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Subcooled Convective Boiling of Binary Mixtures over an Array of Heated Elements

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Boiling data and the critical heat flux conditions are reported for both channel flow and jet impingement flow using varying concentrations of R-11 in R-113. An array of 10 flush-mounted heated elements on one wall of a vertical passage was cooled by subcooled boiling. Data indicate that for channel flow boiling, the addition of R-11 to R-113 does not produce a significant change in the critical heat flux condition. For channel flow boiling, the data indicate that addition of a small amount of a less volatile component slightly increased the critical heat flux, whereas, the addition of a small amount of a more volatile component decreased it. The critical heat flux data for channel flow were also found to agree well with critical heat flux correlations for pure fluids if the mole-weighted mean properties of the mixture were used to compute the critical heat flux from the pure fluid correlation. However, for jet impingement flow with binary mixtures, deviations existed between measured data and pure fluid correlation predictions using mole-weighted mean properties of the mixture. The significance of the findings of this study with regard to the use of binary mixtures of dielectric fluids for immersion cooling of electronic components is discussed in this article.

Nomenclature

c_p = liquid specific heat
D = diagonal length of a square heat source
D_h = channel hydraulic diameter
d = jet diameter
f_i^l = fugacity of component i in the liquid
f_i^v = fugacity of component i in the vapor
g = gravity
H = channel height
h_{lv} = heat of varporization
L = length and width of heater element
p = system pressure
p_i^s = saturation pressure for pure component i
q'' = heat flux
q''_M = critical or maximum heat flux
T_{bp} = bubble-point temperature
T_{fluid} = bulk liquid temperature
T_{jet} = liquid jet inlet temperature
ΔT_{sub} = liquid subcooling, $(T_{bp} - T_{fluid})$
T_{wall} = heater element surface or wall temperature
U = velocity of liquid in channel
U_j = velocity of liquid in jet
W = channel width
We = Weber number, $(\rho_l U^2 L/\sigma)$
x_i = liquid mole fraction of component i
y_i = vapor mole fraction of component i
ρ_l = liquid density
ρ_v = vapor density
σ = liquid surface tension
ϕ_i = fugacity coefficient of component i
φ_i = activity coefficient of component i

Introduction

THERMAL control of electronic components in aerospace systems is becoming an increasingly difficult task as the size of the components continues to shrink and the overall system dissipation rises. Subcooled convective boiling provides a means of efficiently removing heat at the high heat flux levels that frequently are characteristic of the small components used in avionics or aerospace instrumentation systems. A study of fluid selection for electronic immersion cooling applications was performed by Saylor et al.[1] in which attention was given to the commonly used fluids for direct liquid contact. These fluids are highly wetting dielectric fluorinated fluorocarbons or chlorofluorocarbons. Some recent studies have indicated, however, that for the highly wetting dielectric fluids, the onset of boiling may be delayed during start-up of the device which can result in significant temperature overshoots when the device undergoes an increase in its heat dissipation. The temperature overshoot is one of the greatest obstacles in implementing electronic cooling techniques with dielectric fluids.

In order to characterize the boiling incipience of dielectric fluids, You et al.[2] experimentally investigated the irregular initiation of nucleate boiling of R-113 on chromal wires and on a platinum thin-fiber heater. Conducted at atmospheric pressure, they measured heat flux vs wall superheat temperatures to determine the effects of surface characteristics. They found that the superheat excursion at incipience was nonrepeatable and was as high as 72.5°C on the platinum thin-film heater.

One possible means of ensuring that the onset of nucleate boiling will occur at lower surface superheat levels, may be to mix a lower boiling fluid with the primary coolant. Addition of a small amount of a more volatile fluid will lower the bubble-point of the coolant, and may allow nucleation to be initiated at a lower surface temperature. In an investigation of saturated pool boiling at moderate heat flux levels in pure liquids and binary mixtures, Van Stralen and Sluyter[3] observed temperature fluctuations to be significantly decreased when a small amount of a more volatile liquid was added. In addition, Van Stralen and Sluyter[4] indicated that the addition of a second lower boiling point constituent to a pure coolant may, in some cases, increase the critical heat flux, thereby allowing the components to operate at higher heat flux levels without burning out. In a recent study, Sivagnanam and Varma[5] investigated subcooled convective boiling of binary mixtures containing water. Although these experiments were performed at atmospheric pressure with wall temperatures unacceptable to the cooling of electronic components, this study

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illuminated the heat transfer characteristics and demonstrated that heat transfer data for convective subcooled boiling of binary mixtures can be satisfactorily correlated. Despite the apparent potential for improved cooling performance, little information is available in the literature regarding the subcooled convective boiling characteristics of binary mixtures of highly-wetting dielectric fluids. The study summarized here was undertaken specifically to explore the subcooled convective boiling characteristics of a binary mixture of dielectric fluids.

Many recent studies have examined boiling processes in pure dielectric fluorocarbon liquids. Some studies consider convective boiling of a pure fluorocarbon liquid on a single finite heat dissipating element.[6-9] McGillis et al.[10] investigated the critical heat flux conditions for subcooled flow boiling of R-113 over an array of flush elements in a channel. In a later study, McGillis and Carey[11] modified the experiment of McGillis et al.[10] to determine the critical heat flux condition for immersion jet impingement and suction boiling of R-113 over an array of flush heated elements. The study described here experimentally explored and assessed the performance of binary fluid mixtures in the same test apparatus used in the earlier studies of McGillis and Carey.[11] This study considered binary mixtures of R-11 and R-113 because they are both high molecular weight, highly-wetting dielectric fluids, with well-documented physical properties typical to fluids used in electronic immersion cooling applications. Heat transfer characteristics and the critical heat flux condition were determined for channel flow and immersion jet impingement over arrays of flush heated elements using varying concentrations of R-11 in R-113.

Experimental Apparatus

Subcooled binary mixture flow boiling experiments were conducted using the test section shown in Fig. 1. An array of 10 flush-mounted heated elements on one wall of a vertical passage in the test section were cooled by subcooled boiling. Boiling and critical heat flux data were measured for channel flow and jet impingement flow over the elements. For jet impingement flow, modifications where made to the polycarbonate wall opposite the heated elements. The modified cover plate shown in Fig. 2 is a manifold with an array of ports located over the center of each element. Figure 3 illustrates the two flow configurations considered in this investigation.

Experiments were conducted with elements flush with the channel wall. Each element was a 6.4 × 6.4 mm square copper surface. The spacing between the elements was 3.2 mm. The channel width was 12.7 mm and the chip-to-channel spacing was 1.0 mm. In the immersion jet impingement experiments, the jet diameter was 1.0 mm.

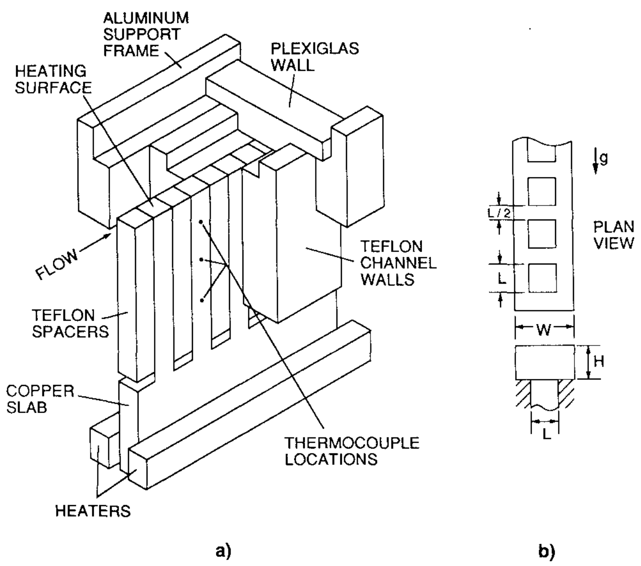

Fig. 1 a) Cutaway view of test section and b) drawing of channel geometry.

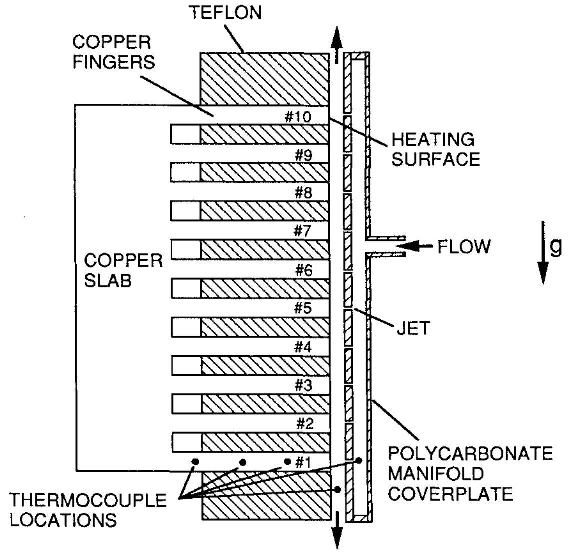

Fig. 2 Test section modifications for immersion jet impingement experiments.

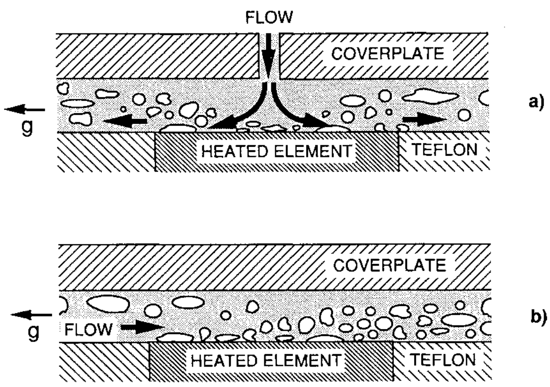

Fig. 3 Flow configurations: a) submerged jet impingement, b) channel flow.

Heat flowed from bar heaters through fingers to the element surfaces, where it was transferred into the fluid by boiling and/or convection. The back of the test section was heavily insulated to minimize heat losses. Heat losses through the Teflon® side walls were experimentally and numerically determined to be less than 3% of the total heat transferred to the fluid.

Temperature gradients were measured with three 0.5-mm copper constantan thermocouples spaced 15-mm apart. The thermocouples were embedded in each copper finger and were used to calculate the heat flux dissipated from the surface of each element. Extrapolation of the temperature profile also allowed us to determine the surface temperature of each element. Heat flux is defined as the total heat flow through the copper finger leading to the heater element divided by the surface area of the heater element exposed to the flow. The surface superheat temperatures of an element was determined by subtracting the bubble-point temperature of the fluid from the surface temperature of each element. Thermocouples were also placed in the flow; one at each end of the channel for channel flow, and an additional one in the manifold at a jet port of interest for the jet impingement flow. The experiment was monitored with three data acquisition boards in a multiplexor which interfaced with a personal computer. Temperatures and heat fluxes were computed by averaging 60 samples in 10-s intervals.

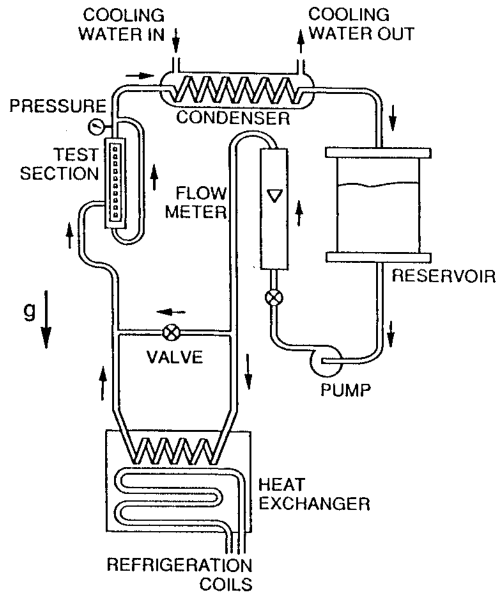

Fig. 4 Test system used in subcooled convective boiling experiments.

The highest heat flux at which the system reached steady state for nucleate boiling was used to determine the critical heat flux. When transition to film boiling occurs, the incremental increase in power input to the heaters produced a runaway surface temperature making exact determination of the heat flux impossible. The power input to the heaters which would correspond to the true critical heat flux for the element was an intermediate power level which lay between these two points. Since the power settings were always changed so that the incremental increase in power was at most 7%, 3.5% was added to the last stable heat flux measured ensuring that the calculated peak heat flux was within 96.5% of the true critical heat flux.

The system flow loop, shown in Fig. 4, provided a steady flow of subcooled liquid to the test section. Different mixture concentrations of R-11 in R-113 stored in the reservoir were pumped through a rotameter and into the test section. The fluid then passed through the condenser. If additional cooling of the test fluid proved necessary, some fluid was directed through a second heat exchanger, consisting of a coil immersed in a cold ethylene glycol bath. This arrangement made it possible to achieve large fluid subcooling levels.

Since the pressure drop through the ports was much greater than the pressure drop through the manifold, the quantity of flow through each port was assumed to be virtually identical. Thus, the total quantity of flow provided to the test section was equally distributed to each port. In single-phase jet impingement experiments, the uniformity of the jet velocities was proved by the observed small variation in the heat flux and surface temperature from one heater to another. Experimental uncertainties in the heat flux and surface temperature measurements were estimated as 2 and 4%, respectively, due primarily to uncertainties in the thermocouple measurements. Experimental uncertainty in the mean fluid velocity was estimated to be 3.5%.

Subcooled flow boiling experiments were conducted using varying mole concentrations of R-11 in R-113 at nominally atmospheric pressure. No decomposition of the fluids was noticed or expected since the system held a large capacity of subcooled fluid and the bulk liquid temperature never exceeded saturation temperatures. To eliminate variations in the critical heat flux (CHF) condition caused by surface conditions, surfaces were cleaned after vapor films covered them.

Phase Equilibrium and Mixture Properties

For mixtures in equilibrium, the fugacity in the vapor is equal to the fugacity in the liquid, $f_i^v = \phi_i y_i p = \varphi_i x_i p_i^s = f_i^l$. For pressures as low as atmospheric ϕ_i can be approximated as unity with high accuracy. R-11 and R-113 are both large molecular weights, nonpolar fluids and do not form an azeotrope as a mixture. For such mixtures, the equilibrium conditions at which phase-change takes place may sometimes be predicted with reasonable accuracy if φ_i is also assumed to be unity. Using the fact that the fugacity and activity coefficients are unity, and that $x_{R11} + x_{R113} = 1$ and $y_{R11} + y_{R113} = 1$, the saturation pressure of the binary mixture may be approximated as

$$p = x_{\mathrm{R11}} p^s_{\mathrm{R11}} + (1 - x_{\mathrm{R11}}) p^s_{\mathrm{R113}} \tag{1}$$

In Eq. (1), the total pressure becomes the mole-weighted average of the component saturation pressures. Figure 5 is the binary phase diagram for R-11 and R-113 at a pressure of 1 atmosphere (101 kPa) constructed using Eq. (1).

Experiments were performed in order to determine whether the R-11/R-113 binary mixture phase equilibrium is accurately predicted by Eq. (1). In these experiments, the pressure, temperature, and liquid mole fractions were measured. The experimental measurements of equilibrium pressures for temperatures of 48.9 and 54.4°C at different R-11 mole fractions are compared with Eq. (1) in Fig. 6. As can be seen in Fig. 6, data is in good agreement with the predictions of the ideal mixture model of Eq. (1). Equation (1) can therefore be used to determine phase equilibrium of the R-11/R-113 mixture with reasonable accuracy.

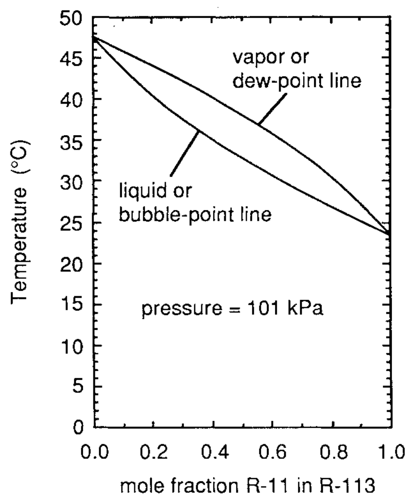

Fig. 5 Equilibrium phase diagram for R-11/R-113 mixture at a pressure of 101 kPa.

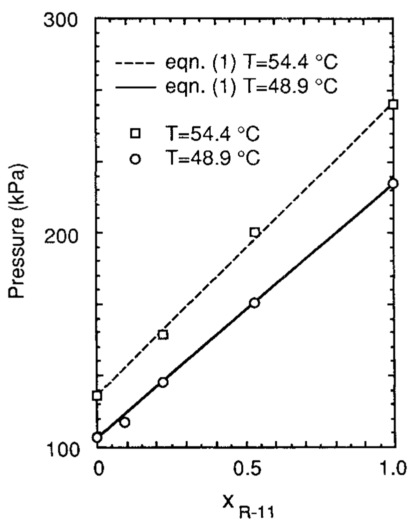

Fig. 6 Equilibrium pressure of R-11/R-113 mixture. Comparison between measured and calculated pressure.

The ideal mixture model was also applied to other mixture physical properties. The physical properties calculated using this interpolative technique were compared to methods discussed in Reid et al.[12] for predicting R-11/R-113 mixture physical properties. Errors were calculated to be less than 4%. In the heat transfer performance analysis of this investigation, the simplified ideal mixture model of phase equilibrium and physical properties will therefore be used.

Results and Discussion

Channel Flow

Typical subcooled boiling heat transfer data obtained for channel flow over the elements are plotted in Fig. 7. For channel flow with an inlet subcooling of 30°C and a bulk flow velocity of 84.4 cm/s, Fig. 7 shows boiling curves of the leading element for pure R-113 and R-11 mole fractions of 0.1 and 0.2. The data are plotted both in terms of the wall-to-bubble-point temperature difference and the wall-to-fluid temperature difference. There is little variation in the nucleate boiling heat transfer performance between the different concentration fractions of R-11 in R-113. Although data were obtained over a limited range of concentrations, in each case the data generally correlated well in terms of the simple boiling curve representation shown in Fig. 7.

For the subcooled channel flow of this investigation, the critical heat flux condition occurred first on the last element in the array where there was the least amount of fluid subcooling. Immediately following the critical heat flux condition, power to all elements was turned off to avoid damaging the test section. For pure component dielectric liquids, the critical heat flux condition for flush-mounted heated elements in a high velocity channel flow was correlated with good agreement by Mudawar and Maddox[9]:

$$\frac{q''_M}{\rho_v U h_{lv}} = 0.161\left(1 + \frac{c_p \Delta T_{\text{sub}}}{h_{lv}}\right)^{7/23} \cdot \left(1 + 0.021\,\frac{\rho_l}{\rho_v}\,\frac{c_p \Delta T_{\text{sub}}}{h_{lv}}\right)^{16/23}\left(\frac{\rho_l}{\rho_v}\right)^{15/23}\left(\frac{L}{D_h}\right)^{1/23} We^{-8/23} \quad (2)$$

McGillis et al.[10] showed that this correlation for single flush-heated elements in a channel flow could be extended to an array of heated elements when the local liquid subcooling is used in the correlation.

For channel flow with a bulk fluid velocity of 84.4 cm/s, Figs. 8 and 9 show the experimentally measured critical heat flux condition for different R-11/R-113 binary mixture concentrations plotted in terms of the local fluid temperature. Figure 8 shows that small additions of R-11 to R-113 decreased the CHF condition. As seen in Fig. 9, the addition of R-113 to R-11 slightly increased the CHF condition. Equation (2) is plotted in Figs. 8 and 9 for different R-11 in R-113 mole concentrations using the local fluid subcooling and binary mixture mole-weighted fluid properties. The experimentally measured critical heat flux condition for the binary mixtures seem to be in fairly good agreement with the critical heat flux predicted with Eq. (2) using the mole-weighted fluid properties.

Jet Impingement Flow

A boiling curve for jet impingement flow is shown in Fig. 10. Heat flux vs the wall to the jet temperature difference data for flush elements are provided for pure R-113 and R-11 mole fraction concentrations of 0.3 and 0.6. At a jet fluid temperature of 17.5°C and a jet velocity of 154 cm/s, Fig. 10 shows that for a given heat flux in the region of low-heat flux levels, the 0.3 and 0.6 R-11 mole fraction concentrations provide lower wall temperatures than the pure R-113. It seems likely that for jet impingement flow, the lower

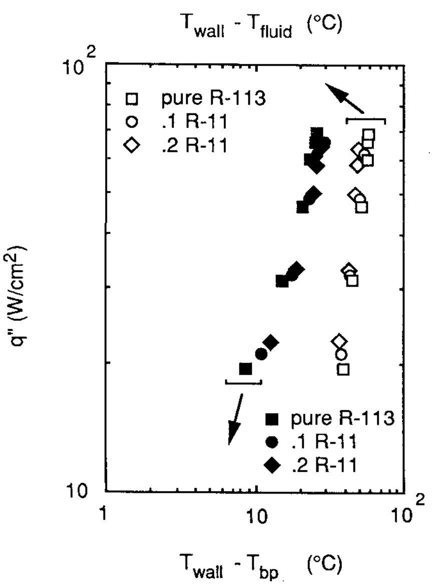

Fig. 7 Boiling data for the leading flush heater element for different mixtures of R-11 and R-113. Boiling data plotted in terms of wall superheat above fluid inlet temperature and binary mixture bubble-point temperature.

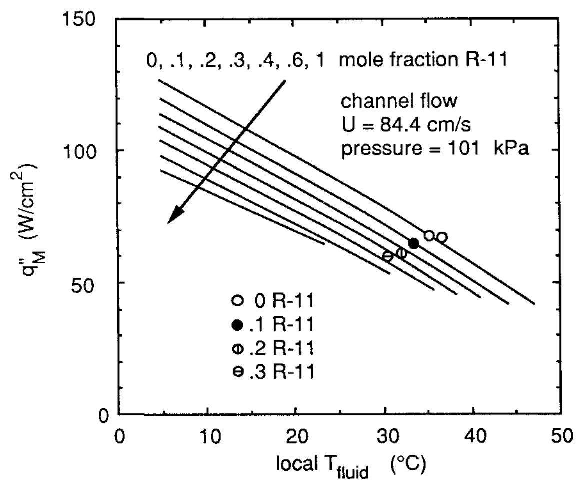

Fig. 8 Critical heat flux of binary mixtures with additions of R-11 to R-113. Solid lines represent the calculated critical heat flux of Eq. (2) using mole-weighted fluid properties.

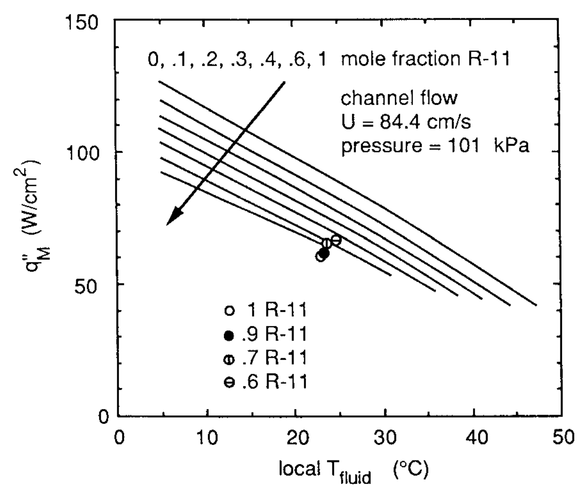

Fig. 9 Critical heat flux of binary mixtures with additions of R-113 to R-11. Solid lines represent the calculated critical heat flux of Eq. (2) using mole-weighted fluid properties.

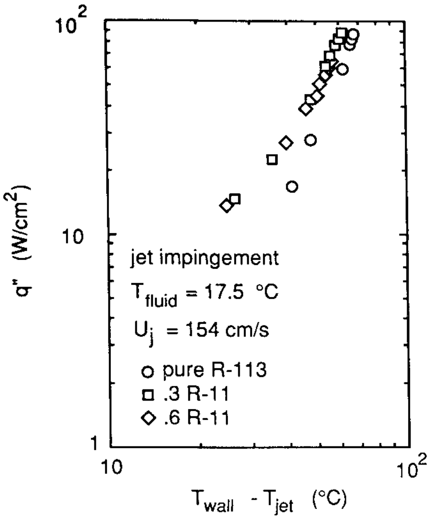

Fig. 10 Boiling data comparison for different mixture concentrations of R-11 and R-113 at the same impingement jet velocity and fluid temperature.

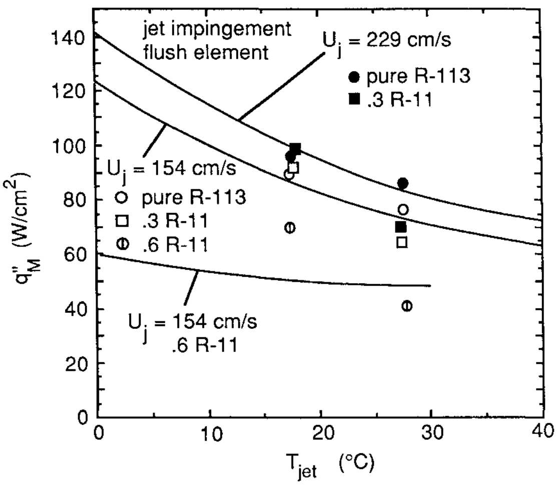

Fig. 11 Critical heat flux data for different mixture concentrations of R-11 and R-113 at two impingement jet velocities and two jet fluid temperatures. Solid lines represent the calculated critical heat flux for pure component R-113 and 0.6 mole fraction R-11 using Eq. (3).

bubble-point temperature of the binary mixtures allows greater boiling activity at low superheats, and consequently, higher heat flux levels are obtained. This boiling curve exhibits typical nucleate boiling behavior expected for jet impingement flow.

CHF data were also obtained for the jet impingement flow over flush elements using different mole fraction concentrations of R-11 in R-113. It is useful to compare the jet impingement critical heat flux data of this investigation to those predicted using the correlation by Nonn et al.[8] for free jet impingement flow boiling of pure liquids and explore its applicability to mixtures:

$$\frac{q''_M}{\rho_v U_j h_{lv}} = 0.074 \left(\frac{\rho_l}{\rho_v}\right)^{0.725} \left(\frac{\sigma}{\rho_l U_j^2 D}\right)^{1/3} (1 + \varepsilon_{\text{sub}}) \quad (3a)$$

The value of ε_{sub} incorporates the effect of subcooling and is defined to be

$$\varepsilon_{\text{sub}} = 0.456 \left(\frac{\rho_l}{\rho_v}\right)^{1/2} \left(\frac{c_p \Delta T_{\text{sub}}}{h_{lv}}\right)^2 \quad (3b)$$

For jet velocities of 154 and 229 cm/s, Fig. 11 shows the pure R-113 CHF data seem to be in close agreement with the predictions using Eqs. (3). This was also observed in the study of McGillis and Carey.[10] For a jet fluid temperature of about 17.5 C, the 0.3 mole fraction R-11 CHF data has a slight increase over the pure R-113 CHF data. This is not apparent, however, for the 0.3 R-11 mole fraction CHF data with an increased jet fluid temperature of about 27.5 C. At this higher jet fluid temperature, the 0.3 R-11 mole fraction CHF data is significantly below the pure R-113 data either predicted or measured.

The 0.6 R-11 mole fraction CHF data is much less than that of the pure or 0.3 R-11 mole fraction CHF data at both the 17.5 and 27.5°C jet fluid temperatures. Equation (3) is also plotted for comparison in Fig. 11 using 0.6 R-11 mole-weighted properties with a jet velocity of 154 cm/s. Although limited 0.6 mole fraction CHF data exists, there seems to be deviations between the measured CHF data and the predictions of Eq. (3). For jet impingement flow, the complexities which are added due to the partially-vaporized secondary bypass flow from upstream elements may be contributing to the deviations from the pure component correlation.

Conclusions

The results of our experimental study of the convective boiling of subcooled binary liquid mixtures of R-11 and R-113 over flush arrays of heated elements imply the following conclusions:

Preliminary experiments indicated that measured pressures at different R-11 mole fraction concentrations in R-113 were found to be in very good agreement with the predictions of an ideal mixture model. This implies that an ideal mixture model may be used to calculate mole-weighted mixture properties with reasonable accuracy for this mixture, and perhaps for other mixtures of dielectric fluids. Good results were obtained when mole-weighted properties were used in the analysis of the heat transfer performance of the mixture of R-11 and R-113.

The addition of R-11 to R-113 will reduce the wall temperature of the heated elements during fully developed boiling due to the lower bubble-point temperature of the binary mixture. For channel flow, the data indicate that addition of a small amount of a less volatile component slightly increases the critical heat flux, whereas, the addition of a small amount of a more volatile component decreases it. However, the changes in the CHF conditions were small. This suggests that the CHF penalty associated with adding a small amount of the more volatile R-11 to R-113 may be small enough to accept in return for the associated improved onset characteristics. The critical heat flux data were also found to agree well with critical heat flux correlations for pure fluids if the mole-weighted mean properties of the mixture were used to compute the critical heat flux from the pure fluid correlation. This implies that CHF levels for subcooled channel flow boiling of other binary fluorocarbon mixtures may also be predicted with reasonable accuracy using this method.

Data indicate that for low fluid temperatures in the jet impingement binary system, small additions of R-11 to R-113 provides a slight increase in critical heat flux. However, for greater mole fraction concentrations of R-11, the CHF data are significantly less than the pure R-113 CHF data. Pure component CHF correlations for jet impingement boiling using mole-weighted properties of the mixture deviated from the measured CHF data.

Acknowledgments

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