimately collapses and disappears. In the meantime, cavitation has restarted at the throat and the cavity grows until another 're-entrant' jet is formed and the whole process is repeated. The main difference between Knapp's explanation and the observations of Furness and ourselves is that generally the cavity breaks off at some point downstream of the throat (actually called partial break-off by Knapp) and only rarely did it break off cleanly at the throat. The reasons for this would appear to be that the re-entrant jet, which could just be discerned on the films, has insufficient energy to penetrate right to the throat. Instead, it makes random contact with the free surface downstream which is far from smooth, particularly towards the trailing edge of the cavity. The waviness of the surface in this region appears to provide more likelihood of contact with the re-entrant jet, since the majority of break-offs occurred in this region. This process leads to a large variation in size of the detached cavity. The sequence of events is depicted in diagrammatic form in Fig 2.

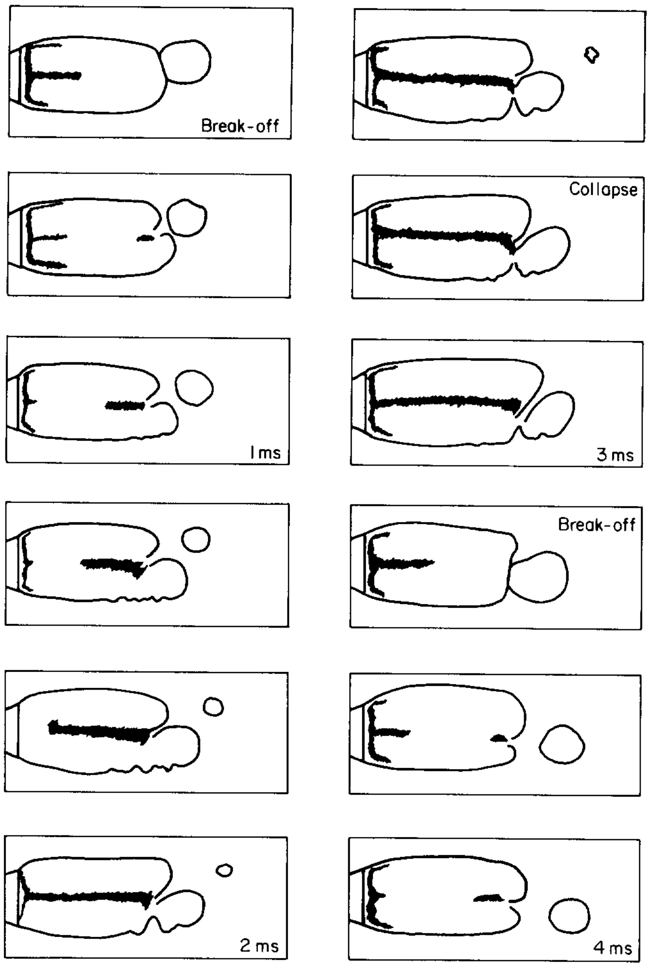

Fig 3 Idealized cavity break-off and collapse sequence for symmetrical wedge inducer

For the symmetrical wedge inducer, the flow pattern in some respects resembles that for a circular cylinder, and the cavity formation is dominated by the vortex shedding which normally occurs for such flows. Nevertheless, a re-entrant jet appears to be responsible for the cavity break-off as before. At all cavitation numbers investigated, the cavitation is severe enough for a vapour-filled wake to form immediately downstream of the inducer. A portion of the cavity is detached from the side of the main cavity and, in common with the vortex shedding for a non-cavitating body, the detachment, a dimple forms on the same side of the main cavity, and this develops into a re-entrant jet which eventually breaks off the opposite trailing portion of the main cavity, thus causing detachment on the other side. The direction of the jet is consistent with the induced flow between diagonal pairs of vortices presumed to be associated with the flow.

At high cavitation number, when the main cavity length is relatively small, the re-entrant jet has sufficient energy to penetrate right to the rear of the wedge. This gives rise to a circulation of liquid already contained wthin the cavity, which produces the detachment from the opposite side. At lower cavitation numbers, when the main cavity is much larger, the jet does not reach the rear of the wedge, but impinges directly on the opposite free surface, causing detachment. The process is shown in idealized form in Fig 3; the shading represents a liquid mass moving within the cavity.

Consideration of the attached cavity

The length of the attached cavity increases at a more or less uniform rate and abruptly reduces at the point of break-off. The cycle is by no means uniform even for the symmetrical wedge inducer, which showed slightly more periodicity than the con–div wedge inducer. The time averaged cavity length generally increases for both inducers as cavitation number is reduced (Fig 4), but the change is more rapid for the con–div wedge. The mean cavity length can also be measured visually using stroboscopic lighting, and some significant differences are found. The visual method yields repeatable results in spite of the difficulty of judging the mean cavity length, but the visual measurement appears to overestimate the length in the case of the con–div wedge and underestimate it for the symmetrical wedge; the reason for this is probably associated with the different method of analysing the data from each inducer. For the con–div wedge data considered here, the cavity lengths were calculated from a relatively small number of samples, in contrast to the symmetrical wedge data where a much larger number of samples was used.

The average shedding frequency, ie the average number of break-offs per unit time over a large number of cycles, does not appear to vary greatly with cavitation number for either inducer. For the con–div wedge the earlier measurements[2] seem to be too small by a factor if between two and three, and so the apparent variation with cavitation number reported should perhaps be discounted. More recent measurements (supplied to use by M. McD. Grant), made on a smaller but geometrically similar configuration at a higher velocity and using the acoustic signal to determine shedding frequency, indicate no correlation with cavitation number. The average value of frequency, corrected for size and fluid velocity assuming a constant Strouhal number, is about 340 Hz and this compares favourably with values of 364 and 368 Hz determined from the cine films using the more recent technique, ie the photographic enlarger. The earlier technique using the film editor produces a smaller, less distinct image which allows a large number of smaller break-offs to be overlooked.

For the symmetrical wedge, the shedding frequency determined from the films is almost constant at about 400 Hz with a tendency to reduce at the lower values of cavitation number, below about 0.1.

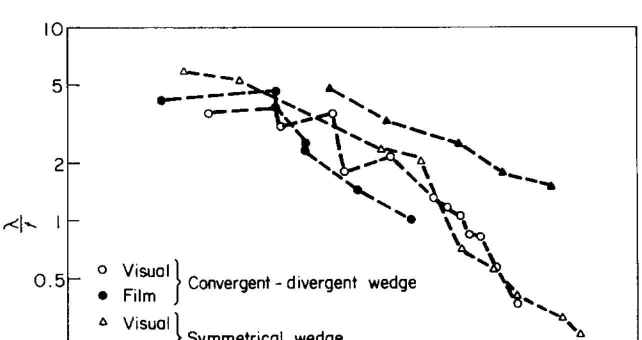

Fig 4 Mean cavity length normalized using flow width at throat as a function of throat cavitation number

Comparisons with Grant's measurements are again favourable, the value of frequency in the constant region being about 380 Hz. Also, the constant region is clearly associated with the regular shedding of vortices from a bluff body as in a Karman vortex street. One interesting point emerges here: the shedding frequency observed is strictly twice the fundamental frequency of the complete cycle, ie shedding from one side only. The acoustic signal would therefore appear to be at the second harmonic and not the fundamental – a point also confirmed recently by Fry[5]. If the frequency is then halved and expressed as a Strouhal number based on mean upstream velocity and total width of the inducer, the value obtained is about 0.42. This is about twice the value expected for vortex shedding from a bluff body in a free stream, ie 0.2. The reason for the discrepancy is probably related to the very high blockage produced by the inducer in the cavitation tunnel, which increases the convection velocity of the vortices compared with the free stream case. Another possible explanation could be the known increase in Strouhal number for vortex shedding from a circular cylinder in the supercritical regime[6]. However, it seems unlikely that this cavitation inducer with its sharp edges would exhibit a supercritical regime, since separation of the flow will always occur at the sharp edges independent of Reynolds number.

Use of the throat velocity instead of the upstream value will compensate to some extent for the increase in convection velocity. In this case the Strouhal number is about 0.18, a value which is much closer to that expected for vortex shedding and in good agreement with the results of Young and Holl[7], who conducted similar experiments on cavitating symmetrical wedges but at much lower tunnel blockage. The Strouhal number for the con–div wedge based on mean throat velocity and width of inducer is about 0.27; this is somewhat larger than the value for the other inducer, but comparison are difficult because of the change in the geometry.

Since mean cavity length varies significantly with cavitation number, in contrast to the lack of variation of shedding frequency, there will not be any special relation between frequency and cavity length which was implied in the earlier paper[2].

Consideration of the detached cavity

Once break-off has occurred, the detached cavity is convected downstream at a uniform rate approximately equal to one half of the throat velocity (Fig 5). For the con–div wedge configuration the convection speed is actually 0.43 of the throat velocity on average, and for the symmetrical wedge it is slightly higher at 0.54 of the throat velocity. Immediately after break-off there is a period of roughly constant cavity radius, or in some cases a slight increase is observed. This may be as a result of the transformation from an essentially two-dimensional shape spanning the duct to a spherical cavity. The cavity then collapses rapidly and eventually disappears; during this process the attached cavity is growing. Then the next detachment occurs and the whole cycle is repeated. For the symmetrical wedge the detachments occur on alterante sides of the cavity in a similar manner to vortex shedding from a cylinder.

Considering now the collapse of the detached cavity in more detail, the change in radius for individual cavities is apparently not a smooth and progressive reduction. It was expedient, if not strictly correct, to smooth the curves by simply averaging the bubble radii for given cavitation conditions at the same time propr to complete collapse. The standard error increases considerably at the larger radii because of a reduction in the number of points available for analysis. The smoothed curves (Fig 6), generally show a reduction in radius and an increase in inward velocity with increasing time.

The average value of the maximum cavity radius, ie shortly after break-off, and the time required for the cavity to collapse from this instant have been determined. The data can be used as an accurate check on whether or not these cavities are behaving as Rayleigh cavities. Rayleigh's theory[8] gives the collapse time t_c in terms of the maximum cavity radius R_m and the pressure difference producing the collapse, Δp, as follows:

$$t_c = 0.915\, R_m \left(\frac{\rho}{\Delta p}\right)^{1/2} \qquad (4)$$

An estimate of pressure external to the collapsing cavities is therefore required, and it would be reasonable to take this as the pressure downstream of the diffusion zone, which is given by the Borda–Carnot pressure

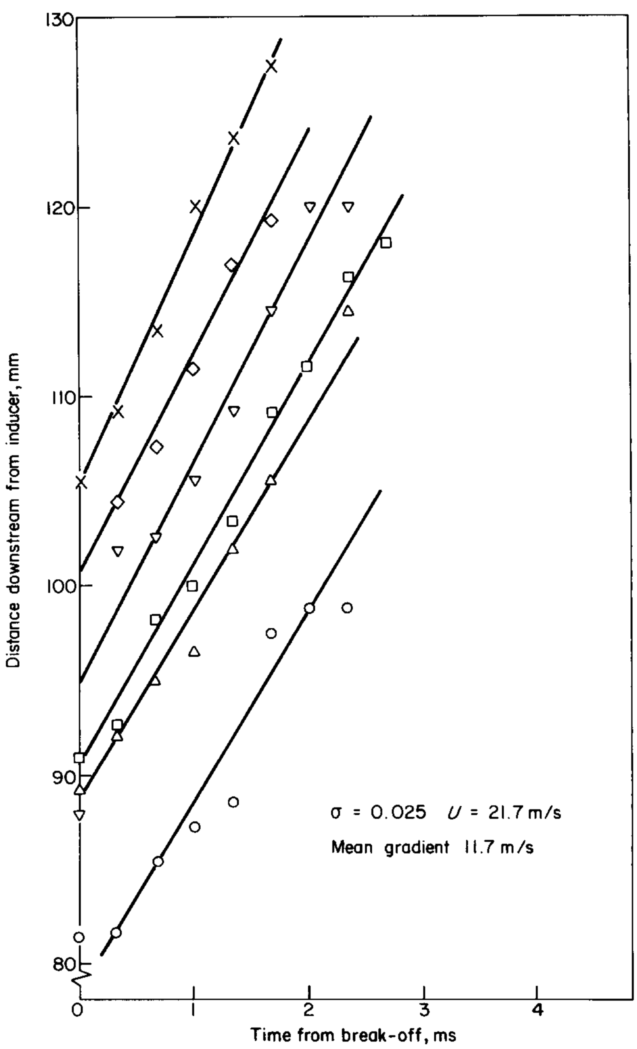

Fig 5 Convection of detached cavity for symmetrical wedge inducer

recovery formula:

$$\Delta p = \frac{1}{2} U^2 \left\{ \sigma \frac{A_1}{A_2} + 2 \frac{A_1}{A_2} \left(1 - \frac{A_1}{A_2} \right) \right\} \tag{5}$$

To improve the accuracy of the estimate, the actual flow area ratio, given by Eq (3) is used; the term involving σ allows for the throat pressure being slightly above the vapour pressure, which is significant for the higher values of cavitation number.

For the con–div wedge inducer, it is found, for the two cases analysed in detail, that the measured cavity collapse time is greater by a factor of about 3.1 than the estimated Rayleigh collapse time. This figure is smaller than the value of 4.4 obtained previously[2] where a rather smaller number of samples was taken. For the symmetrical wedge, the factor, averaged over all the cavitation conditions, is 3.2. There is some scatter in the data from condition to condition, but at about 17 percent, this is not excessively large (Table 1). The size of these factors could be taken to imply that the Rayleigh model is valid but the pressure producing the collapse is about 10 times smaller than the downstream pressure used. Pressures as low as this occur in the throat and can be calculated directly from the cavitation number, ie $\sigma \frac{1}{2} \rho U^2$. When the Rayleigh collapse time is evaluated using throat pressure it is found that although the correct order of magnitude for cavity collapse time is obtained, the scatter in results is unacceptably large and, in any case, the cavities are observed to collapse well downstream of the throat, where the pressure will have recovered if the Rayleigh model is at all applicable.

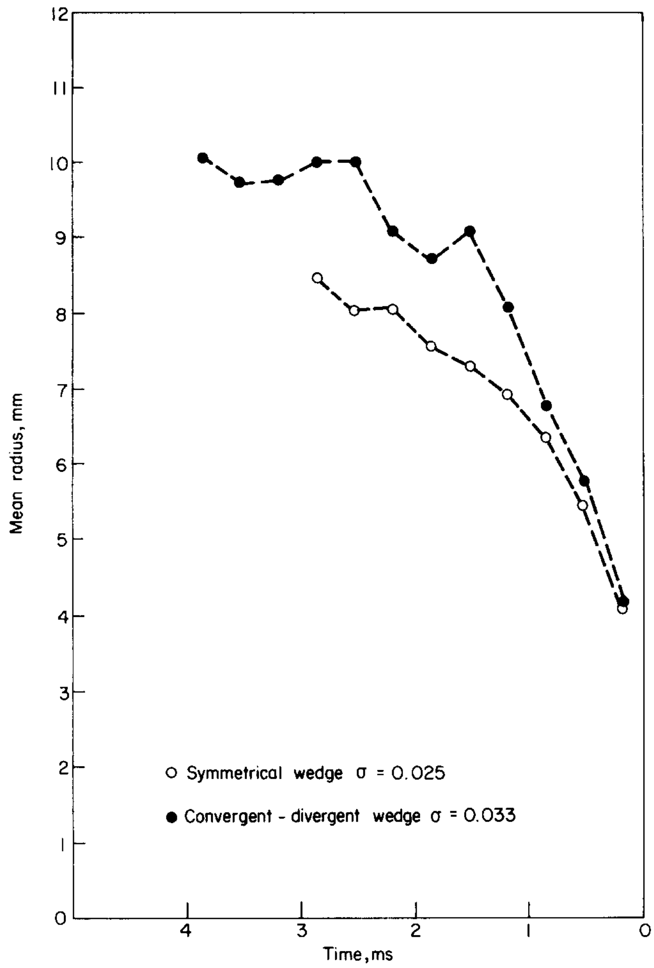

Fig 6 Smoothed variation of mean radius with time prior to cavity collapse for both inducers

The explanation for the increase in collapse time probably lies in the relatively large size of the initial cavity, about 8 mm radius, compared with the duct dimensions of 40 mm × 20 mm. The cavity is not collapsing in a free field as required by Rayleigh's theory until it has reduced in size considerably. For the majority of the time required for collapse, the cavity will be strongly influenced by the duct walls, causing a reduction in collapse rate and a corresponding increase in the collapse time.

The average value of maximum detached cavity radius and time for collapse to occur from maximum radius have been compared respectively with the length of the attached cavity and the average shedding frequency (Table 2). It has been found previously for the con–div wedge[2] that the cavity radius is approximately a constant fraction of the cavity length, equal to 0.14, the largest cavities being about 12.5 mm radius. The new measurements using a larger number of samples indicate that the fraction is slightly smaller, nearer to 0.1; but it is not now clear whether the fraction is a constant or not, because of the limited number of cases considered.

For the symmetrical wedge, the cavity radius does not appear to be related to cavity length, tending to remain fairly constant in size while the cavity length varies considerably. The largest cavity radius of about 10 mm occurs at a cavitation number of 0.117.

The cavity collapse time is with one exception generally somewhat less than the average period between

Table 1 Measured and predicted cavity collapse times

	σ	Measured		Rayleigh pred.	
		R_m (mm)	t_c (ms)	t_c (ms)	Ratio
Con-div wedge	0.0033	8.61	2.21	0.64	3.44
U=25.0 m/s	0.013	7.78	1.55	0.56	2.75
Symmetrical wedge	0.025	8.11	2.52	0.73	3.45
U=21.7 m/s	0.05	7.83	1.71	0.69	2.48
	0.117	8.94	1.90	0.72	2.64
	0.2	8.91	2.75	0.67	4.10
	0.36	7.83	1.82	0.58	3.14

NB: Column headed 'Ratio' refers to measured times divided by predicted times

Table 2 Mean cavity length, shedding frequency, and mean rate of collapse

	σ	λ (mm)	R_m/λ	ν (Hz)	νt_c	V_{av} (dm^3/s)
Con-div wedge	0.0033	87.0	0.100	364	0.804	1.21
U=25.0 m/s	0.013	93.6	0.083	368	0.570	1.27
Symmetrical wedge	0.025	91.2	0.089	279	0.703	0.89
U=21.7 m/s	0.05	63.3	0.124	361	0.617	1.18
	0.117	48.2	0.185	392	0.745	1.58
	0.20	34.6	0.257	413	1.136	1.80
	0.36	29.4	0.266	394	0.717	1.10

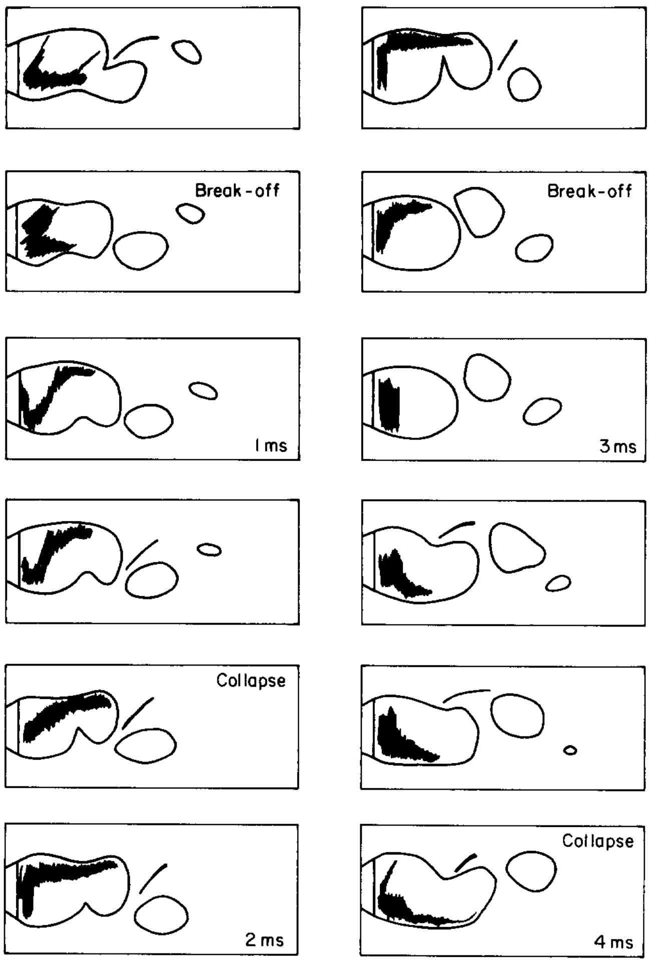

Fig 7 Typical cavity break-off and collapse sequence for symmetrical wedge inducer at $\sigma = 0.2$

detachments for both inducers, being about 0.7 of the period. The exception occurs for the symmetrical wedge at a cavitation number of 0.2, when the collapse time is greater than the period by about 14 percent. The result arises because a second detachment often occurs before the first cavity has completely collapsed (Fig 7) and it appears that the cavity collapse time is noticeably larger that at other cavitation numbers (see Table 1). Possibly the collapse time is influenced by the rotation of the fluid associated with the vortex pattern which is prominent at this cavitation number. It is interesting to note that, also for this case, the average shedding frequency is a maximum, ie the period is a minimum, as well as the collapse time being the longest.

The variation of cavity size and hence volume with time implies that there will be an instantaneous variation in volumetric flow rate. The average value of this variation may be found by simply dividing the initial (maximum) cavity volume by the total collapse time. For the con–div wedge inducer, it has been found in the previous work[2] that the average rate of volume reduction increases with decrease cavitation number from about 0.4 dm^3/s up to about 1.6 dm^3/s, compared with the total volumetric flow rate through the tunnel of about 9.5 dm^3/s. The rates of volume change vary between 4 and 17 percent of the total flow rate. For the new data (Table 2), the values obtained are slightly smaller than the corresponding values at the same cavitation number, giving about 13 percent of the total flow rate. For the symmetrical wedge the rates of volume reduction are similar, reaching a maximum of about 1.6 dm^3/s at a cavitation number of 0.117 and falling off to about 1.0 dm^3/s at both high and low cavitation numbers (Table 2). This represents a higher fraction of the total volumetric flow rate of 7.6 dm^3/s, ranging from 12 to 21 percent approximately. It seems unlikely that such large variations can exist downstream or even upstream of the cavitation zone, because the inertia of the fluid columns would be too large. Therefore the variation applies to the fluid between the attached and detached cavities, which can be likened to a source and sink pair of equal and opposite strength, the value of this being given by the rate of volume change. The largest rate of volume change coincides with the maximum cavity size, and it is known from other work[9] that this also corresponds approximately to the cavitation number for maximum noise and erosion.

Conclusions

Observation of the cavities using cine photography enabled us to investigate the mechanism of cavity growth, detachment and collapse for two cavitation inducers, namely con–div wedge and symmetrical wedge. This mechanism was found to be essentially the same as that described originally by Knapp[3] with the one possible difference that cavity detachment was almost invariably partial, ie the cavity was not detached cleanly from the inducer but rather a portion broke away from the main cavity.

The average length of the attached cavity and the average shedding frequency were determined for both inducers. It was found that in both cases the average cavity length increased with reducing cavitation number. The exact dependence on, say, throat cavitation number is more easily determined by visual means under stroboscopic lighting but there does not appear to be a precise correspondence between the two methods of measuring cavity length. It was found that the average shedding frequency was independent of cavitation number for both inducers, and, when expressed as a Stouhal number based on throat velocity and inducer width, a value of 0.18 was obtained for the symmetrical wedge, which is close to the value expected for vortex shedding from a cylinder. The value for the con–div wedge was slightly higher at 0.27.

The size (mean radius) of the detached cavity at break-off was found to be very similar for both inducers at about 8 mm. For the symmetrical wedge it was found that the cavity size was fairly constant and independent of cavity length. The cavity collapse time was found to be about three times longer than the time expected from Rayleigh's theory[8] for cavity collapse in a free field. The time was a constant fraction of the average period between successive detachments, equal to about 0.7 for both inducers, except for the symmetrical wedge at the cavitation number corresponding to maximum shedding frequency, when the cavity collapse time became greater that the period by about 14 percent.

Acknowledgements

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