ABSTRACT

Binary mixture pool boiling has been extensively studied in literature, and there are well established models to predict the effects of mass diffusion and interfacial temperature rise on the bubble growth and associated heat transfer phenomena. The present work focuses on obtaining the bubble growth and heat transfer characteristics of pure water and water/ethylene glycol mixtures during subcooled flow over a 9.5 mm dia circular heater placed in a narrow channel of 3 mm x 40 mm cross section. The bubble growth is observed using a high speed camera (1000 fps) under a magnification of 290X. The bubble growth is seen to slow down considerably in binary mixtures. The experimental results for the bubble growth rate under flow conditions are compared with the models developed for binary pool boiling conditions. The pool boiling models are observed to apply reasonably well in the early stages of bubble growth.

The heat transfer rate and its dependence on the wall superheat is investigated for the binary mixtures. The heat transfer characteristics are significantly different from those observed for the pure components. The transition to nucleate boiling dominant region at higher wall superheats is affected considerably for binary mixtures. Experimental data is presented showing these effects.

1. INTRODUCTION

Binary fluid mixtures are simply mixtures of two pure fluids. With the exception of any azeotropic points, the saturation temperature of these binary mixtures exhibits a characteristic dependence on the mixture quality and concentration; as the more volatile component of the mixture evaporates at a faster rate, the resulting change in concentration of the phases causes an increase in the saturation temperature.

This behavior can be taken advantage of in the evaporators of highly-efficient refrigeration systems. By using binary mixtures, the temperature in the evaporator can be maintained fairly constant in spite of a decreasing pressure along the length of the evaporator. This would reduce the second law inefficiencies in refrigeration systems. Unfortunately, binary fluids exhibit a significant reduction in the heat transfer coefficient which accompanies boiling, as compared with pure fluids boiling under similar conditions.

This experimentally observed suppression in the flow boiling heat transfer coefficient can be attributed to the differing thermophysical properties of the binary fluids and, uniquely to the binary case, to the effects due to concentration gradients existing around a growing bubble. The current work investigates this suppression in bubble growth rates and heat transfer coefficients for a subcooled flow boiling system of a water and ethylene glycol binary mixture.

Mechanisms controlling bubble growth have been extensively studied in the current literature for conditions of no bulk flow (pool boiling). However, many practical cases involve bulk flow of the liquid and vapor mixture. This flow boiling situation is significantly more complicated, and not as well understood.

2. LITERATURE REVIEW

The empirically observed binary suppression of bubble growth rate and heat transfer coefficient is due in large part to the added effect of mass species...
diffusion in the fluid adjacent to the growing bubble. This section investigates the current literature background pertaining to bubble growth regulating mechanisms which operate in the region of fluid about the growing bubble.

The binary diffusion mechanism takes place in the liquid adjacent to the vapor/liquid interface of a growing bubble. Concentrating our attention on the events in this region, theories pertaining to the growth of free bubbles are considered. Incidental effects, such as the presence of a heating surface, the effect of a nonuniform temperature distribution, or cyclical time varying effects are not considered here.

Table 1 presents a summary of some of the important theories available which deal with the free bubble growth problem. All the theories presented share the same fundamental criterion for bubble growth; Bubble growth will occur when the temperature at the bubble interface is greater than the local saturation temperature at this interface.

Rayleigh’s (1917) model, listed in Table 1, considers only the effect of inertia on bubble growth in pure fluids. Inertial acceleration of the liquid surrounding a growing bubble results in an increase of the local pressure at the interface and hence the interface saturation temperature. Setting the local saturation temperature equal to the bulk liquid temperature, and solving the resulting differential expression results in the bubble growth rate equation. Characteristic of a model incorporating only inertial effects, it expresses a bubble growth rate which is constant in time.

The four items in Table 1 following the Rayleigh model, due to Bosnjakovic (1979), Forster and Zuber (1954), Plessset and Zwick (1954), and Scriven (1959), consider only the effect of thermal diffusion in the pure fluid adjacent to the growing bubble. Heat flux from the bulk fluid to the bubble interface required to satisfy the latent heat of the evaporating fluid results in a temperature gradient about the bubble. This reduces the superheat available at the bubble interface from that of the bulk fluid, regulating the bubble growth rate. Considering the transient thermal conduction, and again setting the bubble interface temperature equal to the local saturation temperature results in a differential expression for the bubble growth rate. Solution of this differential form results in the bubble radius versus time equations, the differences in the equations among the various researchers due to different simplifying assumptions in the solution. Bubble radius is proportional to the square root of time, hence the term asymptotic growth.

Mikic (1970) combined the thermal and inertial models into a single expression for bubble radius versus time in pure fluids. The inertial effect is dominant in the early stages of bubble growth following nucleation, after which the thermal diffusion effect becomes dominant for the remainder of the bubble’s growth life. In Mikic’s expression, a unity value of the nondimensional time $t^*$ corresponds to that point in the bubble growth where the effects of inertia and diffusion are equally effective in controlling the bubble growth rate.

Van Stralen (1979) obtained an expression for the bubble growth in a binary mixture by taking advantage of the analogous nature of mass diffusion and thermal energy diffusion in the liquid. The Plesset and Zwick (1954) expression was extended by taking a modified Jacob number, which compensated for the additional effect of the increase in interface saturation temperature caused by mass concentration gradients about the bubble.

This modified Jacob number gives an indication of the magnitude of the suppression caused by mass diffusion in binary mixtures. As can be seen from the Note 3 in Table 1, the suppression in binary mixtures is related to the ratio of mass to thermal diffusion coefficients and to the $\Delta T/G$ ratio.

3. OBJECTIVES OF PRESENT WORK

In this research, experiments are conducted to obtain the bubble growth and heat transfer characteristics for the subcooled flow boiling of a water and ethylene glycol binary mixture. Data are collected at three distinct concentrations of the mixture to isolate the effects of concentration on the bubble growth and heat transfer.

The suppression in bubble growth rates observed in the present data is related to Van Stralen's diffusion model of binary suppression resulting from mass species diffusion. Van Stralen's diffusion model is for pool boiling; the validity of this pool boiling model in the experimental conditions of subcooled flow boiling is investigated.

Suppression in the experimental heat transfer coefficient is examined, with emphasis on the observed decrease in the heat transfer due to nucleate boiling for the mixtures.

4. EXPERIMENTAL INVESTIGATION

The experimental arrangement used to collect the bubble growth and heat transfer data consists of a test section with a heated and instrumented test surface in contact with the test fluid, a circulating and temperature control system used to establish overall experimental conditions, and the necessary instrumentation for acquisition of the experimental
data. It is very similar to the experimental arrangement employed by Stumm (1994) in his research.

The working fluid is pumped through a 3 mm x 40 mm rectangular channel formed in an aluminum test section, as shown in Figure 1. A 9.5 mm diameter aluminum test surface, insulated from the bulk of the test section and electrically heated from below, is in contact with the working fluid at the approximate midpoint of the channel length. A windowed observation port is provided directly above the test surface point.

A constant temperature circulating bath in combination with a system of control valves is used to maintain the temperature, bulk velocity, and pressure at the point of the test section.

The heated test element is shown in Figure 2. Only the top circular portion of the surface is in contact with the working fluid; the rest of the surface area is insulated. Thermocouples are provided at four points on the cylindrical shaft. Readings taken from these thermocouples are used to calculate the average heat flux to the working fluid and the temperature of the exposed surface, using a simple steady-state thermal model.

The test surface may be observed through a windowed port provided in the test section. A microscope and high-speed (1000 frame/sec) video camera arrangement is used to record the growing bubbles through the windowed port. Bubble diameters and growth rates are determined from an analysis of a recording taken from the high speed camera.

6. EXPERIMENTAL RESULTS
6.1. Experimental Data: Bubble Growth

Bubble growth rates and heat transfer coefficients for pure and binary fluids in flow boiling are measured in the present experimental investigation.

The bubble growth periods recorded in the present investigation were measured using a 1 ms frame period. The first frame taken was therefore anywhere from zero to one millisecond after the instant of nucleation. The first partial millisecond consists of a very small time interval in which the growth is extremely rapid, perhaps inertially controlled at the beginning. After less than one millisecond, the inertial growth controlling mechanism is typically dominated by the diffusion mechanism.

By referring to the Mikic et al. (1970) expression for the combined effects of inertial and diffusion controlled growth, reviewed in Section 2, a rough estimate of the time of transition between the inertial and diffusion controlled modes can be made for the pure fluid data. The binary fluid data would exhibit a smaller duration of inertial growth since diffusion is of a stronger influence on the bubble growth for binary fluids, assuming approximately equal fluid properties and test conditions. At a value of non-dimensional time $t'$ (referring to the Mikic equation in Table 1) equal to unity, the increase in bubble interface saturation temperature resulting from inertial forces is equal to the temperature drop across the thermal boundary layer on the bubble periphery: the effects of the inertial and diffusion controlling mechanisms can
be considered to be equal at this time. Therefore, \( t^* \) equal to unity can be taken as a demarcation between the inertially controlled and diffusion controlled growth modes. Solving for the dimensional time \( t \) corresponding to a unity \( t^* \) gives a value of 68 \( \mu \)s for water at 20\( ^\circ \)C superheat, which is the experimental condition where the inertial mechanism is strongest relative to that of diffusion. Since this value is considerably smaller than the 1 ms frame period, all bubble growth data in this work can be considered as in the diffusion controlled regime.

A typical set of bubble growth histories is presented in Figure 3. One data set for each of the three test mixtures is given, at typical experimental conditions. These results are qualitatively characteristic of all data obtained in this experimental investigation.

After reaching a maximum, the bubble diameter is seen to decrease, after which the bubble eventually collapses. The period between nucleation and bubble collapse was about 3 ms - 5 ms for bubbles growing in pure water, and considerably longer for bubbles in the binary mixtures. Comparing this period with the lifetime of inertial dominance calculated above shows that the diffusion controlling mechanism is strongly dominant on a time average basis for all experimental conditions in this work. This is also typically true for most practical applications of two-phase heat transfer [Van Stralen (1979)].

In the observed experimental conditions, after a growth period ranging from about 3 ms - 20 ms (this includes the binary fluid data, which had longer bubble growth periods), the bubble started to collapse. For most observed cases, the initial collapse period lasted several milliseconds. After several milliseconds of diffusion controlled collapse, the bubble imploded and disappeared. However, the collapse sometimes occurred in a period less than the 1ms frame rate of the high speed camera.

The period of growth which occurs in the early stage of the growth cycle is diffusion controlled, as per the discussion in the preceding paragraphs. As the bubble is growing through a temperature gradient in the boundary layer at the heating surface, the actual growth rate is complicated by the local velocity field, nonuniform temperature gradient, and transport of heat (and species) into the diffusion boundary layer which forms around the bubble.

However, as a first approximation, the pool boiling model should be applicable to the initial portion of the bubble growth cycle when the bubble growth velocity is large compared to the velocity of the fluid in the velocity boundary layer at the heating surface. This is verified by fitting a form of the pool boiling equation given by Plesset and Zwick (1954) which has been modified as shown:

\[
R(t) = A \left( \frac{12}{\pi} \right)^{1/2} J a_o [a(t + b)]^{1/2} \tag{1}
\]

\( A \) is a proportionality constant used in the curve fit and \( b \) is a value of time less than 1 ms which is used to compensate for the 1 ms resolution of the camera. Van Stralen’s expression for the Jacob number in binary mixtures, as reviewed in Section 2, is used for the mixtures.

In the curve fit, \( A \) was adjusted to give good agreement between experiment and theory for the initial portion of the bubble growth curve, and \( b \) was adjusted so that the initial diameters were equal. A typical result is shown in Figure 4. As can be seen, the parameter \( A \) is chosen such that agreement is good in
the first portion of the bubble growth history, although this analysis is limited by the 1 ms frame period used.

The mean values of the parameter $A$ for each experimental condition of bulk fluid concentration are given in Table 2. As can be seen, they are reasonably close to unity. This implies that the diffusion model inherent in the pool boiling theory is approximately valid in the initial portion of the bubble growth histories recorded. The increasing trend with increasing concentration shows that the binary suppression is slightly overestimated for mixtures by the pool boiling model. This may be due in part to the effect of species transport (due to the bulk flow in the flow boiling experiment) into the concentration boundary layer which forms around the bubble, and counteracts the influence of diffusion on the interface saturation temperature.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Mean A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water</td>
<td>.88</td>
</tr>
<tr>
<td>40% ethylene glycol</td>
<td>.91</td>
</tr>
<tr>
<td>80% ethylene glycol</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 2: Average parameter $A$ used to fit experimental bubble growth data

6.2. Experimental Data: Heat Transfer

Figures 5 and 6 show the experimental values of heat transfer coefficient for the experimental fluid and heater surface superheat conditions. Heat transfer coefficients shown in the figures are calculated with reference to the actual fluid temperature. Various trends in this data for both pure and binary fluids are investigated.

The trends in the pure fluid heat transfer coefficient are discussed here as a baseline for comparison with the binary fluid data. The four data conditions shown in the pure fluid chart of Figure 5 are: 95°C bulk temperature at Reynolds numbers of 3900 and 1300, and 80°C bulk temperature at Reynolds numbers of 3100 and 1000.

By taking the vertical axis intercept at low values of superheat, the single phase heat transfer coefficient can be approximated. This value is seen to be approximately 6800 W/m$^2$K for the high flow rate cases, and 3900 W/m$^2$K for the low flow rate data points (the Reynolds number is roughly indicative of the local flow rate and bulk velocity). Elevation of single-phase heat transfer coefficient with increasing Reynolds number is as expected, although correlation with the Reynolds number and bulk fluid properties is not straightforward for the thermally developing heat transfer regime at the heater surface.

For the pure water data, in the range of superheat below approximately 10°C, a gradual rise in the heat transfer coefficient is evident. This can be attributed to more nucleation sites being activated with an increasing mean thickness of the thermal boundary layer, as per the Hsu nucleation model (1962). At approximately 12°C superheat a sharp increase in heat transfer coefficient is obvious for all four combinations of Reynolds number and bulk subcooling. This point, the onset of nucleate boiling (ONB point), is marked by a sharp increase in the area density of active nucleating cavities, and a consequent rise in the heat transfer coefficient.

At superheat values below the ONB point, the Reynolds number has a strong impact on the overall heat transfer coefficient. This is because the single
phase convection mechanism is still dominant in this regime; referring again to Figure 5, the difference in heat transfer coefficient values between the high and low flow rate cases can be seen to be approximately constant up to the ONB point.

For values of superheat beyond the ONB point, the difference in heat transfer coefficient for the high and low flow rate cases fades. The effect of bulk flow rate on local subcooled boiling is complicated and not well treated in literature even for pure fluid cases, however the general trend is as expected since the heat flux at the surface due to nucleate boiling activity will typically be considerably greater than the single phase values for points beyond the ONB threshold.

By comparing the binary data of Figure 6 with the pure fluid data of Figure 5, a considerable suppression of the heat transfer coefficient in the binary fluid data is obvious. This suppression is stronger for the 80% glycol solution than for the weaker 40% solution. Single phase values are somewhat lower for the binary fluid cases, which is reasonable given the variation in Reynolds number and fluid conductivity between the mixtures. Much more significant is the suppression of the sharp rise in heat transfer coefficient at the ONB point. Nucleate boiling is suppressed in the strong (80% glycol) mixture to such an extent that an explicit ONB point is not obvious from the data.

It is obvious from the data that nucleate boiling heat transfer coefficients are suppressed in binary mixtures. The suppression is roughly related to the value of \( \Delta T/G \) at the bulk solution concentration; suppression will be strongest at mixture concentrations which have a maximal \( \Delta T/G \) ratio [Van Stralen (1979)].

The suppression of diffusion controlled bubble growth rates in pool boiling of binary mixtures is also well documented in the literature, and has been quantified by Van Stralen and others by referring to the diffusion laws, as covered in Section 2. Similar to the suppression of heat transfer coefficient, this suppression of bubble growth rate is also related to the \( \Delta T/G \) ratio.

7. CONCLUSIONS

8. NOMENCLATURE

Standard Symbols
- \( A \) Proportionality Constant
- \( B \) Intermediate Constant in Mikic Solution
- \( C \) Concentration of Ethylene Glycol in Bulk
- \( b \) Correction Constant
- \( c \) Mass Specific Heat of Bulk Liquid
- \( G \) Vaporized Mass Diffusion Constant
- \( h_{fg} \) Latent Heat of Evaporation
- \( J_a \) Jacob Number
- \( J_{a_0} \) Modified Jacob Number
- \( l \) Latent Heat of Evaporation
- \( R, r \) Bubble Radius
- \( R' \) Nondimensional Radius
- \( \Delta T \) Saturation Temp Elevation in Mixture
- \( T \) Interface Temperature, Temperature
- \( t \) Time
- \( t' \) Nondimensional Time
- \( x \) Mass Concentration in Liquid
- \( x_o \) Mass Concentration in Bulk Fluid
- \( y \) Mass Concentration in Vapor

Greek Symbols
- \( \alpha \) Heat Transfer Coefficient
- \( \kappa \) Thermal Diffusivity of Bulk Liquid
- \( \lambda \) Thermal Conductivity of Bulk Liquid

9. REFERENCES


Table 1: Summary of relevant bubble growth models available in the literature.

<table>
<thead>
<tr>
<th>Researcher, Year</th>
<th>Bubble Growth Equation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh, 1917</td>
<td>[ R(t) = \left( \frac{2\rho_c h_{fg} \theta_0}{3\rho_l T} \right) t^{1/2} ]</td>
<td>Consideration of only inertial effect on bubble growth. Derived from a force balance and Clausius-Clapeyron relation between saturation pressure and temperature.</td>
</tr>
<tr>
<td>Bosnjakovic, 1979</td>
<td>[ R(t) = \frac{2}{\pi^{1/2}} Ja(\alpha t)^{1/2} ]</td>
<td>Consideration of only thermal diffusion effect on bubble growth. Derived from transient thermal conduction considerations. Simple mathematical derivation ignoring the effect of bubble curvature. (Note 1)</td>
</tr>
<tr>
<td>Forster and Zuber (1954)</td>
<td>[ R(t) = Ja(\pi \alpha t)^{1/2} ]</td>
<td>With thermal diffusion considerations as in Bosnjakovic model (asymptotic growth stage). (Note 1).</td>
</tr>
<tr>
<td>Plesset and Zwick (1954)</td>
<td>[ R(t) = \left( \frac{12}{\pi} \right)^{1/2} Ja(\alpha t)^{1/2} ]</td>
<td>With thermal diffusion considerations as in Bosnjakovic model (asymptotic growth stage). (Note 1).</td>
</tr>
<tr>
<td>Scriven (1959)</td>
<td>[ R(t) = \left( \frac{12}{\pi} \right)^{1/2} Ja(\alpha t)^{1/2} ]</td>
<td>With thermal diffusion considerations as in Bosnjakovic model (asymptotic growth stage). (Note 1).</td>
</tr>
<tr>
<td>Mikic et al., 1970</td>
<td>[ R^+ = \frac{2}{3} \left[ (t^+ + 1)^{3/2} - (t^+)^{3/2} - 1 \right] ]</td>
<td>Mathematical combination of Plesset-Zwick (thermal diffusion) and Rayleigh (inertial) models. (Notes 1 and 2).</td>
</tr>
<tr>
<td>Van Stralen (1979)</td>
<td>[ R(t) = \left( \frac{12}{\pi} \right)^{1/2} Ja_o(\alpha t)^{1/2} ]</td>
<td>Consideration of thermal diffusion and mass species diffusion (binary fluid) effects on bubble growth. Uses analogous nature of thermal and species diffusion phenomena to derive an equivalent Jacob number which accounts for additional species diffusion effect. (Note 3).</td>
</tr>
</tbody>
</table>

1. Ja is the Jacob number, a nondimensional bubble growth parameter defined as
   \[ Ja = \frac{\rho_c c}{\rho_c h_{fg}} \theta_0 \]

2. Expressed in nondimensional form. \[ R^+ = \frac{A}{B^2} R \]

3. \( Ja_o \) is an equivalent Jacob number defined as

   \[ Ja_o = \left( \frac{\rho_{f}/\rho_l}{h_{fg}/c} \right)^{1/2} \left[ \kappa_{v}^{1/2} \left( \frac{\Delta T}{G} \right) \right] \]

   \[ G = \frac{x_{e} - x}{y - x} \]
\[ B = \left( \frac{12}{\pi h_{js}} \right)^{\frac{1}{2}} J \alpha \]