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CAVITATION EROSION IN NON-AQUEOUS LIQUIDS

BY
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Summary

Cavitation erosion rates in the organic liquids formamide, ethanol, acetone and glycerol are compared with the rate in distilled water. As is to be expected, these non-ionizing liquids, which are chemically less reactive with metals than water, show lower damage rates. The cavitation damage rates have also been measured for solutions of these organic liquids in water and all these solutions show a monotonic decrease in going from pure water to the pure organic liquid except glycerol. The water-glycerol solutions go through a minimum damage rate for a solution with molecular ratio of glycerol to water of approximately 1 to 1. Solutions of ethanol in glycerol show a maximum in damage rate for a solution with molecular ratio, glycerol/ethanol, of about 2 to 1. Qualitative differences in the cavitation bubble cloud in the various liquids studied are indicated by short exposure photographs.

Introduction

Some indication of the effect of physical factors on cavitation erosion should be expected from measurements of damage rates of metals, or alloys, in non-ionizing, relatively inactive liquids. For this purpose observations have been made with a few organic liquids and with mixtures of organic liquids with water in various proportions. Some physical properties of the liquids used, formamide, ethanol, acetone, and glycerol, are given in the Table together with corresponding values for water. Formamide has interest because its vapor pressure at room temperature, the temperature of the experiments, is near that of water. Acetone and ethanol have higher vapor pressure and glycerol a much lower vapor pressure than water. The important surface tension difference in the liquids is between water and ethanol and acetone, and the important viscosity difference is between glycerol and all the remaining liquids. The viscosity of glycerol is of the order of 10^3 times that of the other liquids in this group.

The measurements of cavitation damage rates were made by means of a magnetostrictive oscillator and the technique is a familiar one. The particular experimental procedure has been described elsewhere^[1-3].¹ The specimens with which the erosion measurements were made were of the same pure aluminum material throughout. This material was convenient since an easily observed weight loss, of the order of some milligrams, could be obtained in 10 to 30 minutes. The amplitude of the specimen oscillations was held fixed at ± 0.001 in. and the frequency was fixed at 14 kHz. The temperature of the test liquids was 27°C in all the experiments.

¹Numbers in brackets designate References at the end of the paper.

Results and Discussion

The rate of loss of material in the organic liquids compared to the rate of loss of material under the same conditions in distilled water may be denoted as ER (erosion ratio), and the values found were as follows:

$$\begin{array}{ll} \text{ER } \frac{\text{glycerol}}{\text{water}} = 0.46 & ; \quad \text{ER } \frac{\text{formamide}}{\text{water}} = 0.33 & ; \\ \text{ER } \frac{\text{ethanol}}{\text{water}} = 0.070 & ; \quad \text{ER } \frac{\text{acetone}}{\text{water}} = 0.046 & . \end{array}$$

A correlation of these relative cavitation erosion rates with physical properties of the organic liquids is of course speculative, but with this understanding some interpretations may be indicated. It may be observed that the damage rate is greatest for the liquid, glycerol, with the lowest vapor pressure at the temperature of the experiments. As one goes to the other liquids it remains true that the lower the vapor pressure of the liquid the higher is the damage rate. The variation in vapor pressure is large and it is presumably likely that its effect is more important than the variation in the surface tension for the organic liquids. The surface tension of acetone is essentially the same as that of ethanol and yet the damage rate in acetone is noticeably less than that in ethanol. The surface tension of formamide is not much different from that of glycerol and again there is a significant difference in their damage rates. It must be admitted, however, that the liquids with the highest values of surface tension, glycerol and formamide, have large damage rates when compared with the liquids, ethanol and acetone, which have the lowest values. A reluctance to put much significance on the effect of surface tension comes from the observation which has been made in our laboratory of the consequence of reducing the surface tension of water by the addition of wetting agents. This procedure reduces the effective value of the surface tension appreciably, and yet the cavitating damage rates with and without wetting agents are not greatly different. As for the effect of viscosity of the organic liquids, it is indeed remarkable that glycerol with its extremely large viscosity has a value for its ER exceeded in this group only by water. There have been some theoretical speculations^[4] that viscous effects could drastically reduce the collapse speed of

cavitation bubbles and thereby prevent cavitation damage. Actually this picture of cavitation damage is too simple since it is known^[5] that a liquid jet is formed fairly early in the bubble collapse when the bubble is near a solid wall. The jet is directed toward the solid wall and can produce damage. Since this jet forms early in the collapse history, the effect of viscosity need not be significant.

A series of experiments were carried out in which the erosion rate for pure aluminum was measured in solutions of the organic liquids in water in various proportions. The results are shown in Fig. 1 - 4. Figures 1, 2, and 3 show that the damage rate rises monotonically as one goes from pure acetone, pure ethanol, or pure formamide to pure distilled water. The behavior in mixtures of glycerol and water is, however, quite different and remarkable. As distilled water is added to glycerol the damage rate undergoes an appreciable decrease which is then followed by a rise to the value for pure water. The volume ratio at which the minimum erosion rate occurs is approximately at a water to glycerol ratio of 10/90. It should be pointed out that the molecular ratio corresponding to this volume ratio is 1 molecule of water for each molecule of glycerol.

The unexpected behavior of the minimum damage rate for solutions of water in glycerol suggested the study of the solution of another liquid in glycerol. Measurements were made of mixtures of ethanol in glycerol and the results are shown in Fig. 5. The result again has an unexpected feature which in this case is a maximum in the damage ratio for a volume ratio of glycerol to alcohol of about 3/1. The molecular ratio of glycerol to alcohol is about 2 to 1.

In an effort to get some qualitative information which would contribute to an understanding of the erosion behavior found, some very short exposure (less than 1μ sec) photographs were taken of the bubble clouds over the specimens in the various liquids. Figures 6a, 6b, and 6c show the bubble cloud near its maximum in distilled water, in distilled water which has been partially deaerated, and in distilled water to which a surface tension reducing agent has been added. These bubble clouds show very similar appearances. The bubble cloud in pure glycerol looks very different from that in water as is evident from Figs. 7a, 7b, and 7c which have been taken at different times in the oscillating pressure cycle. While

the bubble cloud near its maximum (Fig. 7a) shows a large foamy appearance, most of the cloud disappears near the end of the collapse cycle (Fig. 7c). This extensive structure of the cloud near its maximum is also shown in ethanol (Fig. 8a), and there seems to be some persistence of the cloud (Fig. 8b) as the pressure rises. The behavior of the bubble cloud in glycerol with the addition of some water is shown in Fig. 9a - 9c which refer to a solution of 80% glycerol, 20% water, by volume. This solution is near the minimum in the damage rate for these solutions and, while the bubble cloud appears quite different from that in pure glycerol or in pure water, it is not clear why this change in appearance corresponds to a decrease in damage rate. The final set of bubble cloud photographs, Figs. 10a - 10d are for a solution of 67% glycerol, 33% ethanol, by volume. This mixture ratio is near the peak damage rate for the solutions of these liquids. Again, a marked change in the bubble cloud from pure ethanol or pure glycerol is evident, but it is not clear why this behavior is associated with a maximum in the damage rate.

Conclusion

The cavitation damage rate in the organic liquids listed in the Table is less than in distilled water. This result is to be expected since the organic liquids are chemically less reactive with metals than water. These organic liquids are, of course, non-ionized so that electrochemical effects are not to be expected.

For the most part the behavior of the erosion rate for solutions of acetone, ethanol and formamide in water is as one would expect. These solutions show a monotonic decrease in the damage rate (cf. Figs. 1, 2, 3) as one goes from pure water to the pure organic liquid. For the solution of water and glycerol, on the other hand, a surprising minimum is found (Fig. 4) for a solution with the molecular ratio 1/1 of glycerol to water. A surprising behavior is found again in the damage rate for solutions of ethanol in glycerol. In this case, a maximum in the damage rate is observed for a molecular ratio of about 2/1 for glycerol to ethanol.

Photographs of the cavitation bubble clouds in water, in the pure organic liquids, and in the solutions of interest show marked differences in appearance, yet the manner in which these differences are related to the variations in erosion rates is not evident.

References

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3. M. S. Plesset and R. E. Devine, "Effect of Exposure Time on Cavitation Damage", Journal of Basic Engineering, Trans. ASME, Series D, Vol. 88, 1966, pp. 691 - 705.
4. H. Poritsky, "Collapse or Growth of a Spherical Bubble or Cavity in a Viscous Fluid", Proceedings First U.S. National Congress of Applied Mechanics, ASME, 1952, pp. 813 - 821.
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TABLE OF PHYSICAL PROPERTIES

Liquid	Molecular Weight	Density at 20° C gm/cm ³	Melting Point ° C	Boiling Point ° C	Surface Tension at 20° C dynes/cm	Viscosity at 20° C Centipoise
Water H ₂ O	18.016	1.105	0	100	72.75	1.00
Formamide HCONH ₂	45.04	1.134	2.55	105	58.2	3.30 (at 25° C)
Ethanol C ₂ H ₅ OH	46.07	0.789	-117.3	78.5	22.75	1.20
Acetone (CH ₃) ₂ CO	58.08	0.791	-95.3	56.2	23.7	0.316 (at 25° C)
Glycerol C ₃ H ₅ (OH) ₃	92.10	1.2613	18.6	290	63.4	1,490

WATER

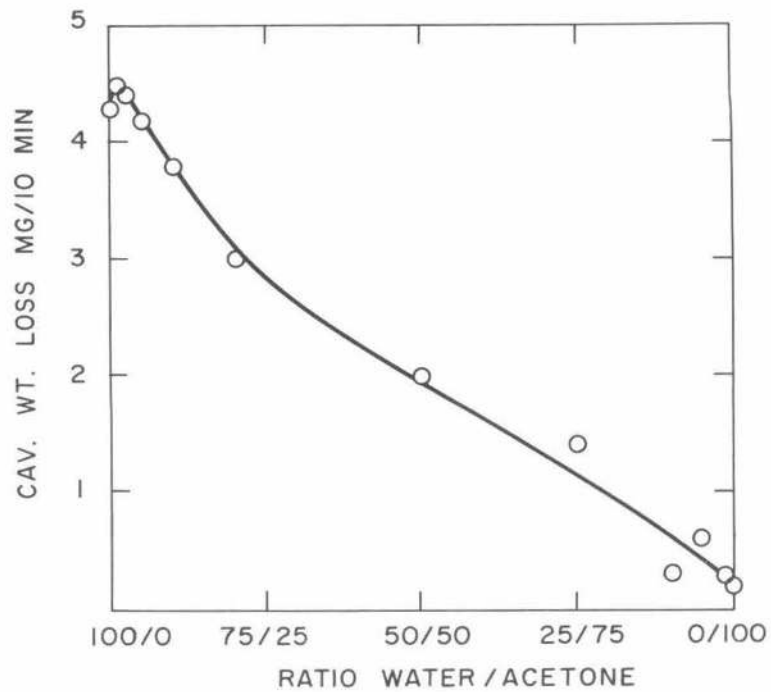


Figure 1 Cavitation damage rate for pure aluminum specimens in solutions of water and acetone. The solution ratios are volume ratios water to acetone.

WATER

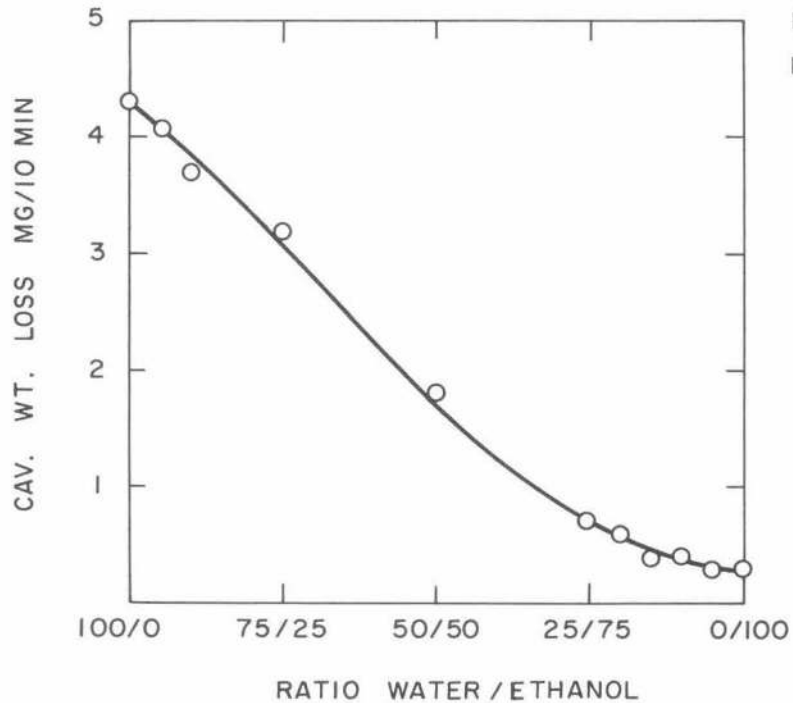


Figure 2 Cavitation damage rate for pure aluminum specimens in solutions of water and ethanol. The solution ratios are volume ratios water to ethanol.

WATER

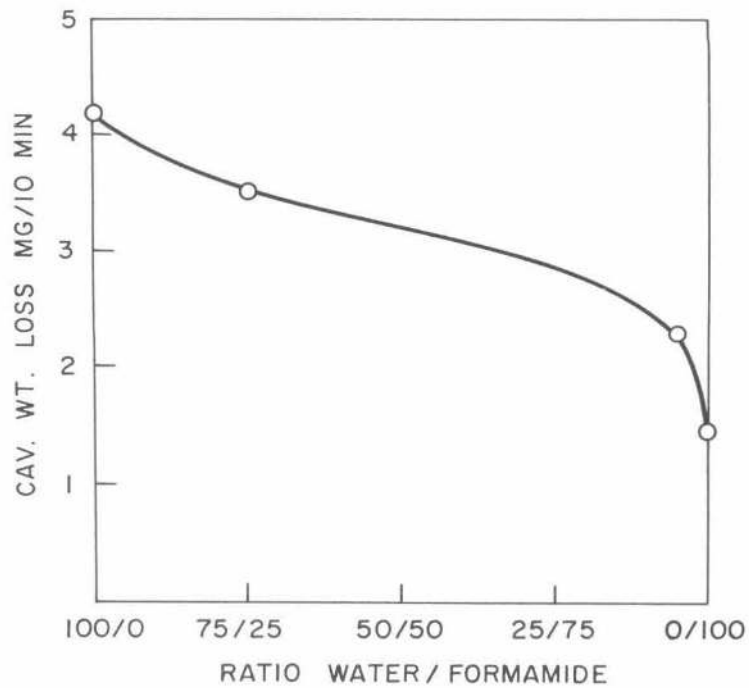


Figure 3 Cavitation damage rate for pure aluminum specimens in solutions of water and formamide. The solution ratios are volume ratios water to formamide.

WATER

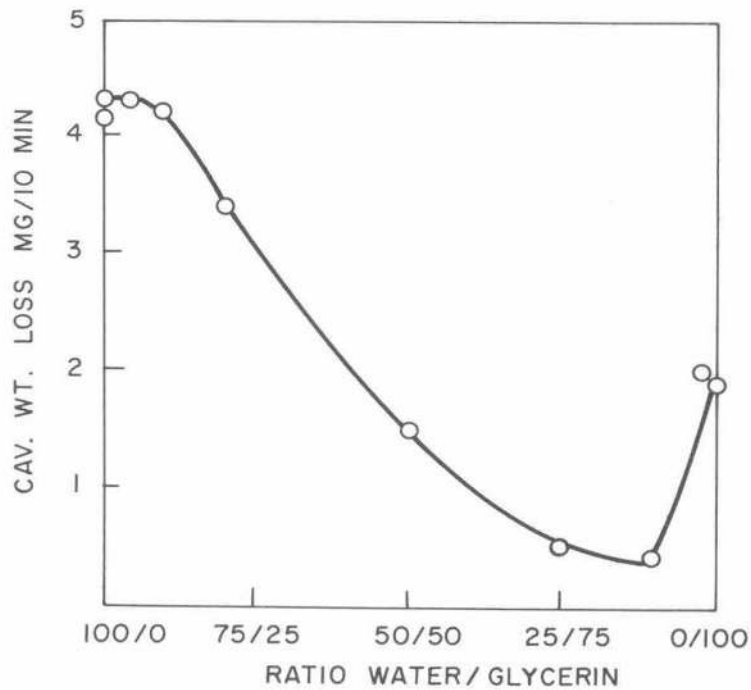


Figure 4 Cavitation damage rate for pure aluminum specimens in solutions of water and glycerol. The solution ratios are volume ratios water to glycerol.

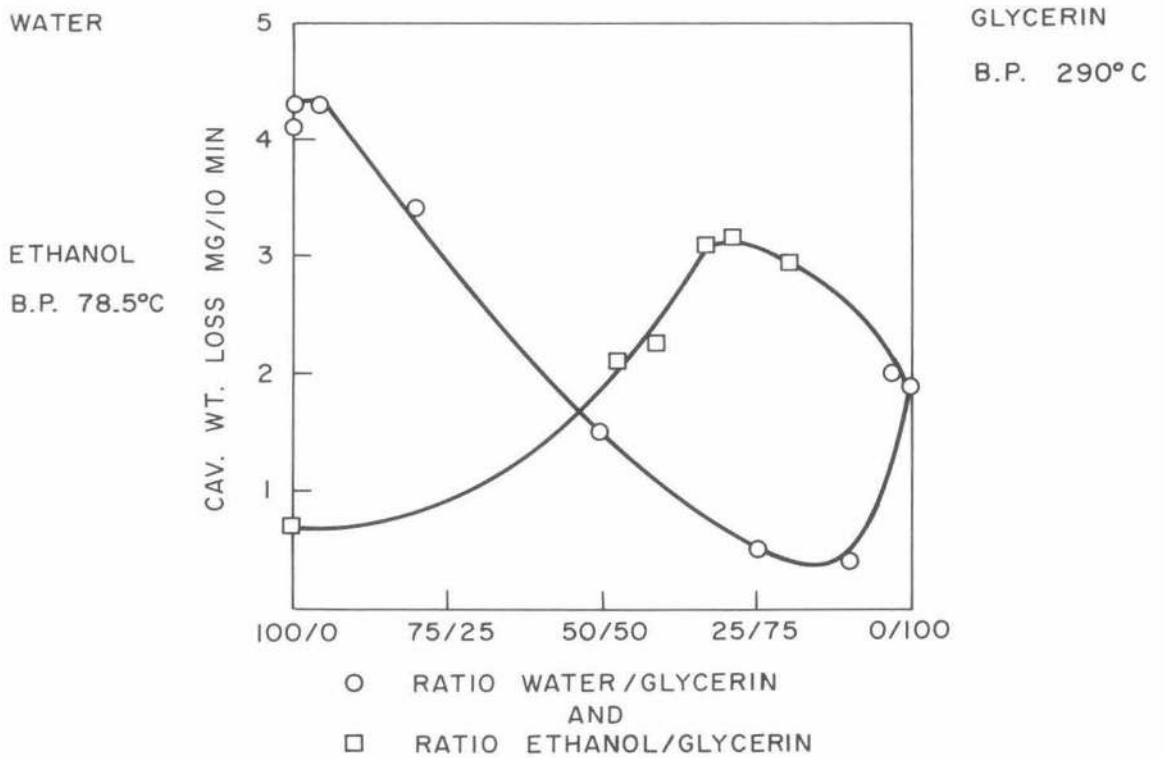
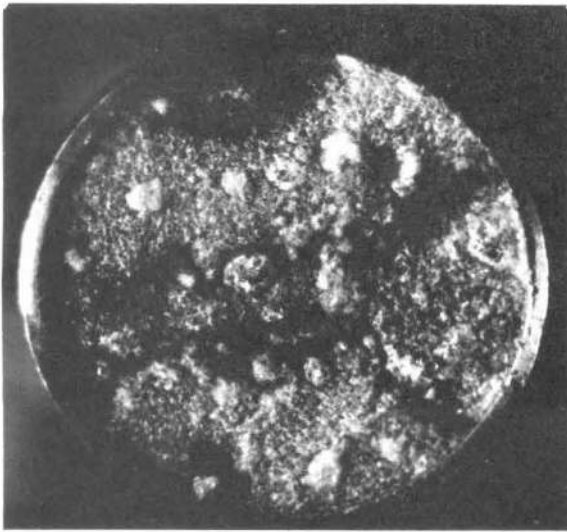
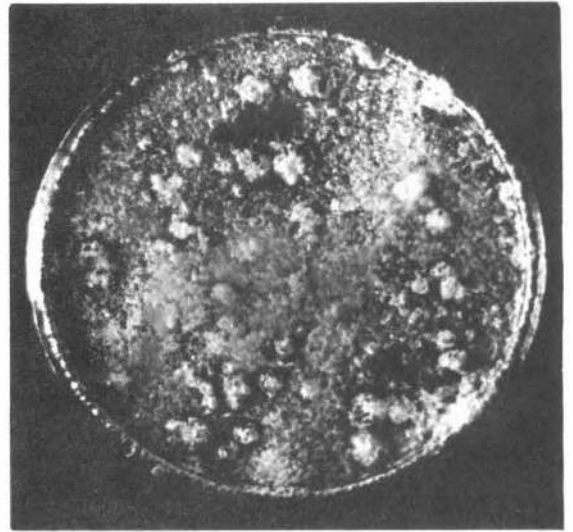


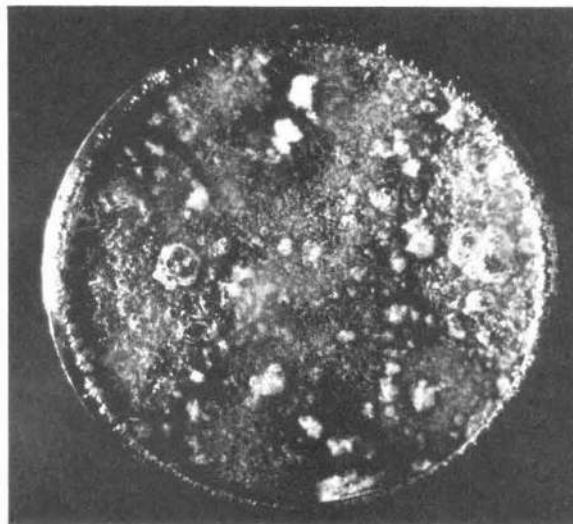
Figure 5 Cavitation damage rates are shown for solutions of water and glycerol (circles) and for solutions of ethanol and glycerol (squares). The ratios are volume ratios.



a. Distilled water



b. Deaerated distilled water

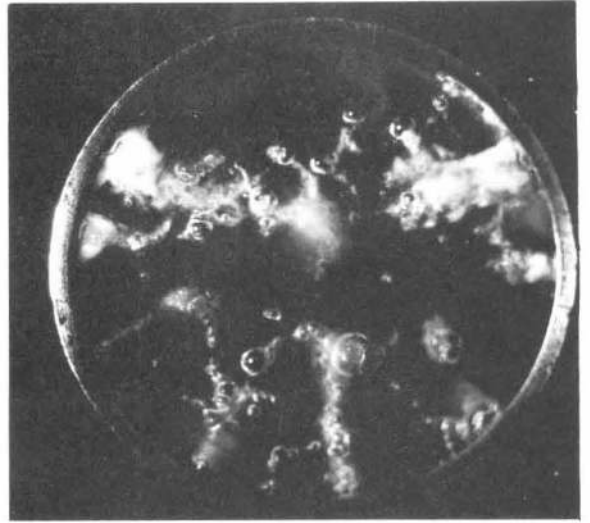


c. Distilled water with surface
tension reducing agent

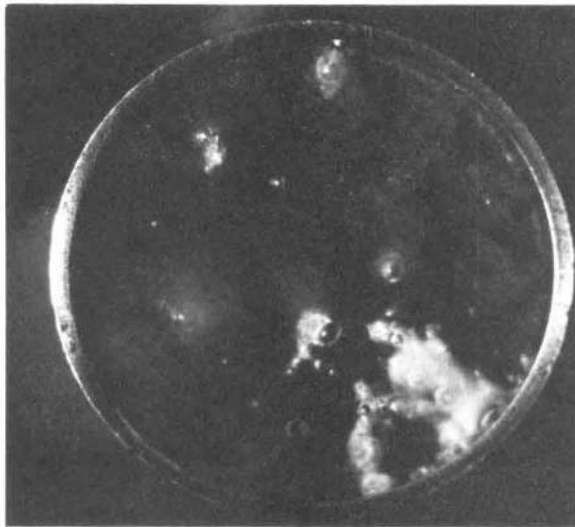
Figure 6 Bubble cloud in water near cloud maximum



a. Near cloud maximum

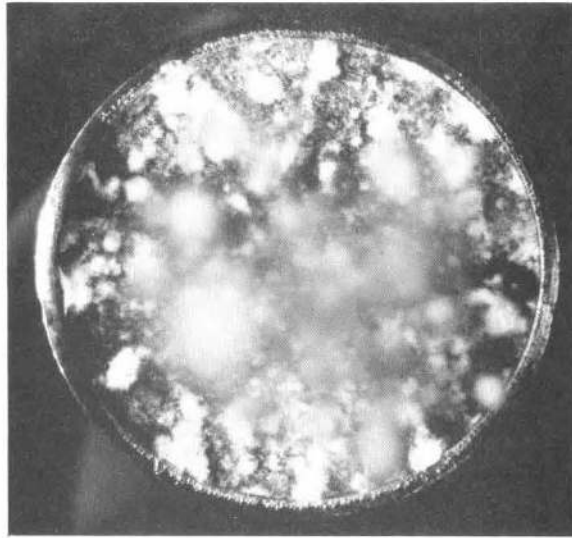


b. Effect of pressure rise on cloud

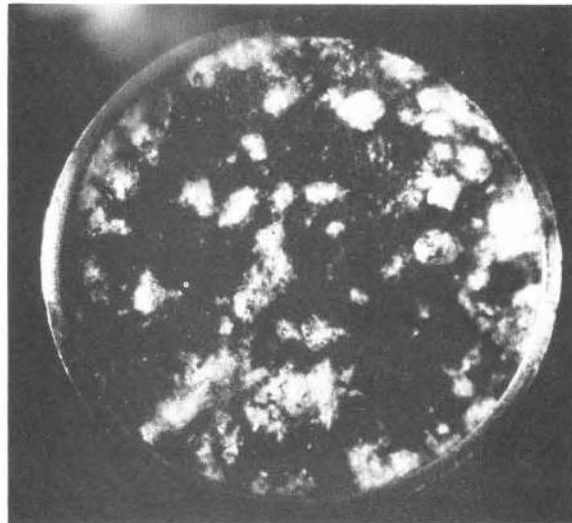


c. Near cloud minimum

Figure 7 Bubble cloud in pure glycerol

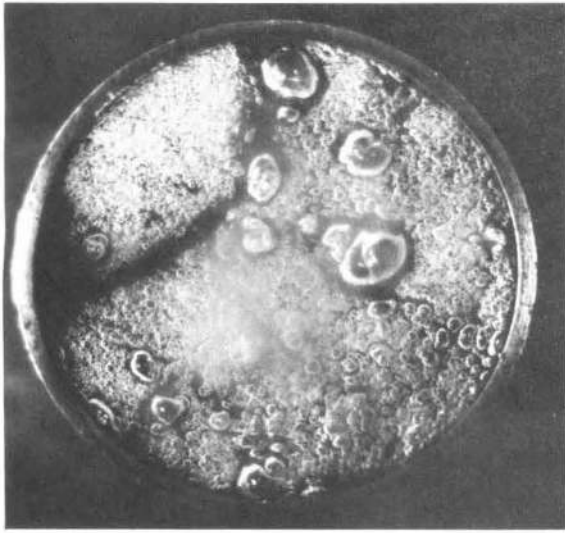


a. Near cloud maximum

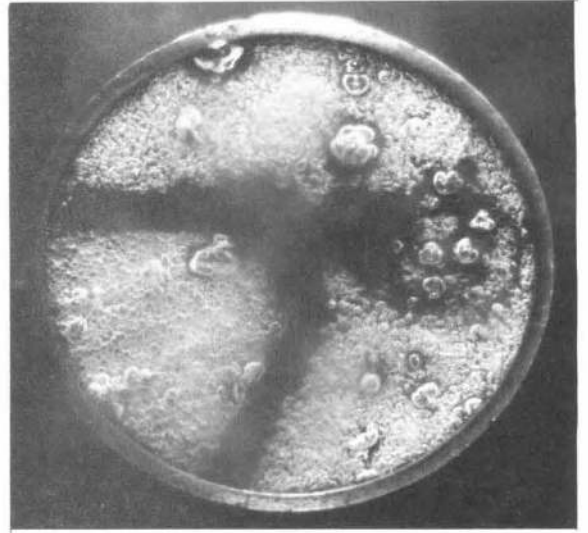


b. Effect of pressure rise on cloud

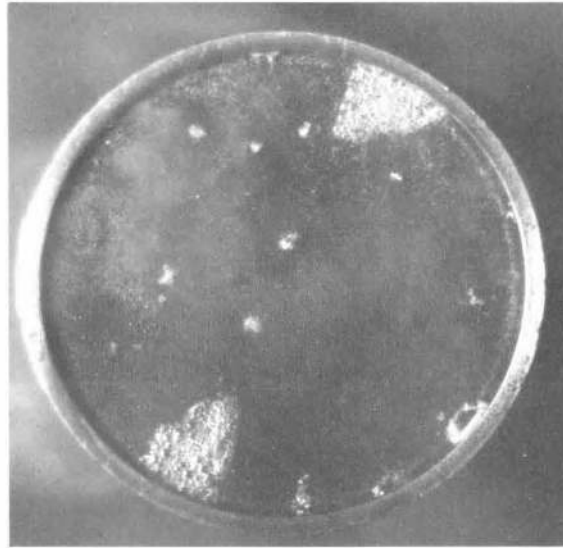
Figure 8 Bubble cloud in pure ethanol



a. Cloud near maximum

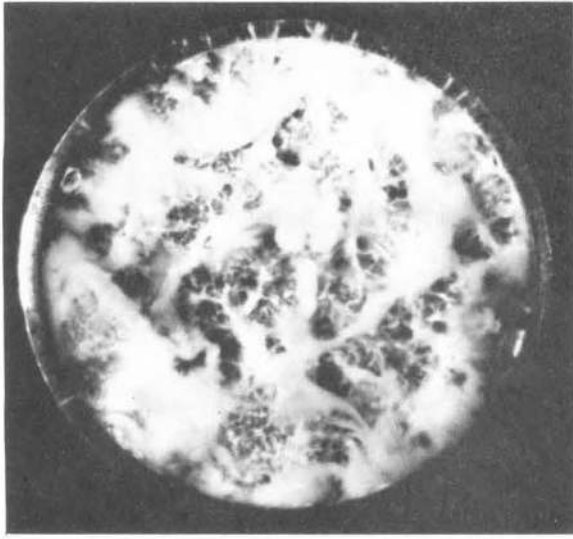


b. Effect of pressure rise on cloud

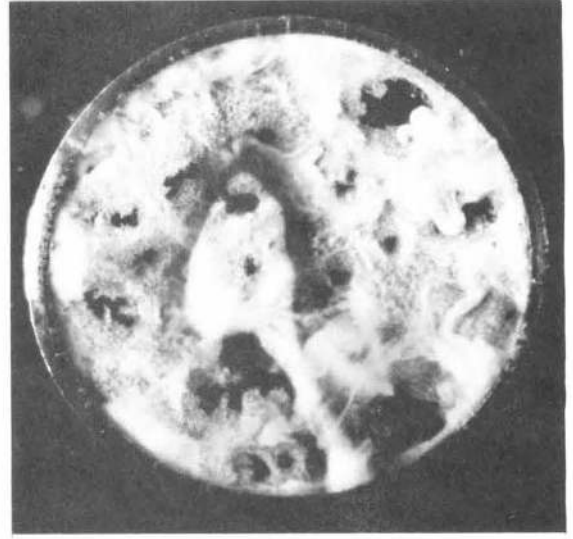


c. Near cloud minimum

Figure 9 Bubble cloud in glycerol-water solution. Volume ratio glycerol/water is 80/20



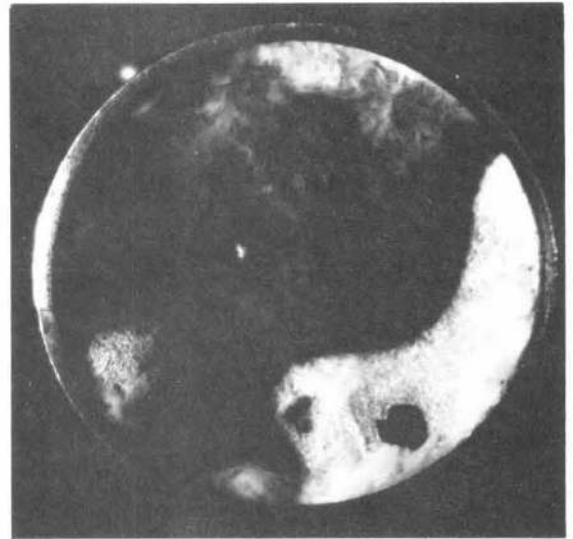
(a)



(b)



(c)



(d)

Figure 10 Bubble cloud in glycerol-ethanol solution. Volume ratio glycerol/ethanol is 67/33. Figures 10a - 10d show the variation in the cloud as the ambient pressure rises.

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13. ABSTRACT Cavitation erosion rates in the organic liquids formamide, ethanol, acetone and glycerol are compared with the rate in distilled water. As it to be expected, these non-ionizing liquids, which are chemically less reactive with metals than water, show lower damage rates. The cavitation damage rates have also been measured for solutions of these organic liquids in water and all these solutions show a monotonic decrease in going from pure water to the pure organic liquid except glycerol. The water-glycerol solutions go through a minimum damage rate for a solution with molecular ratio of glycerol to water of approximately 1 to 1. Solutions of ethanol in glycerol show a maximum in damage rate for a solution molecular ratio, glycerol/ethanol, is about 2 to 1. Qualitative differences in the cavitation bubble cloud in the various liquids studied are indicated by short exposure photographs.			

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