

## DISCUSSION

F. G. Hammitt<sup>2</sup>

The question of the temperature effect upon cavitation damage rates in the standard vibratory open-beaker test is an old one as yet incompletely understood, and hence this new paper on the subject by Dr. Plesset, which will no doubt rekindle discussion of the matter, is highly to be welcomed. I would like to raise the following points à propos to the subject myself.

I had thought it was generally agreed that the strong downward trend at higher temperatures (with increasing temperature) was primarily a result of the increasing importance of "thermodynamic effects," to use the term common in the cavitation literature (e.g., [7]),<sup>3</sup> as vapor density increases, rather than simply a question of the decrease of  $p_{\infty} - p_v$  as Dr. Plesset seems to imply. For example, the decrease in  $p_{\infty} - p_v$  is extremely small in the range 40 C–60 deg C, although for many materials the decrease in damage is large over this range, as the present paper shows. However, the increase in vapor density is large in this range. My viewpoint here is further substantiated by tests we reported [8] relatively recently, where we held  $p_{\infty} - p_v$  constant and raised the temperature. As shown in our Fig. 11 (reproduced from our reference [8] for convenience), the damage-temperature curves are much the same as for Dr. Plesset's open beaker (unpressurized) tests, although the temperature for maximum damage is somewhat increased for our pressurized tests. Fig. 11 also shows a complete mapping of damage-temperature-pressure effects for our facility up to 4 atm  $p_{\infty} - p_v$ . Of course, the detailed data must depend upon the facility parameters of frequency, amplitude and specimen diameter, but in our case, and also in tests at NEL [9] and NASA [10, 11], the damage rate increases very strongly with pressure up to at least 4 atm, while the temperature corresponding to maximum damage increases slightly, as one would expect. Clearly the increase with pressure must level-off at some sufficiently high pressure, and then decrease to zero (depending upon facility frequency, amplitude, and diameter), since at high enough pressure, there would be no cavitation. Hence, as pressure is raised, it is a question of the interplay of a reducing number of bubbles and an increasing violence of collapse. Clearly, the same trends with pressure and temperature should apply in flow machinery, but it is a question then of the detailed flow-field parameters.

Concerning the possibility of explaining the decrease of damage with decreasing temperature (below the temperature corresponding to the maximum damage rate), by increasing air solubility as discussed in this paper and I believe previously suggested by Dr. Plesset, tests have been reported in the last few years by Dr. Hobbs at NEL [9], where he conducted tests of the type here reported by Dr. Plesset, and systematically varied and controlled total gas content over the pertinent range, in order to check out this supposition. The results were negative in that the effects of gas content were far too small to explain the decrease in damage rate at low temperature.

A final comment regarding the present paper: whereas it had commonly been supposed that the temperature corresponding to maximum damage rate in this type of test is about midway between melting point and boiling point of the fluid, i.e., ~50 deg C for water in an open beaker, Dr. Plesset's tests show that the maximum damage temperature varies between about 20 C and 60 deg C, depending both on the material and the fluid, e.g., the addition of salt appears to raise this temperature. This appears to me to support Dr. Plesset's argument that chemical effects, at least in his tests, are of non-negligible importance in the overall situation. Further, temperature effect tests with a liquid-gas-

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<sup>3</sup> Numbers in brackets designate Additional References at end of discussion.

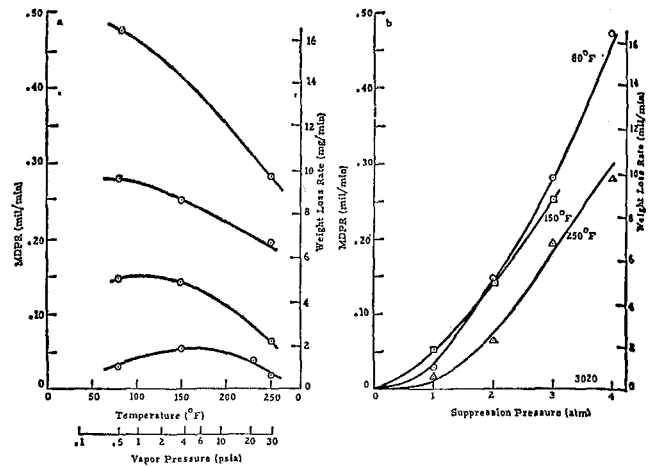


Fig. 11 Cavitation erosion rates based on heavily damaged area as function of temperature and pressure

material combination chosen so that chemical effects are extremely unlikely should shed important new light on the overall situation, and I urge Dr. Plesset to continue his program with such tests.

### Additional References

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### Robert Hickling<sup>4</sup>

The experimental results reported in Professor Plesset's paper are of great interest, particularly as they highlight the decrease in the cavitation damage rate that occurs as the temperature of the liquid decreases toward the freezing point. A similar trend [12]<sup>5</sup> occurs with the weak luminescence from cavitation (sometimes referred to as sonoluminescence). Results such as these indicate a general weakening of cavitation intensity as the liquid temperature approaches the freezing point.

There seems to be no evidence that this weakening in cavitation intensity is associated with a noticeable change in the overall behavior or appearance of the cavitation cloud, although this aspect does not appear to have been investigated by workers in the field. Usually it is presumed that the effect comes about from a change in the characteristics or behavior of the individual bubbles.

It seems difficult to find an explanation for the effect that will fit all the facts. The two theories proposed in Professor Plesset's paper, namely the gas solubility theory and the chemical activity theory, have to contend with some serious counter-evidence. As the temperature of the water decreases from about 30 C to 0 deg C, the solubility of ordinary gases in water does not increase more than about 40 percent. This does not seem large enough to account for the observed decrease in cavitation damage. Also,

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<sup>5</sup> Numbers in brackets designate Additional References at end of discussion.

the rate of diffusion of gas into the bubbles can be expected to decrease with temperature, and this would tend to offset the effect of any increase in dissolved gas content. Further, there is experimental evidence [13] that the amount of dissolved gas in the liquid, above a certain minimal level, plays a relatively unimportant role in the kind of ultrasonic cavitation tests described in the paper. It might be of interest to run the temperature dependence tests in a helium atmosphere, since the solubility of helium in water is relatively insensitive to temperature.

With regard to the chemical activity theory, the effect on the cavitation erosion rate in water due to additives is undeniable. However, these data are not sufficient to prove that a significant amount of chemical activity is taking place in the cavitation erosion process, because additives can affect physical as well as chemical properties. Unfortunately, there appears to be no data in the literature about chemical products from cavitation erosion. Such data would provide direct evidence of chemical activity. In an experiment by the writer using an ultrasonic test rig similar to that used by Professor Plesset, the debris from the erosion of an aluminum specimen in tap water at 50 C deg was collected. Its weight differed by less than 1 percent from the weight of the metal lost from the specimen, and the chemical composition of the debris was found to be the same as that of the specimen. Obviously, in this instance, chemical activity played an insignificant role in the erosion. In the light of this result, it seems unlikely that the variation in the erosion rate for aluminum shown in Fig. 5 of the paper can depend in any significant way on chemical activity, and one might suspect that the same is true for the rest of the data shown in this figure. (It is known, of course, that very weak chemical reactions are associated with cavitation in water [14], but the rate at which these occur is orders of magnitude slower than the rate of cavitation erosion.)

An alternative theory to the two theories proposed in the paper was put forward by the writer a few years ago [15]. Given the transient high pressures that are likely to occur in the liquid close to the wall of a collapsing bubble [16], it can be estimated that a momentary change from liquid to solid phase can occur that would mitigate the force of the collapse. This effect will grow stronger as the liquid temperature approaches the freezing point. In reference [15], the case of water is presented as a particular example of the proposed mechanism. It was pointed out also that, in addition to explaining the decrease in cavitation intensity near the freezing point, the mechanism will explain the nucleation of freezing in subcooled liquids by cavitation. This latter effect has been discussed in the literature on solidification [17].

This last theory has not gained a ready acceptance, possibly because a direct verification appears to be almost out of the question and because the application of the hypothesis to explain the range of existing data on cavitation erosion is hampered by a lack of information on the thermodynamic behavior of liquids and solids at high pressure. However, there are good reasons for believing that sufficiently high pressures do occur over a sufficient interval of time during cavity collapse and, such being the case, the theory does bear consideration.

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#### J. Z. Lichtman<sup>6</sup>

This paper is a significant contribution to the growing literature concerned with cavitation erosion of materials in a broad spectrum of liquid conditions. Since the earliest investigations of the effects of liquid temperature on erosion, by Schumb, Peters, and Milligan [18],<sup>7</sup> Kerr [19], and Nowotny [20], interest has expanded most recently to include liquid metals in investigations by Young and Johnson [21], Leith and McCaig [22], and others.

The temperature-erosion characteristics obtained by the other investigators cited above are similar to those of the author, generally showing a peak value in the range of 30 to 70 percent of the freezing-to-boiling point range. Kerr [19] had concluded that the erosion intensity was a function of the gas content or vapor pressure, or both. The dissolved gas content increases with decrease in temperature. The release of dissolved gases during cavitation would cushion the bubble collapse, and decrease the resulting erosion intensity. The cushioning effect decreases with increase in temperature to the peak intensity. As the liquid temperature increases to the boiling point with associated increase in vapor pressure, bubble collapse is dampened by the liquid vapor. The hypothesis proposed by Kerr to explain the decreases from the peak erosion intensity is in agreement with those proposed by other investigators cited in the foregoing. He recognized the practical importance of the temperature-cavitation erosion relationships in performance of process industry or power generation systems. Young and Johnston [21] also recognized the practical importance of these relationships, as well as the associated factor of liquid pressure in determining the degree of erosion in power conversion systems.

Schumb, Peters, and Milligan [18] also investigated the contributions of liquid corrosivity (chemical effects) to the temperature-erosion relationship and observed an increase in peak erosion value for corrosion-sensitive materials. Changes in peak values (increases or decreases) associated with corrosion stimulators or inhibitors were observed by Schulmeister [23]. The author also observes the influence of corrosion stimulators (3 percent NaCl solution) on the degree of erosion of corrosion-sensitive materials. The contribution of corrosion to an upward temperature shift of the peak erosion rate, associated with the increase in chemical activity with increase in temperature is not shown by the performance of 4340 steel, Fig. 9.

The experimental procedures described by the author indicate that measurements were made in the linear range, following the nonlinear initial incubation period. It appears that the linear range (or phase) is the maximum rate period referred to by Hobbs [24], and the incubation period includes the incubation and accumulation phases described by Eisenberg [25]. The efforts of ASTM Technical Committee G-2 on Erosion to standardize the terminology associated with erosion measurements will contribute to eliminating misinterpretation caused by different meanings associated with the same terms.

#### Additional References

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## Author's Closure

In his discussion, Dr. Hammitt has brought up the subject of "thermodynamic effects" which he associates with the role of vapor density rather than with vapor pressure. Apparently, Dr. Hammitt suffers from some confusion regarding thermodynamics. It is, of course, very familiar that both vapor pressure and vapor density are thermodynamic variables which are, in addition, related by the equation of state. Dr. Hammitt observes that the vapor pressure,  $p_v$ , is small in the range 40C-60 deg C compared with the mean pressure  $p_\infty$ . In this range, the vapor pressure is about  $1/10$  the mean pressure of 1 atm. He might have observed that the vapor pressure is even smaller compared to the amplitude of the impressed pressure oscillations which was 14 atm. Dr. Hammitt, on the other hand, regards the vapor density as large in this range. In order to give some meaning to this observation, we should have another characteristic density in the problem with which to compare this vapor density. Another density which comes to mind is the liquid density which, in this case, is 1 gm/cm<sup>3</sup>. In the temperature range of concern, the vapor density is about  $10^{-4}$  gm/cm<sup>3</sup> which is extremely small in comparison.

Of course, it should be quite obvious that static comparisons of the kind proposed by Hammitt are meaningless. It is necessary to consider the dynamics which enter into the problem. I believe that a qualitative understanding of the difference between the cavitation damage in a "cold" liquid and a "hot" liquid is relatively straightforward. It follows from the consideration of the bubble collapse behavior at different bulk liquid temperatures. A "thermodynamic effect" is always present, both for a cold liquid and for a hot liquid. During vapor bubble collapse, heat of condensation is liberated, and the temperature in the bubble rises. With this temperature rise is associated a rise in the vapor pressure in the bubble. In a cold liquid, however, this rise in temperature and vapor pressure becomes significant only very late in the bubble-collapse history after large collapse velocities have already developed. For example, in water at 20 deg C, a vapor bubble with an initial radius  $R_0 = 0.25$  cm which collapses under an external pressure  $p_\infty = 0.5$  atm follows an essentially isothermal collapse until it reaches a radius  $R \lesssim 0.02$  cm. Its collapse velocity near the end of this isothermal range is in excess of 200 m/sec even with this moderate value of  $p_\infty$ . The cavitation damage capability is clearly attained. If the collapse were to continue as a spherical collapse, the temperature in the bubble and the vapor pressure would rise in a nearly vertical manner to very large values, but as we are well aware major deformations occur for  $R/R_0 \lesssim 0.2$  [26, 27].<sup>8</sup> The implications of these major deformations for the damage mechanism are now generally understood.

In a warm liquid, the behavior is quantitatively, but not qualitatively, different. The heat liberated during condensation is greater because of the greater vapor density, and becomes important earlier in the collapse history. The vapor pressure rise correspondingly begins earlier. As a consequence, collapse velocities are greatly reduced, and the damage capability is also thereby reduced. These effects will be pronounced even through the initial vapor pressure is much less than  $p_\infty$ , or the oscillatory pressure amplitude  $P$ . Simply stated, as the bubble collapse proceeds in a warm liquid, the deviations from the isothermal condition appear earlier in the collapse. The vapor pressure rise slows down the collapse before large collapse velocities can be produced. Lower collapse velocities, in turn, mean that the jet produced by the major deformation of the bubble [27] will have

<sup>8</sup> Numbers 26-27 in brackets designate Additional References at end of Closure.

lower impact velocity, or may not form at all.

One may get a quantitative determination of these differences between the collapse behavior in a cold and in a warm liquid by solving the following problem. A vapor bubble undergoes a spherical collapse which is followed until the temperature and the pressure in the bubble reach their critical values. These critical values correspond to a temperature of 374 deg C and to a pressure of approximately 220 atm. Beyond this stage, collapse velocities will decrease and with this decrease goes a decrease in damage capability. If we take as an example collapse under a pressure  $p_\infty = 1$  atm, we have the following results for the radius  $R_c$  at which critical conditions of temperature and pressure are attained:

$$\begin{aligned} t = 20 \text{ deg C: } R_0 = 0.1 \text{ cm; } R_c/R_0 &= 0.019 \\ t = 20 \text{ deg C: } R_0 = 1.0 \text{ cm; } R_c/R_0 &= 0.033 \\ t = 90 \text{ deg C: } R_0 = 0.1 \text{ cm; } R_c/R_0 &= 0.64 \\ t = 90 \text{ deg C: } R_0 = 1.0 \text{ cm; } R_c/R_0 &= 0.75 \end{aligned}$$

We may see from these numerical results that at low liquid temperatures jet formation will take place well before there is a significant decrease in collapse velocities. This behavior does not hold at high temperatures. Details on these calculations, with additional values, will be presented in another place.

I turn now to Dr. Hickling's remarks. Both he and Hammitt express reservations regarding the effects of dissolved air on cavitation damage. I would agree that air content may be of secondary importance in many situations, but I am reluctant to dismiss air-content effects altogether. From an experimental point of view, it is difficult to get equilibrium values for dissolved air, and it is also difficult to get changes in air content without changing other experimental parameters at the same time. I would expect that dissolved gas content may play a role through its effects on nuclei from which the cavitation bubble must grow. In any case, I believe that further studies of the effects of dissolved gases would be fruitful in the complicated physical situation which characterizes cavitation damage.

With regard to possible effects of dissolved air, it also seems quite possible that the dissolved gas may contribute an additional factor to the chemical effects in cavitation. I do not agree with Dr. Hickling that chemical activity is not important. I would again call attention to the damage behavior with silver. With this element, the damage rates did not show a well-defined maximum. Rather, the damage rate was nearly constant at the lower temperatures. While silver is not entirely inactive, it is much less active than most of the other materials used.

With regard to the alternative theory which has been proposed by Dr. Hickling, I must say that his idea of ice formation within the collapsing cavity seems to me to be completely unacceptable. As we now know well, the vapor bubble forms a jet fairly early in its collapse history. The temperatures and pressures are obviously not such as to lead to the highly subcooled conditions which Hickling's idea requires. The idea is extremely novel, but is completely incompatible with physical reality.

Mr. Lichtman, in his discussion, has listed several references in which cavitation damage has been discussed. We are indebted to him for these. With Mr. Lichtman's reminder regarding the work of the ASTM Committee G-2 on Erosion, we must agree that their efforts toward a unified terminology are commendable. I tried to be most explicit in my description of the terms and conditions of the present experiments, and I would hope that the confusion regarding those terms and conditions would be minimal. Certainly, precision in terminology is most commendable, but a very fundamental need in this field, as in any other, is an understanding of the significant physical effects in the phenomena which we are observing.

## Additional References

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