

Review of Recent Research on Boiling and Condensation Heat Transfer With Mixtures

S. P. Wang and J. C. Chato

ACRC TR-23

August 1992

For additional information:

Air Conditioning and Refrigeration Center
University of Illinois
Mechanical & Industrial Engineering Dept.
1206 West Green Street
Urbana, IL 61801

(217) 333-3115

*Prepared as part of ACRC Project #01
Refrigerant-Side Evaporation and Condensation Studies
J. C. Chato, Principal Investigator*

The Air Conditioning and Refrigeration Center was founded in 1988 with a grant from the estate of Richard W. Kritzer, the founder of Peerless of America Inc. A State of Illinois Technology Challenge Grant helped build the laboratory facilities. The ACRC receives continuing support from the Richard W. Kritzer Endowment and the National Science Foundation. The following organizations have also become sponsors of the Center.

Acustar Division of Chrysler
Allied-Signal, Inc.
Amana Refrigeration, Inc.
Bergstrom Manufacturing Co.
Caterpillar, Inc.
E. I. du Pont de Nemours & Co.
Electric Power Research Institute
Ford Motor Company
General Electric Company
Harrison Division of GM
ICI Americas, Inc.
Johnson Controls, Inc.
Modine Manufacturing Co.
Peerless of America, Inc.
Environmental Protection Agency
U. S. Army CERL
Whirlpool Corporation

For additional information:

*Air Conditioning & Refrigeration Center
Mechanical & Industrial Engineering Dept.
University of Illinois
1206 West Green Street
Urbana IL 61801*

217 333 3115

Review of Recent Research on Boiling and Condensation
Heat Transfer With Mixtures

by
Shi-Ping Wang and John C. Chato

Abstract

The fundamental physics and application of boiling and condensation of mixtures have attracted more and more attention. In this paper, the recent research in this field is reviewed. More than one hundred papers concerned with pool boiling, flow boiling, falling film evaporation, free and forced convective condensation of mixtures inside and outside tubes are summarized.

Review of Recent Research on Boiling and Condensation Heat Transfer With Mixtures

by
Shi-Ping Wang¹ and John C. Chato

Introduction

Recently boiling and condensation heat transfer with mixtures have attracted much attention for several reasons. First, interest increased recently in the use of zeotropic refrigerant mixtures (NARMs) as working fluids in heat pump and refrigeration systems, due to potential advantages in efficiency and capacity. Second, CFC refrigerants (such as R12 and R11) will have to be replaced soon by new refrigerants (such as R134a, R123a, R152a, and some mixtures). However, before the refrigerant mixtures will be put in use in heat pump, refrigerator, and air conditioning systems, the problem of possibly reduced heat transfer performance in boiling and in condensation processes has to be solved to realize the claimed advantages. Thus, it is necessary to study the mechanisms of boiling and condensation with mixtures.

In this report, the recent research on boiling and condensation heat transfer with mixtures is reviewed. In the boiling part, some important points are summarized, such as

- * the main reasons for the degradation of heat transfer with mixtures,
- * the circumferential variation of the wall temperature for flow boiling of mixtures inside horizontal tubes,
- * the suppression of nucleate boiling,
- * the improved peak heat flux,
- * and some models for boiling or evaporation of mixtures.

In the condensation part the main points are

- * the thermal resistance of the vapor diffusion layer affecting the condensation,
- * the influence of the flow direction of vapor on the condensation, and
- * the turbulence in the vapor generated by the fins.

This review is mainly concerned with the boiling and condensation of miscible mixtures, especially with NARMs. Only a few selected papers related to immiscible mixtures are reviewed here.

¹ Visiting Scientist; Professor, Chemical Engineering Research Institute, South China University of Technology, Guangzhou, China

Boiling Heat Transfer in Mixtures

Nucleate Pool Boiling

Nucleate pool boiling of mixtures is distinct from single component boiling in that the heat transfer coefficient (HTC) can be considerably lower than those of an equivalent pure fluid with the same physical properties as the mixture (Fig.1), and that the HTC does not change linearly with composition (Schlunder 1986, Pandey 1986). This deterioration is more pronounced at very high pressures than at low and medium saturation pressures, and it increases continuously up to the critical point (Bier 1982). Thome (1983) suggested that this reduction in heat transfer performance might be caused by:

(1) a rise in the local boiling point due to preferential evaporation of the more volatile component during bubble growth,

(2) additional mass diffusion resistance of the volatile component in the vapor bubble,

(3) significant changes in the physical properties of the mixture with composition,

(4) lower boiling site densities due to the effect of composition on nucleation, and

(5) the retardation of the principal heat transport mechanisms (bubble micro-layer evaporation, cyclic thermal boundary layer removal, and bubble induced convection).

In order to determine the main cause for this reduction, Thome conducted systematic research on pool boiling of mixtures. First, Thome (1982) measured incipient superheats on binary liquid mixtures and found that

(1) the nitrogen/argon mixture demonstrated no change in the incipient or deactivation superheats with composition;

(2) the ethanol/water mixture had a high maximum incipient superheat of 44 K, around 0.5 mole fraction ethanol, compared to the pure water and ethanol values of 7 and 23 K, respectively;

(3) the dynamic contact angle controlled the variation of the incipient superheat with composition via the vapor trapping process.

Thome later (1983) measured both the boiling site densities and HTCs as a function of composition, subcooling, and heat flux for ethanol/water and ethanol/benzene mixtures on a heated, vertical brass disk. He observed a strong effect of composition on the boiling site density, which was attributed to the nature of the activation of the boiling surface and to mass diffusion effects. For ethanol/water and for compositions of ethanol/benzene on one side of the azeotrope, the boiling site densities (Fig.2) were much smaller than those expected from a simple linear

interpolation between the single component and the azeotropic values. While subcooling decreased the HTC in mixture boiling relative to the ideal values, the reduction decreased as the level of subcooling increased. Also, the reduction was less for the mixtures than those for the single components or for the azeotropic mixtures. In comparing the pure water and ethanol/water azeotropic mixture results, the author concluded that the HTC at a given heat flux level was quite insensitive to a very large increase in boiling site density.

Alpay and Balkan (1989) studied the nucleate pool boiling performance of acetone/ethanol and methylene chloride/ethanol binary mixtures. They found that the deterioration in heat transfer was greatly affected by mass transfer conditions which depended on both pressure and heat flux, besides on the difference between the concentrations of the volatile component in the vapor, y , and in the liquid, x (i.e. $y-x$).

(1) The maximum worsening of heat transfer was always observed at the concentration at which the $y-x$ values were the greatest.

(2) The deterioration in heat transfer increased as the heat flux increased at a given pressure and concentration, and increased as the pressure increased at a given heat flux and concentration.

Gorenflo (1988) measured the phase equilibrium and the HTCs at pool boiling with R22, R114 and their mixtures. He found that

(1) at the lowest saturation pressure the greatest difference between the compositions of vapor and liquid was 35%, and this difference vanished at the critical point;

(2) the HTCs of mixtures decreased below the corresponding molar average of those for the pure components, the effect becoming more and more pronounced when the saturation pressure approached the critical pressure (Fig.3); and

(3) the dependence of the HTCs on heat flux and saturation pressure was less with the mixtures than with the pure components.

Reddy and Lienhard(1989) examined the peak boiling (burnout) heat transfer in saturated ethanol/water mixtures. They found significant improvement of the peak heat flux for mixtures over that of pure fluids, resulting from the subcooling created by selective distillation at the liquid/vapor interface. This improvement was most pronounced at low ethanol mass fractions. The burnout heat flux in binary mixtures is determined, in part, by the shape of the equilibrium phase diagram and is sensitive to the heat transfer boundary condition (uniform heat flux or uniform wall temperature). The experimental results of Shi (1991) showed that the HTCs for R134a/R152a mixtures agreed quite well with the molar average values of the HTCs of the pure substances (Fig. 4) because the dew and bubble point curves of the mixtures are almost identical, i. e. they behave nearly like pure fluids.

Enhancement of Pool Boiling

The High Flux tube, the mechanically made porous surface tube, and the Gewa-T Tube, which have been successfully used to enhance pool boiling heat transfer of pure fluids, can also be used to enhance nucleate pool boiling of mixtures. Wang found that the mechanically made porous tube, with ridges on the fins bent over to form tunnels, could efficiently enhance pool boiling heat transfer of mixtures of water/ethanol, water/methanol, and ethanol/methanol. The enhancement factors for mixtures were very large, up to more than 20 times, especially at low heat flux.

Shakir and Thome (1986) observed that the boiling activation and deactivation superheats were complex functions of composition and they were much smaller for the enhanced boiling surface (High Flux) than for the smooth surfaces. Further, Thome (1987, 1989) reported that the boiling performance of enhanced boiling tubes was affected differently by mixtures because the heat transfer mechanisms controlling their performances were not the same. For aqueous mixtures the boiling HTC's experienced less degradation than smooth tubes for the same conditions, because the liquid Prandtl numbers for binary, aqueous mixtures were observed to pass through high maxima at intermediate compositions, which augments the two-phase convection process inside the enhancement matrix and counteracts the negative effects of mass diffusion on the thin film evaporation process. The liquid Prandtl number for the ethanol/benzene mixture varied nearly linearly with composition, hence, its performance deteriorated on the enhanced tube to the same extent as for a plain tube due to the mass diffusion effect. The boiling performance of the Gewa-Tx tube was found to increase with increasing pressure for the five-component hydrocarbon mixture tested. A qualitative model for describing the enhanced boiling of mixtures was also developed.

Flow Boiling

Similar to pool boiling, the heat transfer performance of flow boiling inside horizontal or vertical tubes with zeotropic mixtures are significantly lower than those for a pure component. The forced convective boiling of a R11/R113 mixture flowing normal to a cylinder showed the same tendency (Fig.6, Fink, 1982). Singal (1983b), however, found that the average HTC's for binary mixtures of R13 (5-20%) and R12 were slightly greater than those for pure R12, but he did not perform experiments with pure R13.

The mechanisms of flow boiling of mixtures are more complicated than those of flow boiling of a pure component or pool boiling of mixtures. There are several issues addressed in the literature:

(1) What are the main reasons for the degradation of HTC's with flow boiling of mixtures?

(2) Is the full suppression of nucleate boiling (FSNB) easier to achieve with mixtures than pure components?

(3) Does the Prandtl number affect the flow boiling of both pure components and mixtures?

(4) What are the functions of heat flux, mass flux, quality, and pressure on flow boiling with mixtures?

(5) Is the circumferential boiling behavior of mixtures similar to that of pure components?

Based on their research on flow boiling in a vertical tube with water, ethylene, glycol, and aqueous mixtures of ethylene and glycol, Bennett and Chen (1980) attributed the significant reduction in HTC's to mass transfer effects and suggested a previously unrecognized Prandtl number effect on the boiling heat transfer for both pure components and mixtures.

The flow boiling performance of ethanol/cyclohexane mixtures showed that (Toral, 1982):

(1) in the region dominated by nucleate boiling, the mixture effects were similar to those in pool boiling; and

(2) the exponents, m , of the q vs ΔT^m curves for mixtures were smaller than those for single components.

Jain and Dher's (1983) results of flow boiling with R12/R13 mixtures in a horizontal tube at low heat flux showed that the HTC's in the convective boiling region were only affected by changes in thermophysical properties. In the nucleate boiling region a significant reduction of HTC's was observed.

Ross (1987) studied the horizontal flow boiling of R152, R13B1 and their mixtures. He presented the following conclusions.

(1) The mixtures yielded significantly lower HTC's than either pure refrigerant.

(2) FSNB could be achieved with pure refrigerants and their mixtures at low pressures. This finding contradicts Toral's (1979) suggestion that FSNB conditions are not achievable under most conditions with pure and mixed refrigerants due to their relatively low thermal conductivity.

(3) FSNB was easier to achieve with mixtures than pure fluids because mixture composition affected boiling site density and reduced bubble growth rates for mixtures as compared to an equivalent pure fluid.

(4) The degradation of HTC's for mixtures seems due to the effective suppression of nucleate boiling. This result is in sharp contrast to Bennett and Chen's (1980) mixtures model.

In order to understand the detailed mechanisms of flow boiling with mixtures, Ross et al. (1987) investigated the local, circumferential behavior in flow boiling. The wall temperatures around the tube outside circumference were measured at 90° intervals, and the inside wall temperatures were calculated by use of the steady-state, radial conduction equation. A unique phenomenon was observed: contrary to the pure components' behavior, the wall temperature at the bottom was lower than the one at the top, so that the HTC at the bottom was higher than at the top. Ross conjectured that the cause for this phenomenon might be a variation in composition around the circumference of the tube.

Jung (1989a) investigated horizontal flow boiling with R22, R114 and their mixtures. The boiling temperature difference between these fluids is 52 °C and the composition differences between the liquid and vapor phases is as much as 0.4 mole fraction. His results were as follows.

(1) For both pure and mixed refrigerants, the HTCs, for qualities less than 20-30%, were functions of heat flux, indicating the existence of nucleate boiling. In this "partial boiling" region, both the forced convective and nucleate boiling mechanisms were significant. The gradual suppression of the latter led to a reduction of the HTCs in a limited range of increasing quality. This was also observed by Ross (1989).

(2) In the "partial boiling" region, the HTCs for pure refrigerants and their mixtures were strongly dependent on the quality (Fig.7), in contrast with Kenning and Hewitt's (1986) results that HTCs were relatively independent of quality in the "partial boiling" region with water. This difference was probably due to the relatively low thermal conductivity of the refrigerants as compared to that of water.

(3) The transition point from partial boiling to the two-phase convective region was shown to be a function of heat flux such that it moved to a higher quality as heat flux increased for a given mass flow rate.

(4) Beyond this transition quality, however, the influence of heat flux vanished, indicating that nucleate boiling was suppressed. In the convective evaporation region, the HTCs of mixtures were as much as 36% lower than the ideal values under the same flow condition (Fig.8).

(5) The HTCs for mixtures were a function of an overall composition. Nothing abrupt happened as a small amount of a second component was added to a pure refrigerant. Jung indicated that non-ideal variations in physical properties accounted for 80% of the heat transfer degradation seen with mixtures and the other 20% was believed to be caused by mass transfer resistance in the convective evaporation region.

In order to explain the unique behavior that the temperatures at the bottom were lower than those at the top for horizontal flow boiling of R22/R114 (Fig.9) [Hihara (1990) also noticed this phenomenon with

R22/R114] and R152/R13B1 (Ross, 1987), Jung measured the circumferential variations of both temperatures and compositions. A composition variation of up to 0.07 mole fraction was measured in the annular liquid film between the top and the bottom of the tube (Fig.10), which caused a corresponding circumferential variation of wall temperature with mixtures. When the local equilibrium fluid temperature was used in calculating the HTC's, the values at the top were actually greater than the ones at the bottom even with mixtures, which was similar to the behavior observed with pure components. This result indicated that a portion of the degradation in heat transfer with mixtures might be an artifact of how the HTC's were calculated.

Jung (1989b) also used azeotropic mixtures of R12/R152a to do experiments and found the following results.

(1) The maximum degradation of measured HTC's from the ideal value was only 17% and it occurred in the composition range of 0.45-0.55).

(2) The circumferential wall temperature variation was similar to that for a pure fluid even though it was a mixture. This result was in contrast to their previous one with the NARM R22/R114. The discrepancy was explained as follows: mass transfer resistance for the R22/R114 mixture would be much larger than that for the R12/R152a mixture, because of the larger composition difference between the phases, $(Y-X)$ [i.e. $(Y-X) = 0.45$ for R22/R114 versus 0.11 for R12/R152a]. Here X and Y are the molar fractions of the volatile component in the liquid and in the vapor, respectively. The measured local compositions around the circumference for the R12/R152a were identical, indicating that the mixtures with a small volatility difference would not have circumferential variation even though they were mixtures, and that the mass transfer resistance could be negligible in the evaporative region for such mixtures.

Yoshida (1990) showed experimental results of flow boiling heat transfer performance of R22, R114 and their mixtures in a smooth tube:

(1) In the low mass flux ($G < 100 \text{ kg/m}^2\text{-s}$) and medium heat flux ($q = 10 \text{ kW/m}^2$) region, for both the pure refrigerants and mixtures, the HTC's at the top of the tube were very low, due, probably, to the stratified flow in this region. The average HTC's of the mixtures were always lower than those of pure components, no matter what the quality was.

(2) In the high mass flux ($G = 300 \text{ kg/m}^2\text{-s}$), high heat flux ($q = 20 \text{ kW/m}^2$) (Fig.11), and low quality ($x < 0.4$) region, the average HTC's for the mixtures were lower than those for pure components. However, in the high quality region ($x > 0.4$), the average HTC's of the mixture (each mass fraction 50%) were between those of R22 and R114. The higher the quality, the lower were the HTC's of R114, while the HTC's of both the mixture and R22 increased slightly. This was contrary to Jung's results (1989). Yoshida explained this phenomenon by noting that because the latent heat of R114

was smaller, it was easy to dry out at the top of the tube in the high quality region. One may wonder why Jung did not notice such phenomena?

Murata (1990) measured the local HTC's for flow boiling of mixtures of refrigerants R11 and R114 (The difference in boiling point is about 20 K) in a horizontal smooth tube. In the boiling-dominant region a large reduction of the HTC's was seen compared with those for pure components due to mixture effects. In the convection-dominant region, however, the reduction of HTC's could be explained mainly by the change of fluid properties, similarly to Jung's (1989) findings. However, their later (1991) experimental results with R123/R134a (The difference in boiling point is about 54 K) showed that even in the convection-dominant region there was some reduction in HTC's compared with those of an equivalent pure fluid, although not as significant as that in the boiling-dominant region. Based on their experimental research, they proposed a correlation for HTC's, based on the model in which the reduction in the HTC of the mixture is attributed to the effects of mixing on nucleate boiling and sensible heating of vapor phase accompanying the rise of saturation temperature in the flow direction. The correlation agreed qualitatively with their experiment results.

By using a 16mm, high-speed camera, Kedzierski and Didion (1990) visualized the bubble nucleation during flow boiling inside a horizontal electrically heated quartz tube for R22, R114, and their mixture (37.7 mol% R22). They found that

(1) the number of bubbles present decreased as quality increased for all fluids studied;

(2) for a given quality, R114 exhibited more bubbles than either R22 or the mixture;

(3) the amount of nucleation by R22 and the mixture seemed to be approximately the same, even though the mixture was mostly R114 by mole%, in contrast to the assumption that the bubble activity ought to be a mole-weighted activity. These observations showed that it is easier to achieve FSNB in the mixtures than in the pure components and could be used to explain why in the "partial boiling" region of flow boiling, the HTC's for mixtures were considerably lower than those for the pure components with similar properties.

The HTC's for a ternary blend of R124/R22/R152a (40/36/24%) flow boiling inside a horizontal smooth tube (Eckels 1991) were 12-20% higher than those for pure R12 at similar mass fluxes, but slightly lower than those for pure R12 at similar heat fluxes. The mass flow rate for the blend was 30-40% lower than for pure R12 under similar conditions.

Niederkruger (1992) studied horizontal flow boiling of R846/R12 mixtures at high pressures and in the nucleate boiling regime, and observed stratified, stratified-wavy, or wavy flows caused by small

density ratios resulting from the relatively high pressure. The results showed that there was a significant effect of mass velocity on the HTC for the mixtures (but no effect with pure refrigerants) due to the change in mass transfer resistance. The reduction in HTC for mixtures was significant (15–70%) compared to HTC for pure R846 or R12. The higher the heat flux, the larger was this reduction. This reduction is not due to changes in hydrodynamic conditions, but to the depletion of the more volatile component, R846, in the liquid phase as a result of the evaporation process.

The results for low and moderate qualities showed that the average HTC did not vary with quality, which was different from other researchers' results that the HTC increase as the quality increases at low pressures. There was no systematic dependence of local HTC on hydrodynamic parameters, i.e. mass velocity and quality. The local HTC increased with increasing pressure, mainly due to the decrease of the excess temperature necessary to form a stable nucleus of a given radius. The local HTC had the lowest value at the top of the tube.

Enhancement of Flow Boiling

Takamatsu (1988,1990) presented the performance of flow boiling in a horizontal, internally finned tube (Fig.12, 60 fins, 30° helix angle, 0.15 mm fin height) with R22, R114, and their mixtures (25, 50, 75 molar% of R114). He found that

(1) the refrigerant temperature of the mixture increased along the tube in a different manner depending on the bulk concentration. The temperature curve was convex downward for 25 mol% R114 and convex upward for 50 and 75 mol% R114;

(2) the temperature difference between the cooling water and the refrigerant mixture kept nearly constant along the tube when the water flow rate was properly adjusted.

They also proposed a correlation equation for HTC in the region before the dryout occurs, which was about 90–120% higher than that for smooth tubes. Their paper showed only the local HTC curves, but if we compare the local HTC curves for mixtures and for pure R22, we can see that the degradation of the average HTC (before the dryout point) for mixtures of R22 /R114 from those for R22 is significant, more than 40%. This is even larger than the degradation of HTC in smooth tubes with the same refrigerants [less than 36% found by Jung et al.(1989)]. This phenomenon may be explained as follows. One of the main mechanisms of enhancing flow boiling with fins in a tube is the provision of much more nucleate boiling sites. In flow boiling of mixtures, however, the FSNB is easier to

achieve (as described above), so that the enhancement effect on flow boiling for mixtures could be less than that for a pure component.

Murata's (1991) experimental results of R123/R134a condensation showed that the HTC's for the internally finned tube (60 fins, 30° helix angle, 0.3 mm fin height) decreased significantly from those of the pure components in both boiling- and convection-dominant regions. However, the enhancement factors were still significant (over 80%, Fig.13), especially with low mass fluxes ($G=100\text{kg/m}^2\text{s}$).

Conklin and Vineyard (1990) studied flow boiling of R22 and mixtures of R143a/R124 with two enhanced tubes, an internally finned and a fluted one (Fig.14). Both the HTC's and the pressure drops were higher in the fluted tube than in the finned tube at the same refrigerant mass and heat fluxes. When plotted as a function of the mass fraction of R143a the HTC's for the fluted tube were minimal at approximately 40% by mass fraction (51 mol%) of the R143a (Fig.15). The HTC's for the finned tube did not show a degradation as a function of R143a mass fraction, but they appeared to be a linear function of the mass fraction of R143a for a given mass flux. This phenomenon might be explained as follows. The swirl induced mixing in the tube with internal fins was stronger than that in fluted tube. There was no difference in liquid composition between the top and the bottom and the mass transfer resistance was reduced. Thus no degradation of the evaporating HTC occurred as compared to the pure constituents. From the above, we can expect that combining internal fins and flutes together in a tube will yield higher enhancement of flow boiling in mixtures. Further investigations are recommended using such combined tubes.

Sami (1991, 1992a) presented experimental results of flow boiling of refrigerant mixtures R22/R114 and R22/R152a through an annular passage on enhanced surface tubing (double fluted tube):

(1) The enhanced tube data showed a significant enhancement (about 2-3.2 times, Fig.16) of the heat transfer compared to an equivalent smooth tube. The value depended on the mixture's components and their concentration.

(2) The enhancement factor seemed to have a weak dependence on the mass flux.

(3) Increasing concentration of R114 in the mixture decreased the enhancement factor, indicating that the flow boiling of this particular mixture was experiencing a suppression of nucleate boiling with higher concentrations of R114.

(4) For R22/R152a (10, 20, 30 mol%), the HTC's were slightly higher than that of R22.

(5) The curves of HTC's of R22/R152a versus composition for various inlet qualities showed that the curves for the smooth tube were nearly

linear. The curves for the fluted tube were concave upward with a minimum at 35% fraction of R22.

Falling Film Evaporation

Berntsson (1985) presented the performance of R12/R114 mixtures in a falling film evaporator (a vertical, smooth tube). The HTC's at a given heat flux for mixtures fell between the corresponding values for the two pure component refrigerants (Fig.17) both at surface evaporation and nucleate boiling conditions, indicating that the additional mass transfer resistance was small or negligible in falling film evaporation. This effect was probably due to the small film thickness.

Gropp (1985) studied heat and mass transfer of R11/R113 mixtures in falling film evaporation and observed a reduction in HTC's during nucleate boiling. This reduction was attributed to the mass transfer resistance in both liquid and gas phases.

Correlations and Models For Boiling of Mixtures

Because the pool and flow boiling mechanisms of mixtures are very complex, currently there are no theoretical models for predicting the boiling heat transfer performance for every mixture of interest. There exist some semi-empirical equations which can be applied only to specific mixtures under specific conditions corresponding to the experimental data used.

For the relations of pool boiling of binary mixtures Thome (1983) proposed a simple method using only phase equilibrium data, which predicted the measured data fairly well.

$$h = \left[\frac{X_1}{h_1} + \frac{X_2}{h_2} \right]^{-1} \left[\frac{\Delta T_i}{\Delta T_i + \Delta T_{bp}} \right]$$

Where, X_1 and X_2 are the mole fractions of the mixtures; h_1 and h_2 are the HTC's for pool boiling of the pure components; ΔT_i is the ideal mixing law superheat; ΔT_{bp} is the temperature difference between the dew line and the bubble line at the bulk liquid mole fraction.

For flow boiling of mixtures Bennett and Chen (1980) developed an expression, based on the standard Chen correlation used to predict the performance of flow boiling of a pure component, which accounted for the effects of both Prandtl number and mass transfer, and correlated the experimental data (mixtures of water, ethylene, and glycol and some aqueous mixtures) quite well.

$$h_{TP} = h_{l0} F Pr_l^{0.296} + h_i S$$

where h_{TP} , h_{l0} and h_i are the HTC's for the two-phase, for the liquid only, and for pool boiling of ideal mixtures, respectively. F and S are factors determined by experimental data.

From his research on flow boiling of R12/R13 mixtures, Singal (1983b) concluded that

(1) liquid and vapor phase Prandtl numbers affected the generalized correlations for predicting the local HTC's;

(2) the heat transfer behavior of a binary mixture was similar to that of pure refrigerants, and, therefore, empirical correlations [such as Lavi-Young (1965)], which are similar to the those of pure fluids but contain an allowance for an additional component could be developed.

$$h_{TP}/h_{L0} = 115.84[(1+x)/(1-x)]^{2.88}(1-x)^{3.03}(Bo)^{0.20}(Pr_L * Pr_G)^{-1.99}$$

$$Bo = [(q/A)/(G h_{fg})] \text{ -- boiling number}$$

It should be noted that the exponent of Pr in Singal's correlation is negative, in contrast to the positive value (0.296) in Bennett and Chen's correlation.

The effects of mass diffusion and Prandtl number on (h_{TP}/h_{L0}) were discussed by Ross and Jung. Ross (1987) found that mass diffusion did not complicate the problem substantially under FSNB conditions (it just affects the FSNB point), and the mixture data were correlated fairly well by the F function without Prandtl number correction, particularly at high quality. Jung et al. (1989b) indicated that the dimensionless HTC, (h_{TP}/h_{l0}) , in the evaporative region should be independent of Prandtl number. They developed a method to predict the transition quality from the partial boiling to the convective evaporation region. When it was extended for mixtures, the method required only additional phase equilibrium information. A mixture correlation was also developed based on Ünal's (1986) method using only phase equilibrium data in conjunction with Stephan and Abdelsalam's (1980) nucleate boiling correlation, which predicted their experimental data with a mean deviation of 9.6%. Jung's correlations are:

$$h_{TP} = (N/C_{UN}) h_i + C_{me} F_P h_{L0}$$

where

$$N = \begin{matrix} 4048 X_{tt}^{1.22} Bo^{1.13} & \text{for } X_{tt} < 1 \\ 2 - 0.1 X_{tt}^{-0.28} Bo^{-0.33} & \text{for } 1 \leq X_{tt} \leq 5 \end{matrix}$$

$$C_{UN} = [1 + (b_2 + b_3)(1 + b_4)](1 + b_5)$$

$$b_2 = (1-X) \ln [(1.01 - X)/(1.01 - Y)] + X \ln (X/Y) + |X - Y|^{1.5}$$

$$b_3 = 0 \quad \text{for } X \geq 0.01$$

$$b_3 = (Y/X)^{0.1} - 1 \quad \text{for } X < 0.01$$

$$b_4 = 152 (p/p_{cmvc})^{3.9}, \text{ where } p_{cmvc} \text{ is the critical pressure of the more volatile component}$$

$$b_5 = 0.92 |Y - X|^{0.001} (p/p_{cmvc})^{0.66}$$

$$X/Y = 1 \quad \text{for } X = Y = 0$$

$$h_i = (X_1/h_1 + X_2/h_2)^{-1} \text{ -- pool boiling HTC for an ideal mixture}$$

$$C_{me} = 1 - |Y - X|^{1.56}$$

$$F_p = 2.37 (0.29 + 1/X_{tt})^{0.85}$$

X and Y are mole fractions of the more volatile component in the liquid and in the vapor, respectively

The single phase HTC with only liquid flowing, h_{l0} , is given by the Dittus-Boelter correlation using the equilibrium liquid phase properties.

Kandlikar (1991) modified his correlation for pure refrigerants (1990) to predict the flow boiling performance of NARMs without introducing any empirical constants. The nucleate boiling term was modified to account for the mass diffusion effects in the liquid near the liquid-vapor interface of a growing bubble. The convective boiling term remained the same, but the properties were calculated at the local equilibrium composition.

$$h_{TP}/h_{L0} = \text{larger of } \begin{cases} [h_{TP}/h_{L0}]_{CBD} \\ [h_{TP}/h_{L0}]_{NBD} \end{cases}$$

where CBD stands for the convective boiling dominant region and NBD stands for the nucleate boiling dominant region. The following equations apply.

$$[h_{TP}/h_{L0}]_{CBD} = 1.136 (Co)^{-0.9} (1-x)^{0.8} f(Fr) + 667.2(Bo)^{0.7} (1-x)^{0.8} / [1+|X-Y| (a/D_{12})^{0.5}]^{0.7} F_{f1}$$

$$[h_{TP}/h_{L0}]_{NBD} = 0.6683 (Co)^{-0.2} (1-x)^{0.8} f(Fr) + 1058 (Bo)^{0.7} (1-x)^{0.8} / [1+|X-Y| (a/D_{12})^{0.5}]^{0.7} F_{f1,m}$$

$$f(Fr) = (25 Fr_{l0})^{0.3}; \text{ but the maximum value (and for vertical tubes)}$$

is 1.

$$Fr_{L0} = G^2/(r_L^2 gD) \text{ -- Froude number with all flow as liquid}$$

$$F_{f1,m} = X_1 F_{f1} + X_2 F_{f1,2} \text{ -- fluid dependent parameter for mixture}$$

$$X_1, X_2 \text{ -- molar concentration of the two components in the liquid}$$

$$F_{f1}, F_{f1,2} \text{ -- fluid dependent parameters for the two components, values given by Kandlikar (1991)}$$

$$Co = [(1-x)/x]^{0.8} (\rho_g/\rho_l)^{0.5} \text{ -- convection number,}$$

h_{L0} , the liquid phase HTC is calculated as follows:

For $0.5 \leq Pr_L \leq 2000$ and $10^4 \leq Re_{L0} \leq 5 \times 10^6$ (Petukhov-Popov equation)

$$Nu_{L0} = h_{L0} D / k_L = Re_{L0} Pr_L (f/2) / [1.07 + 12.7 (Pr_L^{2/3} - 1) (f/2)^{0.5}]$$

For $0.5 \leq Pr_L \leq 2000$ and $2300 \leq Re_{L0} \leq 10^4$ (Gnielinski equation)

$$Nu_{L0} = h_{L0} k_L / D = (Re_{L0} - 1000) Pr_L (f/2) / [1.0 + 12.7 (Pr_L^{2/3} - 1) \times (f/2)^{0.5}]$$

$$f = [1.58 \ln(Re_{L0}) - 3.28]^{-2}$$

The ratio of thermal to mass diffusivity, (α / D_{12}) , represents the ratio of the heat to mass transfer rates in the liquid surrounding a bubble, and is calculated at the local, equilibrium, liquid phase composition and the corresponding saturation temperature.

Murata (1990) proposed a correlation for HTCs in flow boiling of R11/R114, where mixture effects were taken into account only for the nucleate boiling term and the convection term was regarded as equal to that for pure fluid with equivalent properties.

$$h_{TP} = \{h_{id} / [1 + 1.65(Y-X)]\} * S + h_{L0} * F$$

where

$h_{id} = X h_{pb114} + (1-X) h_{pb11}$, and h_{pb114} , h_{pb11} are pool boiling HTCs for R114 and R11, respectively.

$$F = 2.44 (1/X_{tt})^{0.863}$$

$$S = (k_L / h_{L0} F d) [1 - \exp(-h_{L0} F d / k_L)]$$

$$\delta = 0.08 \{ \sigma / [g(\rho_l - \rho_g)] \}^{0.5}$$

Recently, Granryd (1990) and Conklin (1991) pointed out that the non-equilibrium phenomena (in both composition and temperature due to the heat and mass transfer resistances) and variable specific heat of the fluid might be other causes of the decrease in heat transfer in forced convective evaporation and condensation of refrigerant mixtures. They posed a variable specific heat method (in terms of the number of transfer units NTU and effectiveness ϵ) to estimate this effect and to predict the thermal performance of the evaporator and condenser with NARMs. Based on similar hypotheses, Granryd (1991) also developed a correlation to predict the HTCs of NARMs in the annular flow regime with suppressed nucleation.

$$h_{TP} = h_{L0} F_p / (1 + A)$$

$$\text{where } h_{L0} = k_l / D * 0.023 [(1-x) G D / \mu_l]^{0.8} Pr_l^{0.4}$$

$$F_p = 2.37(0.29 + 1/X_{tt})^{0.85}$$

$$A = (F_p/C_{1g})x^2\{[(1-x)/x](\mu_g/\mu_l)\}^{0.8}(Pr_l/Pr_g)^{0.4}(k_l/k_g) \\ *(c_{pg}/c_{pw})$$

C_{1g} --enhancement of heat transfer between the liquid and vapor interface compared to flow in a smooth tube. For evaporation $C_{1g} = 2$.

c_{pg} --specific heat of the vapor

c_{pw} --apparent specific heat for the NARM at quality x , $= (\partial i/\partial t_f)_x$ where i is the enthalpy.

t_f -- equilibrium temperature, $= (1-x) t_l + x t_g$

For flow boiling of R22/R114 mixtures inside a horizontal, internally finned tube, Takamatsu (1988, 1990) proposed a correlation as follows:

$$h_{TP}/h_{L0} = C_1Bo*10^4 + C_2(1/X_{tt})C_3$$

$h_{L0} = k_l/D*0.023[(1-x)GD/\mu_l]^{0.8}Pr_l^{0.4}$ -- the HTC's of the liquid flowing in a smooth tube.

$$C_1 = 1.60 - 8.08 Y + 22.0 Y^2 - 28.4 Y^3 + 14.2 Y^4$$

$$C_2 = 6.71 - 13.0 Y + 28.2 Y^2 - 37.5 Y^3 + 20.0 Y^4$$

$$C_3 = 0.95 - 1.91 Y + 5.92 Y^2 - 6.67 Y^3 + 2.66 Y^4$$

Y -- molar fraction of R114

Sami (1991) developed a correlation for HTC's of R22/R114 mixtures in flow boiling in the annulus of a double fluted tube, which was treated as a plain tube with an equivalent annulus diameter.

$$h_{TP}/h_{L0} = M_{TR}(4.0X_{tt}^{-0.45})$$

$$h_{L0} = k_l/D*0.0254 Re^{0.8} Pr_l^{0.4} (d_o/d_n)^{0.45}$$

Re -- Re number in the annulus based on the total flow

d_o -- inner diameter of outer tube

d_n -- nominal diameter of the annulus

$M_{TR} = 0.42|x-y|^{1.57}$ -- mass transfer term

Condensation Heat Transfer in Mixtures

Free Convective Condensation

Tamir and Merchuk (1979) investigated condensation of several binary mixtures (acetone/methanol, acetone/ethanol, methanol/ethanol) and a ternary mixture (acetone/ methanol/ethanol) on a cooled vertical wall and obtained the following results. Because of the accumulation of the more volatile component at the vapor-liquid interface, the temperature at the interface was lower than that in the bulk, thereby reducing the

condensation rate. This reduction was larger when the components were less similar in boiling point temperature and properties. This reduction was accentuated at low temperature differences between the cooled wall and the bulk vapor. At relatively high condensation rates (corresponding to $\Delta T > 5K$), the composition of the condensate became identical with that of the bulk vapor. Their results successfully verified the Taitei-Tamir (1974) model.

The patterns of gravity controlled condensation of several types of binary mixtures on a smooth horizontal tube were observed by Fujii (1989a, 90):

(1) for methanol (mass fraction 0.08-0.85)/water mixtures, the condensation pattern was dropwise and the HTC's were 2-6 times higher than the theoretical values for filmwise condensation;

(2) for ethanol/water mixtures, four condensation patterns were observed (Fig.18), for y (ethanol mass fraction) = 0.28-0.60, the pattern was dropwise, while for $y=0.73-0.83$ it changed from streak to ringwise to filmwise with the increase of heat flux. HTC's were 1 to 6 times higher than the theoretical values for filmwise condensation depending on concentration and condensation pattern;

(3) for methanol-ethanol mixtures the pattern was filmwise and the HTC's were in good with the theoretical values.

Fujii (1989b) also studied theoretically the laminar film condensation of gravity-controlled convection for ternary vapor mixtures on a vertical flat plate, and found the effects of mutual intervention of buoyant forces due to temperature and concentration differences on convective heat and mass transfer in the vapor boundary layer.

Lukin and Zakirov (1988) presented the results of condensation of water/acetone (acetone content varied from 10 to 90%) mixture on vertical surfaces with transverse grooves. The depth of the grooves, h , was 0.4-0.85 mm and their spacing, t , was 4-12 mm. The profiled surface could significantly enhance the HTC's. For example, the HTC's on the grooved surface ($h=0.85$ mm, $t=4$ mm) was 45% higher than those on the smooth surface, mostly because the transverse grooves caused turbulence in the condensate boundary layer.

Goto (1982, 88) studied the condensation performance of NARMS (R114/R11, R12/R114) on a single smooth tube and developed a method, based on two-phase boundary layer theory, to correlate the experimental data for R114/R11 and R12/R114 condensing on the tube in a uniform filmwise manner. Four condensation patterns of R114/R11 (Fig,19) were observed:

(1) in the R12 mass fraction ranges of 0-0.3 and 0.8-1 and with very low and high heat fluxes, the film was smooth;

(2) in the range of 0.3-0.8, the ringwise film varied from faint to turbulent to stationary as the heat flux decreased. The highest HTC's were found with the turbulent, ringwise film pattern, about 50% higher than those in the smooth film and faint ring patterns. This result suggests that the turbulent motion of the rings increased the HTC's.

Goto and Fujii also studied the influence of air on the condensation of NARMs. Their early paper (1982) showed the strange result that small amounts, less than 1%, of air in the binary vapor of R12 (mass fraction 0.7) and R114 (mass fraction 0.3) increased the HTC's (Fig.20). They explained this effect by the increase of the buoyant force in the vapor boundary layer due to air. Later, however, they (Fujii 1985, 91) presented contrary experimental and theoretical results indicating that even a little amount of air could reduce the HTC's significantly.

Hijikata (1986) presented the following characteristics of free convective, film condensation of binary mixtures of vapors on flat and finned vertical plates:

(1) For condensation of R113/R11 on a flat plate, all results tended to the Nusselt solution. As ΔT increased, however, in the small ΔT region, the reduction of the HTC's with an increase of the concentration of R11 was smaller than that of R113/R114 mixture (Fig.21). The difference may be explained by the difference of the molecular weight between two vapors: it was large for R113/R11 and, consequently, the buoyancy force was larger and the thermal resistance of the diffusion layer was smaller in the R113/R11 mixture for a given concentration as compared to R113/R114.

(2) The experimental results of HTC's for a binary mixture could be explained by a pseudo-similar solution in which the thermal resistances of the liquid film and the vapor diffusion layer were considered to independently coexist in series.

(3) In the small ΔT region, the HTC's were rate controlled by the diffusion layer. If the thickness of the diffusion layer was larger than the fin height, the effective area for condensation was equal to the projected area.

(4) In the large ΔT region, the thermal resistance of the diffusion became less and the HTC's could be estimated by the theory of a pure vapor. Consequently, the heat transfer enhancement by the finned surface was also effective for the condensation of binary mixtures of vapors.

(5) For condensation of the azeotropic mixture of PFP and water, the experimental results on a flat plate agreed well with the Nusselt solution, except for the 25% mass fraction of water, where the HTC's became lower as ΔT decreased because the thermal resistance of the diffusion layer became important. The characteristics of condensation on a finned plate

were quite the similar to those for the flat plate. The surface tension effect on the condensation on a finned surface was weak.

Forced Convective Condensation of Vapor Mixtures on Tubes

Hijikata (1987, 89b, 90) studied systematically the performance of forced convective condensation of binary mixtures of R113/R114 vapors (the difference in boiling temperatures was 43.8 K) on a smooth tube and on several kinds of horizontal and vertical finned tubes, including the influence of the vapor flow direction on the heat transfer performance. The following results were obtained:

(1) In the small ΔT and low vapor Reynolds number regions the HTC's of the binary vapor mixture, especially in the low fin tube, were significantly reduced from those of each pure vapor component because the vapor diffusion layer created a thermal resistance on the vapor side.

(2) In the large ΔT region, less reduction of the HTC's was observed and the effect of the vapor flow velocity became negligible.

(3) In the high Reynolds number region, there was less reduction of the HTC's even within the small ΔT region.

(4) The turbulence generated by fins and the wave motion of the liquid film at the tube surface increased markedly the heat transfer in the mass diffusion layer covering the condensing surface. An enhancement factor was used to express the effects of fins and the wave motion of the liquid film on the heat and mass transfer . Table 1 lists the enhancement factor in each situation.

Table 1 The enhancement factor

tube type	vertical tube			horizontal tube in vertical flow			horizontal tube in horizontal flow			
	Re	1300	3500	8100	1300	3500	8100	1300	3500	8100
smooth		2.7	2.7	2.7	2.2	2.2	2.2	3.5	3.5	3.5
high-fin		2.1		3.0	1.9	2.0	2.6	2.4	2.7	2.8
low-fin		1.9	2.0	2.6	1.0	1.3	1.4	0.9-2.2	1.0-2.2	1.3-2.2

(5) For the smooth tube the heat transfer in the diffusion layer was enhanced mostly for horizontal vapor flow because the wave motion of the liquid film became the most violent.

(6) Among the finned tubes the "high fin" tube had the highest heat transfer performance because the turbulence generated by the fins depended primarily on the fin height.

(7) Among the finned tubes a vertical tube with axial fins showed good heat transfer performance, even with the "low-fin" tube, because the fin was effective in turbulence generation.

(8) The HTC's in the diffusion layer could be estimated accurately by using the analogy between heat and mass transfer.

The results of Nozu et al. (1988, 89, 91, 92) on condensation of R114/R113 mixtures in a horizontal annulus with an enhanced inner tube (Fig.22 shows the corrugated tube with soldered wire fins on the outer surface) showed that:

(1) The HTC's for mixtures was considerably smaller than those for pure R113 (Fig.23). The decrease was more significant for low mass velocity.

(2) The enhanced tube showed a significant heat transfer enhancement, about 1.5-2 times over the smooth tube values.

(3) The radial distribution of the vapor temperature was affected by the vapor velocity, becoming flatter at the outer edge of the annulus and steeper near the liquid-vapor interface as the vapor velocity increased.

(4) The frictional pressure gradient data for R114/R113 mixtures were correlated fairly well by using the Lockhart-Martinelli parameter. An expression for the vapor phase mass transfer coefficient was derived, based on previous results for turbulent single-phase flow in tubes with and without suction. A dimensionless correlation was also developed to predict the vapor phase mass transfer coefficient, where the dimensionless parameters for forced convective condensation from a vapor-gas mixture flowing normal to a cylinder was extended to the case of mixtures.

Murphy (1990) tested the heat transfer performance on titanium finned tubes with R114/R12 mixtures. Even low R12 concentration reduced the HTC's substantially (Fig.24 shows up to 55% performance reduction for 5% R12) due to an additional transport resistance caused by preferential concentrations of the more volatile component in the condenser. This result was also supported by gas chromatography composition analyses of the shell vapor samples.

The condensation performance of NARMs on horizontal, doubly fluted tubes (Sami and Schnotale, 1992b) showed that the enhancement factor depended on the mixture components and their concentrations. For R22 the average enhancement factor was 3.29, while for the NARM R22/R114 (Fig.25) the factor, about 1.5-2.5. The HTC's were a function of the mass flux and the concentrations. It increased nearly linearly with R22 mass fraction at constant mass flux. For the NARM R22/R152a, the enhancement factor was about 4, the HTC's varied non-linearly with the mixture composition.

They developed a correlation for predicting the condensation HTC on such tubes.

$$Nu = 0.04 X^{0.48} Re^{0.4} Ph^{0.25} Ga^{0.75} Pr^{0.25}$$

where $Ph = h_{fg}/[c_p(T_v - T_w)]$ -- phase change number (1/Jakob No.)

$Ga = \rho_L(\rho_L - \rho_g)gD_e^3/\mu^2$ -- Galileo number

D_e -- equivalent diameter of the annulus based on bore diameter

Forced Condensation in Horizontal Tubes

Bokhanovskiy (1985) studied the heat transfer performance of R12, R22 and their mixtures in a coiled-tube condenser and showed that only in the low heat flux region ($q/A < 18 \text{ kW/m}^2$) was the reduction in HTC's significant due to the diffusion resistance in the vapor. As the heat flux increased, this reduction decreased and the HTC's tended to obey the same relationship as in pure refrigerants.

Tandon (1985) visually observed the flow patterns of condensing binary mixtures of R22/R12 inside a horizontal tube and showed that the flow regime maps of Baker, Soliman and Azer, and Breber agreed with the mixture flow pattern data only in certain flow regimes and had some deficiencies in others. Tandon's map (1982) was more consistent and reliable.

Stoecker and Kornota (1985) studied the condensation performance of binary mixtures of R12/R114 and pointed out that it was in the mid-range of the condenser where the influence of the mixture was most dominant in reducing the HTC's. The observations and photos (Degrush and Stoecker, 1987) made in a glass-tube condenser indicated that the flow was wavy or stratified in the mid-range, where the greatest amount of vapor-liquid slip occurred, which could explain the reduction of HTC's. They suggested a way to prevent the reduction of the HTC's by installing turbulence promoters or circuiting the condenser to higher velocities. They also recommended that Tandon's correlation (originally developed for pure component condensation) could be used to predict the HTC's for condensation R12/R114 mixtures.

For $Re_v < 30,000$: $h = 23.1 Pr_L^{1/3} (h_{fg}/c_{pL} \Delta T)^{1/6} Re_v^{1/8}$

For $Re_v > 30,000$: $h = 0.084 Pr_L^{1/3} (h_{fg}/c_{pL} \Delta T)^{1/6} Re_v^{0.67}$

Mochizuki (1988) and Inoue (1988) studied complete condensation of the NARMs R113/R11 and R113/R114 in a smooth tube and found that:

(1) The change in vapor and liquid composition along the flow passage could be estimated by applying Raoult's law,

(2) In the high Reynolds number region, the local and average HTC's for R113/R11 were between those for pure R113 and R11 (Fig.26), indicating that the condensation heat transfer performance of a nonazeotropic, binary mixture is not always inferior to that of pure vapor.

(3) At all mass fluxes the average HTC's for the R113/R114 mixture were slightly lower than those for pure components. The maximum

reduction of the average HTC's occurred when the fraction of R113 was 50%. The different results for different mixtures might be explained by the differences in boiling temperatures and properties which were larger between R113 and R114 than between R113 and R11, and (Y-X) for the former was larger than that for latter. At high mass fluxes of the mixture of R113/R11 two-phase flow in the tube could mix very well and the mass transfer resistance could be neglected. The mixture of R113/R114 did not mix as well, and the mass transfer resistance caused the reduction of HTC.

Koyama (1988, 90, 91) investigated the condensation of refrigerant mixtures R22/R114 inside smooth and internally finned tubes and reported the following results.

(1) The local HTC's for the mixtures inside both smooth and internally finned tubes were less than those for the pure refrigerants. The HTC's depended on the composition and the mass flux.

(2) The internally finned tube could enhance condensation heat transfer of NARMs, especially in the upstream region. The average enhancement factor was about 1.3, which was less than that for pure refrigerants (about 1.6). The frictional pressure drop was higher than that of a smooth tube by a maximum of about 30%.

(4) In the internally finned tube the maximum reduction, compared to pure R22 data, of the average HTC's (about 20%) occurred for mixtures with 50-60 mol% fraction of R22.

(5) The combination of the correlation equations for condensate heat transfer and vapor mass transfer could accurately predict the heat transfer characteristics of NARMs.

(6) The circumferential temperature distribution in the finned tube wall was different for the pure refrigerant R22 and the mixture (Fig.27). With the pure R22 the temperature at the right-side, top, bottom, left-side decreased in sequence, and the temperature difference became slightly larger along the flow direction to a point about 3/4 of the length of the tube. With the R22/R114 mixture, however, the circumferential temperatures were about the same. These phenomena were explained as follows. Because the internal fins had 30° angle to the right of the tube axis, during condensation of pure R22 the thin film of liquid moved from the top to the right-side of the tube and the thick film of liquid moved from the bottom to the left-side of the tube. During condensation of the R22/R114 mixture, there might have been a circumferential distribution of (liquid-vapor) interfacial temperature, which varied in the opposite direction. This explanation needs to be further investigated.

Koyama's (1990) correlation for average HTC is:

$$Nu = 0.53(L/d_i)^{-0.4} Ph^{-0.6} (Re_1 Pr_1 / R)^{0.8} (1 - 0.73X + 0.37X^2 + 0.36X^3)$$

where $Nu = h L / k_L$

L -- tube length

d_i -- tube inside diameter

$Ph = c_{pL}(T_{sat} - T_w) / [h_{vsat})_{z=0} - (h_{Lsat})_{z=L}]$

$Re_1 = \rho_L U_v L / \mu_L$

$R = [\rho_L \mu_L / \rho_v \mu_v]^{0.5}$

X -- bulk molar fraction of R114

Vineyard (1991) showed that the finned surface (fin height 0.432mm at an angle of 47° from the axis) could improve the condenser performance more significantly than the fluted tube, and that the refrigerant-side heat transfer enhancements in the condenser and evaporator improved the COP of the system more with the NARM than with R22.

The HTC's for a ternary blend of R124/R22/R152a (40/36/24%) condensing inside a horizontal smooth tube (Eckels 1991) were 12-20% higher than those for pure R12 at similar mass fluxes, but they were slightly lower than those for pure R12 at similar heat fluxes because the mass flow rate of the blend was 30-40% lower than for pure R12 under these conditions.

Forced Convective Condensation in Vertical Tubes

Mochizuki (1984) studied the performance of condensation of R11/R114 vapor mixtures in a vertical smooth tube in countercurrent flow with the coolant. He found that

(1) the R11/R114 mixtures behaved like ideal nonazeotropic binary mixtures; and

(2) the local HTC curve of the mixtures fell between those of pure R11 and R114.

The authors also developed semi-empirical equations to predict the heat transfer performance in laminar and combined laminar/turbulent flows which agreed well with experimental data.

Hijikata (1987, 88, 89a) and Himeno (1988) presented condensation performance in a vertical, internally finned tube (fin pitch and height were 0.5, 0.2mm, respectively) with mixtures of R113 (80, 90%)/R114 (20,10%). They found that:

(1) The condensation HTC for R113/R114 suddenly decreased in the small ΔT region because the volatile component was accumulated in the bulk along the flow direction.

(2) A minimum temperature difference was required for the vapor to condense completely at the outlet of the tube, corresponding to the

difference between the condensation (dew point) and the boiling (bubble) points at the same composition as the inlet vapor.

(3) In the large ΔT region the dependence of the HTC's on ΔT for the mixture R113/R114 was quite similar to that of pure R113, except that it was about 30-40% lower (Fig.28).

(4) When the fin height was 0.2 mm, the enhancement of the heat transfer due to the fins occurred only in the liquid film, and the diffusion layer in the vapor was barely affected by the fins.

(5) The HTC's for binary condensation in a vertical tube could be estimated closely by a theory based on the assumption that the falling liquid film was well mixed.

Forced Convective Condensation of Mixtures in Plate Condensers

Chilipenok (1988) reported experimental data on heat transfer in condensation of a R12/R11 mixture in a vertical plate condenser. The equivalent diameter of the channel was 1.9 mm, the fin height was 2.5 mm, the pitch was 4.15 mm. The dependence of the HTC's on the molar fraction of R11 had a minimum value at about 35 mol%, which was only about 20-35% of the HTC's for pure R12 (Fig.29), indicating that, in the case of condensation of a mixture with a large difference in boiling temperatures, the diffusion layer affected significantly the condensation process.

Methods of Condenser Design for Mixtures

Existing methods for designing condensers for multi-component mixtures are of two basic kinds:

(1) Equilibrium methods, which have been widely used in industrial design, because they are simple, rapid in computation (there is no need to compute intermediate vapor composition or to obtain diffusivity data);

(2) Nonequilibrium (or differential) methods, which are more soundly based and appear to attract increasing interest (Taylor,1986). In this class of methods, one-dimensional differential material and energy balances are integrated numerically along the length of the condenser. Each step of the integration requires the local mass and energy rates to be calculated by using equations based on a film model.

Butterworth (1983) summarized both the equilibrium and the one-dimensional nonequilibrium approaches, which covers the fundamentals of fluid mechanics. Recently, some nonequilibrium methods have been developed, such as the turbulent eddy diffusivity model of Krishna (1982). Taylor (1986) proposed a new way to solve the model equations. The differential conservation equations were approximated by finite

differences and the resulting set of algebraic equations were solved simultaneously with the nonlinear equations representing the process of the interphase transport and interfacial equilibrium. Webb (1987, 90) suggested a new procedure for condenser design using the "film theory" method. This has been demonstrated to work for steam/air and mixed hydrocarbon systems by an experimental study of single tubes and industrial condensers.

Pressure Drop in Forced Convective Boiling and Condensation

Miyara (1988) studied the pressure drop in forced convective boiling and condensation of R22/R114 mixtures inside a horizontal, internally finned tube and found:

(1) The frictional pressure drop of refrigerant mixtures for both boiling and condensation could be correlated fairly well by the Lockhart-Martinelli parameter, independently of molar concentration;

(2) The pressure drop in an internally finned tube was about 40% higher than that in a smooth tube.

Murata (1991) reported that the frictional pressure drop of a R123/134a mixture condensing in an internally finned tube were similar to Miyara's, but were slightly (<20%) higher than those in a smooth tube.

Single (1983a) investigated pressure drop during horizontal flow boiling of pure refrigerant R12 and the mixture R13/R12 and found that the Martinelli-Nelson correlation mostly over-predicted the pressure drop data for pure R12 and tended to under-predict the ones for the mixtures of R13/R12. The deviation increased with increasing fraction of R13, proving that the pressure drop was a function of mixture composition. They also developed two separate models each for total and frictional pressure drop, adding a modifying parameter of composition to the Martinelli-Nelson model. Their model, however, did not allow application to the case when the fraction of R13 was more than 25%.

$$\text{For total pressure drop} \quad \Delta p_{TP} = \Delta p_{MN} * 0.87(1+X)^{2.66}$$

$$\text{For frictional pressure drop} \quad \Delta p_f = \Delta p_{f,MN} * 0.86(1+X)^{2.86}$$

where X -- concentration of R13 in the binary mixture

Δp_{MN} , $\Delta p_{f,MN}$ -- total and frictional pressure drops calculated by the Martinelli-Nelson correlation

Jung and Radermacher (1989) compared their experimental data for pressure drop during horizontal flow boiling of pure and mixed refrigerants of R22, R114, R12, and R152a against well known correlations.

(1) Bo Pierre's correlation based on the homogeneous model failed to correlate half of their data, especially when the heat flux was high at a low mass flow rate.

(2) The Martinelli and Nelson correlation over-predicted their data by 20%. It was, however, applicable in the entire ranges of heat and mass fluxes, proving that the basic assumptions in the model were closely met by the flow patterns observed in the major portion of the evaporator.

(3) When pressure drop data were nondimensionalized by introducing proper dimensionless variables with the properties evaluated at local compositions, pressure drops with both pure and mixed fluids were equally well correlated by a single parameter, X_{tt} . A new correlation was developed by modifying the Martinelli and Nelson correlation. Specifically, the F_{TP}^2 in the Martinelli and Nelson correlation was modified as follows.

$$F_{TP}^2 = 30.78 X^{1.323} (1-X)^{0.477} P_r^{-0.7232}$$

This change predicted their data for both pure and mixed refrigerants with a mean deviation of 8.4%.

It seems that there are disagreements between Single and Jung. Jung's results and statements may be more reliable and reasonable because he did experiment with more refrigerants, accounted for the nonlinear variation of properties of the mixtures, paid attention to the local phenomena during condensation inside tubes, and used an integral method to correlate the pressure drop.

Recommendations for Further Research

Most of the previous researches on flow boiling were concerned with smooth tubes and uniform heat flux conditions. Only a few conducted experiments using enhanced tubes or a tube-in-tube countercurrent evaporator, which are most used in industrial practice. Further research should be done on the latter cases and with new refrigerants, such as R134a, R123, and their mixtures. Such data are urgently needed in industry. A double enhanced tube, combining the internally finned tube and the fluted one may augment heat transfer more efficiently than the previously used enhanced tubes.

There have been many papers concerned with condensation enhancement of mixtures, however, only two-dimensional fins (inside or outside) were used. The enhancement effects were not so good in most of these cases, especially under the low heat flux conditions (Takamatsu 1991). Three-dimensional fins should be used to enhance the condensation of mixtures, which will augment heat transfer more efficiently than common fins by

introducing stronger turbulence in the two-phase flow and by reducing the mass transfer resistance.

There have been some disagreements among the researchers on the behavior and mechanisms of condensation and boiling with mixtures, which are very complicated and sensitive to the operating conditions. Further, detailed research is needed to determine the actual phenomena and mechanisms of boiling and condensation of mixtures.

The influence of air on the condensation performance of NARMs should be studied and ways should be found to reduce the unfavorable effect of the air in the refrigerator and heat pump systems.

More attention should be paid to the local phenomena of flow and heat transfer in order to discover the mechanisms of boiling and condensation of mixtures, and, consequently, enabling the proper choice of the optimum surface structure to enhance heat transfer efficiently. Jung's method for getting the inside circumferential wall temperature distribution from the outside wall temperature, by solving the one-dimensional conduction equation, was simple but not very good. If we could measure temperatures at more points, and solve a more exact conduction equation, we could get a more accurate circumferential temperature distribution on the inside tube wall and predict the local phenomena in more detail and more accurately.

References

Alpay, H. E. and Balkan, F., 1989, "Nucleate Pool Boiling Performance of Acetone-ethanol and Methylene Chloride-ethanol Binary Mixtures," *Int. J. Heat Mass Transfer*, 32(12), 2403-2408.

Bennett, D. and Chen. J. C., 1980, "Forced Convective Boiling in Vertical Tubes for Saturated Pure Components and Binary Mixtures," *AIChE Journal*, 26(3), 454-461.

Berntsson, T. et al., 1985, "Heat Transfer of Nonazeotropic Mixtures in a Falling Film Evaporator," *ASHRAE Trans.*, Vol.91 (part 2B), 1337-1350.

Bier, K. et al., 1982, "Pool Boiling Heat Transfer to Mixtures of SF₆ and CF₃Br at Elevated Saturation Pressures," *Proc. 7th Int. Heat Transfer Conf.*, Munich, Vol.4, 35-40.

Bokhanovskiy, Yu. G., 1980, "Heat Transfer from Freon-12, Freon-22 and Their Mixtures in a Coiled-tube condenser," *Heat Transfer -Soviet Research*, Vol.12(4), 43-45.

Butterworth, D., 1983, "Heat Exchanger Design Handbook," Schlünder, E. U., ed. Hemisphere Publ., Washington, D.C., 2.

Chilipenok, YU. S. et al., 1988, "Heat Transfer In the Condensation of an R12/R11 Freon Mixture in a Finned Plate Condensation," *Heat Transfer-Soviet Research*," 20(5), 676-683.

Conklin, J. C. and Vineyard, E. A., 1990, "Tube side Evaporation of Nonazeotropic Refri-gerant Mixtures from Two Enhanced Surfaces," Heat Transfer in Advanced Systems, HTD-Vol.151, AES-Vol.18, ASME, New York, USA, 1-7.

Conklin, J. C. and Vineyard, E. A., 1991, "Heat Exchanger Thermal Performance for Two Nonazeotropic Refrigerant Mixtures," Proc. 18th Int. Congress of Refrigeration, Montreal, Vol.3. 1270-1274.

Degrush, D. and Stoecker, W. F., 1987, "Measurements of Heat-Transfer Coefficients of Nonazeotropic Refrigerant Mixtures Condensing Inside Horizontal Tubes," Oak Ridge National Laboratory Report 81-7762.

Eckels, S. J. and Pate, M. B., 1990, "Evaporation and Condensation Heat Transfer Coefficients for a HCFC-124/HCFC-22/HFC-152a Blend and CFC₁₂," USNC/IIR Refrigeration and ASHRAE-CFC Conference, Purdue Univ., 234-241.

Fink, J. et al, 1982, "Forced Convection Boiling of a Mixture of Freon-11 and Freon-113 Flowing Normal to a Cylinder," Proc. 7th Int. Conf., Munich, Vol.4, 207-212.

Fujii, T., et al., 1985, "Effects of Air upon Gravity Controlled Condensation of Non-Azeotropic Binary Refrigerant Vapor on a Horizontal Tube," Trans. JSME (B), 51(7), 2442-2450.

Fujii, T., et al., 1989a, "Gravity Controlled Condensation of an Ethanol and Water Mixture on a Horizontal Tube," Trans. JSME (B), 55(509), 210-215.

Fujii, T., et al., 1989b, "Laminar Film Condensation of Gravity-Controlled Convection for Ternary Vapor Mixtures on a Vertical Flat Plate," Trans. JSME (B), 55(510), 434-441.

Fujii, T., et al., 1990, "Experimental Study of Gravity Controlled Condensation of Binary Vapor Mixtures on a Smooth Horizontal Tube," Proc. 9th Int. Heat Transfer Conf., Vol.3, 109-114.

Fujii, T., et al., 1991, "Various Formulas and their Accuracy Concerning Convective Heat Transfer and Convective Mass in the Vapor Boundary Layer in the Case of Laminar Film Condensation of binary Vapor Mixtures," Trans. JSME (B), 57(9), 295-3160.

Gorenflo, D. et al., 1988, "Heat Transfer at Pool Boiling of Mixtures with R22 and R114," Int. J. Refrig., Vol.11, 257-263.

Goto, M. and Fujii, T., 1982, "Film Condensation of Binary Refrigerant Vapors on a Horizontal Tube," Proc. 7th Int. Heat Transfer Conf., Munich, Vol.5, 71-76.

Goto, M., 1988, "Condensation on Single Horizontal Tube of Freon Refrigerants and Their Mixtures," Scientific Achievement Reports on Phase Change in Multicomponent System, Japan, 66-67.

Granryd, E. and Conklin, J. C., 1990, "Thermal Performance Analysis for Heat Exchangers Using Non Azeotropic Refrigerant Mixtures," Heat

Transfer in Advanced Systems, HTD-Vol.151, AES-Vol.18, ASME, New York, USA, 25-32.

Granryd, E., 1991, "Heat Transfer in Flow Evaporation of Non Azeotropic Refrigerant Mixtures--A Theoretical Approach," Proc. 18th Int. Congress of Refrigeration, Montreal, Vol.3. 1330-1334.

Gropp, U., 1985, "Wärme- und Stoffübertragung bei der Oberflächenverdampfung und beim Blasensieden eines binären Gemisches am Rieselfilm," Dissertation, Universität Karlsruhe (TH).

Hihara, E. and Saito, T., 1990, "Forced Convective boiling Heat Transfer of Binary Mixtures in a Horizontal Tube," Proc. 9th Int. Heat Transfer Conf., Isreal, Vol.2, 123-128.

Hijikata, K. et al., 1986, "Free Convective Filmwise Condensation of a Binary Mixture of Vapors," Proc. 8th Int. Heat Transfer Conf., San Francisco, Vol.4, 1621-1626.

Hijikata, K. et al., 1987, "Forced Convective Condensation of a Binary Mixture of Vapors," JSME Int. Journal, 30(270), 1951-1956.

Hijikata, K. et al., 1988, "Condensation of a Binary Mixture of Vapors in a Vertical Tube," Scientific Achievement Reports on Phase Change in Multicomponent System, Japan, 58-63.

Hijikata, K. et al., 1989a, "Condensation of a Binary Mixture of Vapors in a Vertical Tube," Trans. JSME (B), Vol.55(10), 3183-3189.

Hijikata, K. et al., 1989b, "Forced Convective Condensation of a Binary Mixture of vapors (2nd Report, Condensation on Vertical and Horizontal Tubes," Trans. JSME (B), Vol.55(10), 3190-3198

Hijikata, K. et al., 1990, "Forced Convective Condensation of a Nonazeotropic Binary Mixture on Vertical and Horizontal Tubes," Proc. 9th Int. Heat Transfer Conf., Isreal, Vol.3, 271-276.

Himeno, N. et al., 1988, "Study on the Condensation Inside Vertical Tube with Binary Mixtures," Proc. 25th Japan National Heat Transfer Symposium," 457-459.

Hui, T. O. and Thome, J. R., 1985, "A Study of Binary Mixture Boiling: Boiling Site Density and Subcooled Heat Transfer," Int. J. Heat Mass Transfer, 28(5), 919-928.

Inoue, T. et al., 1988, "Condensation of Nonazeotropic Binary Mixtures in a Horizontal Tube (R113+R114)," Proc. 25th Japan National Heat Transfer Symposium," 460-462.

Jain, V. K. and Dher, P. L., 1983, "Studies on Flow Boiling of mixtures of REfrigerants R21 and R13 inside a horizontal tube," Proc. of 16th Int. Cong. Refrig., Paris.

Jung, D. S. et al., 1989a, "Horizontal Flow Boiling Heat Transfer Experiments with a Mixture of R22/R114," Int. J. Heat Mass Transfer, 32(1), 131-145.

Jung, D. S. et al., 1989b, "A Study of Flow Boiling Heat Transfer with Refrigerant Mixtures," *Int. J. Heat Mass Transfer*, 32(9), 1751-1764.

Jung, D. S. and Radermacher, R., 1989c, "Prediction of Pressure Drop During Horizontal Annular Flow Boiling of Pure and Mixed Refrigerants," *Int. J. Heat Mass Transfer*, 32(12), 2435-2446.

Kandlikar, S. G., 1990, "A General Correlation for Saturated Two-Phase Flow Boiling Heat Transfer inside Horizontal and Vertical Tubes," *ASME Journal of Heat Transfer*, 112, 219-228.

Kandlikar, S. G., 1991, "Correlating Flow Boiling Heat Transfer Data in Binary Systems," *HTD-Vol.159, Phase Change Heat Transfer*, 163-169.

Kedzierski, M. A. and Didion, D. A., 1990, "Visualization of Nucleate Flow Boiling for an R22/R114 Mixture and Its Components," *Experimental Heat Transfer*, 3(4), 447-463.

Kenning, D. B. R. and Hewitt, G. F., 1988, "Boiling Heat Transfer In the Annular Flow Region," 8th Int. Heat Transfer Conf., San Francisco, 2185-2190 (1986).

Koyama, S. et al., "Condensation of Refrigerant Mixtures R22+R114 inside a Horizontal Tube," *Trans. JSME (B)*, 54(6), 1447-1452.

Koyama, S. et al., 1990, "Condensation Heat Transfer of Binary Refrigerant Mixtures of R2 and R114 inside a Horizontal Tube with Internal Spiral Grooves," *Int. J. Refrig.*, 13(7), 256-263.

Koyama, S. et al., 1991a, "An Experimental Study of Condensation of Nonazeotropic Refrigerant Mixtures HCFR22+CFR114 inside a Horizontal Smooth Tube," *Trans. JSME (B)*, 57(6), 2032-2038.

Koyama, S. et al., 1991b, "Enhancement of In-Tube Condensation of Nonazeotropic Refrigerant Mixtures with a Micro-Fin Tube," *Proc. 18th Int. Congress Refrig, Montreal, Vol.2*, 439-443.

Krishna, R. 1982, "A Turbulent Film Model for Multicomponent Mass Transfer," *Chem. Eng. J. Vol.24*, 163-172.

Lavin, G., and Young, E. H., 1965, "Heat Transfer to Evaporating Refrigerants in Two-Phase Flow," *AIChE J*, Vol.11, 1124.

Lukin, V. N. and Zakirov, S. G., 1988, "Condensation of Water-Acetone Mixture on Vertical Surface," *Chemical and Petroleum Engr.*, 24(5-6), 281-283.

Miyama, A. et al., 1988, "Pressure Drop of Condensation and Boiling Inside a Horizontal Tube With Refrigerant Mixtures R22+R114," *Proc. 25th Japan National Heat Transfer Symposium*, 85-87.

Mochizuki, S. et al., 1984, "Convective Filmwise Condensation of Nonazeotropic Binary Mixtures in a Vertical Tube," *ASME Journal of Heat Transfer*, 106, 531-538.

Mochizuki, S. et al., 1988a, "Condensation of Nonazeotropic Binary Mixtures in a Horizontal Tube," *Scientific Achievement Reports on Phase Change in Multicomponent System, Japan*, 64-65.

- Mochizuki, S. et al., 1988b, "Condensation of Nonazeotropic Binary Mixtures in a Horizontal Tube (R113+R11), Trans. JSME (B), 54(503), 1796-1801.
- Mochizuki, S. and Tominaga, M., 1990, "Condensation Heat Transfer of Nonazeotropic Binary Mixture (R113+R11) inside Horizontal Tubes," Heat Transfer Japanese Research, 19(2), 33-42.
- Murata, K. et al., 1990, "An Investigation of Forced Convection boiling of Nonazeotropic refrigerant Mixtures," Heat Transfer Japanese Research, 19(2), 95-105.
- Murata, K. et al., 1991, "An Experimental Investigation on Forced Convection boiling of refrigerant Mixtures," Proc. 18th Int. Congress Refrig, Montreal, Vol.2, 494-498.
- Murphy, R. W. et al., 1988, "Condensing Heat Transfer for R114/R12 Mixtures on Horizontal Finned Tubes," Int. J. Refrig., 11, 361-366.
- Niederkrüger, M. et al., 1992, "Horizontal Flow Boiling Experiments of Saturated Pure Components and Mixtures of R864-R12 at high Pressures," Int. J. Refrig., Vol.15(1), 48-58.
- Nozu, S. et al., 1988, "Condensation of Mixed Vapor in a Horizontal Annulus Passage," Proc. 25th Japan National Heat Transfer Symposium, 463-465.
- Nozu, S. et al., 1989, "Condensation of Non-Azeotropic Refrigerant Blends of R114+R113 in a Horizontal Annulus with an Enhanced Inner Tube," Trans. of the JAR, 6(1), 57-66.
- Nozu, S. et al., 1991a, "Condensation of Non-Azeotropic Refrigerant Mixture R114/R113 in a Horizontal Annulus with an Enhanced Inner Tube (Experimental Results)," Trans. JSME (B), 57(3), 645-652.
- Nozu, S. et al., 1991b, "Condensation of Non-Azeotropic Refrigerant Mixture R114/R113 in a Horizontal Annulus with an Enhanced Inner Tube (Correlation of Frictional Pressure Drop and Vapor Phase Mass Transfer)," Trans. JSME (B), 57(5), 1002-1008.
- Nozu, S. et al., 1992, "Condensation of Non-Azeotropic Refrigerant Mixture R114/R113 in a Horizontal Annuli with an Enhanced Inner Tube," Journal of Heat Transfer, 114(1), 201-209.
- Pandey, S. K. et al, 1986, "Heat Transfer Studies During Pool Boiling of Binary Liquid Mixtures," Proc. 8th Int. Conf., San Francisco, Vol.4, 2087-2092.
- Reddy, R. P. and Lienhard, J. H., 1989, "The Peak Boiling Heat Flux in Saturated Ethanol-Water Mixtures," ASME Journal of Heat Transfer, 111, 480-486.
- Ross, H. et al., 1987, "Horizontal Flow Boiling of Pure and Mixed Refrigerants," Int. J. Heat Mass Transfer, 30(5), 979-992.
- Sami, S. M. and Dung, T. N., 1991, "Experimental Study of the Heat Transfer Characteristics of Refrigerant Mixture R22/R114 in the Annulus

of Enhanced Surface Tubing," *Int. Communications in Heat and Mass Transfer*, 18(4), 547-558.

Sami, S. M. and Schnotule, J., 1992a, "Comparative Study of Two Phase Flow Boiling of Refrigerant Mixture and Pure Refrigerant Inside Enhanced Surface Tubing," *Int. Communications in Heat and Mass Transfer*, 19(1), 137-148.

Sami, S. M. and Schnotule, J., 1992b, "Prediction of Two Phase Flow condensation of Pure and Refrigerant Mixture and on Enhanced Surface Tubing," *Int. Communications in Heat and Mass Transfer*, 19(2), 191-202.

Schmadl, J., 1982, *Heat Transfer in High-Pressure Nucleate Boiling of Binary Mixtures*, Thesis, University of Karlsruhe.

Schlünder, E. U., 1986, "Heat Transfer Studies Nucleate Boiling of Mixtures," *Proc. 8th Int. Conf., San Francisco, Vol.4*, 2073-2079.

Shakir, S. and Thome, J. R., 1986, "Boiling Nucleation of Mixtures on Smooth and Enhanced Surface," *Proc. 8th Int. Heat Transfer Conf., San Francisco, Vol.4*, 2181-2086

Shi, E. et al., 1991, "Pool Boiling Heat Transfer In HFC-134a, HFC-152a and Their Mixtures," *Proc. 18th Int. Congress Refri., Montreal, Vol.2*, 459-463

Single, L. C. et al., 1983a, "Pressure Drop During Forced Convection Boiling of Binary Refrigerant Mixtures," *Int. J. Heat Mass Transfer*, 9(3), 309-323.

Singal, L. C. et al., 1983b, "Experimental Heat Transfer Coefficient for Binary Mixture of R13-R12," *ASHRAE Trans, Vol. 89. Part 1A*, 175-188.

Singal, L. C. et al., 1984, "Heat Transfer Correlations for the Forced Convection Boiling of R12-R13 Mixtures," *Int. J. Refrig.*, 7(5), 278-284.

Stephan, K. and Abdelsalam, M., 1980, "Heat Transfer Correlation's for Natural Convection Boiling," *Int. Heat Transfer*, 23, 73-87.

Stoecker, W. F. and Kornota, E., 1985, "Condensing Coefficients When Using Refrigerant Mixtures," *ASHRAE Trans. Vol.91(part 2B)*, 1531-1367.

Taitel, Y. and Tamir, A., 1974, *Int. J. Multiphase Flow*, 1, 697-714.

Takamatsu, H. et al., 1988, "Forced Convective Boiling of Nonazeotropic Mixture of R22 and R114 in side a Horizontal Tube," *Scientific Achievement Reports on Phase Change in Multicomponent System, Japan*, 34-39

Takamatsu, H. et al., 1990, "Forced Convective Boiling of Nonazeotropic Mixture of R22 and R114," *Heat Transfer Japanese Research*, 19(3), 68-82.

Takamatsu, H. et al., 1991, "Heat Pump System with R22/R114 Mixture as Working Fluids (2nd Report, Experiment on Double-Tube Evaporator and Condensation with Grooved Tubes," *Trans. JSME (B)*, 57(7), 2377-2382.

Tamir, A. and Merchuk, J. C., 1979, "Verification of a theoretical Model for Multicomponent Condensation," *Chemical Engr. Journal*, 17, 125-139.

- Tandon, T. N. et al , 1982, "A New Flow Regimes Map for Condensation Inside Horizontal Tubes," ASME Trans. J. Heat Transfer, Vol.104(4), 763-768.
- Tandon, T. N. et al , 1985, "Prediction of Flow Patterns During Condensation of Binary Mixtures in a Horizontal Tubes," ASME Trans. J. Heat Transfer, Vol.107(2), 424-430.
- Taylor, S. et al., 1986, "Condensation of Vapor Mixtures, 1, Nonequilibrium Models and Design Procedures," Int. Engr. Chem. Process Des. Dev., 25(1), 83- 96 .
- Thome, J. R., 1982, "Effect of Composition on Boiling Incipient Superheats in Binary liquid Mixtures," Proc. 7th Int. Heat Transfer Conf., Munich, Vol.4, 95-100.
- Thome, J. R., 1983, " Prediction of Binary Mixture Boiling Heat Transfer Coefficients Using Only Phase Equilibrium Data," Int. J. Heat Mass Transfer, 26(7), 965-974 .
- Thome, J. R., 1987, "Enhanced Boiling of Mixture," Chem. Engr. Science, 42(8), 1909-1917.
- Thome, J. R., 1989, " Nucleate Pool Boiling Of Hydrocarbon Mixtures on a Gewa-TX Tube," Heat Transfer Engr., 10(1), 37-44.
- Toral, H., 1979, Flow Boiling Heat Transfer in Mixtures, Ph.D. Thesis, Univ. of Oxford.
- Toral, H. et al., 1982, "Flow Boiling of Ethanol/Cyclohexane Mixtures," Proc. 7th Int. Heat Transfer Conf., Munich, Vol.4, 255-260.
- Ünal, H. C., 1986, " Prediction of Nucleate Boiling Heat Transfer Coefficient for Binary Mixtures," Int. J. Heat Mass Transfer, 29(4), 637-649.
- Vineyard, E. A. and Conklin, J. C., 1991, "Cycle Performance Comparison Between a Non-azeotropic Refrigerant Mixture and R22," Proc. 18th Int. Congress of Refrigeration, Montreal, Vol.3. 543-547.
- Wang, S. P. et al., 1990, "Condensation Heat Transfer Enhancement by Ridges on Integral Fin Tubes," Experimental Heat Transfer, 3(4), 341-354.
- Wang, S. P. et al, "Enhancement of Pool Boiling Heat Transfer by Mechanically Made Porous Tube with Ridges on Tunnel," in preparation.
- Webb, D. R. and Panagoullias, D., 1987, "An Improved Approach to Condenser Design Using Film Models," Int. J. Heat Mass Transfer, 30(2), 373-378.
- Webb, D. R., 1990, "Multicomponent Condensation," Proc. 9th Int. Heat Transfer Conf., Vol.1, 287-305.
- Yoshida, S., et al., 1991, "Heat Transfer to Non-azeotropic Mixtures of Refrigerants Flowing in a Horizontal Evaporator Tube," Trans. JSME (B), 56(4),1084-1089.

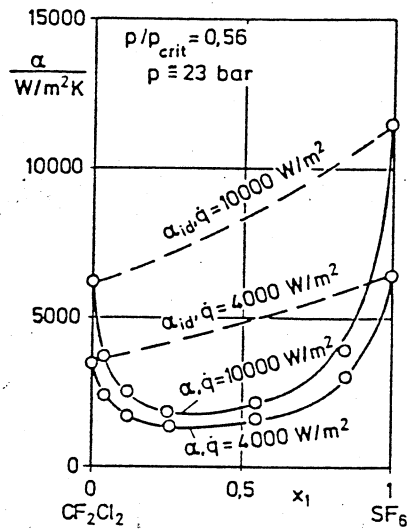


Fig.1 HTCs in pool boiling of SF6-CF2CL2 mixture (curve from Schlünder, empirical data from Schmadl)

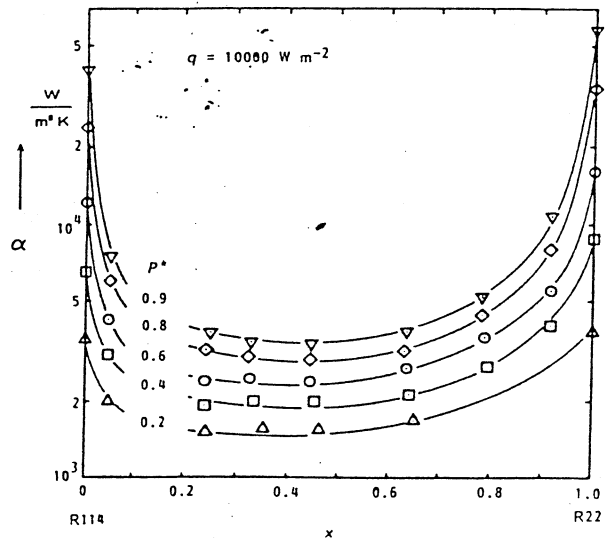


Fig.3 Influence of pressure and composition on HTCs of pool boiling of R114/R12 mixture at constant heat flux (Gorenflo).

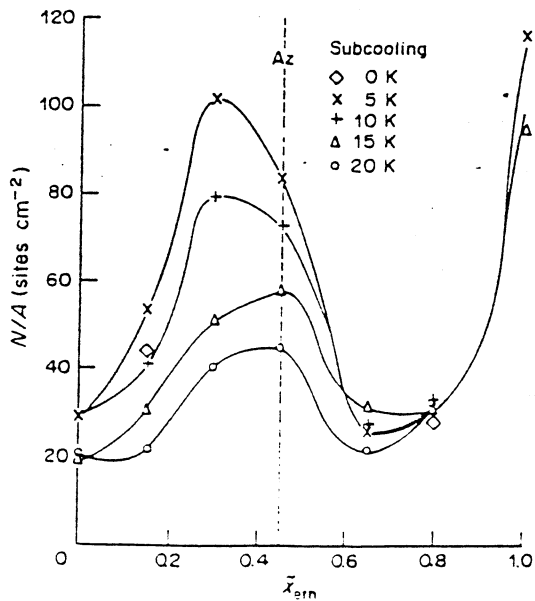


Fig.2 Boiling site density for ethanol/benzene mixtures at 55 kW/m² and various subcooling (Hui & Thome)

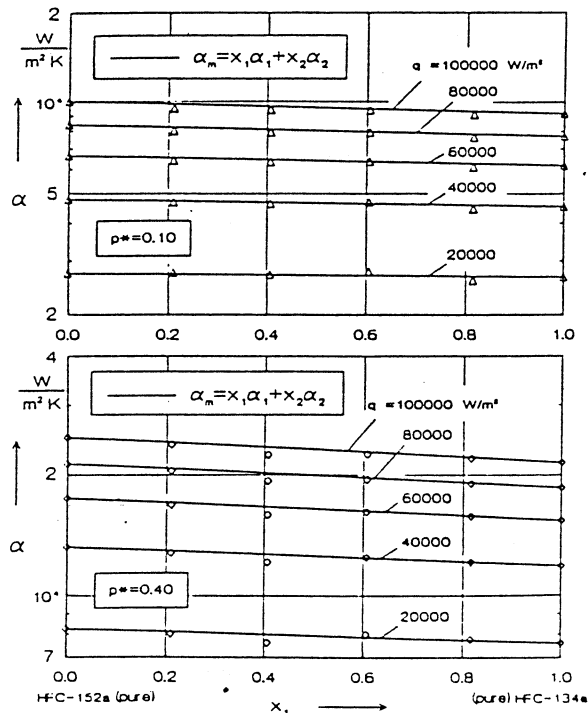
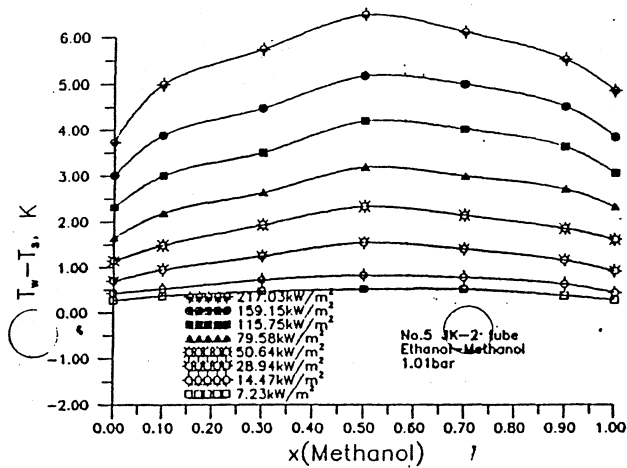
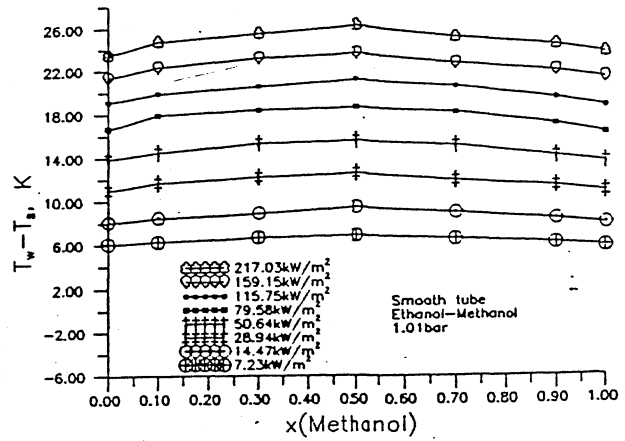


Fig.4 Effect of mole fraction of R152a on the HTCs of pool boiling of R152a/R134a at P*=0.1 and P*=0.4 (Shi)



(a) mechanically made porous tube with ridges on the tunnel



(b) smooth tube

Fig. 5 Comparison of HTC's in pool boiling of ethanol/methanol mixture for enhanced tube and smooth tube at different heat fluxes (Wang)

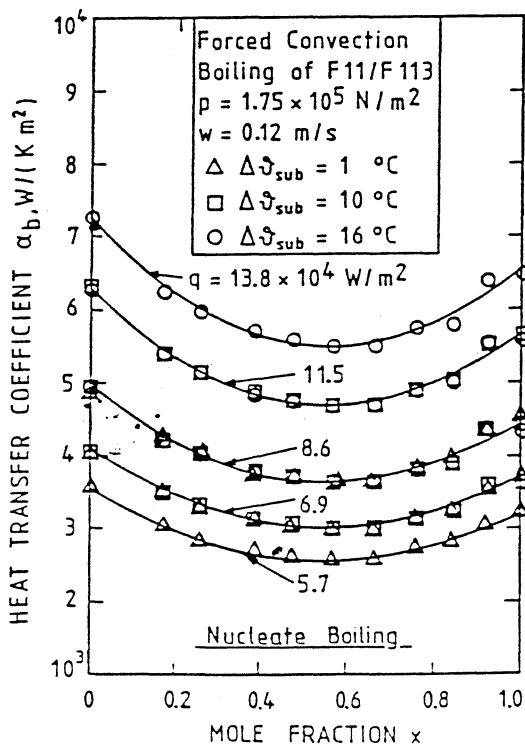


Fig.6 Effect of mole fraction and subcooling on the HTC's in flow boiling of R11/R113 mixture flowing normal to a cylinder (Fink).

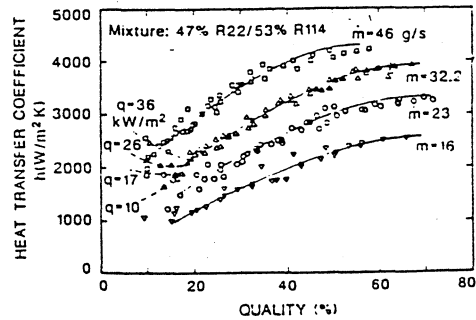


Fig.7 Flow boiling HTC's for R22/R114 as a function of quality at various mass flow rates. Heat flux dependence at low qualities shown only for $m=32.8$ g/s (Jung 1989b).

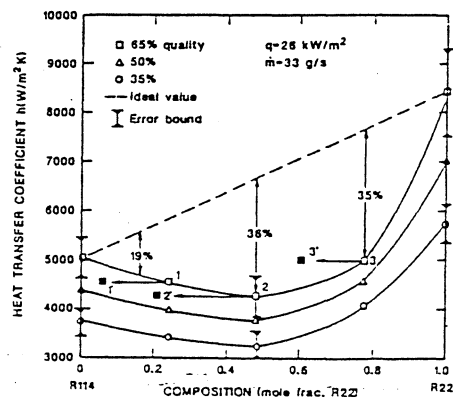


Fig.8 Flow boiling HTC's of R22/R114 in convective evaporation region as function of composition and quality (Jung 1989b).

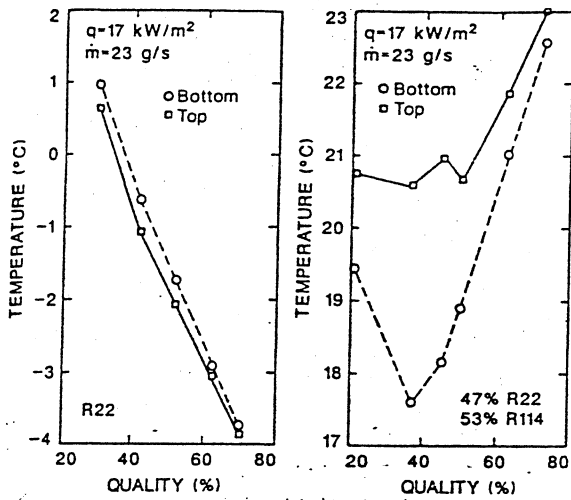


Fig.9 Circumferential variation of wall temperatures for R22 and R22/R114 in flow boiling (Jung 1989b).

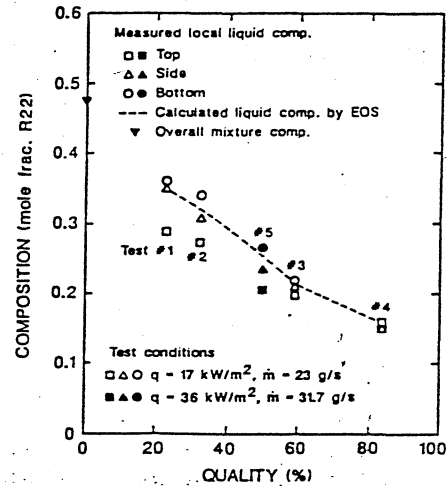


Fig.10 Comparison of the measured and calculated liquid compositions in flow boiling (Jung 1989b).

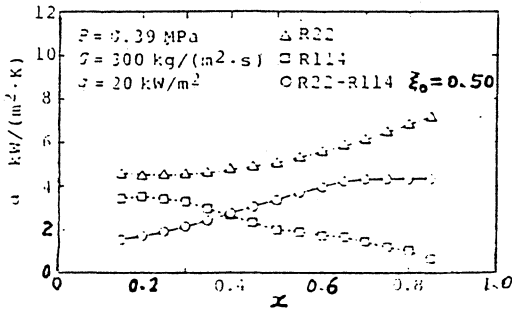


Fig.11 The influence of quality on local HTCs of flow boiling of R22, R114, and their mixture at high mass fluxes (Yoshida)

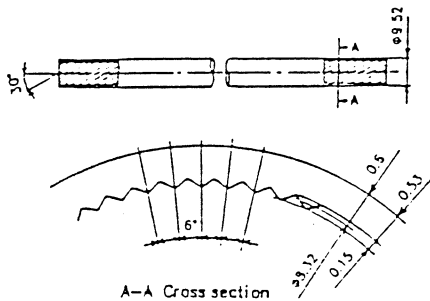


Fig.12 Structure of an internally finned tube (Takamatsu 1988)

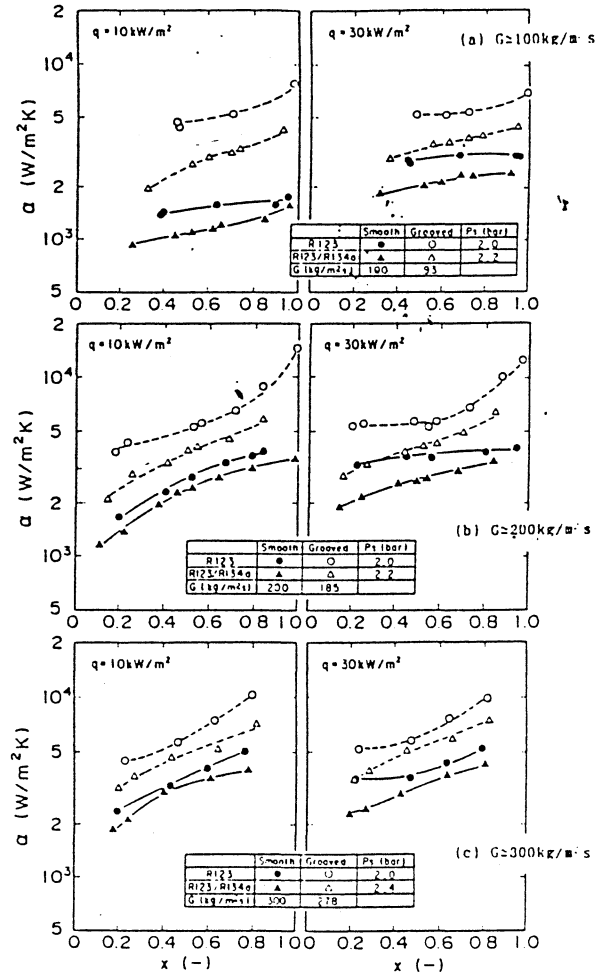


Fig.13 Flow boiling HTCs of R123 and R123/R134a for grooved tube and smooth tube (Murata 1991).

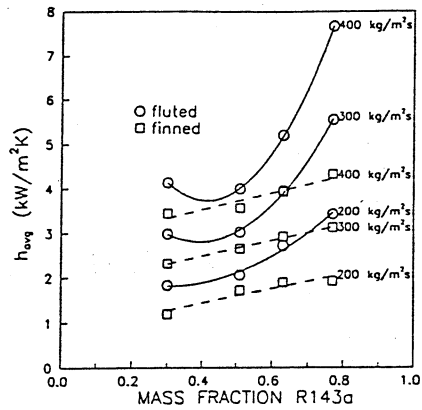


Fig. 15 Flow boiling HTCs of R143a/R124 mixture for a finned and a fluted tube (Conklin 1990).

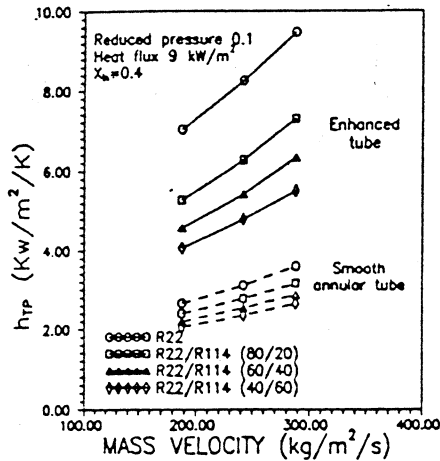


Fig. 16 Comparison of flow boiling HTCs of R22/R114 between an enhanced and a smooth tube as function of mass velocity (Sami 1991).

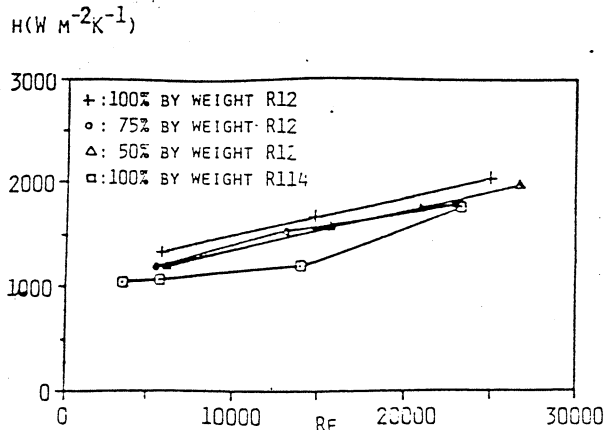


Fig. 17 HTCs in a falling film evaporator versus Re number with composition as parameter (Berntsson).

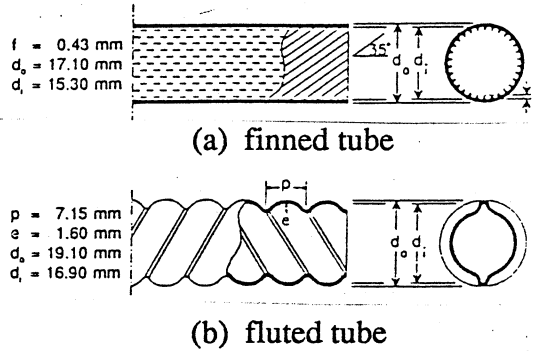
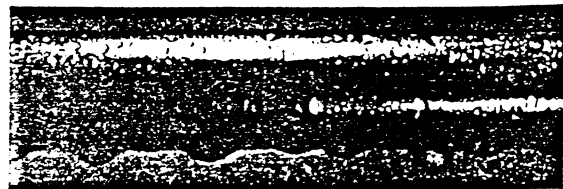
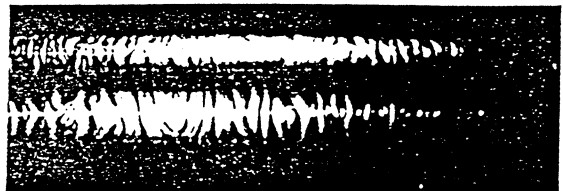


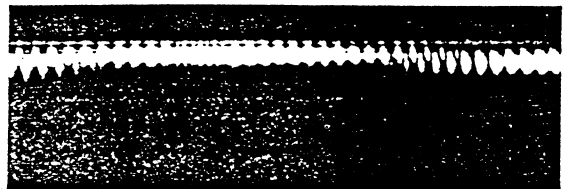
Fig. 14 Tube geometry (Conklin 1990)



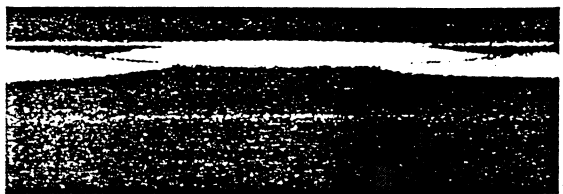
(a) $y_{1Gb}=0.59$, $q_w=7.85 \times 10^4$ W/m², $T_{Gb}-T_w=10.2$ K



(b) $y_{1Gb}=0.80$, $q_w=2.48 \times 10^4$ W/m², $T_{Gb}-T_w=3.0$ K



(c) $y_{1Gb}=0.80$, $q_w=7.74 \times 10^4$ W/m², $T_{Gb}-T_w=13.9$ K



(d) $y_{1Gb}=0.79$, $q_w=9.50 \times 10^4$ W/m², $T_{Gb}-T_w=23.0$ K

Fig. 18 Observation of the condensation pattern for ethanol/water mixtures (Fujii 1990)

- (a) dropwise
- (b) streakwise
- (c) ringwise
- (d) filmwise

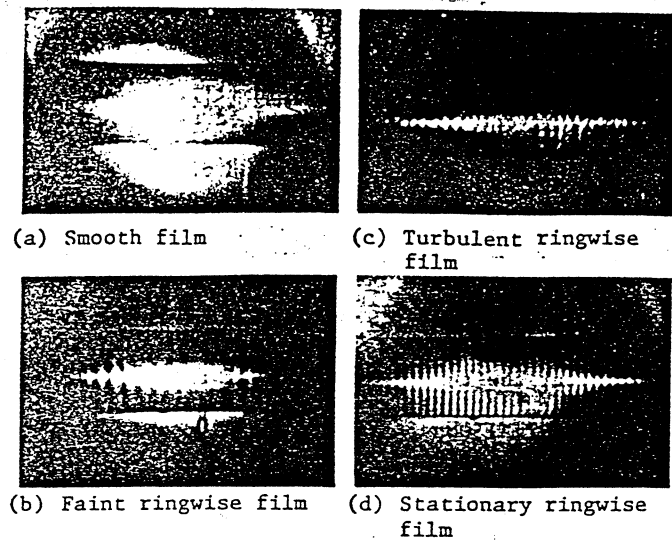


Fig.19 Photographs of condensation film of R114/R11 mixture, $d=15.85\text{mm}$ (Goto 1982).

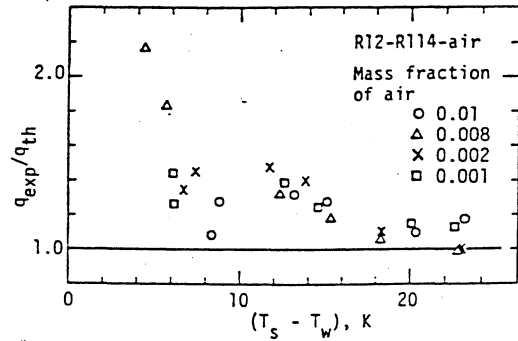
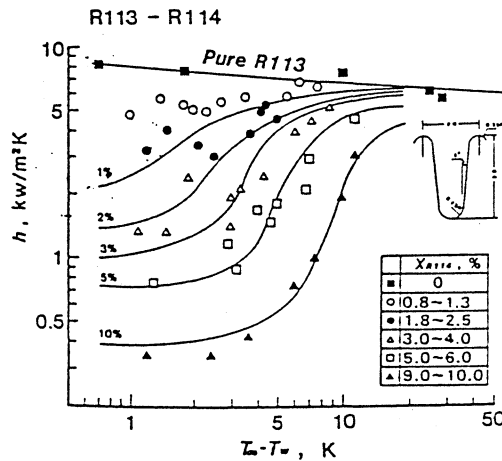
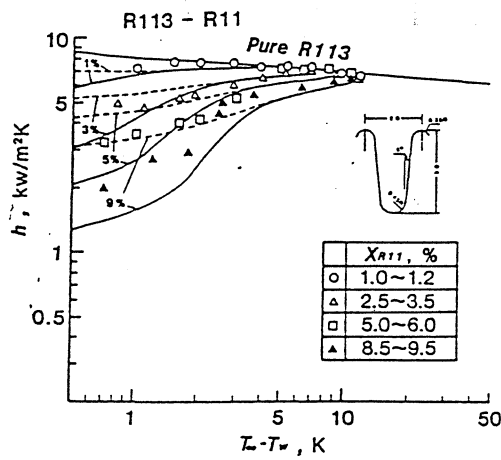


Fig.20 Influence of air in R12/R114 (Goto 1982)



(a) R113/R11

(b) R113/R114

Fig.21 HTC's of forced convective condensation of mixtures on a high-fin tube(Hijikata 1986)

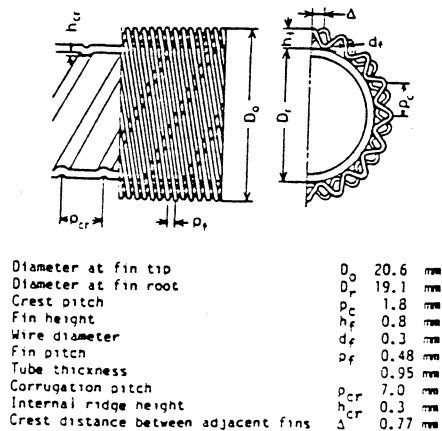


Fig.22 Structure of an enhanced tube (Nozu 1989)

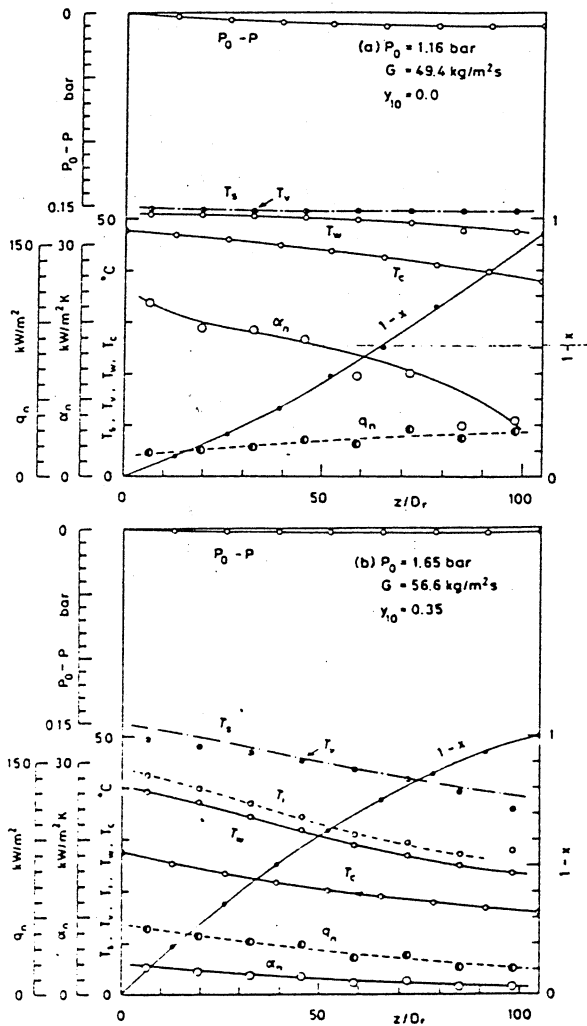


Fig.23 Comparison of distribution of measured quantities along test section for pure R113 (a) and R114/R113 (b) during condensation on an enhanced tube (Nozu 1989).

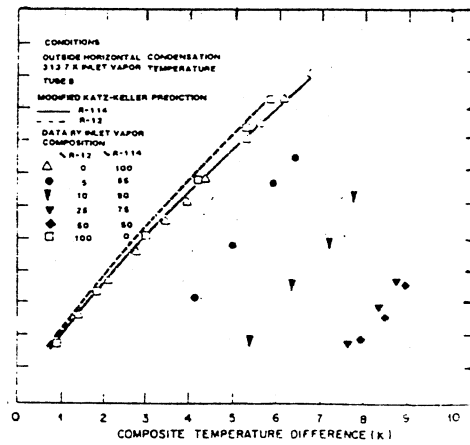


Fig.24 Measured condensing performance of R114/R12 mixtures on a titanium finned tube (Murphy).

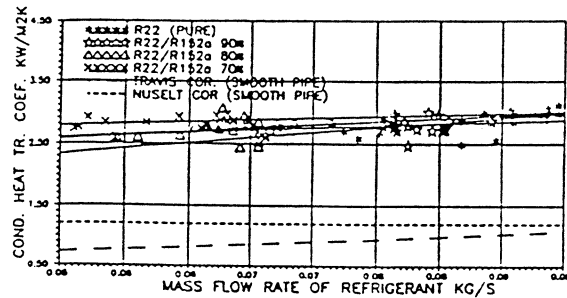


Fig.25 HTCs of condensation on a doubly fluted tube versus mass flux rate (Sami 1992b)

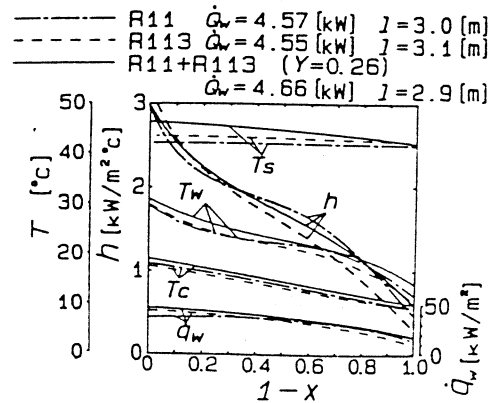


Fig.26 Comparison of condensing performance in a smooth tube for R11, R113 and their mixture (Mochizuki 1988b).