FINAL REPORT

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Analysis of Microlayer Evaporation in Subcooled Nucleate Boiling

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The objective of this research program was to analyze further the role of microlayer evaporation (latent heat transport) in highly subcooled nucleate boiling. This objective has been met and our conclusions differ significantly from the recent study of Plesset and Prosperetti. In particular, while they concluded that microlayer evaporation was relatively insignificant, accounting for only 10-20% of the heat transfer per bubble, we have found that microlayer evaporation plays a significant role, accounting for about 40% of the heat transfer. Furthermore, their results are very sensitive to the choice of initial microlayer thickness while our results are much less sensitive to the initial microlayer thickness profile. Hence, we conclude that microlayer evaporation is a significant heat transfer mechanism in highly subcooled nucleate boiling.

Essentially two mechanisms, microlayer evaporation and microconvection, have been advanced to explain the very high heat transfer rates observed in highly subcooled nucleate boiling. Both mechanisms are associated with the growth and collapse of vapor bubbles at the solid surface. As a vapor bubble grows at a solid surface a thin film of liquid, the microlayer, is left beneath the hemispherical bubble. This microlayer is on the order of a few micrometers in thickness and may evaporate during the bubble lifetime thus transferring substantial energy through the latent heat of vaporization. Microconvection refers to an increased convective heat transfer due to the fluid motion at the solid surface associated with the bubble dynamics.

For the case of highly subcooled nucleate boiling, microlayer evaporation is amenable to analysis for a number of reasons. First, Gunther and Kreith [1] found that the vapor bubbles grow and collapse at the solid surface and maintain a hemispherical shape throughout the bubble lifetime. Because of the hemispherical shape, bubble dynamics for spherical bubbles may be reasonably applied. Secondly, because the microlayer is so thin, the viscous forces rapidly damp out any radial motion. Hence the evaporation may be treated as a transient heat conduction moving boundary problem. In the moving boundary problem it is customary in the literature to assume that the interface is at the saturation temperature (equilibrium assumption). However, for highly subcooled nucleate boiling the solid surface may be superheated on the order of 30°C so that a strong nonequilibrium condition exists. In this case one must appeal to the theory of evaporation in kinetic theory to obtain an expression for the evaporative mass flux as a function of the liquid surface temperature and the pressure of the surrounding vapor. Because the evaporative mass flux depends on the pressure inside the bubble, the microlayer evaporation is coupled to the bubble dynamics.

Plesset and Prosperetti [2] have used the above model to analyze microlayer evaporation. The bubble growth and collapse data of Gunther and Kreith [1] were used as an input to the bubble dynamics equation to determine the pressure of the vapor inside the bubble as a function of time. The evaporative mass flux then depends only on the surface temperature and time so that the microlayer evaporation is a well-posed transient heat conduction problem which can be solved computationally.

In the present research program the basic model of Plesset and Prosperetti as outlined above is retained but the analysis is extended. The present research program is divided into two parts. In the first part, the technique for solution of the moving boundary problem was improved. Plesset and Prosperetti used an approximate integral technique which is open to some question. In the present study, a more accurate finite difference solution was developed. In the second part of the research program, the model is extended to include two major features:

1. Plesset and Prosperetti assumed a microlayer of uniform thickness and performed a sensitivity study to the intial thickness. Their conclusions were based on an order of magnitude estimate of the initial thickness. In the present study the model is extended to account for the microlayer profile. The microlayer profile measurements of Koffman and Plesset [3] provide a more accurate input on which to base conclusions.

2. The theory of evaporation from kinetic theory has been a subject of recent controversy. Of interest here, recent calculations suggest that the evaporative mass flux expression used by Plesset and Prosperetti should be larger by a factor of 1.66. The effect of this correction is examined in the present study.

Finite Difference Solution

The first part of the research program, in which a finite difference solution was developed, formed the basis for the M.S. program of Mr. D. W. Karschner. Mr. Karschner was supported with a Graduate Research Assistantship by the Georgia Institute of Technology. His thesis [4] serves as the detailed report for this part of the research program.

Several methods for solving moving boundary problems can be found in the literature. For the one-dimensional problem considered here, a fixed grid, variable time step, implicit, finite difference formulation was chosen. This approach is simple to formulate, the position of the moving boundary is tracted directly, and the implicit formulation provides good accuracy and stability with a relatively coarse grid so that computing time is minimized. A fixed uniformly spaced grid is used and an iteration is performed on the time step so that the interface moves precisely to the next nodal point. The basis for the iteration is the energy balance at the interface in which the heat flux from the liquid must equal the latent heat of vaporization requirement for the evaporative mass flux. The evaporative mass flux is very sensitive to the liquid interfacial temperature so that a modified Newton-Raphson method must be used to obtain convergence to the time step.

The above method has been successfully developed to solve the microlayer evaporation model. Since the spatial grid is fixed, the accuracy of the solution can be expected to increase as a finer grid is used. The sensitivity of the solution to the number of spatial divisions is demonstrated in Karschner's thesis [4] and we found that a relatively small number of divisions is sufficient. In fact, for a comparable accuracy, the finite difference calculation and the approximate integral formulation of Plesset and Prosperetti take about the same amount of computing time. Dr. Prosperetti kindly sent us a copy of his program so that a direct comparison could be made. As shown by Karschner [4] and pointed out by Koffman [5], for small microlayer thickness, e.g. 1 μm, the integral method and the finite difference method are in reasonable agreement. However, for thicker microlayers, e.g. 10 μm, there is a significant discrepancy. It appears that the integral method overpredicts the initial evaporation rates until the wall effect becomes important. We should note that this error has little effect on Plesset and Prosperetti's overall heat transfer calculations which are integrated over time. However, it is clear that the finite difference solution is preferable especially since it is no more expensive or difficult to use.

In addition to comparing the solution techniques, we also compared the model using the kinetic theory evaporative mass flux to a model which assumes the interfacial temperature becomes the saturation temperature immediately. We would expect that for thick microlayers (for which the wall effect is unimportant) that the results would be similar. This is shown to be the case and examples are given by

Karschner [4] and Koffman [5]. However, for a thin microlayer, e.g. 1 μm, there is a significant error incurred if saturation is assumed at the interface. As would be expected, the assumption of saturation results in an overprediction of the evaporation rates. The time to total evaporation differs by as much as 30%. This comparison is quite interesting and we are beginning to understand the importance of nonequilibrium effects in microlayer evaporation.

Extension of the Plesset and Prosperetti Model

The second part of the research program extended the Plesset and Prosperetti model to account for the microlayer profile and for the correction to the kinetic theory evaporative mass flux expression. This work formed the basis for a research project for Mr. David Kemp as an Undergraduate Research Assistant supported by an Olin Corporation Summer Project Grant. This work also forms the basis of the M.S. program for Ms. L. B. Herrig which is in progress. Ms. Herrig is supported with a Graduate Research Assistantship by the Georgia Institute of Technology.

The effect of the correction to the kinetic theory evaporative mass flux expression by a factor of 1.66 is difficult to guess since a higher mass flux will produce greater surface cooling and in turn the cooler surface will result in a lower mass flux. Karschner [4] shows that there is a difference with the correction of 1.66 but it appears that the effect on the microlayer evaporation calculation is on the order of only a 10-20% difference.

The inclusion of a microlayer profile in the model was expected to be the most significant extension. With the initial microlayer profile measurements of Koffman and Plesset [3] used as an input, the one-dimensional calculation is performed at several sections so that an overall picture of the microlayer evaporation can be created. Koffman [5] shows the detailed results of such a calculation. Two points are of interest. First, the fraction of the initial microlayer which evaporates can be determined; the total latent heat extracted results in a contribution of microlayer evaporation to the overall heat transfer per bubble of about 40%. This is significantly higher than the result of 20% obtained by Plesset and Prosperetti for a uniform thickness microlayer. The second interesting feature of the detailed calculation is that the microlayer evaporation as a function of time appears to be very similar to the experimental measurements of Koffman and Plesset [3]. In particular, the profiles maintain a similar shape in time and the contact angle remains less than 2°. A direct comparison with experiment can not yet be made, but these results are quite encouraging that a good model is now in hand to analyze experimental results as they become available.

Since the initial microlayer thickness profile measured by Koffman and Plesset may not be the same as for the Gunther and Kreith data, a sensitivity study to the profile was performed. Koffman [5] shows that the overall microlayer evaporation is relatively insensitive to the initial profile. This unexpected result differs from that of Plesset and Prosperetti who found great sensitivity to the initial thickness (when assumed uniform). We also included the kinetic theory evaporative mass flux correction of 1.66 and found very little difference. In fact, the results were even less sensitive to the initial profile for this case. As a result of this lack of sensitivity to initial microlayer profile, we have good reason to believe that microlayer evaporation can account for 30-40% of the heat transfer in the Gunther and Kreith data, with 40% being the most probable estimate based on our present knowledge of initial microlayer profile.

Conclusions

- A finite difference formulation has been developed which is capable of tracking a one-dimensional moving boundary with a nonequilibrium interfacial boundary condition.
- The integral method of Plesset and Prosperetti is found to overpredict the initial evaporation rates, especially for thicker microlayers. However, their overall heat transfer calculation is not greatly affected by this error.
- By accounting for the microlayer profile in the model of Plesset and Prosperetti, we have shown that the contribution of microlayer evaporation is much larger than they predicted. Furthermore, our result is relatively insensitive to choice of initial microlayer profile.
- The correction factor of 1.66 to the kinetic theory evaporative mass flux expression is shown to change detailed calculations by only 10-20% and overall heat transfer results are less affected.
- Based on our present knowledge of initial microlayer profile, we estimate that microlayer evaporation accounts for about 40% of the heat transfer per bubble for the data reported by Gunther and Kreith.

References

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3rd Multi-Phase Flow and Heat Transfer Symposium - Workshop
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MICROLAYER EVAPORATION IN SUBCOOLED NUCLEATE BOILING

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ABSTRACT

The role of microlayer evaporation as a heat transfer mechanism in highly subcooled nucleate boiling is considered. The model of Plesset and Prosperetti is extended to account for microlayer profile. The measurements of Koffman and Plesset provide a reasonable estimate for the initial microlayer profile. The experiments of Gunther and Kreith are used as a basis for the analysis and conclusions. The contribution of microlayer evaporation is found to represent about 40% of the total heat transfer per bubble. Furthermore, this result does not appear to be very sensitive to the estimate of the initial microlayer profile.

1. INTRODUCTION

The problem of concern in the present study is the role of microlayer evaporation as a heat transfer mechanism in highly subcooled nucleate boiling. Essentially two mechanisms, microlayer evaporation and microconvection, have been advanced to explain the very high heat transfer rates observed in highly subcooled nucleate boiling. Both mechanisms are associated with the growth and collapse of vapor bubbles at the solid surface. As a vapor bubble grows at a solid surface a thin film of liquid, the microlayer, is left beneath the hemispherical bubble. This microlayer, which is on the order of a few micrometers in thickness, may evaporate during the bubble lifetime and transfer substantial energy through the latent heat of vaporization. Microconvection refers to an increased convective heat transfer due to the local fluid motion at the solid surface associated with the bubble dynamics. The relative roles of these two mechanisms in nucleate boiling have been studied by numerous investigators but most studies have dealt with near saturated and slightly subcooled boiling. Few studies have considered the case of highly subcooled nucleate boiling and the available conclusions are contradictory.

The experiments of Gunther and Kreith [1] and Gunther [2] have been used as the basis for analysis of the heat transfer mechanisms in highly subcooled nucleate boiling. These investigators report single bubble radius as a function of time as well as bubble population, bubble frequency, nominal wall temperature and heat flux, and liquid subcooling. These data can be used to analyze the role of a single vapor bubble in the heat transfer. On the basis of observed vapor bubble volume Gunther and Kreith attributed only 1-2% of the heat transfer to the latent heat of vaporization requirement and hence they argued that microconvection was the dominant heat transfer mechanism. A few years later the postulated existence of the microlayer and the proposed microlayer evaporation mechanism [3] led to a reexamination of the Gunther and Kreith data. Bankoff [4-6] considered microlayer evaporation as well as possible condensation over the bubble cap extending into the subcooled liquid (so that latent heat transport could be significantly greater than observed vapor volume). He suggested that the role of latent heat transport was an order of magnitude greater than previously estimated by Gunther and Kreith. Snyder and Robin [7-9] proposed an elaborate model from which they attributed nearly 100% of the heat transfer to microlayer evaporation. Recently, Plesset and Prosperetti [10] have proposed a direct model for the analysis of microlayer evaporation in the Gunther and Kreith data. They came to the conclusion that microlayer evaporation could account for only 10-20% of the heat transfer which is somewhat surprising since in recent years it has often been assumed that at high subcooling microlayer evaporation would be the dominant mechanism.

In the present study the model of Plesset and Prosperetti is extended to include some features which may impact on their conclusion. The primary extension is the inclusion of the microlayer profile for which the recent measurements of Koffman and Plesset [11] may be used. Plesset and Prosperetti used an approximate integral technique to solve the moving boundary problem and we have compared this solution to a more accurate finite difference solution. Finally, the kinetic theory expression for evaporative mass flux at an interface has been the subject of recent controversy and we consider the impact of a modified expression. The preliminary results reported here indicate that microlayer evaporation may account for 30-40% of the heat transfer in the Gunther and Kreith data.

2. FORMULATION OF THE MODEL

In the following the basic model of Plesset and Prosperetti is retained and the extensions and differences of the present study are noted. The microlayer is formed during rapid bubble growth but, as Cooper and Lloyd [12] have pointed out, because the microlayer is so thin it may be assumed that the viscous forces rapidly damp out any radial motion. Hence the microlayer evaporation may be treated as a transient heat conduction moving boundary problem. Furthermore, since the microlayer is thin compared to the radius of the bubble it is reasonable to assume that conduction in the radial direction is negligible compared to conduction normal to the wall. Hence a one dimensional form of the heat equation is sufficient to calculate microlayer evaporation at a given radial location,

$$\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial z^2} \quad ,$$

where D is the thermal diffusivity of the liquid. For the initial condition we assume that the microlayer is initially at the wall temperature T_W. The Gunther and Kreith data were taken on stainless steel strips and Plesset and Prosperetti have shown that a constant wall temperature may be assumed since stainless steel has a high thermal conductivity compared to water.

The proper choice of an interfacial boundary condition presents some difficulty. In many moving boundary problems the interfacial temperature is set equal to the saturation temperature. However, for the Gunther and Kreith data the wall is superheated about 30-35°C and nonequilibrium at the interface may be quite important. For this type of situation Plesset [13] has suggested use of the Hertz-Knudsen formula from kintic theory which gives the evaporative mass flux J as

$$J = \alpha(2\pi R T_b)^{-1/2} \, [p^e(T_b) - p_v] \qquad (1)$$

where α is the accommodation coefficient for evaporation, R is the universal gas constant divided by the molecular weight of the vapor, T_b is the liquid interfacial temperature, $p^e(T_b)$ is the equilibrium vapor pressure at temperature T_b, and p_v is the pressure in the vapor at the interface. For the case of bubble dynamics Plesset and Prosperetti [14] have shown that p_v in (1) may be taken to be the internal pressure in the bubble, $p_i(t)$. The value of the accommodation coefficient is not well known but is taken to be unity since the microlayer is a freshly formed surface. The mass flux J can be used in an energy balance at the interface,

$$-k \frac{\partial T}{\partial z} = LJ \quad ,$$

where L is the latent heat of vaporization.

While the Hertz-Knudsen formula (1) has often been used, it was suggested by Schrage [15] some time ago that the expression for J should actually be larger by a factor of about 2 to account for the effect of a mean flow. More recent kinetic theory calculations suggest the correction should be 1.665 although the theory is still controversial [16]. Since there seems to be some agreement on the functional form in (1) and disagreement only in the numerical coefficient, the effect of a correction of 1.665 is considered in the present study.

A needed input in the problem formulation is the initial microlayer thickness δ_0 which can be regarded as a function of the bubble growth rate. Few measurements of microlayer thickness are available, especially for the case of water. The only detailed measurements of microlayer profile available are due to Cooper and Lloyd [12] for toluene and isopropyl alcohol, Voutsinos and Judd [17] for methylene chloride, and Koffman and Plesset [11] for water and ethanol. These latter measurements were unavailable to Plesset and Prosperetti and they chose to assume that the microlayer maintained a uniform thickness $\delta(t)$ over the base of the bubble; they then ran a sensitivity study to the initial microlayer thickness δ_0. In the present study the measurements of Koffman and Plesset are used to provide a more accurate input for the initial microlayer profile.

The remaining unknown in the problem is the internal pressure in the bubble, $p_i(t)$, which appears in (1) for the mass flux J. The internal bubble pressure couples the microlayer evaporation to the bubble dynamics. Gunther and Kreith observed that the vapor bubbles maintained a hemispherical shape while they grew and collapsed at the solid surface. In this case it is reasonable to apply the Rayleigh-Plesset equation which governs spherical bubble growth,

$$R \frac{d^2R}{dt^2} + \frac{3}{2} \left(\frac{dR}{dt}\right)^2 = \frac{1}{\rho} \left[p_i(t) - p_\infty - \frac{2\sigma}{R}\right] \quad , \qquad (2)$$

where $R(t)$ is the bubble radius, σ is the surface tension, p_∞ is the ambient pressure, and ρ is the liquid density. Plesset and Prosperetti used the data of Gunther and Kreith for $R(t)$ to compute $p_i(t)$ from (2). With $p_i(t)$ known the problem is closed.

We summarize the model used by Plesset and Prosperetti:

- uniform thickness microlayer $\delta(t)$ with initial thickness δ_0 given

- transient heat conduction in the microlayer $\frac{\partial T(z,t)}{\partial t} = D \frac{\partial^2 T(z,t)}{\partial z^2}$ (3)

- initial condition (microlayer at wall temperature) $T = T_w$ at $t = 0$ (4)

- wall boundary condition $T = T_w$ at $z = 0$ (5)

- interfacial boundary condition $-k \frac{\partial T}{\partial z} = LJ$ at $z = \delta(t)$ (6)

- kinetic theory mass flux $J = (2\pi RT_b)^{-1/2}[p^e(T_b) - p_i(t)]$ (7a)

  where $T_b(t) = T(\delta(t),t)$

- microlayer evaporation (moving boundary) $\frac{d\delta}{dt} = \frac{-J}{\rho}$ (8)

- $p_i(t)$ known from $R(t)$ data used in (2).

In order to evaluate the contribution of microlayer evaporation, the total latent heat extracted from the microlayer, Q, is compared to the heat transfer per bubble reported by Gunther and Kreith. The evaporating area of the bubble base as a function of time must be accounted for in determining Q. For the uniform thickness microlayer Plesset and Prosperetti add to the above model the equation

$$\frac{dQ}{dt} = \pi R^2 LJ \quad . \tag{9}$$

Figures 1 and 2 are presented as an example of such a calculation by Plesset and Prosperetti. In Fig. 1 the $R(t)$ data of Gunther and Kreith are shown along with the parabolic curve fit used in (2) to determine $p_i(t)$. The total heat extracted from the microlayer, Q, is plotted as a function of the assumed initial microlayer thickness δ_0 in Fig. 2. The total energy per bubble from Gunther and Kreith is also shown in Fig. 2. These results will be discussed subsequently when compared to the present results.

In the present study the basic model of Plesset and Prosperetti, equations (3)-(8), is retained. The correction to the kinetic theory mass flux may be included by replacing (7a) with

$$J = 1.665\ (2\pi RT_b)^{-1/2}[p^e(T_b) - p_i(t)] \quad . \tag{7b}$$

The primary extension of the model is the inclusion of a microlayer profile rather than assuming a uniform thickness profile. Since radial conduction is assumed negligible compared to conduction normal to the plate we may use the above model at various radial positions from which a picture of the overall microlayer evaporation can be obtained. We note that the calculation at each radial position depends on the time at which the bubble growth reaches that position which in turn couples the microlayer evaporation to the existing internal bubble pressure.

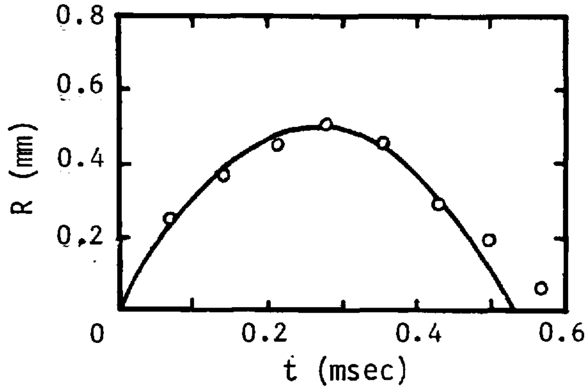

Fig. 1. The circles are observed values for bubble radius, R(t), from Gunther and Kreith [1]. The line is the fit to the data used in the analysis of Plesset and Prosperetti [10]. Experimental conditions: $T_W = 132.2°C$, $T_\infty = 36.7°C$, $q = 3.26$ MW/m², bubble density = 43 bubbles/cm², bubble frequency = 1000 bubbles/sec.

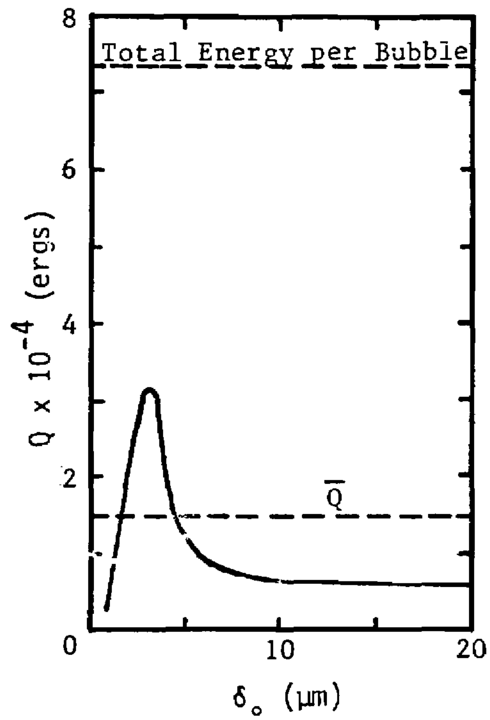

Fig. 2. The calculated total heat, Q, extracted from the microlayer over a single bubble lifetime is shown as a function of the initial thickness δ_0. (From Plesset and Prosperetti [10].)

3. COMMENTS ON THE SOLUTION TECHNIQUE

Equations (3)-(8) with given δ_0 and given $p_i(t)$ represent a well defined problem. The governing heat equation is a partial differential equation in time and one space variable and a numerical solution is required for this nonlinear problem. Plesset and Prosperetti chose to use an approximate integral method in which a parabolic profile is assumed for the temperature. The spatial dependence could then be eliminated and the set of ordinary differential equations in time are solved with a Runge-Kutta method. Although the approximate integral method often gives good results, the parabolic profile appears to be fairly crude for this problem. We felt that the accuracy of this method should be checked with a finite difference solution.

Several methods for solving moving boundary problems can be found in the literature. For the one-dimensional problem considered here, a fixed grid variable time step implicit finite difference formulation was chosen. This approach is simple to formulate, the position of the moving boundary is tracked directly, and the implicit formulation provides good accuracy and stability with a relatively course grid so that computing time is minimized. A fixed uniformly spaced grid is used and an iteration is performed on the time step so that the interface moves precisely to the next nodal point. The basis for the iteration is the energy balance at the interface given by (6). The evaporative mass flux J is very sensitive to the liquid interfacial temperature T_b so that a Newton-Raphson method must be used to obtain convergence to the time step.

The method described above has been successfully developed to solve the microlayer evaporation model; the details of the calculation are presented elsewhere [18]. Fig. 3 shows the calculation of the microlayer evaporation for an initial microlayer thickness of δ_0 = 1μm and Fig. 4 for δ_0 = 10μm. In each figure the results of the approximate integral method of Plesset and Prosperetti and the present finite difference method are shown as applied to equations (3)-(8). In addition, a finite difference solution is given for the model in which the interface is taken to be at saturation temperature; in this case (7) is replaced by the condition $T = T_{sat}$ at $z = \delta(t)$ and the energy balance (6) is still used as the basis for the iteration on the time step.

For the thin microlayer in Fig. 3 it is apparent that the integral method agrees well with the finite difference method. However for the thick microlayer in Fig. 4 the integral method differs considerably from the finite difference method. We note that the solution shapes differ near the beginning of the calculation but are similar near the end for both figures. Plesset and Prosperetti broke the solution into two parts: the solution before the wall effect is felt and the solution after the thermal layer reaches the wall. It appears that the profile in the first part may be too crude and the error from this part becomes more pronounced as the initial microlayer thickness increases.

The comparison of the T_{sat} boundary condition with the evaporative flux boundary condition is interesting. For the thick microlayer in Fig. 4 there is little difference between the two solutions. This is not surprising since the wall effect is small and the interface rapidly reaches equilibrium. However, for the thin microlayer in Fig. 3 nonequilibrium at the interface is significant and the T_{sat} solution overestimates the rate of evaporation. It seems clear that the nonequilibrium condition should be used to correctly model

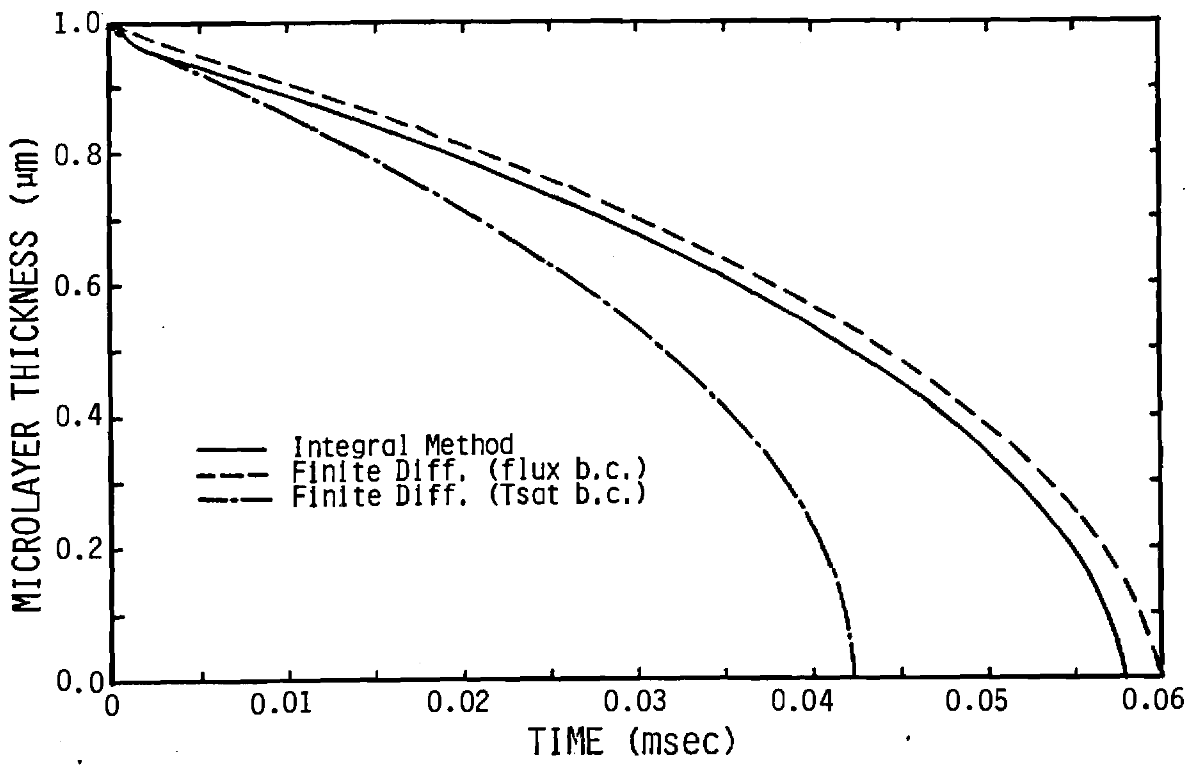

Fig. 3. Calculation of microlayer evaporation for an initial microlayer thickness of δ_0 = 1 μm.

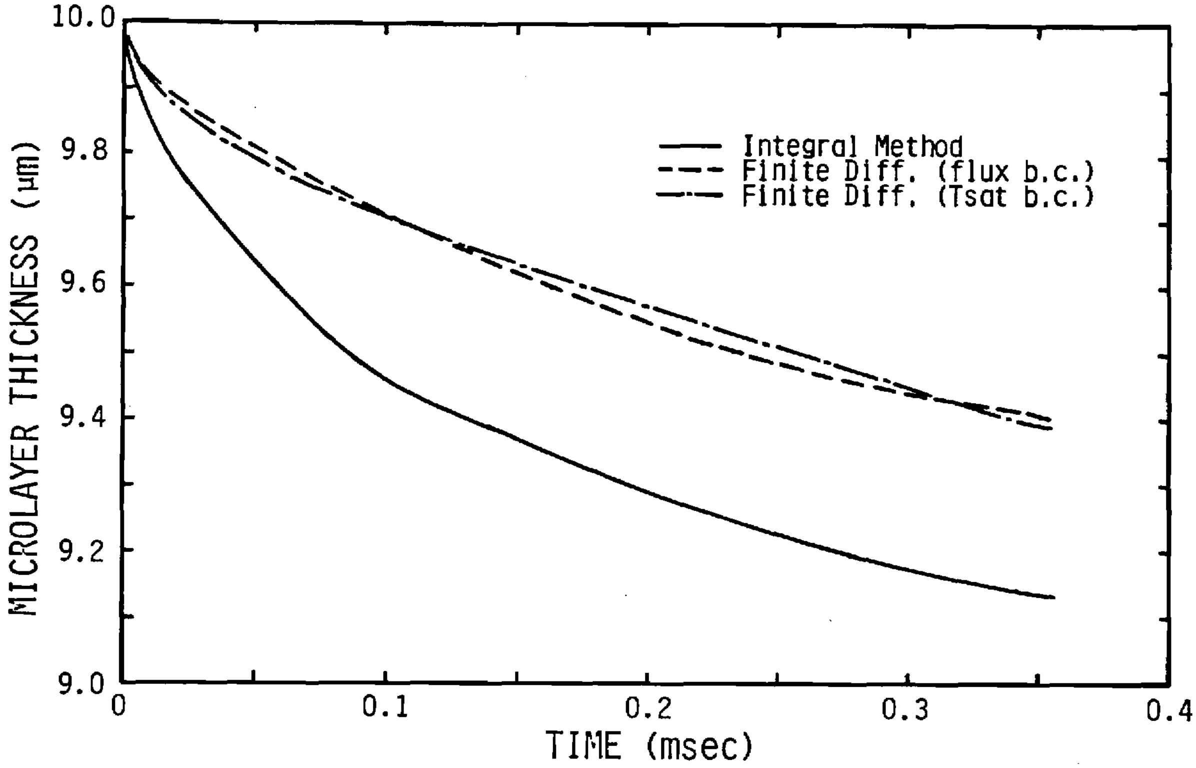

Fig. 4. Calculation of microlayer evaporation for an initial microlayer thickness of δ_0 = 10 μm.

the thin portion of the microlayer. This point may be quite important in trying to compare detailed measurements of microlayer evaporation with a model.

4. RESULTS

We have considered the same bubble shown in Fig. 1 in the following calculations. The initial microlayer thickness profile is taken from the measurements of Koffman and Plesset [11] shown in Fig. 5. In this figure the microlayer profile is shown at sequential instants of time. This data gives the initial microlayer thickness and the microlayer evaporation. We note that the experimental conditions in Fig. 5 are quite different than those in Fig. 1. However, the bubble growth rates are similar and since microlayer formation is thought to be a function of bubble growth rate we may reasonably assume that the initial microlayer profiles are similar. With the initial microlayer profile known, we solve equations (3)-(8) at various radial locations from which we can form a plot similar to Fig. 5. The result of this calculation is shown in Fig. 6. We have used Plesset and Prosperetti's integral method in constructing Fig. 6 but since the microlayer is thin we can expect reasonable results as discussed in the last section.

In Fig. 6 the initial microlayer profile is shown as a dashed line. Equations (3)-(8) were solved at twenty evenly spaced radial positions. At each radial position we plotted the position of the microlayer at sequential instants of time taken in increments of 0.015 msec. We then connected the points corresponding to each instant of time to give a picture of the microlayer profile at sequential instants of time. The similarity between the calculation in Fig. 6 and the experimental measurement in Fig. 5 is quite encouraging although no direct comparison can be made because of the widely

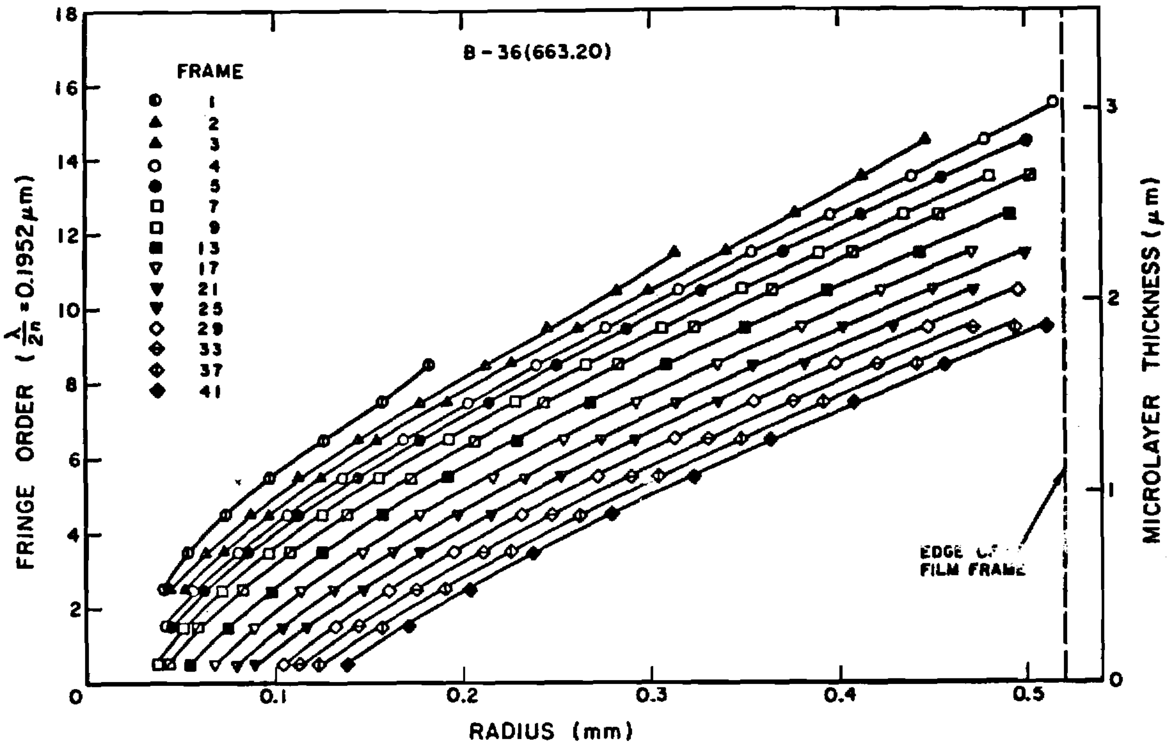

Fig. 5. Observed microlayer profiles for a water vapor bubble at atmospheric pressure with a mean heat flux of 204 kW/m² and a subcooling of 21.7°C; 0.066 msec/frame. (From Koffman and Plesset.)

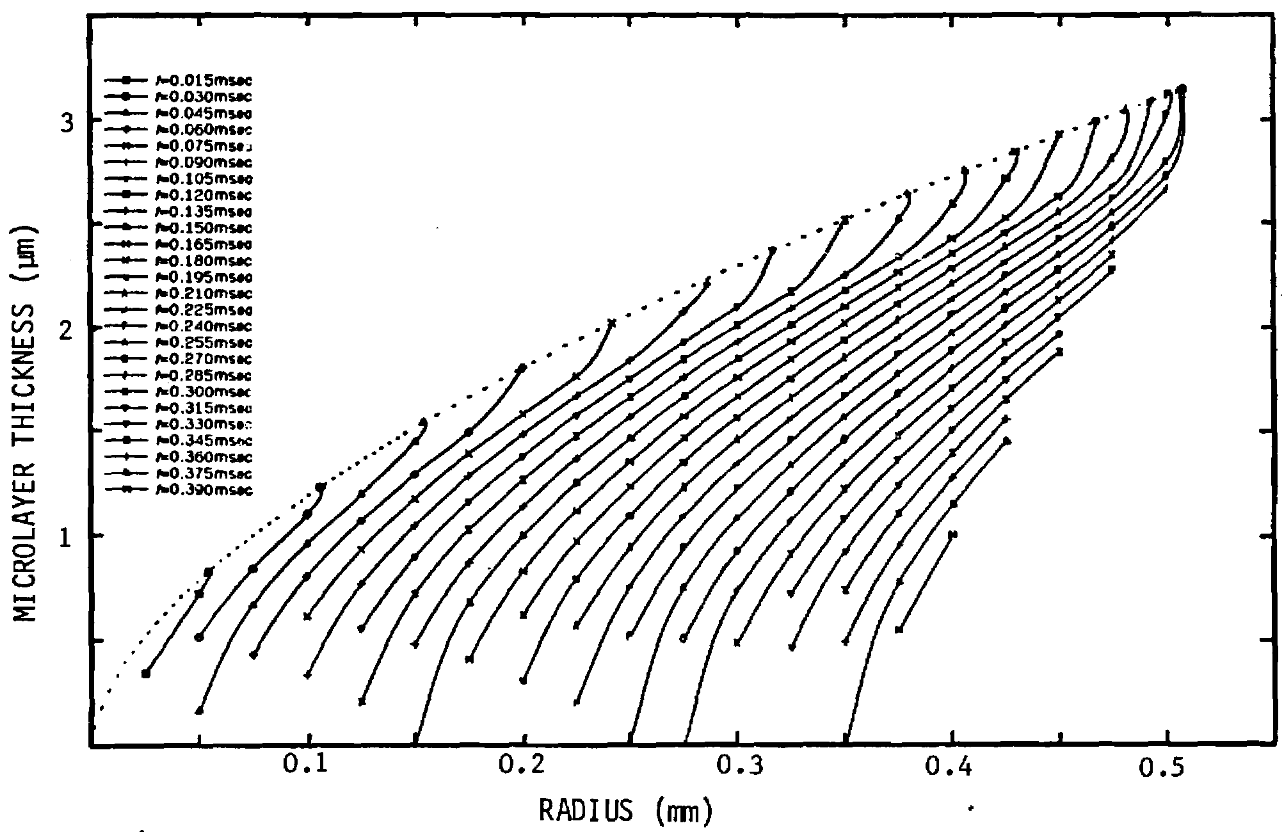

Fig. 6. Calculated microlayer profiles for the bubble growth, R(t), shown in Fig. 1 and for the initial microlayer profile given by the dashed line. The solid lines depict the microlayer profile at sequential instants of time in increments of 0.015 msec.

different experimental conditions.

From Fig. 6 we can determine the total evaporation and hence the total latent heat extracted from the microlayer. The resulting value of 2.9×10^4 ergs can be compared to Fig. 2. We see that this value represents approximately 39% of the total heat transfer per bubble. Plesset and Prosperetti estimated the order of magnitude of the initial microlayer thickness to be 9μm and thus concluded from Fig. 2 that the microlayer contribution was only about 9% for their uniform thickness model. They also performed a calculation to estimate the effect of a profile and this result is denoted as $\bar{Q}$ in Fig. 2; this calculation gave a microlayer contribution of 21%. We see that the present calculation gives a significantly higher contribution of microlayer evaporation.

We note that had Plesset and Prosperetti assumed an initial microlayer profile of 3μm that their conclusion from Fig. 2 would be quite different and more in line with the present result. A difficulty with their uniform thickness model is that the microlayer thickness is decreasing as the bubble base radius increases. Since this is counter to the experimental observation it is not clear how their initial microlayer thickness should be compared to experimental measurements.

Another feature of Fig. 2 is that the result for Q is very sensitive to the choice of initial microlayer thickness. Because we are estimating the initial microlayer profile it is of interest to consider the sensitivity of our result to changes in the initial microlayer profile. To consider this sensitivity we have modified the curve fit to the initial microlayer profile used in Fig. 6 as

$$\delta_0 = C\ (0.00188\ R^{0.6}) \tag{10}$$

where R and δ_0 are both in centimeters. The value of C = 1 corresponds to the curve shown in Fig. 6 and by varying C we can consider thicker and thinner initial microlayer profiles. The result of the calculations for various values of C is given in Fig. 7. We see that Q is much less sensitive to the initial profile than is indicated in Fig. 2. For values of C in the range $0.6<C<3.0$ we see that the calculated contribution of microlayer evaporation is 30-40% of the total heat transfer per bubble.

We have considered the correction to the kinetic theory mass flux by using (7b) in place of (7a) in the previous calculations. The results are given in Fig. 8 and can be compared to Fig. 7. We see that there is some effect of the correction but it is not dramatic. The calculated Q is even less sensitive to C in this case and the contribution of microlayer evaporation is seen to be about 40% of the total heat transfer per bubble.

5. CONCLUSIONS

The model of Plesset and Prosperetti used to analyze microlayer evaporation for the Gunther and Kreith data has been extended to include the microlayer profile. Using data for one case from Gunther and Kreith and using the measured initial microlayer profile of Koffman and Plesset, we have found that the contribution of microlayer evaporation represents about 40% of the total heat transfer per bubble. This is to be compared to Plesset and Prosperetti's estimate of 21%. Furthermore, while Plesset and Prosperetti found their results to be very sensitive to the initial microlayer thickness, we have found that inclusion of the microlayer profile reduces this sensitivity.

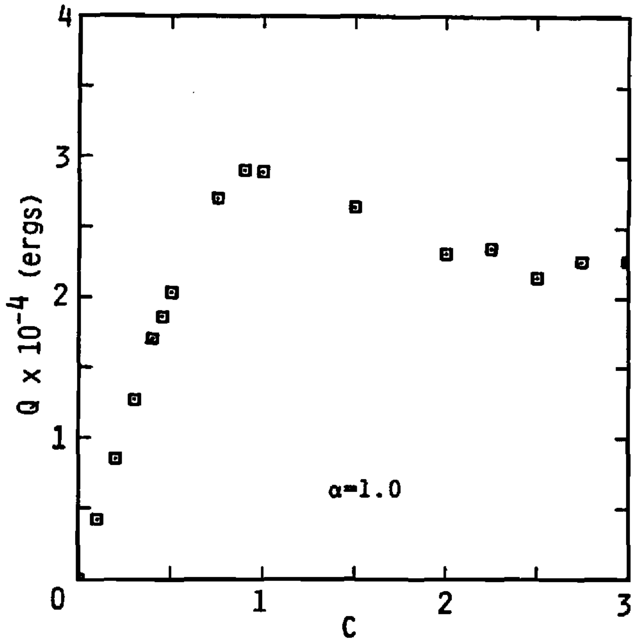

Fig. 7. The calculated total heat, Q, extracted from the microlayer as a function of the thickness parameter, C, used in Eqn. (10). The Hertz-Knudsen formula, Eqn. (7a), is used.

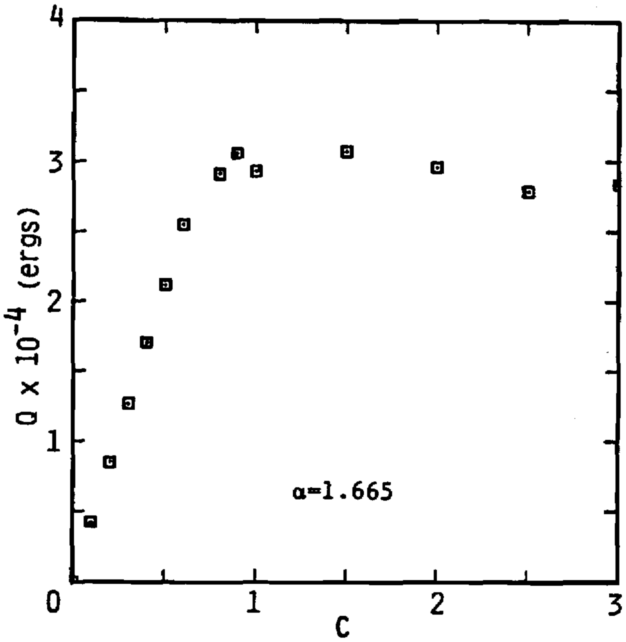

Fig. 8. The calculated total heat, Q, extracted from the microlayer as a function of the thickness parameter, C, used in Eqn. (10). The modified kinetic theory mass flux, Eqn. (7b), is used.

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