

A NOVEL HYPOTHESIS CONCERNING THE ORIGINS OF CAVITATION BUBBLES

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1. Some Previous Theories and Experimental Work

Various explanations have been put forward for the origins of cavitation bubbles. Amongst these have been the theories of Fox and Herzfield (1), Pease and Blinks (2) and of Harvey et al (3); the theory of Harvey et al is now widely held. Harvey suggested that, in water, a tapered hydrophobic depression could host a pocket of gas and that, given a suitably small semi-vertical angle, such a 'gas nucleus' would be stabilised against diffusion (see figures 1 and 2). Strasberg (4) and Apfel (5) have developed Harvey's theory, assuming that the contact angle is greater for the liquid/gas interface advancing towards the bottom of the depression than it is for the receding interface. Strasberg and Apfel argued that a tapered gas-nucleus could 'remember' the 'prepressure'; the nucleation pressure would be proportional to the prepressure. The 'memory' effect would occur because the liquid/gas interface would be stuck at a certain position and not move until just before nucleation.

Knapp (6) and Iyengar and Richardson (7) have reported 'memory' effects. In one of his experiments Knapp prepressurised water at hundreds of bar to obtain boiling points equivalent to pressures (presumably vapour pressures) ~15 bar. Iyengar and Richardson (7) found that the acoustic pressure amplitude required to produce cavitation depended on the prepressure; in the range 1 to 40 bar, the acoustic pressure amplitude and the prepressure were approximately equal for air-saturated tap water.

The Harvey/Strasberg/Apfel model of gas nuclei is attractive but there seem to be two difficulties with it.

The first difficulty concerns the semivertical angles of gas-nuclei sites. If there is a population of hydrophobic gas-nuclei in a liquid why should it not be that some have sufficiently narrow semivertical angles so that when the liquid is saturated their gas-liquid interfaces recede spontaneously from the bottoms of the nuclei sites ? Under these circumstances the pressure required to nucleate a bubble from the gas nucleus would be determined by the size of the mouth of the nucleus site rather than by the history of the nucleus.

The second difficulty concerns the availability of oleophobic substrates suitable for cavitation in oil. Banks and Mill (8) have reported cavitation in medicinal paraffin and in castor oil at modest negative pressure (~ -1 bar); the writer is unaware of any common oleophobic solids and so does not believe that the Harvey/Strasberg/Apfel model can be used to explain this result. Hayward's (9) theory of 'tribonucleation' (generation of bubbles by some stress-concentration mechanism occurring when solid surfaces rub) is not applicable to the experiments of Banks and Mill because they used rollers separated by gaps ~ 0.1 mm. The theory of Pease and Blinks (2) does not appear to be applicable either as it requires the presence of a solid surface with exposed non-polar groups. The status of the Fox and Herzfield (1) organic skin theory is not clear in this context.

2. The Concept of an Unrestricted Population of Cove-Nuclei - Stability against Diffusion - Nucleation Threshold.

Bikerman (10) (pp.348-354) has stated that surface roughness can be a significant factor in the hysteresis of contact angle. This led the writer to consider the possibility of a gas nucleus which had an overall positive semivertical angle but also maximum and minimum semivertical angles on a 'liquiphilic' surface. By suitable adjustment of the geometrical parameters such a nucleus could behave as if it were liquiphobic to an advancing interface. The lips of the constrictions are represented in figure 3 as being sharp; the effect of finite curvature will be discussed in section 4.

It was soon realised that it was unnecessary for the constrictions to be 'stacked' as in figure 3; instead the idealised assumption was made that, unless positive action had been taken to remove or avoid them, a population of liquiphilic gas nuclei sites unrestricted in size and shape would be present in a liquid.

To simplify the mathematics, equations will only be derived for (hypothetical) nuclei sites of the hole-type (i.e. exhibiting rotational symmetry about an axis perpendicular to the solid surface).

In order for a gas nucleus to be stabilised against diffusion the following inequation must be fulfilled:

$$\Delta P_{bulk} \geq 2\,\sigma/a_o \qquad (1)$$

$$\Delta P_{bulk} = p_{tens} + p_v - p_h$$

p_{tens}	The gas fluids (the (partial) pressure of gas which would be in equilibrium across an interface with the dissolved gas).
p_v	The (saturated) vapour pressure
p_h	The hydrostatic pressure
σ	Surface tension
a	The interfacial radius of curvature (convex to the liquid is positive)
a_o^{-1}	The minimum value of a^{-1} for a particular gas nucleus.

$$\therefore \quad b_o = \frac{2\,\sigma \operatorname{Sin} X}{(\Delta P_{bulk})_{min}} \qquad (2)$$

b_o The mouth half-width (half the length of the chord corresponding to a_o , see figure 4).

Ψ The local semivertical angle

Φ The angle of contact

χ $90^o - \Phi + \Psi$

In order for a gas nucleus not to be destroyed in locally undersaturated conditions the gas/liquid interface must be concave to the liquid; subject to the assumption that in the population there are liquiphilic gas nuclei with all values of semivertical angle between 0 and -180°, among the nuclei which survive the ones with the widest mouths will have the following mouth half-width:

$$b_{opt} = \frac{-2\sigma}{(\Delta P_{bulk})_{min}} \qquad (3)$$

This corresponds to setting χ equal to -90^o which implies that Ψ is negative. A gas nucleus with a negative semi-vertical angle in a liquiphilic surface will be referred to as a 'cove-nucleus' (see figure 4).

If the pressure due to permanent gas may be ignored, the pressure required to 'nucleate' an individual cove-nucleus is given by:

$$p_{nuc} = p_v - 2\sigma/b_o \qquad (4)$$

'Nucleation' means the formation and continued growth of a bubble. The nucleation theshold pressure of a population of cove-nuclei will be that of the nucleus with the largest mouth. If the population of cove-nuclei was initially unrestricted and was culled by local undersaturation then equation (3) is applicable and may be substituted into equation (4) to give:

$$p_{nuc} - p_v = (\Delta P_{bulk})_{min} \qquad (5)$$

Equation (6) may be rewritten:

$$p_{nuc} - p_v = (p_v + p_{tens} - p_h)_{min} \qquad (6)$$

If the liquid is saturated

$$p_h = p_{tens} \qquad (7)$$

so that setting

$$p_{nuc} = p_h + \text{þ}_{nuc} \qquad (8)$$

and assuming the vapour pressure may be neglected makes (7) become:

$$\text{þ}_{nuc} = (-p_h)_{max} \qquad (9)$$

which agrees with the result obtained by Iyengar and Richardson (7) for the cavitation threshold.

In order to obtain equation (9) it has been assumed that liquiphobic gas nuclei play no part; in water the presence of hydrophobic nuclei cannot be ruled out - particularly if no special cleaning measures have been taken. Arguments put forward in section 1 would lead one to suspect that liquiphobic nuclei resistant to prepressurisation could be nucleated at relatively high pressures; this might account for experimental results obtained by Hayward (11).

3. Cove-Nuclei and sudden Increases in Pressure

It is common practice to place the test liquid and container under vacuum prior to cavitation experiments. If there is still gas dissolved in the liquid the moment when the vacuum is released can be a critical one for a cove-nucleus. In fig.5 a cove-nucleus is depicted. In (i) the liquid is under vacuum; if buoyancy, viscous, and inertial forces may be neglected a bubble breaks away when

$$(p_g)_{out} + p_v - (p_h)_{vac} \simeq 2\,\sigma/b_o \qquad (10)$$

$(p_g)_{out}$ Permanent-gas pressure in nucleus when gas/liquid interface is hemispherical - convex towards liquid.

$(p_h)_{vac}$ Hydrostatic pressure when liquid is under vacuum.

Suppose that at the moment just before the bubble breaks away, the vacuum is suddenly released so that (see fig.5(ii))

$$(p_g)_o\, V_o = (p_g)_{out}\, V_{out} \qquad (11)$$

$(p_g)_o$ Permanent-gas pressure in nucleus when radius of gas/liquid interface is a_o

V_o Gas volume corresponding to $(p_g)_o$

V_{out} Gas volume corresponding to $(p_g)_{out}$

If the nucleus is to survive:

$$(p_g)_o + p_v - (p_h)_{atm} \gtrsim 2\,\sigma/a_o \qquad (12)$$

$(p_h)_{atm}$ Hydrostatic pressure when liquid is under atmospheric pressure.

Now if there had been an unrestricted population before diffusion, the cove-nuclei of interest (the ones which will nucleate first) will have:

$$b_o = b_{opt} \quad \text{and} \quad a_o = -b_{opt} \qquad (13)$$

so that substitution of (10), (11) and (13) into (12) gives

$$\frac{V_{out}}{V_o} \gtrsim \frac{(p_h)_{atm} - p_v - 2\,\sigma/b_{opt}}{(p_h)_{vac} - p_v + 2\,\sigma/b_{opt}} \qquad (14)$$

as the requirement that the nuclei of interest can survive the sudden increase in pressure; cove-nuclei with large mouths can survive because of the cushioning effect of the permanent gas.

Although only the case of a sudden increase in pressure from below atmospheric pressure has been considered in detail, it is believed that this calculation may be a useful starting point for consideration of the effects on cove-nuclei of any sudden increases in pressure.

4. Criticisms of the Cove-Nuclei Hypothesis

The first criticism of cove-nuclei concerns their general shape. In effect the problem of finding suitable substrates for the Harvey (3)/Strasberg (4)/Apfel (5) model has been transformed into a problem of finding suitably shaped sites in common substrates. It is certainly difficult to envisage how such holes with cove-like cross-sections could be made by the straightforward machining of a homogeneous solid. It is possible for there to be sites suitable for nuclei on motes in a liquid; such motes might be particles of human skin, or paper, or carbon for example.

A second criticism of cove-nuclei concerns a particular aspect of their shape. It was suggested to the author that low curvature of the lip of a cove-nucleus could affect the pressure required for nucleation. This would be the case if the line of contact were to creep along with the interface during nucleation, but if the nucleation takes place rapidly then a bubble may form before the line of contact has moved far. Cine work by Crum (12) indicated that bubbles did form from a "macromote" before the line of contact had moved far; if this were true for a small gas nucleus, the curvature of the lip would not be an important factor.

5. Concluding Remarks

Bearing in mind the technological significance of cavitation, the lack of information about the origins of cavitation bubbles cannot be a good thing; the ideas presented in this paper are speculative and are no substitute for such hard facts. Nevertheless, it is hoped that by putting forward a new hypothesis the paper will stimulate research to improve our understanding of the origins of cavitation bubbles.

6. Terms and Symbols

Bottom, lip, mouth (of a gas nucleus) : see figure 2.
Cove-nucleus: a gas nucleus with a negative semivertical angle (see figures 4 and 5).
Liquiphobic : (solid) having a contact angle greater than 90° with the liquid (see figure 1).
Liquiphilic : (solids) having a contact angle less than 90° with the liquid.
Local undersaturation : negative ΔP_{bulk} .
Nucleation pressure : The pressure required for the formation (and continued growth) of a bubble from a gas nucleus.
Prepressure : The maximum pressure to which a sample has been subjected prior to test.
Semivertical angle of a gas nucleus: see figs.2,3 and 4.

Terms & Symbols (Contd)

a	:	The gas-liquid interfacial radius of curvature (convex to the liquid is positive).
a_o^{-1}	:	The minimum value of a^{-1} for a particular nucleus.
b_o	:	The mouth half-width (half the length of the chord corresponding to a_o, see figure 4).
b_{opt}	:	For liquiphilic nuclei, the largest possible mouth half-width which could survive $(\Delta P_{bulk})_{min}$ (see equation (4)).
p_{nuc}	:	The nucleation threshold pressure
$\not{p}_{nuc}$	:	$= p_{nuc} - p_h$
p_h	:	Hydrostatic pressure
p_{tens}	:	The gas tension (the (partial) pressure of gas which would be in equilibrium with the dissolved gas across an interface.)
p_v	:	The (saturated) vapour pressure.
V	:	Gas volume in nucleus
$(\ )_{atm}$	:	The value of ( ) when the liquid is under atmospheric pressure.
$(\ )_{max}$	:	The maximum value of ( )
$(\ )_{min}$	:	The minimum value of ( )
$(\ )_{out}$	:	The value of ( ) when the gas/liquid interface is hemispherical - convex toward the liquid.
$(\ )_{vac}$	:	The value of ( ) when the liquid is under vacuum.
$(\ )_o$	:	The value of ( ) when the radius of curvature of the gas/liquid interface is a_o.
ΔP_{bulk}	:	$p_{tens} + p_v - p_h$
χ	=	$90^o - \Phi + \Psi$
Φ	:	angle of contact (see figure 1)
Ψ	:	Semivertical angle
σ	:	Surface tension.

7. References

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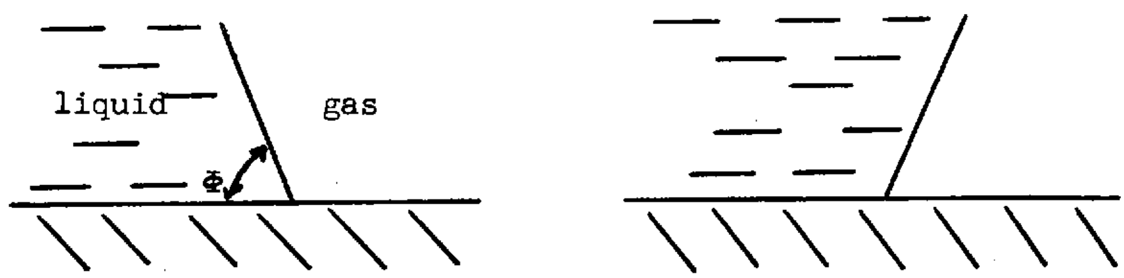
Figure 1 Contact angles



liquiphilic solid

(e.g. hydrophilic or oleophilic)

liquiphobic solid

(e.g. hydrophobic or oleophobic)

Figure 2 Tapered gas nucleus

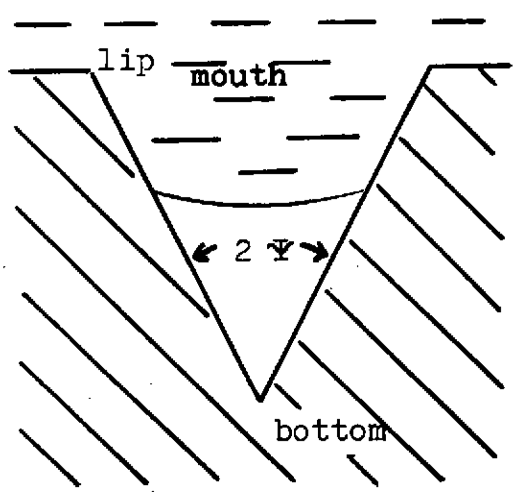


Figure 3 Tapered gas nucleus with surface roughness

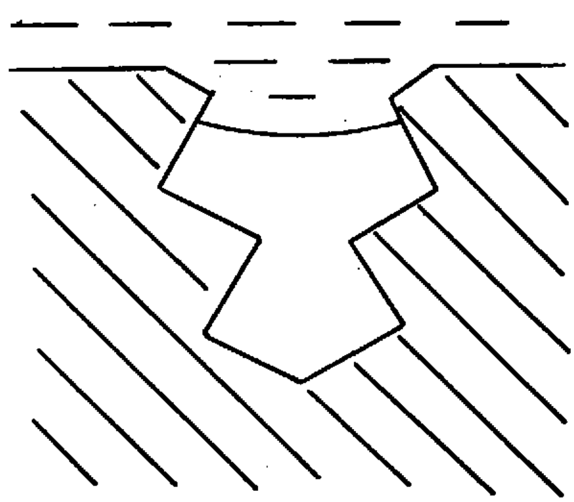


Figure 4 Suggested and idealised shapes for cove-nuclei

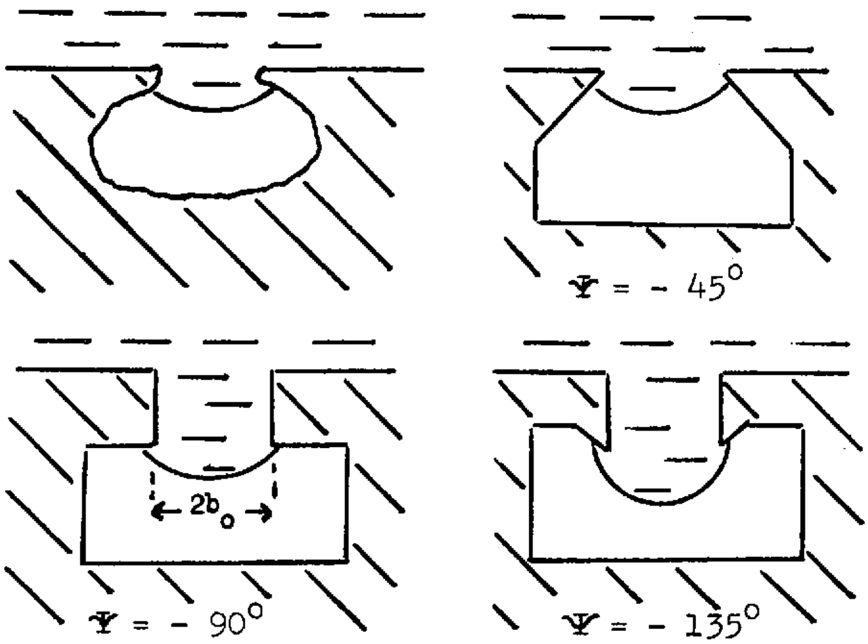
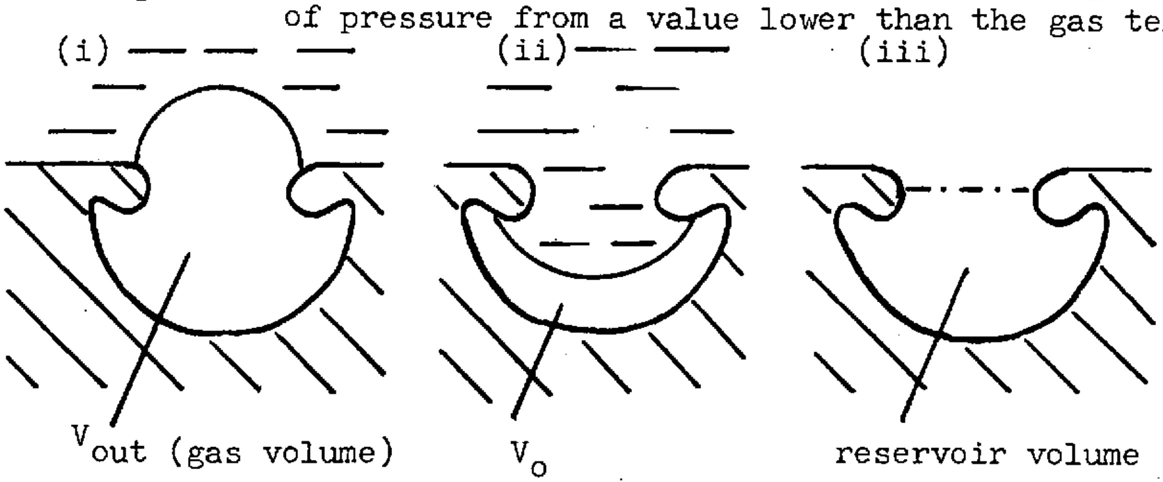


Figure 5 Behaviour of cove-nucleus on sudden increase of pressure from a value lower than the gas tension.



DISCUSSION

Cavitation occurs readily in low-viscosity oils, such as paraffins and transformer oils. The audience was unable to suggest any common types of solid contaminants that would be "oleophobic" and could therefore serve as nucleation sites in these liquids. This seems to be a positive objection to the Harvey/Strasberg/Apfel model.