Viscous Effects in the Inception of Cavitation

V. H. Arakeri
Department of Mechanical Engineering,
Indian Institute of Science,
Bangalore, India

Allan Acosta
Division of Engineering and
Applied Science,
California Institute of Technology,
Pasadena, California

The inception of cavitation in the steady flow of liquids around bodies is seen to depend upon the real fluid flow around the bodies as well as the supply of nucleating cavitation sources – or nuclei – within the fluid. A primary distinction is made between bodies having a laminar separation or not having a laminar separation. The former group is relatively insensitive to the nuclei concentration whereas the latter is much more sensitive. Except for the case of fully separated wake flows and for gaseous cavitation by diffusion the cavitation inception index tends always to be less than the magnitude of the minimum pressure coefficient and only approaches that value for high Reynolds numbers in flows well supplied with nuclei.

Physical Background

One of the earliest photographic observations of cavitation bubble growth history near inception is that due to Knapp and Hollander [1]. Their findings were predicted with good accuracy by Plesset [2] employing the Rayleigh equation of bubble dynamics. One of the assumptions in this analysis was that the bubble travels at a velocity equal to that of the surrounding liquid velocity neglecting the effect of the boundary layer. However, based on a similar assumption Parkin [3] found that the predicted incipient cavitation number was in some cases an order of magnitude different from the observed one on hemispherically nosed axisymmetric bodies. He then suggested that the neglect of the role of the boundary layer or the viscous effects in the dynamics of cavitation bubbles may not be justified for the particular headform studied by him. This suggestion by Parkin was perhaps motivated from Kermeen's [4] photographic observations of a region of macroscopic and microscopic cavitation bubbles in the immediate vicinity of the surface of a hemispherically nosed test body at incipient conditions. These findings no doubt must have prompted Parkin and Kermeen [5] to conduct their now classic experiments which clearly demonstrated that there are viscous effects important for cavitation inception. Two types of cavitation are observed then on a smooth body; one, that of the traveling bubble type not apparently influenced by the viscous effects, and the other, that of the surface or an attached type of cavitation which is influenced by the viscous effects.

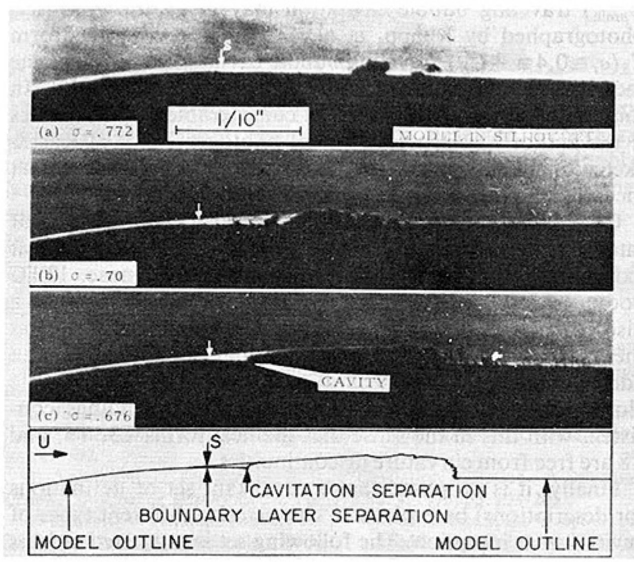

Fig. 1 Form and extent of cavitation originating within the viscous separated region of the hemispherical nose at three different levels of tunnel pressure. (U = 40 fps, Re_D = 6.04 × 10^5). The dark patches above the model outline are the cavitating areas. Arrow shows the location of separation. Flow from left to right. (Arakeri and Acosta, 1973).

The work of Parkin and Kermeen though quoted extensively in later works does not seem to have been pursued further until very recently when Arakeri and Acosta [6] repeated their observations on a hemispherically-nosed body augmented, however with the schlieren technique of flow visualization. A photograph from this recent work is shown in Fig. 1. Since the schlieren technique is an optical method of flow visualization one can observe the cavitation inception process and the viscous flow past the test body simultaneously. From the first photograph of Fig. 1 the macroscopic bubbles readily visible to the naked eye are to appear in the reattachment zone of a laminar separated region. Subsequent reduction in pressure results in the separated region being filled with an attached cavity which has a glossy smooth surface at the leading edge as can be seen in the third photograph of Fig. 1. In a later study [7] similar observations on a 1.5 cal ogive showed that macroscopic cavitation bubbles occurred within the turbulent transition region of an attached boundary layer at desinent cavitation conditions. These observations shown in Fig. 2 were made

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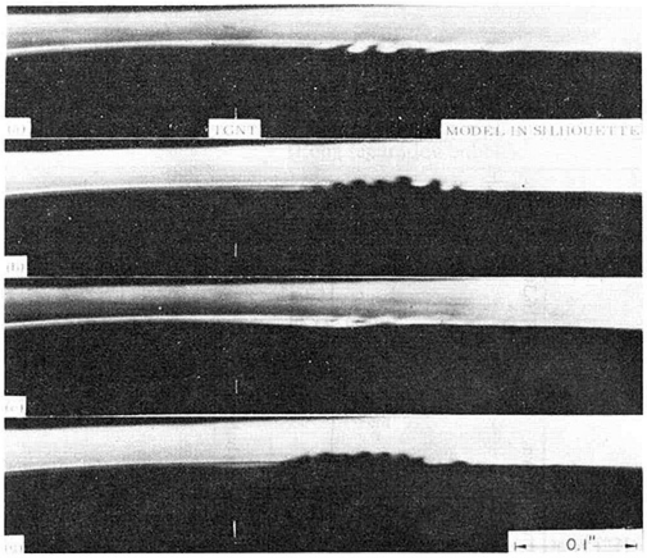

Fig. 2 Photographs showing relationship between boundary layer transition and cavitation. (*a*) and (*c*) – Schlieren photographs at 30 fps and 40 fps respectively showing transition. (*b*) and (*d*) extent of cavitation at the same velocities. The model is a two inch 1.5 cal ogive and the flow is from left to right, (Arakeri and Acosta, 1974).

under desinent conditions i.e., as the cavitation was made to disappear, since at inception the cavity appeared in an attached and developed stage. Thus, the critical zone for cavitation inception with laminar separation is found to be the reattachment region and in the absence of laminar separation it appears to be the region of turbulent transition. These findings suggest that certain special features of turbulent transition and reattachment must play a significant role in the mechanism of cavitation inception.

Features of Turbulent Transition and Reattachment

One of the special features of turbulent transition and reattachment of laminar free shear layers is the intense pressure fluctuations there [8,9]. These fluctuations are an order of magnitude greater than those existing down-stream in the fully developed turbulent flow. It is possible then that the transient pressure in the zones critical for cavitation may be lower than the minimum static pressure on the body (determined by measurements of theoretical computations). Measurements of pressure fluctuation quoted earlier indicate that this is a likely possibility for the hemispherically nosed body but not for the 1.5 cal ogive. However, even in the case of the 1.5 cal ogive limited cavitation was observed in the turbulent transition region rather than the location of minimum pressure point. This strongly suggests that additional features of turbulent transition and reattachment are involved for making these zones critical or important for cavitation inception.

There are a number of additional physical scale parameters that are normally identified with turbulence such as the magnitude and time scale of the velocity fluctuations within the boundary layer that may be important in cavitation. For example turbulent fluctuations may actually stall the local flow near the wall leading to a brief period of separation (Schlichting [10]) or a turbulent burst with reverse flow may occur (Kline and Runstadler [31]). Then it is easy to imagine that cavitation nuclei within these regions may be exposed to a low pressure longer than would otherwise be the case, thereby promoting cavitation by microscopic bubble growth. Time scales for such events are not known but as an illustration let us take the period of the most unstable Tollmein-Schlichting wave in the laminar boundary layer just prior to transition as a representative time for such a process. The frequencies of such motion on a 1.5 cal ogive in a particular water tunnel experiment were found to be about 5 KHz [8]; our reference time period for growth then would be about 0.2 ms which is about the same as that observed for a bubble lifetime on a hemisphere cavitation test (0.1 ms (5)). Thus we find it most plausible that turbulence and pressure fluctuations may definitely help the inception process. Direct experimental evidence within transition regions of microbubble growth into cavitation inception, however, still remains to be provided. Nevertheless, it seems plain that these fluctuations are the reason that the reattachment region downstream of a laminar separation is so critical. On bodies not having a laminar separation the fluctuations associated with transition are undoubtedly important but it has not been possible yet to quantify these effects.

Classification of Axisymmetric Bodies

In the preceding paragraphs we have noted that viscous effects can play a fundamental role in the mechanism of cavitation inception. Thus, for example, one may expect the cavitation characteristics of a separating class of bodies to be different from the cavitation characteristics of nonseparating class of bodies. Beyond that it seems reasonable to propose additional sub-categories as is done in Table 1. The separating class of bodies will exhibit laminar separation only for Reynolds numbers, Re, below a critical $\mathrm{Re}_{\mathrm{crit}}$. Our estimations[1] show that for the bodies of group C $\mathrm{Re}_{\mathrm{crit}} \approx 5 \times 10^5$ to 10^6. Similarly, we estimate that $\mathrm{Re}_{\mathrm{crit}}$ for group B bodies is at least 5×10^6. Guided by the shape of the pressure distribution [11] for the disk and zero (0) cal ogive, $\mathrm{Re}_{\mathrm{crit}}$ for

[1] By use of e^D, n, 7 method and stability charts computed Wazzan et al., Rept. No. DAC 67086, McDonnell Douglas Corp., Calif. Sept. 1968. Also see appendix of reference [6].

Nomenclature

a,b,c = constants in Table 1
C_p = pressure coefficient, $(p - p_\infty)/\frac{1}{2}\rho u_\infty^2$
C_{pm} = minimum value of C_p
C_{ps} = C_p at the position of laminar separation
C_{ptr} = C_p at the position of turbulent transition
$C_{p'}$ = C_p based on magnitude of fluctuating pressure at reattachment
D = diameter of the axisymmetric headform
k = roughness height
p = local static pressure
p_m = minimum static pressure
p_v = vapor pressure of water
p_∞ = reference static pressure
Re = Reynolds number, $u_\infty D/\nu$
$\mathrm{Re}_{\mathrm{crit}}$ = critical Reynolds number at which laminar separation disappears
Re_k = roughness Reynolds number, $u_k k/\nu$
u_k = velocity at roughness height in the boundary layer
u_∞ = reference velocity
ν = kinematic viscosity
ρ = density
σ = cavitation number, $(p_\infty - p_v)/\frac{1}{2}\rho u_\infty^2$
σ_i = incipient cavitation number

Table 1 Cavitation of Axisymmetric Bodies

Body Shape	$-C_{pm}$	$-C_{ps}$	Measured σ_i range	Group	Viscous Flow Characteristics	Inception Scaling Trends "Few" Nuclei	 "Copious" Nuclei	References
Disk	0.5	0.5	1.4-2.0	*A*	Transition in the free shear layer. Formation of strong and large vortices downstream of separation.	Strong Reynolds number dependence. Scaling determined by vortices and mixing in the free shear layer. $\sigma_i \doteq a + b\,\mathrm{Re}^c$		[20,21,23,42]
0 cal ogive	0.61	0.57	1.4-1.75					
1/8 cal ogive (long separation bubble)	0.83	0.69	1.4-1.75					
1/8 cal ogive (short separation bubble)	–	–	2.05-2.2	*B*	Transition determined by reverse flow velocity profile stability. Formation and strength of vortices affected by the near wall. Measurements show strong wall pressure fluctuations near reattachment.	Weak Reynolds number effect $\sigma_i \doteq -C_{ps} + c_p{}'$ Attached band or sheet cavities	(equation (1)) Attached and traveling bubbles	[6,13,18,22]
1/4 cal ogive	1.1	0.96	1.15-1.35					
1/2 cal ogive	0.74	0.63	0.6-0.7					
1 1/2 cal ogive	0.4	0.24	0.2-0.25 (below Re_{crit})	*C*	Transition determined by velocity profile stability. No wall pressure fluctuation measurement exist for this class of bodies.	Reynolds number effect not well known $\sigma_i \doteq -C_{ps}$		[7,13,16,36]
ITTC Body	0.6	0.45	0.35-0.45					
NSRDC Body	0.8	0.4	0.4 (below Re_{crit})					
Blunt Body (Other bodies *of Group B,C* above Re_{crit})	0.75	no separation	0.28-0.60	*D*	Transition determined by velocity profile stability. Measurements show mild pressure fluctuations in transition region.	Potential strong Reynolds number effect $\sigma_i \doteq -c_{ptr}$ Attached cavities	$\sigma_i = -c_{pm}$ Traveling bubbles	[12,16,32,33, 34]

Table 2 Similarities of Viscous Flow Regimes

Group	Examples of Axisymmetric Bodies	Likely practical situations with similar viscous flow regime
A	Disk 0 cal ogive 1/8 cal ogive (Long separation bubble)	Tip vortex flows Flow downstream of partially closed valves Flow downstream of orifices Flow downstream of hydraulic gates
B	1/8 cal ogive (Short separation bubble) 1/4 cal ogive 1/2 cal ogive	Flow on the suction side of ship propellers, blades of hydraulic machinery and strut elements at angles of attack. Flow down-stream of isolated roughness elements present in the laminar boundary layer.
C	1 1/2 cal ogive ITTC body NSRDC body	Underwater bodies and appendages
D	Blunt body Bodies in other groups for $Re > Re_{crit}$	Flow on the pressure side of ship propellers, blades of hydraulic machinery and strut elements at angles of attack. Flow past ship propellers, blades of hydraulic machinery and strut elements at zero angles of attack.

Note: One important viscous flow regime that of fully developed turbulent boundary layer flow in the region of interest is not included here. However, this regime has been covered by Arndt and Daily [23].

these two bodies in group A is expected to be of the order 10^7 to 10^8. Flow visualization studies [12] on a 1/8 cal ogive have indicated another relatively high critical Re judged by the marked change in the length of the region of laminar separation. This phenomenon is commonly termed "bursting" and its connection with cavitation scaling has been noted recently by Huang and Peterson [13]. The magnitude of $-c_{ps}$ noted in Table 1 was predicted with the use of Thwaites & Smith [14, 15] method for NSRDC, ITTC, 1 1/2 cal and 1/8 cal bodies and from inferences from the pressure distributions for 0 cal body and disk. The Thwaites method as well as more accurate methods do not predict laminar separation for the blunt body and this is consistent with observations of van der Muelen [16]. (Sufficiently accurate pressure distribution measurements on the 1/8 cal ogive with a short separation bubble are now not available to permit accurate boundary layer calculations.) The inception data given in Table 1 are for a nominal Re range of 10^5-10^6 and are taken from references [17–19, 35].

It may be noted from Table 1 that bodies in different groups exhibit differing viscous flow characteristics and, as suggested, these differences in turn play a role in cavitation scaling characteristics. The prominent viscous flow feature for the bodies in group A is the formation of strong freestream vortices downstream of a laminar separation and, at least for the disk, cavitation has been observed [20] to commence at the center of these vortices. It is worthy of note that even though the three bodies in group A possess differing magnitudes of $-C_{pm}$ and $-C_{ps}$, the measured σ_i values indicate a strong dependence only on Re. Thus, an empirical rule of the type proposed by Arndt [21] may work quite effectively for the class of bodies in this group. The separated shear layer is close to the wall for the class of bodies in group B so that its stability characteristics and formation of reattachment fluctuations are strongly influenced by the presence of the wall. These flows as discussed exhibit strong pressure fluctuations in the reattachment region. Thus, for this type of body we propose that the cavitation index should be of the form,

$$\sigma_i = -C_{ps} + C_p{}' \tag{1}$$

as has been suggested by Huang and Peterson [13]. They further indicate that $C_p{}'$ should be taken as a constant; it is most likely a function of at least the maximum height of the separated free shear layer from the wall and would seem therefore Reynolds number dependent. A laminar separation still prevails for the bodies in group C but with free shear layer extremely close to the surface. Thus, the normal reverse flow region in the mean and the constant pressure region commonly associated with separated flows may not even exist for these bodies. Based on experimental observations [6,22] the fluctuating pressure term of equation (1) seems not too important here and it is proposed that

$$\sigma_i = -C_{ps} \tag{2}$$

for this group.

There remains, finally, the smooth bodies of group D those not having a separation. It follows that under practical conditions of flow a turbulent transition is inevitable. It has been traditional to assume for this kind of shape that cavitation will occur when $p_m \le p_v$ or that

$$\sigma_i = -C_{pm}. \tag{3(a)}$$

There is much evidence that this rule may be applicable to some flows. Silberman [32] and Schiebe [33] earlier use this idea to infer from the rate of individual traveling bubble cavitation events for $\sigma < \sigma_i$ the number density of the cavitation nuclei within the free stream. There is also evidence that in flows not so well supplied with free stream nuclei that $\sigma_i < -C_{pm}$ (without a significant number of events taking place). In this circumstance it seems plausible and it has been proposed based on experiments [7,18] that

$$\sigma_i = -C_{ptr}. \tag{3(b)}$$

This suggestion was made based on tests made on bodies for $Re > Re_{crit}$ belonging to group C although there is recently direct evidence based on bodies of group D (e.g., Huang and Santelli [34], Carrol and Holl [19] and Gates, et al. [35]). It seems clear then that inception scaling for this group of bodies may depend strongly on both Reynolds number and nuclei content.

We have suggested certain scaling rules for differing viscous flow regimes. Even though these have been derived from axisymmetric bodies, they are of practical value since these viscous flow regimes are encountered in a wide variety of applications as indicated in Table 2.

Remark on Scaling

It is clear that σ_i can be Reynolds number dependent. This dependence varies greatly within the groups of Table 1, however. It is interesting to compare the Reynolds number

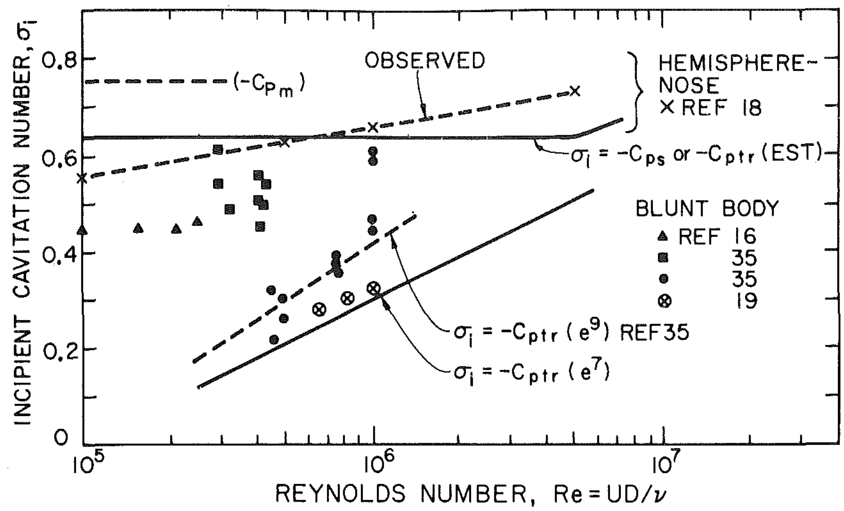

Fig. 3

effect on two bodies having nearly the same minimum pressure coefficient, $-C_{pm} = 0.75$. These are the hemisphere nose and the blunt half body. (This body formed by a source disk is described in detail in references [32,33]; the authors of reference [35] have adopted the name 'Schiebe' body for this blunt body although van Tuyl, Schiebe ibid, was the first to describe this shape). The hemisphere nose, it will be recalled, has a laminar separation to a fairly high Re of about 5×10^6; within the laboratory range, σ_i remains less than $-C_{pm}$ but does not vary more than about 30 percent. (There is a size effect or unit Reynolds number effect still not resolved (see, e.g., reference [36]). The blunt body, however, is quite a different story. Data from several sources show nearly a 3:1 change in σ_i with most of the change occurring in overlapping (lower) Reynolds numbers. Estimates have been made of the location of transition and the pressure coefficient there. Those together with experimental results are shown in Fig. 3 for both bodies. The dominant Re effect on transition of the blunt body is clear. Much of the data tend to follow this trend. Yet there are also extensive findings on the same shape showing a higher value σ_i but still rather well below $-C_{pm}$. (It should perhaps be mentioned again that the blunt body does not experience a separation and that the hemisphere body does.)

From these results we see that although there is a definite difference in σ_i levels for the hemisphere body with Re, equations (2) and (3(*b*)) provide a good guide over a wide range. Thus the presence of the laminar separation does not seem to lead to as large of a scale effect as on an unseparated flow. The two groups of data shown for the blunt body appear to follow different trends. The conditions under which the various tests were made are also rather different. In particular those results following equation (3(*b*)) ($\sigma_i \sim -C_{ptr}$) are for tunnel flows having "few" free-stream nuclei. Those data having a higher value of σ_i (but lower Re certainly) originate in flows of "generous" or "copious" nuclei. There are more basic differences, however; freestream traveling bubble cavitation is the predominant form of cavitation in nonseparating flows having many nuclei. When these nuclei become fewer, attached forms of cavitation are seen; these appear often to be associated with transition as is shown on Fig. 2. Thus, the freestream supply of nuclei is very important for cavitation inception on group *D* bodies and group *B*, *C* bodies too when beyond the critical Reynolds number. Thus we see that the σ_i = const. rule works considerably better for bodies which possess a laminar separation. It would be better than in model testing say at Re = 5×10^5 for prototype values Re = 10^7 to use the rule $(\sigma_i)_{\text{prototype}} = (\sigma_i)_{\text{model}}$ if a laminar separation is observed or predicted on the geometrical similar body during model testing, this despite the fact that a change in the viscous flow regime may be involved in going from model to prototype conditions (as would be the case for the 1/2 cal ogive). Even though a change in viscous flow regime is not involved for flows on bodies lacking a laminar separation a significant error is possible in predicting the prototype σ_i by using the rule $(\sigma_i)_{\text{prototype}} = (\sigma_i)_{\text{model}}$. Eventually for sufficiently large Re, $\sigma_i \rightarrow -C_{pm}$ provided sufficient nuclei are present.

Influence of Disturbances

The means (theory or experiment) employed in determining the viscous flow regimes are always based on certain ideal assumptions. These include, for example, negligible levels of freestream turbulence, surface roughness, and mechanical vibration as well as symmetry and uniformity of the flow field. "Natural" or "stimulated" disturbances lead to flow modifications, and possibly to transition and have occupied a central role in applied fluid mechanics for decades. In respect to cavitation we now categorize some of these features:

(*a*) Natural disturbances. These can include the free stream turbulence level, body vibrations and either distributed or isolated roughness elements. The roughness effect on cavitation inception has been studied quite extensively in the past and a comprehensive compilation of these and other related findings has been made recently by Bohn [24]. Here, we concentrate on the effects of an isolated roughness since this may have a bearing on the explanation for the commonly observed "spot" type of cavities [18] observed on bodies of group *C* above their critical Reynolds numbers or those of group *D* at higher velocities.

As pointed out by Holl [25] one can view the effect of isolated roughness as a local modification of the pressure field from which changes in σ_i can be inferred. Of course it is plain that the velocity field is modified too; Klebanoff and Tidstrom [26] have observed experimentally that a flat plate boundary layer velocity profile develops locally a separating velocity profile downstream of an isolated roughness. Furthermore, they point out that this is the mechanism by which roughness elements induce an earlier turbulent boundary layer transition. Any such region of flow offering residence time for growth of nuclei becomes a candidate for a cavitation mechanism. The important parameters determining this local flow are the relative height of the roughness with respect to the local boundary layer thickness and the roughness Reynolds number $Re_k = u_k k/\nu$, k being the roughness height, and u_k the velocity there. Traditionally, $\mathrm{Re}_k < 25$ to forestall transition; this empirical result is however largely based on experience in flows with mild pressure gradients, not the extremely adverse one of bodies in group D, for example. We find it very plausible then as do Huang and Peterson [13] to suspect that very small isolated roughness elements, perhaps much less than $\mathrm{Re}_k = 25$ are the origin of the spot and wedge forms of cavitation seen at inception for higher values of Reynolds number. One would further imagine that the predominant form of cavitation in flows not having "many" nuclei at large Reynolds numbers would be these attached "spots".

Systematic work concerning the role of body vibrations in determining the location of turbulent transition appears to be lacking. But there has been a recent rejuvenation of interest in freestream turbulence on transition (e.g., Mack [37]). Interest in these flow characteristics of some of the bodies traditionally used for cavitation inception work is recent and we may cite the work of Gates [27] and van der Muelen [16] as examples. Gates found that the boundary layer flow of the 1/2 cal ogive (belonging to group B) was insensitive to a change in the freestream turbulence level of over an order of magnitude! A similar change in the turbulence level on the NSRDC body lowered the critical Re to 1.6×10^5 at a freestream turbulence level of 3.75 percent from the observed critical Re of 5×10^5 at a freestream turbulence level of 0.2 percent. The response of the NSRDC body was expected because the test Reynolds numbers were close to the predicted critical Re for the NSRDC body and were significantly lower than the predicted critical Re for the 1/2 cal ogive. In any case, these findings by Gates are significant since cavitation inception studies are routinely carried out in flow facilities having greatly differing levels of freestream turbulence. Gates also found another type of disturbance which may be classified as "natural" to the flow field; namely, that an existing laminar separation could be eliminated by the presence of a significant number of macroscopic air bubbles in the freestream. This change resulted in traveling bubble type cavitation at inception instead of a normally occurring "band" or attached type of cavitation at inception.

(b) Stimulated disturbances. One usually means here a boundary layer "trip" consisting either of an isolated roughness element or a distributed surface roughness. It is necessary that these disturbances be located in the high pressure regions of the flow so that they themselves do not cavitate prematurely. It may seem attractive to use these boundary layer trips to simulate a high Reynolds number as commonly done for drag measurements. This may be a misleading practice for cavitation inception studies, however. For example, the σ_i value was found to decrease with increase in Re to very low values (0.25) on a tripped 1/2 cal ogive contrary to the normal expectation (reference [18]). As noted there this behavior is attributed to drastic alteration in the location of turbulent transition by tripping and to the presumed smaller concentration of nuclei in the test facilities used. Therefore, when boundary layer stimulation used the turbulent transition location in the test model it should be carefully matched to the expected location at the higher prototype Re. In practice, this is exceedingly difficult to achieve. Thus, even though use of a boundary layer trip certainly helps to simulate high Reynolds number for normal test work cavitation inception may be delayed.

The addition of dilute polymer solutions to the test fluid has a pronounced effect on cavitation inception namely, to suppress the onset of cavitation, as does stimulation by a trip. The effect was first observed by Ellis [28] and since it has been repeated by many investigators [29,30,27]. Essentially identical effects have been found either by injecting the dilute polymer solution at the nose of the body or by dissolving the polymer solution in the tunnel water. In either case the suppression of the cavitation index has been the subject of much speculation: In particular, is the growth of the cavitation bubbles themselves inhibited by the polymer or is there another cause? It does appear that bubble growth and collapse can be affected by these non-Newtonian additives but the primary cause was later shown by van der Muelen [16] and Gates [27] to be an early boundary layer transition caused by the polymer solution. The polymer in effect stimulates the boundary layer sufficiently to remove the pre-existing laminar separation on the hemisphere nosed body used for investigation. The suppression effect on the cavitation index is due then principally to the different real fluid flow regime on the body. Bodies such as those in group D and B, C (beyond the critical Reynolds number) tend to follow the scaling laws of equation (3(b)) (depending) on nuclei content with the eventual high Reynolds number behavior of equation (3(a)).

Discussion

We see then that there is substantial experimental evidence that the characteristics of the viscous flow about a body can influence the inception of cavitation. Intuitively, we would expect this to be true for flows with gross separated regions as is the case for class of bodies in group A of Table 1. Similarily, we may expect for other types of separated flows these viscous effects to be important in the inception process when

$$-C_{ps} + C_{p'} \geq -C_{pm} \tag{4}$$

$C_{p'}$ being the amplitude of the transient pressure fluctuations. There is now a considerable amount of evidence that the nuclei content of the fluid or cavitation "susceptibility" of the fluid is not so important when the flow satisfies equation (4). When this is not so, we infer that inception will be influenced more heavily by the number of freestream nuclei. Thus we would propose that bodies of groups C, D are more "nuclei sensitive" than those of group B, say. When a copious supply of nuclei are present we would expect a preponderance of traveling-bubble cavitation, the type originally photographed by Knapp. Then, as argued by Silberman, for example, σ_i approaches $-C_{pm}$ as a limiting case. But such copious supplies of nucleating sources are not always available – even in the natural waters of the ocean – and then the suggested rules of Table 1 appear on the basis of experiment to be the appropriate guide lines. We are left then with a facility-dependent environment, one depending on the freestream nucleation content, in determining the particular inception value as has been demonstrated by the water tunnel experiments of Keller [38]. It may be possible, for cavitation indices to be smaller than even those indicated in Table 1, for example, in utterly deaerated quiescent liquids. (It is readily possible for these indices to be much greater than $-C_{pm}$, particularly for group B bodies when the liquid is supersaturated in respect to air; then air diffusion controls as Holl has shown[2] and gaseous cavitation is said to occur.)

The preceding comments have all been directed towards well-defined laboratory types of experiments. What may be said concerning cavitation inception in the more realistic flow environments of engineering applications such as large pumps and turbines? We may say as a preliminary comment, certainly for applications to pumps, that inception per se is rarely of interest. Instead, questions of erosion and performance change by cavitation are more of interest and the inception point merely marks the boundary of the application wherein these features become important. Pumps, for example, often operate with up to three percent head decrease at cavitation

[2] "Cavitation State of Knowledge," Robertson, J.M., Wislicenus, G. (Eds.), ASME, 1969.

indices, far beyond the inception value (see e.g., the discussion of Hammitt [39]). Once cavitation is developed, additional factors enter into the effect on performance; one of these effects, the subcooling of evaporating fluid, is often termed the "thermodynamic scale effect" and has been the subject of much attention over the years (e.g. references [40,41]). This is, however, beyond the present scope of concern. There is no reason to think, however, that pumps, indeed turbines, propellers, and other fluid machines are not subject to the viscous scale effects described herein for inception, although, except for propellers, there seems to have been relatively little effort devoted to this aspect of fluid machine cavitation.

In any case, it is clear from the trends of the scaling laws summarized in Table 1 and mentioned in the discussion that quantification of the nuclei concentration in all these flow environments is now of primary importance in cavitation inception and even developed cavitation phenomena.

Summary and Conclusions

The inception of cavitation is a complex physical process dependent on the concentration of nucleating sources within the flow and many features of the real fluid flow around bodies. Except for separating wake flows the inception index is almost always less than the magnitude of the minimum pressure coefficient and this latter value is only approached as a high Reynolds number limit in flows well-supplied with nuclei. It has been found useful to group the flows into those bodies having or not having a separation and the former category into those having large or small regions of laminar separation. In general, the bodies having a reattaching laminar separation are found to be less sensitive to the nuclei content of the freestream and to have cavitation indices between that of pressure coefficient magnitude at laminar separation and the minimum pressure point. Nonseparating bodies may have the inception phenomenon related to the turbulent transition pressure coefficient but in any case are sensitive to the concentration of free-stream nuclei. No single overriding factor is seen to be responsible for inception so that it does not appear likely that a single scaling law will ever suffice. Nor is there a universal kind of cavitation seen at inception so that a single physical model for cavitation onset will not be sufficient.

Acknowledgment

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