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SUPPRESSION OF NUCLEATE BOILING OF PURE AND MIXED REFRIGERANTS IN TURBULENT ANNULAR FLOW

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Abstract—The following issues are addressed: (a) Is suppression of nucleate boiling an appropriate physical mechanism to explain experimental heat transfer coefficient behavior? (b) Is suppression possible under reasonable conditions with refrigerants? (c) Is suppression more or less likely with a binary mixture of refrigerants as compared with either pure fluid? Issue (a) is resolved in favor of traditional suppression theory by critical review of the literature. Issue (b) is resolved by experimental evidence suggesting one must have rather low pressures to suppress nucleation with refrigerants. Issue (c) is resolved by experimental and correlative evidence suggesting systematic differences with mixtures.

1. INTRODUCTION

The most common explanation of the physical mechanism of heat transfer in annular flow boiling is that of a superposition of a forced convection evaporative process and a nucleate boiling process. With increasing vapor quality the liquid film thins and the core vapor accelerates, as required by continuity. Heat transfer to the core is improved by this acceleration and the thinning of the liquid film also serves to lessen its conductive resistance. Heat transfer is thought to improve sufficiently and to occur with such rapidity that bubble growth in the wall region disappears. At this point, the nucleate boiling process is said to be suppressed, and vapor generation is due strictly to evaporation from the vapor–liquid interface.

It is critical to know if nucleate boiling is suppressed. First, if the process becomes purely convective/evaporative, then the heat transfer coefficient should be independent of wall heat flux, and depend on flow and fluid parameters (e.g. mass flow rate, eddy diffusivity, Prandtl number), as in single-phase shear-driven flow. In this case, the heat transfer process might be modeled strictly from single-phase considerations. If, on the other hand, nucleate boiling exists, then the liquid film viscous sublayer may be destroyed, and the fluid flow and heat transfer processes become more difficult to predict. In the case of mixtures, chaotic concentration profiles may occur when nucleate boiling is not suppressed.

2. CONVENTIONAL THEORY OF ONSET AND SUPPRESSION OF NUCLEATE BOILING AND AN ALTERNATIVE HYPOTHESIS

The onset and suppression of nucleate boiling are effectively the same problem, differing only in the direction from which the heat flux required to sustain nucleation/bubble growth is approached. In the case of a heated surface the liquid temperature surrounding the bubble will not be uniform generally, but instead diminish with distance from the heated surface. Hsu & Graham (1976) showed the liquid surrounding the bubble must be superheated by

$$T_{\mathrm{L}} - T_{\mathrm{sat}} = \frac{2\sigma}{\left(\frac{c_2}{c_1}\right) y_{\mathrm{B}}} \frac{\Delta h_{\mathrm{v}}}{T \Delta V_{\mathrm{v}}}, \qquad [1]$$

where

T_L = liquid temperature,
T_{sat} = saturation temperature,
σ = surface tension,
Δh_v = latent heat of vaporization,
$c_2 = 1/\sin\theta$,
$c_1 = 1 + \cos\theta$,
Y_B = bubble height,
ΔV_v = difference in specific volume of saturated vapor and liquid

and

θ = contact angle.

Hsu & Graham (1976) assumed bubble growth to be possible only if the liquid temperature at the bubble cap was superheated to satisfy [1]. For a linear temperature field, as might be reasonably approximated with a thin boundary layer, the wall heat flux q_w and temperature field are represented by

$$q_w = \frac{\lambda_L}{\delta_F}(T_w - T_{sat}) \qquad [2]$$

and

$$T(y) = T_w - \frac{T_w - T_{sat}}{\delta_F}y = T_w - \frac{q_w}{\lambda_L}y, \quad 0 \leqslant y \leqslant \delta_F, \qquad [3]$$

where λ_L is the liquid thermal conductivity, T_w is the wall temperature, y is the distance from the wall and δ_F is the boundary layer thickness, with the temperature at the vapor–liquid interface assumed saturated.

Equations [1] and [3] may be used to determine the range of cavity sizes which may be active.

Collier *et al.* (1964) recommended for turbulent flow boiling a dimensionless viscous sublayer thickness, y^+, equal to 7. In the single-phase turbulent flow literature, the viscous sublayer thickness has been presented with values from $y^+ = 5$ to $y^+ = 10$. In fact turbulent eddies carrying cool fluid from the vapor–liquid interface may penetrate the sublayer down to $y^+ = 1$ (Lacey *et al.* 1962). Bejan (1982) has studied analytically the buckling and rolling of liquid layers in shear-driven flow, as occurs in annular flow boiling. He determined the value of $y^+ = 7.62$ as the viscous sublayer thickness which persists regardless of possible buckling or rolling.

The conventional suppression theory has been questioned initially by Mesler (1976, 1977) and subsequently by Beattie (Beattie & Lawther 1979; Beattie & Green 1984). Mesler (1977) suggested that the heat transfer process, rather than becoming completely convective/evaporative at high quality, is due even in thin turbulent films to *nucleate boiling*. The high heat transfer rates, experimentally measured with thin films (high compared to pools or thick films), are due to an *enhancement of nucleate boiling* with thin films. The high heat transfer rates seen with thin films are hypothesized to be due to evaporation of the thin liquid microlayer and *rapid replenishment* of the microlayer. The replenishment process with thin films is *improved* over usual pool boiling. With thin films, the bubble ruptures the film surface and vapor escapes through the top of the broken bubble, causing the liquid film to be reestablished quickly. An improved replenishment process which is related to film thickness might account for the observed improvement in heat transfer with increasing quality.

A second issue was raised by Toral (1979), who suggested that complete suppression of nucleate boiling will not occur under common conditions in annular flow boiling of *organic fluids*. These fluids, which include refrigerants, have a thermal conductivity much lower than water, and as such will tend to yield high wall superheats, sufficient for nucleation.

The issues then are:

1. Can the physical process by which vapor is generated be entirely evaporative or is it best described by nucleate boiling theory, or a combination of both?

2. Is it possible for organic fluids, specifically refrigerants, with their relatively low thermal conductivity, to be vaporized by an entirely evaporative mechanism in annular flow?
3. Can conventional suppression theory or various other suppression criteria be verified (and modified for mixtures) to quantify the point at which nucleate boiling is absent?
4. Are there unique mechanisms which occur with nonazeotropic mixtures.

The paper critically analyzes the literature for pure and mixed fluids in order to resolve issues 1 and 2. Then new experimental evidence for single and binary refrigerants is presented. A criterion for determining the suppression point for mixtures is hypothesized.

3. LITERATURE REVIEW AND ANALYSIS

Pure Fluids

To resolve the issues, one might employ visual evidence or experimental evidence of the dependence of heat transfer coefficients on various parameters.

Nearly all visualization studies show some isolated bubbles within the liquid film; the number of sited bubbles diminishes with increasing quality. The authors attribute the continued vapor generation to evaporation from the vapor–liquid interface. Many visualization studies used tubes which had been milled smooth or which were of materials without large cavity sizes; vapor generation can then take place in the absence of such cavity size availability, suggesting that a mechanism other than nucleate boiling is the cause of such vapor generation. It is possible however that bubbles were so small or short-lived as to escape visualization, thus visual evidence is not itself definitive.

The experimental evidence involves an analyses of the behavior of heat transfer coefficients as critical parameters are varied. For example, when no dependence on heat flux is observed $[\alpha \neq \alpha(q_w)]$, nucleate boiling is suppressed, and $\alpha = \alpha(G)$, where α is the heat transfer coefficient and G is the mass flux. On the other hand, when nucleate boiling *dominates*, the heat transfer coefficient is a strong function of heat flux and a weak function of mass flux, G. Thus, the dependence of α on g or q_w may define the *dominant* heat transfer mechanism, and if the heat transfer coefficient is entirely independent of heat flux $[\alpha \neq \alpha(q_w)]$, then the *sole* mechanism is evaporative.

A recent study with water by Aounallah *et al.* (1982) showed clearly $\alpha \neq \alpha(q_w)$ for a range of qualities, heat and mass flux values. Care was taken in their experiment to ensure that measurements at the same spatial location were compared. In direct response, Beattie & Green (1984) cited work by Bertoletti *et al.* (1964) with a similar experimental apparatus and also using water as the working fluid; the Bertoletti *et al.* data showed a strong dependence on heat flux and was correlated well by a pool boiling correlation.

The conclusions of Aounallah *et al.* (1982) contradict those of Beattie & Green (1984). However, the discrepancy is resolved by examining the test conditions used by the two groups. The latter, where nucleate boiling was observed to be dominant, involved higher pressures and heat fluxes where conventional theory suggests a smaller superheat requirement. The much higher heat fluxes most likely produce a vapor generation process dominated by nucleate boiling.

In a separate publication, Beattie & Lawther (1979) describe their own successful work in predicting pressure drop at high quality by theorizing the existence of attached bubbles within a liquid film. They point to their success as a proof of bubble existence. The heat flux level of their experiment was also very high, since their observations were made in a critical heat flux experiment. Here again, the existence of attached surface bubbles are entirely possible, and explained by the conventional theory.

In several experiments, a gradual reduction in heat transfer coefficient has been observed despite increasing *quality*. At times the measured reduction disappears as quality is further increased. Such behavior, originally attributed to an entrance length effect (Gouse & Couman 1965), has been seen at ratios > 100, with pure refrigerants, water and with refrigerant mixtures (Chaddock & Noerager

1966; Chawla 1967; Radermacher *et al.* 1983). The experiments show in the nucleate boiling *dominated* region, α decreases with increasing quality. Such observations are in sharp contradiction to the enhanced nucleate boiling theory which requires α to increase with reduced film thickness, i.e. an increased quality.

More recently, nucleation processes near the annular interface of these films have been photographed by Mesler and coworkers. Many small bubbles were observed to emerge near a single large, ruptured bubble. This secondary nucleation occurs relatively far from the wall, and its possible effect on the heat transfer process in flow boiling is not known at this time.

Mixed Fluids

The introduction of a second component has several consequences in the analysis of the onset and suppression of nucleate boiling.

Surface tension may be drastically affected by even small additions of a second component. The theoretical value of the slope of the saturation dP_{sat}/dT line is less for mixtures than for an equivalent pure fluid, suggesting an increased superheat requirement; however, the actual superheat requirement may be less than for either pure component, due to the change in surface tension.

Three experimental studies of the onset of nucleate boiling (ONB) with binary mixtures were found in the literature. Thome *et al.* (1981) performed a careful study of the activation of a single first boiling site on a polished heated surface with mixtures of liquid nitrogen–argon and ethanol–water. The composition of the cryogenic mixture had no effect on the activation of the single site. However, composition yielded a strong effect on their results with ethanol–water. The results in both cases are due to the wetting characteristics of the mixtures. The cryogenic mixture components have similar contact angles, whereas the addition of slight amounts of ethanol to water has a drastic effect on surface tension and therefore the wetting characteristics. The authors did not consider the effect of mass transfer resistance in their results. However, the ONB point for ethanol–water is underpredicted by analyzing the fluid behavior as an equivalent pure fluid.

Shock (1977) evaluated binary mixtures of ethanol–water and ethanol–benzene with similar conclusions regarding the influence of wetting characteristics. The ONB point was found by wall temperature measurement in his flow boiling experiments. He suggests that suppression of boiling of mixtures might not be strictly equivalent to the ONB problem, due to the possible existence of local concentration gradients around established nuclei. He leaves open the possibility of mass transfer resistance (MTR) effects.

Toral (1979) studied ethanol cyclohexane, whose properties are more ideal than the previous ethanol mixtures, in a flow boiling apparatus similar to Shock's. He differentiates between activation of an isolated cavity and the sudden transition to multiple cavity activation. The latter mechanism, more relevant to the applications of the authors, is called the ONB point by Toral. He concludes that composition has a considerable influence on multiple cavity activation, "indicating the presence of MTR effect and suggesting that ONB is governed by bubble growth dynamics . . .". If Toral's conclusions are correct, then MTR should be considered in subsequent prediction methods for mixtures.

4. APPLICATION OF CONVENTIONAL THEORY TO PURE REFRIGERANTS AND REFRIGERANT MIXTURES

The Hsu/Collier and Pulling suppression criterion was applied to the two pure refrigerants used in the experiments to be described here. The pressure gradient, needed to determine the wall shear stress and subsequently the thickness of the viscous sublayer, was estimated using the Martinelli & Nelson (1948) correlation, as modified by Chisholm (1967). Contact angle was assumed to be 35°, typical for refrigerants (Stephan 1982). Measured mass fluxes and pressures were used. Thermodynamic properties were estimated from an accurate equation of state (Morrison & McLinden 1985). Transport properties were estimated using heat transfer and fluid flow service data for pure fluids and mixing rules from Reid *et al.* (1979), for the binary mixtures. Assuming all cavities to be available, the criterion suggests a very small unrealistic superheat requirement. Instead, a heat flux needed to activate a critical cavity size of 1.0 μm was calculated. Cavities of size $> 1.0\,\mu$m were assumed to exist either in an insufficient number to affect the heat transfer, or to be fully wetted by refrigerant. This assumption then modifies the basic suppression criterion, so that a greater wall superheat is needed to initiate boiling than if all sizes were available in large numbers and were unwetted.

For this given cavity size, [1]–[3] may be combined to give the heat flux required to initiate boiling, i.e.

$$q = \frac{2\lambda\sigma\Delta h_{\mathrm{v}}}{\left(\frac{\mathrm{c}_2}{\mathrm{c}_1}\right) T_{\mathrm{sat}}\Delta V_{\mathrm{v}} y(\delta_{\mathrm{vs}} - y)}, \qquad [4]$$

where q_{s} is the calculated heat flux below which no nucleation will take place and δ_{vs} is the viscous sublayer thickness. If $q_{\mathrm{w}} < q_{\mathrm{s}}$, boiling is predicted to be suppressed.

Three factors complicate the analysis, leading to substantial uncertainty. First, the estimate of the critical viscous sublayer thickness is not exact. It depends both on the determination of pressure drop and on a selected critical value (Collier & Pulling's $y^+ = 7$). Secondly, the selection of a critical cavity size may be in error. Collier (1980) suggested $0.5\,\mu$m as a rough guideline for refrigerants. This leads to a larger estimate of the suppression heat flux. Thirdly, vaporization may take place nearer the bubble base even in the absence of vaporization at the bubble cap. The required heat flux in this case would be less than that calculated. These complications lead to an estimated uncertainty of about ±40%. Despite the large uncertainty, it will be shown that the criterion can be used with success.

Figure 1 displays sample results of the procedure, showing the effects of changes in pressure and mass flux. As pressure is lowered or as mass flux is raised, the criterion predicts a greater suppression heat flux. If the experimental heat flux was below the calculated "suppression heat flux" value, the heat transfer coefficient should be independent of heat flux and instead depend proportionately on mass flux and quality. Conversely, if the criterion predicts sufficient heat flux, a dependence on heat flux should be observed.

A similar analysis can be done for *mixtures* and was applied here to the R13B1/R152a mixture. The governing equation is effectively the same for mixtures. Properties (such as $\Delta\bar{v}_{\mathrm{v}}$ and $\Delta\bar{h}_{\mathrm{v}}$) were evaluated at different compositions, so

$$\Delta\bar{h}_{\mathrm{v}} \cong \bar{h}_{\mathrm{v}}(\bar{Y}^*) - \bar{h}_{\mathrm{L}}(\bar{X}_{\mathrm{B}})$$

and

$$\Delta\bar{V}_{\mathrm{v}} \cong \bar{V}_{\mathrm{v}}(\bar{Y}^*) - \bar{V}_{\mathrm{L}}(\bar{X}_{\mathrm{B}}),$$

where $\bar{h}_{\mathrm{v}}(\bar{Y}^*)$ and $V_{\mathrm{v}}(Y^*)$ are the vapor enthalpy and specific volume at equilibrium molar composition Y^*, $\bar{h}_2(\bar{X}_{\mathrm{B}})$ and $V_2(\bar{X}_{\mathrm{B}})$ are the liquid enthalpy and specific volume at the molar composition, $\bar{X}_{\mathrm{B}}$, X_{B} is the bulk molar composition of the liquid and Y^* is the vapor composition in equilibrium with X_{B}.

The suppression criterion was then applied, assuming the liquid layer was well-mixed, i.e. without any MTR. This treatment then considers the mixtures as an equivalent pure fluid (EPF). Two possible approaches to correct for mixture effects were also hypothesized. An exact solution is available in the literature for the growth rate of an isolated spherical bubble located in a quiescent, uniformly superheated liquid. When the basic equations are solved, a reduction in bubble growth rate for a mixture over that of an equivalent pure fluid can be calculated. the reduction due to MTR is given by the correction factor, C_{BUB} (e.g. Scriven 1959):

$$C_{\mathrm{BUB}} = \left| -\frac{C_{\mathrm{pL}}}{\Delta h_{\mathrm{v}}}\frac{a_{\mathrm{T}}}{a_{\mathrm{D}}}(Y^* - X_{\mathrm{B}})\frac{\partial T}{\partial X_{\mathrm{B}}} \right. \qquad [5a]$$

and

$$q_{\mathrm{s,MIX}} = q_{\mathrm{s,EPF}}\, C_{\mathrm{BUB}}, \qquad [5b]$$

where C_{pL} is the specific heat of the liquid, a_{T} is the thermal diffusivity, a_{D} is the mass diffusivity and $\partial T/\partial X_{\mathrm{B}}$ is the slope of the bubble line. The subscripts MIX and EPF refer to mixture and equivalent pure fluid values, respectively.

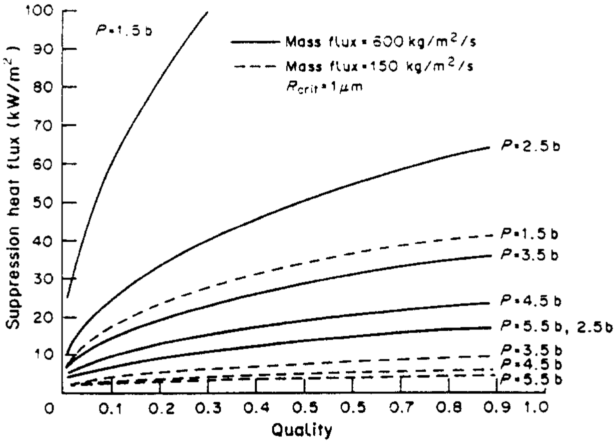


Figure 1. Effect of pressure and mass flux on suppression heat flux (R152a).

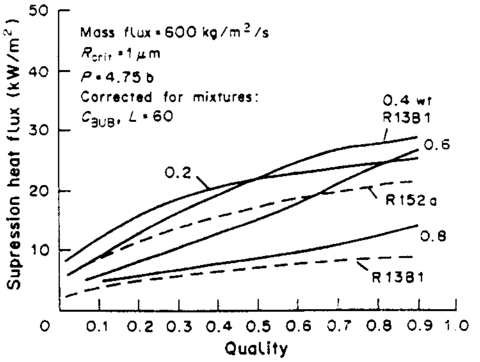


Figure 2. Calculated suppression heat flux for mixtures—isolated bubble theory.

When this factor, C_{BUB}, is applied to the suppression criterion, the required heat flux to sustain ebullition is raised typically by about 25% with $a_{\mathrm{T}}/a_{\mathrm{D}} = 5$ or 40–80% with $a_{\mathrm{T}}/a_{\mathrm{D}} = 60$, as shown in figure 2. The concentrations shown in figure 2 are "feed concentrations", i.e. the initial concentration of a subcooled liquid being evaporated/boiled. At the larger value of $a_{\mathrm{T}}/a_{\mathrm{D}}$, the mixture effect may be sufficient to increase the suppression heat flux above either pure component.

An alternative correction factor can be calculated from the literature on pool boiling of mixtures. Equation [5a] underpredicts the measured reduction in heat transfer coefficient for the pool boiling of mixtures. A variety of empirically based correction factors are available for predicting the reduction. None has been tested adequately for flow boiling of mixtures. However, the method of Stephan & Korner (1969) has been used widely with some success in pool boiling. When it is used, the increase in the suppression heat flux, q_s, may be sufficiently substantial to raise the suppression heat flux for mixtures above that of either pure component.

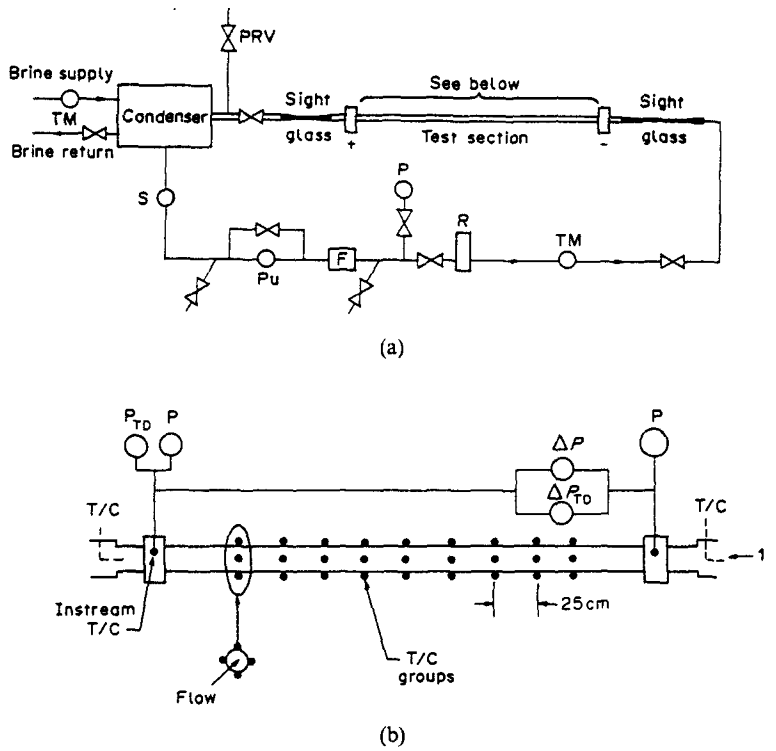
5. GENERAL DESCRIPTION OF TEST RIGS USED IN THIS INVESTIGATION

Through the course of this investigation, two experimental rigs were built and utilized. Both employed a horizontal stainless-steel tube (length, 2.7 m; i.d., D = 0.9 cm; o.d. = 0.95 cm) which was electrically heated.

Rig 1 is shown in figure 3a. A semi-hermetic, oil-free pump delivered subcooled liquid refrigerant to the test section. Heat was generated in the tube wall by applying a d.c. voltage difference along the tube. The test section itself was heavily insulated (approx. 15 cm radial thickness) to reduce heat gain from the surroundings; the minimal heat gain was accounted by calibration. The vapor generated in the test section was reliquified in an oversized condenser/receiver. The pump then drew on the liquid reservoir in the condenser and the cycle completed. Inlet subcooling and flow rate were controlled by valves in the liquid line. Subcooling and pressure level could also be modified by altering the condenser temperature (by changing flow rate or supply temperature on the brine side of the condenser).

Thermocouple stations were located at the axial positions shown in figure 3b. At each station, thermocouples were clamped at 90° intervals around the outer tube circumference. Instream thermocouples were centered in the flow, extended and pointed upstream for a distance of at least 2 cm, at the single-phase inlet and two-phase outlet. Pressures were also measured at these locations but not in the heated section. Fluid temperatures in the heated section were estimated to within 0.1–0.2 K from an assumed pressure drop distribution and thermodynamic equilibrium. Sight glasses located at the test section inlet and outlet allowed visual verification of the flow pattern. Flow rates were determined by means of a calibrated turbine meter in the subcooled liquid line.

One of the features of rig 1 was the use of a uniform heat flux q along a fixed tube length L



Figures 3a, b. Experimental test rig 1: uniform heating. No preheat section. PRV, pressure relief valve; TM, turbine meter; R, rotameter; S, sight glass; P, pressure gauge; F, filter/drier; Pu, pump; ΔP, differential pressure; P_{TD}, transducer.

with diameter D. With a given heat and mass flux $\dot{m}$, and degree of inlet subcooling, the outlet quality x_{out}, is fixed at

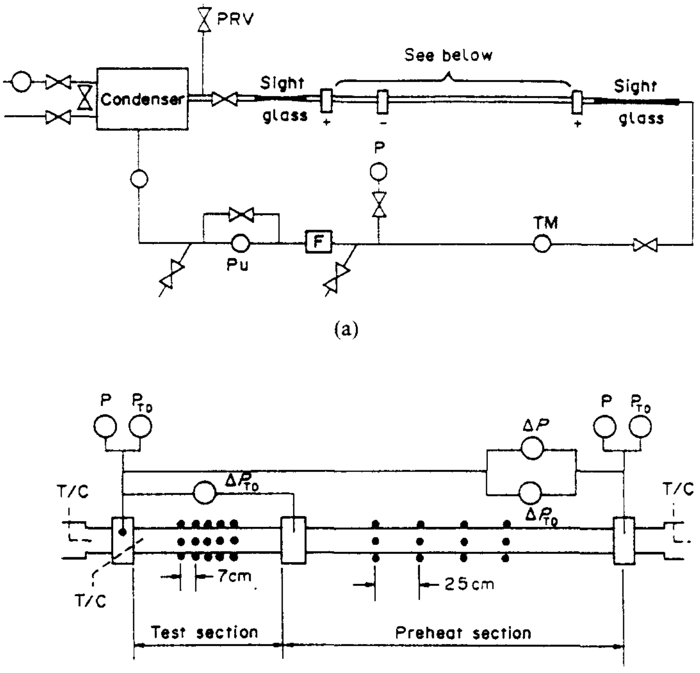
$$x_{out} \cong \left(\frac{q}{\dot{m}\Delta h_v}\right)\pi DL, \qquad [6]$$

where Δh_v is the enthalpy change of the fluid. In order to reach high exit qualities with low heat flux a tube length >20 m is required in some cases. In order to obtain data over the full quality range at the required heat and mass fluxes and without using a tube length >5 m (available space), a second experimental rig was constructed, displayed in figures 4a, b. The principal change is to employ two distinct heating sections. The tube itself was continuous, but heated separately by two independent d.c. power supplies. The first serving as a preheater provides partially evaporated fluid to the new shorter test section.

By using a large, at times unrealistic, preheat flux, qualities available in the test section could be made greater than with rig 1. In the test section itself, lower more realistic heat fluxes were used to further vaporize the fluid. The test section itself was 0.6 m in length, so that quality changes across the test section were relatively small. The measured effect of the preheat flux on the test section results was negligible, as determined from several different test checks (Ross 1985).

With rig 2, each wall thermocouple was referenced to an electronic ice bath temperature (precision of electronic ice bath ± 0.02°C typically, ± 0.05 maximum).

The use of more closely spaced test-section thermocouple stations provided redundancy to verify the goodness of the measured data. Since the flow was oriented horizontally, top-to-bottom differences in heat transfer coefficient up to 15% were observed. Larger differences are possible at low vapor quality. However, in this paper, only annular flow at qualities $>5\%$ are used in reporting the local averaged heat transfer coefficient. The higher precision of the data collected with rig 2 was necessary because of the lower heat fluxes employed in the test section of rig 2, although the data of rig 1 is of a satisfactory quality.



(a)

(b)

Figures 4a, b. Experimental test rig 2: preheat and test sections employed via separate d.c. power supplies. Key as in figure 3.

6. EXPERIMENTAL RESULTS

Pure Refrigerants

The first experimental results to be examined are those for pure R152a at low pressure (1.5–2.5 b); the tests were conducted with rig 1. If measured data taken at the same mass flux and pressure but different heat flux levels yield identical heat transfer coefficients, then boiling is considered completely suppressed. The suppression point can also be inferred approximately by the dependence of $d\alpha/dx$ on quality. When $d\alpha/dx$ becomes strongly positive, forced convection/evaporation is dominant. Complete or near complete suppression should occur in this range. Figure 5 plots the effect of heat flux at constant flow rate. A strong heat flux dependence

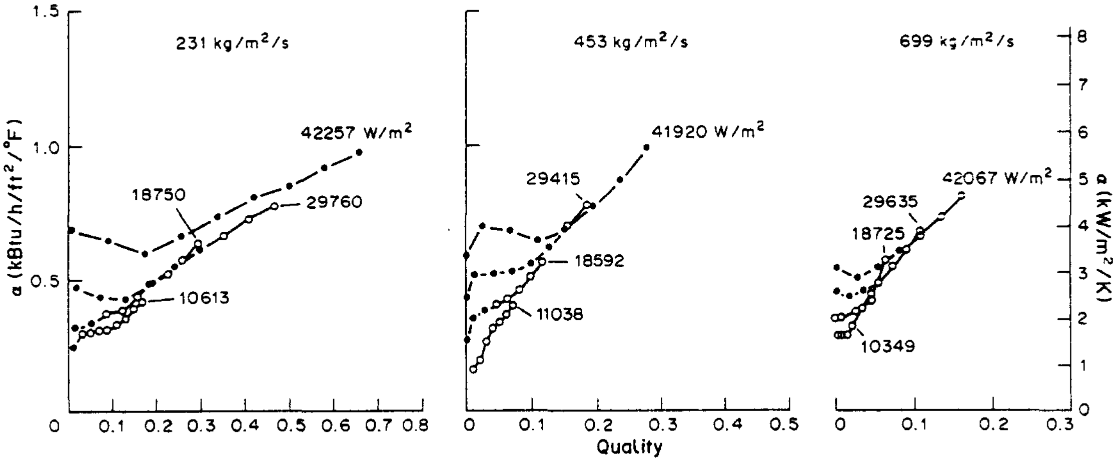


Figure 5. Effect of heat flux on pure R152a at low pressure: ○, complete suppression predicted; ●, sustained nucleate boiling predicted.

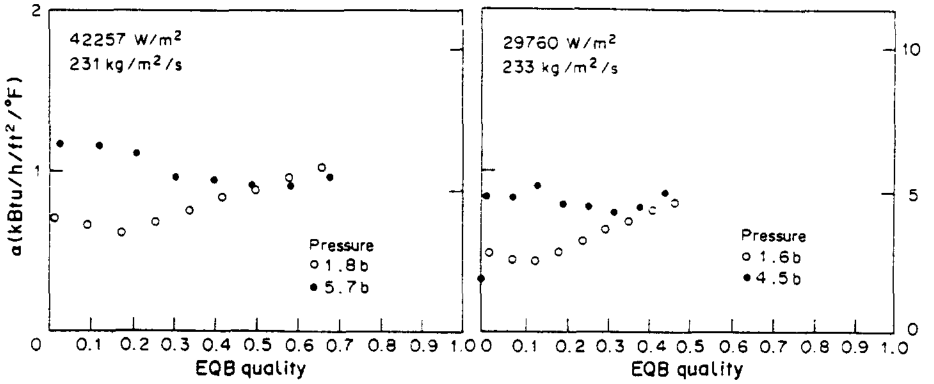


Figure 6. Effect of pressure on measured heat transfer coefficient for pure R152a. At low pressure, the evaporative contribution dominates.

is observed at low qualities, but this effect is reduced with increasing quality. Shown also is the prediction of the suppression criterion for the heat flux level required to initiate boiling as a function of quality and the given flow rate. The criterion predicts quantitatively the quality at which complete suppression occurs.

Figure 6 shows the effect of pressure on the heat transfer coefficient. The experimental value is greater at high pressure initially, but the difference is reduced or disappears at high qualities. These results indicate nucleate boiling, easier to achieve at high pressure, to be dominant at low quality. The boiling process then diminishes in favor of forced convection evaporation at high quality. The transition point is a function of heat flux: the lower the heat flux, the lower the quality at which nucleate boiling diminishes. The enhanced nucleate boiling theory described earlier does not yet predict this observation; it in fact suggests the opposite behavior.

These results support the traditional theory of nucleation and suppression. They suggest that nucleate boiling can be suppressed even at significant heat flux levels with relatively low conductive fluids such as refrigerants; however suppression becomes much more difficult as pressure is increased.

All pure refrigerant tests with rig 2 were done at a slightly higher pressure, around 4.75 b ($+0.2/-0.02$ preheat inlet, ± 0.05 test section outlet). Measurements were made in the preheat section where heat flux levels were varied over a wider range (10–95 kW/m^2 R152a; 10–55 kW/m^2 R13B1). The preheat data is shown in figures 7 and 8. Here a clear dependence on heat flux is observed, indicating a strong nucleate boiling contribution which was well-correlated by the method of Stephan & Abdelsalam (1980). The suppression criterion predicts that at this pressure level the actual heat fluxes were sufficient to sustain nucleate boiling.

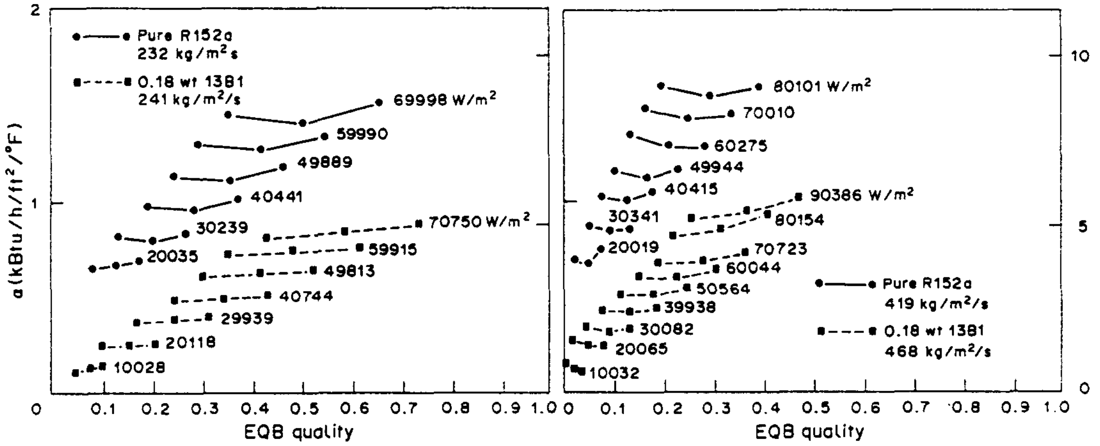


Figure 7. Effect of heat flux [4.75 ($+0.2/-0.1$)b] on pure R152a and R152a/R13B1 mixture: preheat data.

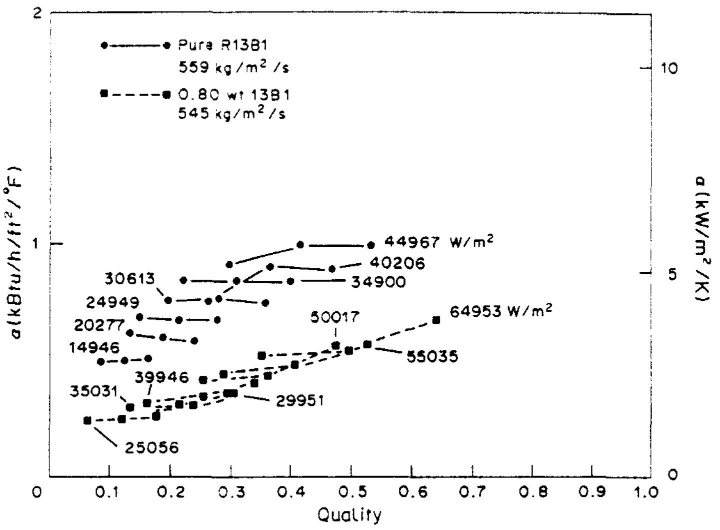


Figure 8. Effect of heat flux [4.75 (+0.2/−0.1)b] on pure R13B1 and R152a/R13B1 mixture: preheat data.

The test section data is for low heat flux but high vapor quality. The data is shown in figure 9. Tests were done with R152a and 10 and 20 kW/m² in the test section at three different mass fluxes. The figure shows a weak dependence on heat flux. The dependence on mass flux is seen clearly in all the figures. The dependence on quality increases with increasing mass flux as was observed with rig 1 and by others in the literature Anderson *et al.* (1966). These results suggest the *dominant* vapor generation mechanism is by evaporation, but that complete suppression may not be achieved. The criterion predicts sufficient heat flux to prevent complete suppression. The validation of this prediction will be discussed shortly.

Rig 2 allowed a unique examination of the effect of a step change in heat flux, since preheat and test section heat fluxes were set independently. If the process were completely independent of heat flux, then one would expect the measured heat transfer coefficient in the test section to be greater than that measured in the preheat section due to a continued increase in vapor quality. If, on the other hand, heat flux was dominant, then a large decrease in heat transfer coefficient should accompany a large decrease in heat flux.

One can compare the ratio of measured heat transfer coefficients between the last preheat measuring station and the test section with the ratio of preheat to test section heat fluxes. Figure 10 plots such a comparison. Note that as the preheat flux q_{pre} is raised relative to the test section

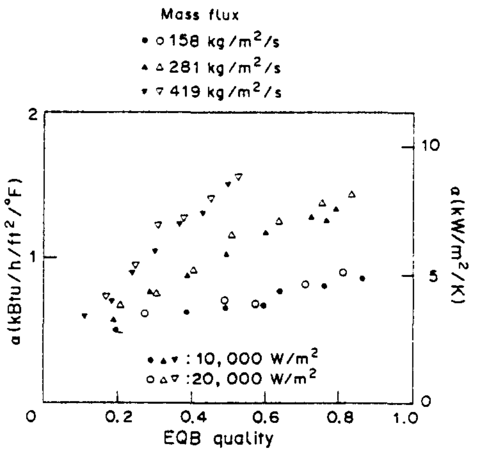


Figure 9. Effect of heat flux [4.75 (±0.05)b] on pure R152a test section data.

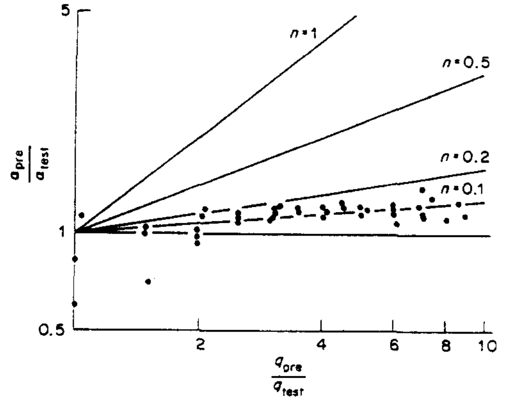


Figure 10. Effect of step change in heat flux: pure refrigerants R152a, R13B1.

q_{test}, the heat transfer coefficient ratio $\alpha_{pre}/\alpha_{test}$ increases also but to a lesser degree. If nucleate boiling were entirely dominant in both cases, then an expected value of n, defined from $\alpha_{pre}/\alpha_{test} = (q_{pre}/q_{test})^n$, would be between 0.5 and 0.8, reflective of the dependence of α on heat flux. If $n \leqslant 0$, then the heat transfer coefficient would be independent of heat flux, and the vapor generation process would be strictly evaporative. As can be seen, n lies between 0.1 and 0.2. It has a smaller value at larger mass fluxes. These comparisons suggest that both mechanisms, boiling and evaporation, are contributing to the heat transfer at this pressure level, though evaporation is dominant. It thus serves as a further verification of the suppression criterion.

Mixtures

The suppression methods discussed earlier were tried for mixtures. The first treats the mixture as an EPF. The next two account for mixture effects via isolated bubble theory, [6], and by the Stephan & Korner (1969) method discussed earlier.

Figures 11 and 12 display representative data for the effect of heat and mass flux on the heat transfer coefficient at fixed flow rate and initial composition for rig 1. A strong dependence on heat flux is clearly observed; a weaker dependence on mass flux is also seen. The dependence on pressure appears greater than the dependence on mass flux; this is an indication that boiling is not only present, but dominant. All criteria predict sufficient heat flux to sustain ebullition.

The rig 1 tests were conducted with various pressure levels. In rig 2, pressure was maintained generally around 4.75 b level. The preheat tests were conducted again with heat fluxes varied between 10 and 90 kW/m². As before, a dependence on heat flux was observed—indicating nucleate boiling to be present (representative figures 7 and 8); however, the heat flux dependence is weaker for the 0.80 wt R13B1 data. At this composition the $|Y - X|$ value is greatest for this mixture.

The preheat results suggest that boiling is likely not fully suppressed, except possibly at high quality for 0.80 wt R13B1. For all concentrations, the suppression criteria are verified for the case of nucleate boiling existence. It is now necessary to validate the criterion under fully suppressed conditions.

For the rig 2 test section data conditions were again set to try to achieve suppression (i.e. low heat flux, high quality). The EPF method predicts boiling is possible since $q_w > q_{sup}$ at all compositions and flow rates. However, the exact method with a Lewis number of 60 and the empirical method of Stephan & Korner (1969) predict suppression at all compositions at high flow rates. The measured data showed a clear and strong dependence on mass flux. As was done for pure components, the effect of a step change in heat flux was examined (figure 13). At high heat flux ratios, a greater value of n is observed compared to pure fluids; this could be due to nucleation occurring at high heat flux but not low heat flux. At *low* heat flux ratios, the data shows a positive $d\alpha/dx$ so that evaporation is much more effective, and could again support the notion of complete suppression.

These results show that forced convection/evaporation effects dominate in the test section, but are inconclusive regarding complete suppression of nucleate boiling. However, *correlative* evidence

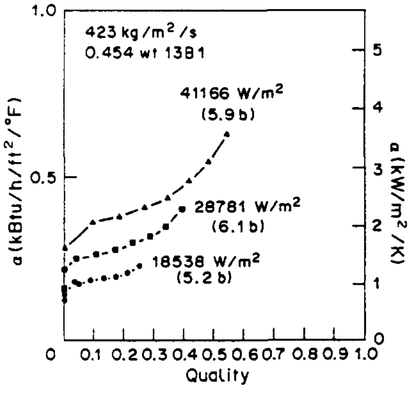


Figure 11. Effect of heat flux on heat transfer coefficient for 0.454 wt R13B1 mixture.

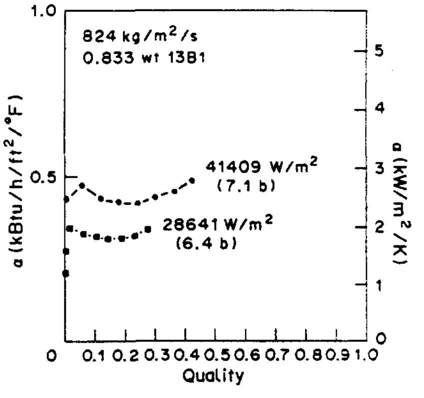


Figure 12. Effect of heat flux on heat transfer coefficient for 0.833 wt R13B1 mixture.

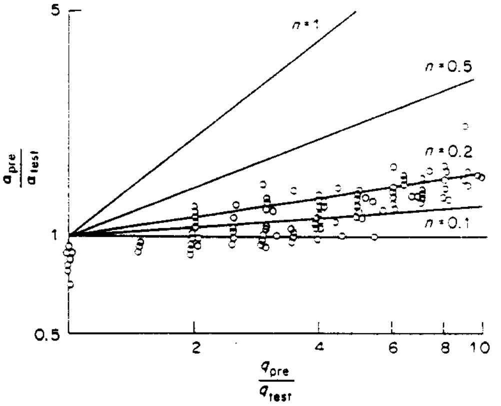


Figure 13. Effect of step change in heat flux: mixed refrigerants R152a/R13B1.

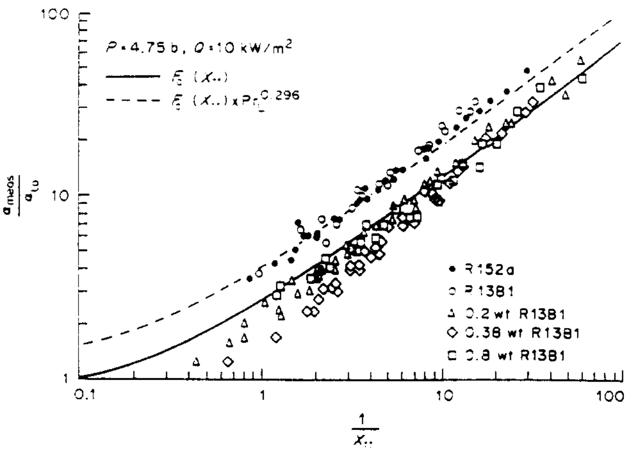


Figure 14. Comparison of Chen's method to pure and mixed refrigerants. Pure fluids require Prandtl number correction, suggesting sustained nucleate boiling. Mixtures are fitted fairly well by the same correlation without Prandtl correction, suggesting suppression of nucleate boiling.

can be used to determine if complete suppression has been achieved. Figure 14 plots the rig 2 test section data for both the pure components and the mixtures. The mixtures show a degradation in heat transfer from either pure component. However, theory suggests that in turbulent evaporative flow, the degradation is not due to MTR between the bulk streams and the vapor–liquid interface (Shock 1973). More likely, the difference is due to the nucleate boiling contribution. The suppression criterion predicts sustained ebullition for the pure components but not for the mixtures. Recently Bennett & Chen (1980) suggested the need for a Prandtl number correction to the evaporative contribution in flow boiling whenever ebullition exists. The evaporative portion of their correlation is plotted in figure 14 with and without the Prandtl number correction. As can be seen, the inclusion of the Prandtl correction predicts the pure components very well; and exclusion of the correction predicts the mixtures well, particularly at high quality. These results suggest that complete suppression has been achieved for the mixtures but not for the pure components at the same test conditions, and that mixture effects, probably mass diffusion dominated, must be accounted in suppression of nucleate boiling prediction.

7. CONCLUSIONS AND RECOMMENDATIONS

Conventional suppression theory is supported by experimental tests as well as a critical review of the literature. Contradictory findings in the literature can in fact be explained by conventional theory. The alternate hypothesis of enhanced nucleate boiling with annular flow boiling is not supported analytically or experimentally.

At pressure, flow and heat flux levels of most residential heat pump evaporators, complete suppression of nucleate boiling is not commonly observed with pure refrigerants. However, as pressure is lowered, nucleate boiling may be absent even with low conductive fluids such as refrigerants.

The conventional suppression criterion is verified quantitatively for pure refrigerants. For mixed refrigerants the criterion was modified to include MTR effects. The result is to lower the heat flux at which complete suppression occurs. Methods were hypothesized from "exact" and pool boiling theory. These methods were validated via correlation and to some extent empirically.

It may be possible to have complete suppression for mixtures and not for either pure component at the same test condition.

More incipient and suppressed boiling experiments need to be conducted for mixed fluids in flow boiling. The literature is particularly sparse in this critical area.

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