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バージョン：

Prediction Method of In-tube Condensation of Multi-component Vapor Mixture

Shigeru KOYAMA and Sang-Mu LEE*

This paper deals with a prediction method for the condensation of multi-component refrigerant mixture inside a horizontal smooth tube. Based on some reliable assumptions, the governing equations for the local heat and mass transfer characteristics are derived, and the prediction calculation for the condensation of ternary zeotropic refrigerant mixtures composed of HFC32/HFC125/HFC134a, including R407C, is carried out; the local values of vapor quality, thermodynamic states at bulk vapor, vapor-liquid interface and bulk liquid, mass flux etc. are obtained for a constant wall temperature and a constant wall heat flux conditions. The effects of the composition of HFC32/HFC125/HFC134a on the heat transfer characteristics are clarified, and the heat transfer characteristics of R407C are compared with those of R22.

Introduction

The HCFC refrigerants such as R22 are ozone-depleting substitutes, which should be phased out early in the next century. Therefore, the search for environmentally acceptable refrigerants as working fluid has been intensified in recent years, and binary and/or ternary mixtures composed of HFC refrigerants have attracted a great deal of attention. In this situation, a refrigerant mixture R407C, composed of 23wt%HFC32, 25wt%HFC125 and 52wt%HFC134a, has been considered as one of the candidates for R22 that is widely used as working fluid in air-conditioning and refrigeration systems until now.

Recently several experimental studies on the condensation of ternary mixtures in a horizontal tube have been carried out by Sami et al.[1), 2)], Doerr et al.[3)], Linton et al.[4)], Ebisu et al.[5), 6)], Zhang et al.[7)] and Hihara-Zang [8)]; some experimental correlations for averaged heat transfer and local pressure drop have been proposed. In these studies, however, the general method to predict the heat and mass transfer characteristics of multi-component refrigerant mixture has not been established yet.

In our previous study [9)], a general method to predict the condensation characteristics of binary vapor mixture in a horizontal smooth tube was developed. In the present study this method is extended to the condensation of multi-component vapor mixture, and the prediction calculation of ternary zeotropic refrigerant mixtures of HFC32/HFC125/HFC134a, including R407C, is carried out.

Nomenclature

C_{lg}	= enhancement factor of vapor mass transfer
D_{kj}	= coefficient of diffusion
D_{kj}^{M}	= diffusivity of pair (k-j) in multi-component mixture
D_{kj}^{*}	= coefficient of diffusion
d_w	= inner diameter
G	= mass velocity
Ga	= Galileo number
h	= enthalpy
M_k	= molecular weight of component k
$\dot{m}$	= total condensation mass flux
$\dot{m}_k$	= condensation mass flux of component k
Nu	= Nusselt number
P	= pressure
Ph	= phase change number
Pr	= Prandtl number
q	= heat flux
Re	= Reynolds number

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Sc	= Schmidt number
Sh	= Sherwood number
T	= temperature
W	= mass flow rate
x	= vapor quality
y_k	= mass fraction of component k
z	= refrigerant flow direction
α	= heat transfer coefficient
β	= mass transfer coefficient
δz	= length of control volume
λ	= thermal conductivity
μ	= dynamic viscosity
ρ	= density
ξ	= $\dot{m}_k$ to $\dot{m}$ ratio
Φ_V	= two-phase multiplier
χ_{tt}	= Lockhart-Martinelli parameter
ψ	= void fraction

Subscripts

B	= bulk
i	= vapor-liquid interface
in	= refrigerant inlet
k	= component k (k=1, 2, ..., n-1, n)
L	= liquid
V	= vapor
W	= wall

Prediction Method

Physical model

Figure 1 shows the physical model employed in the present prediction method. The multi-component refrigerant vapor mixture flowing into a horizontal smooth tube with a mass flow rate W_{in} (mass velocity G) starts to condense at an axial position $z=0$ through a single-phase region. At position z in two-phase region, the bulk vapor is represented by thermodynamic state $(P, T_{Vb}, h_{Vb}, y_{1Vb}, y_{2Vb}, \ldots, y_{nVb})$, the vapor-liquid interface is of state $(P, T_i, y_{1Vi}, y_{2Vi}, \ldots, y_{nVi}, y_{1Li}, y_{2Li}, \ldots, y_{nLi})$, and the bulk liquid is of state $(P, T_{Lb}, h_{Lb}, y_{1Lb}, y_{2Lb}, \ldots, y_{nLb})$. Symbols T_w, q_w, x and $\dot{m}$ denote the wall temperature, the wall heat flux, the vapor quality and the total condensation mass flux,

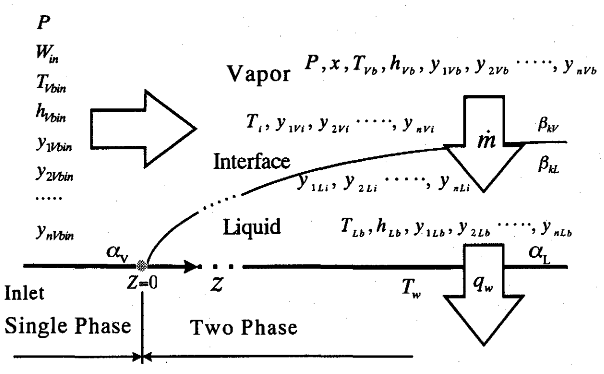

Figure 1 Physical model

respectively. Symbols α_L and α_V are the heat transfer coefficients of liquid film and vapor, respectively, and symbols β_{kL} and β_{kV} are the liquid and vapor mass transfer coefficients of component k $(k = 1, 2, \ldots, n)$, respectively. In this model the following assumptions are employed:

(1) The phase equilibrium is only established at the vapor-liquid interface.
(2) The bulk vapor is in saturation, while the bulk liquid is subcooled.
(3) The heat transfer coefficient of the liquid film is estimated from the correlation equation shown in Table 1. This equation[10] was developed for the condensation of pure refrigerant in a horizontal smooth tube.
(4) In the liquid film the concentration distribution is uniform, and the mass transfer coefficient is infinitely large.
(5) The interaction effect of mass transfer between components k and j in vapor core is neglected, and the mass transfer coefficient of component k is calculated by the correlation equation shown in Table 2. This equation[9] is derived from the experimental results for binary refrigerant mixture, based on the Chilton-Colburn analogy.
(6) The pressure drop is negligible small.

Table 1 Correlation equation of Haraguchi et al.[10]

Correlation equation of condensation heat transfer Of pure refrigerant in a horizontal smooth tube

$$Nu \equiv \frac{\alpha_L d_w}{\lambda_L} = \left(Nu_F{}^2 + Nu_B{}^2\right)^{1/2}$$

for forced convective condensation term:

$$Nu_F = 0.0152(1 + 0.6Pr_L^{0.8})(\Phi_V / X_{tt}) Re_L^{0.77}$$

for free convective condensation term:

$$Nu_B = 0.725 H(\psi) \left(\frac{Ga Pr_L}{Ph}\right)^{\frac{1}{4}}$$

where:

$$\Phi_V = 1 + 0.5 \left[\frac{G}{\sqrt{g d_w \rho_V (\rho_L - \rho_V)}}\right]^{0.75} X_{tt}^{0.35}$$

$$H(\psi) = \psi + \{10[(1-\psi)^{0.1} - 1] + 1.7 \times 10^{-4} Re\} \sqrt{\psi}(1 - \sqrt{\psi})$$

$$\psi = \left[1 + \frac{\rho_V}{\rho_L}\left(\frac{1-x}{x}\right)\left(0.4 + 0.6\sqrt{\frac{\frac{\rho_L}{\rho_V} + 0.4\frac{1-x}{x}}{1 + 0.4\frac{1-x}{x}}}\right)\right]^{-1}$$

$$Re_L = \frac{G(1-x) d_w}{\mu_L}$$

$$Re = \frac{G d_w}{\mu_L}$$

Table 2 Correlation equation of Koyama et al.[9]

Correlation equation of vapor mass transfer Coefficient
$Sh_{kV} \equiv \dfrac{\beta_{kV}\, d_w}{\rho_V D^*_{kk}} = C_{lg} \cdot 0.023 \cdot Re_V^{0.8} Sc_{kV}^{0.3}$
where:
$Re_V = \dfrac{G\, x\, d_w}{\mu_V}$
$Sc_{kV} = \dfrac{\mu_V}{\rho_V D^*_{kk}}$
$D^*_{kj} = D_{kn} - D_{kj}$
$D_{kj} = M_k D^M_{kj}\left(\sum_{m=1}^{n} \dfrac{y_{mVb}}{M_m}\right) - \dfrac{M_k}{M_j}\left(\sum_{m=1}^{n} D^M_{km} y_{mVb}\right)$

Basic equations

Based on the above assumptions, the governing equations for heat and mass transfer characteristics in the two-phase region are derived as:

Heat balance of refrigerant

$$q_w = -\frac{W_{in}}{\pi\, d_w}\frac{d}{dz}\{x\, h_{Vb} + (1-x) h_{Lb}\} = \alpha_L (T_i - T_w) \qquad (1)$$

where d_w is the inner diameter of the tube. The liquid film heat transfer coefficient α_L is calculated using the correlation equation in Table 1.

Mass balance of component k (k =1, 2, ⋯ , n-1) in vapor core

$$\dot{m}_k = -\frac{W_{in}}{\pi\, d_w}\frac{d}{dz}(x\, y_{kVb}) = -\frac{W_{in}\, y_{kVi}}{\pi\, d_w}\frac{dx}{dz} - \beta_{kV}(y_{kVi} - y_{kVb}) \qquad (2)$$

The vapor mass transfer coefficient is calculated using the correlation equation in Table 2.

Mass balance of component k (k =1, 2, ⋯ , n-1) in liquid film

$$\dot{m}_k = \frac{W_{in}}{\pi\, d_w}\frac{d}{dz}\{(1-x)\, y_{kLb}\} = -\frac{W_{in}\, y_{kLi}}{\pi\, d_w}\frac{dx}{dz} + \beta_{kL}(y_{kLi} - y_{kLb}) \qquad (3)$$

From the assumption $\beta_{kL} \to \infty$, the following relation is reduced from equation (3).

$$y_{kLb} = y_{kLi} \qquad (4)$$

Relation between vapor quality and mass fraction

$$x = (y_{kVbin} - y_{kLb})/(y_{kVb} - y_{kLb}) \qquad (5)$$

where y_{kVbin} is the bulk mass fraction at the refrigerant inlet.

In the single-phase region, the heat balance of refrigerant is given by,

$$q_w = -\frac{W_{in}}{\pi\, d_w}\frac{dh_{Vb}}{dz} = \alpha_V (T_{Vb} - T_w) \qquad (6)$$

where the vapor heat transfer coefficient α_V is calculated from the Dittus-Boelter equation.

Calculation procedure

Considering a control volume between z and $z+\delta z$ in the two phase region, the finite difference equations are derived from the governing equations (1) and (2). These finite difference equations are solved numerically on condition that the tube wall condition (temperature or heat flux distribution) and the thermodynamic state and mass flow rate of refrigerant at the tube inlet are specified as known parameters. The calculation procedure in the case of given T_w distribution is as follows:

(1) The calculation condition is specified: T_w, $(W_{in}, P, T_{Vbin}, h_{Vbin}, y_{1Vbin}, y_{2Vbin}, \ldots, y_{n\text{-}1Vbin})$. The quality change δx through a control volume δz is also given as a known parameter.

(2) Assuming the vapor mass fraction of component k at vapor-liquid interface y_{kVi} (k=1, 2, ⋯, n-1), the temperature T_i and the liquid mass fraction y_{kLi} (k=1, 2, ⋯, n-1) at the interface are calculated from the equation of thermodynamic state.

(3) The reference bulk liquid temperature and mass fraction in the control volume are calculated as,

$$T_{Lb} = (T_w + T_i)/2, \quad y_{kLb} = y_{kLi} \quad (k=1, 2, \cdots, n\text{-}1)$$

(4) The bulk liquid temperature and mass fraction at the downstream end of the control volume are estimated as,

$$T_{Lb}\big|_{z+\delta z} = T_{Lb}$$

$$y_{kLb}\big|_{z+\delta z} = \frac{\left(2 - x|_z - x|_{z+\delta z}\right) y_{kLb} - \left(1 - x|_z\right) y_{kLb}|_z}{1 - x|_{z+\delta z}}$$

Then, the bulk liquid enthalpy $h_{Lb}|_{z+\delta z}$ is calculated from the equation of state.

(5) The bulk vapor mass fraction at the downstream end of the control volume is calculated as,

$$y_{kVb}\big|_{z+\delta z} = y_{kLb}\big|_{z+\delta z} + \left(y_{kVbin} - y_{kLb}\big|_{z+\delta z}\right)/x\big|_{z+\delta z}$$

Then, the bulk vapor temperature $T_{Vb}|_{z+\delta z}$ and enthalpy $h_{Vb}|_{z+\delta z}$ are also calculated.

(6) The reference bulk vapor mass fraction in the control volume is calculated as,

$$y_{kVb} = \frac{(x\, y_{kVb})_z + (x\, y_{kVb})_{z+\delta z}}{x|_z + x|_{z+\delta z}}$$

(7) The control volume length δz_{HB} is obtained form the finite difference equation for the heat balance of refrigerant. The control volume length δz_{kMB} (k=1, 2, ⋯ , n-1) is also calculated from the finite difference equation for the mass balance of component k.

(8) The procedure (2) to (7) is repeated by modifying y_{kVi} (k=1, 2, ⋯, n-1) until the following relation is satisfied within the convergence radius.

$$\delta z_{HB} = \delta z_{1MB} = \delta z_{2MB} = \ldots\ldots = \delta z_{n\text{-}1MB}$$

(9) When the above convergence condition is satisfied, the procedure (2) to (8) is carried out successively

toward the downstream until $x=0$.

Results and Discussion

The prediction calculation is carried out for ternary zeotropic refrigerant mixtures of HFC32/HFC125/HFC134a condensing in a horizontal smooth tube with an inner diameter of 6.4 mm. Thermodynamic and transport properties of the mixtures are calculated using the program package REFPROP Ver. 5.0[11].

Figure 2 shows the phase equilibrium diagram of a ternary system composed of HFC32, HFC125 and HFC134a, which are denoted by components 1, 2 and 3, respectively. Consider the condensation of a mixture of bulk mass fraction (y_{1b}, y_{2b}, y_{3b}). The vapor and liquid states at dew point are represented by points A and A', respectively, while those at bubble point are represented by points B and B', respectively. The lines AA' and BB' represent constant fugacity lines. If the condensation proceeds maintaining thermodynamic equilibrium, the bulk vapor and liquid states change along a line AB and a line A'B', respectively. It should be noted that in the actual situation the bulk vapor and the bulk liquid states follow different tracks from a line AB and a line A'B', respectively, because the phase equilibrium is only established at the vapor-liquid interface.

Figure 3 shows the axial distribution of temperature, condensation mass flux and mass fraction in the case of T_w=312 K, P=1.988 MPa (T_{Vbin}=323 K) and G=150 kg/(m^2 s). In Fig. 3(a), it is shown that the values of T_{Vb}, T_i and T_{Lb} decrease in the refrigerant flow direction and the temperature difference $(T_{Vb}-T_i)$ due to mass transfer resistance is not so large. In Fig. 3(b), it is shown that the values of $\dot{m}_1$, $\dot{m}_2$ and $\dot{m}_3$ decrease toward the downstream; the decrease of component 3 is the largest. In Figs. 3(c) and (d), it is shown that the values of y_{1Vb}, y_{1Vi} and $y_{1Lb}(=y_{1Li})$ increase toward the downstream, whereas those of y_{3Vb}, y_{3Vi} and $y_{3Lb}(=y_{3Li})$ decrease. This means that component 1 (HFC32) is concentrated toward the downstream, while component 3 (HFC134a) is diluted. It is also shown that the $\dot{m}_k$ to $\dot{m}$ ratio ξ_k coincides with y_{kLb} at the beginning point of condensation and approaches to y_{kVb} in downstream region. This reveals that the mass transfer is controlled by the resistance in the vapor side at the beginning point of condensation and the resistance in the liquid side increases gradually as the condensation proceeds.

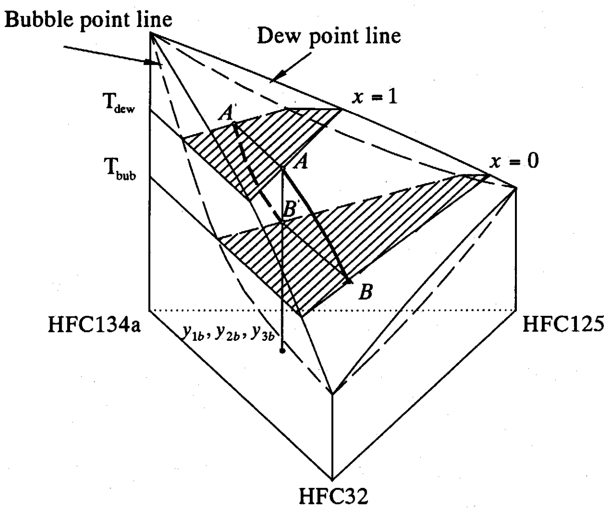

Figure 2 Phase equilibrium diagram

Figure 4 shows the axial distribution of temperature, condensation mass flux and mass fraction in the case of q_w=7.5 kW/m^2, P=1.988 MPa and G=150 kg/(m^2 s). The condensation characteristics in Fig. 4 are almost the same as those in Fig. 3 except for the trend of mass flux.

Figure 5 shows the effect of the composition on the heat transfer characteristics. In this calculation the value of y_{2Vb} is varied as a parameter while keeping the y_{1Vb} to y_{3Vb} ratio at 3 : 7. In this case, the heat flux increases with the decrease of y_{2Vb}, and the total condensing length increases a little. It is noted that the total heat transfer rates in the cases represented by a broken and a chain lines are about 5 and 11 % higher than that of a solid line, respectively.

Figure 6 shows the effect of the leakage of volatile components HFC32/HFC125 from R407C on the heat transfer characteristics. In this calculation the leakage is assumed to occur while keeping the y_{1Vb} to y_{2Vb} ratio at 23 : 25. The axial heat flux distribution and the total condensing length are little affected by the leakage of volatile components.

Figure 7 shows the comparison of the heat transfer characteristics between R407C and R22. The calculation of R22 is done for three cases of the saturation temperature T_{sat}: (1) $T_{sat}=T_{dew}$, (2) $T_{sat}=(T_{dew}+T_{bub})/2$, (3) $T_{sat}=T_{bub}$, where T_{dew} and T_{bub} represent the dew and bubble point temperature of R407C at the refrigerant inlet, respectively. The calculation result of R407C is represented by a solid line, and the results of R22 are represented by a broken, a dotted and a chain lines, which correspond to cases (1), (2) and (3), respectively. The result of R407C is the closest to that of R22 in case (2).

Conclusions

The prediction method for the condensation of multi-component refrigerant mixture inside a horizontal smooth tube is developed based on some reliable assumptions. Using this method, the prediction calculation for ternary zeotropic refrigerant mixtures composed of HFC32/HFC125/HFC134a is carried out, and the following results are obtained.

(1) The mass transfer is controlled by the resistance in the vapor side at the beginning point of condensation and the resistance in the liquid side increases gradually as the condensation proceeds.

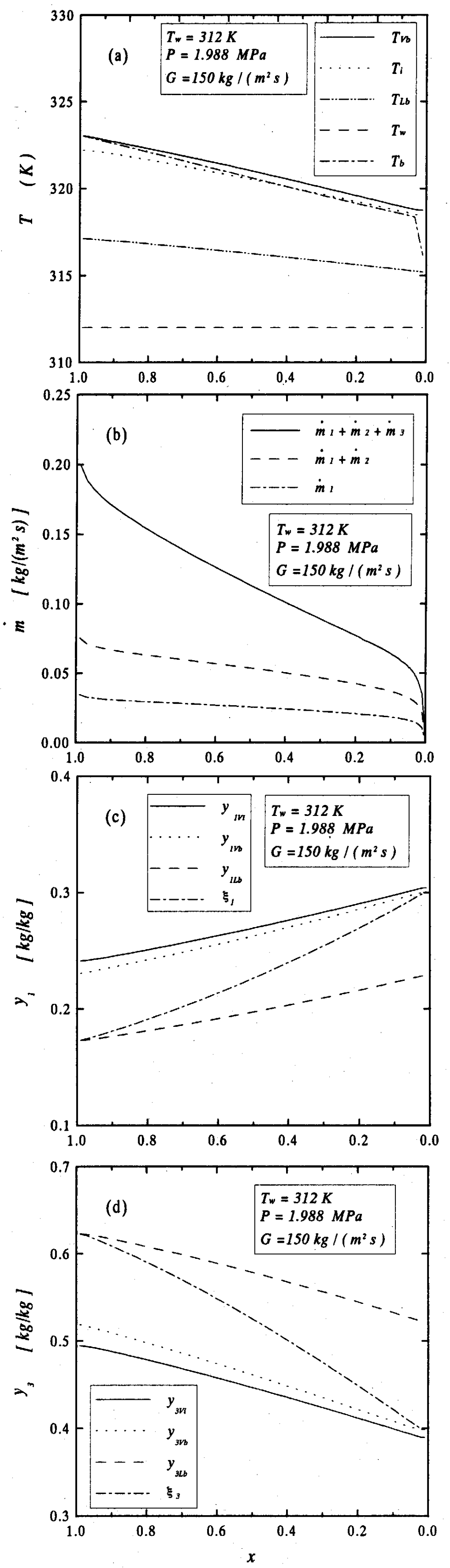

Figure 3 Condensation characteristics of R407C at a constant T_w

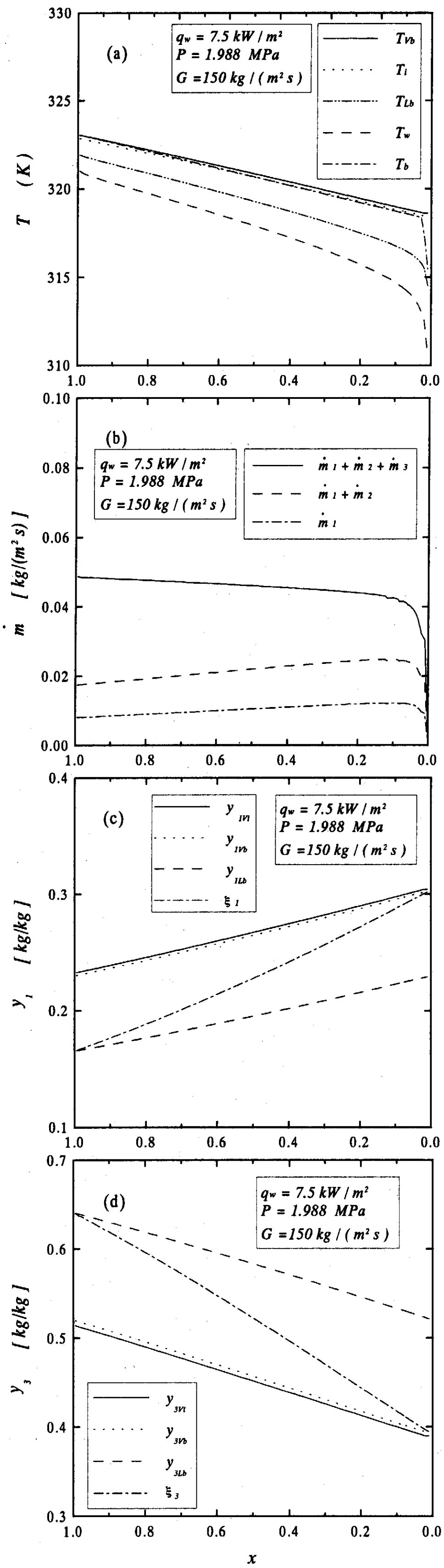

Figure 4 Condensation characteristics of R407C at a constant q_w

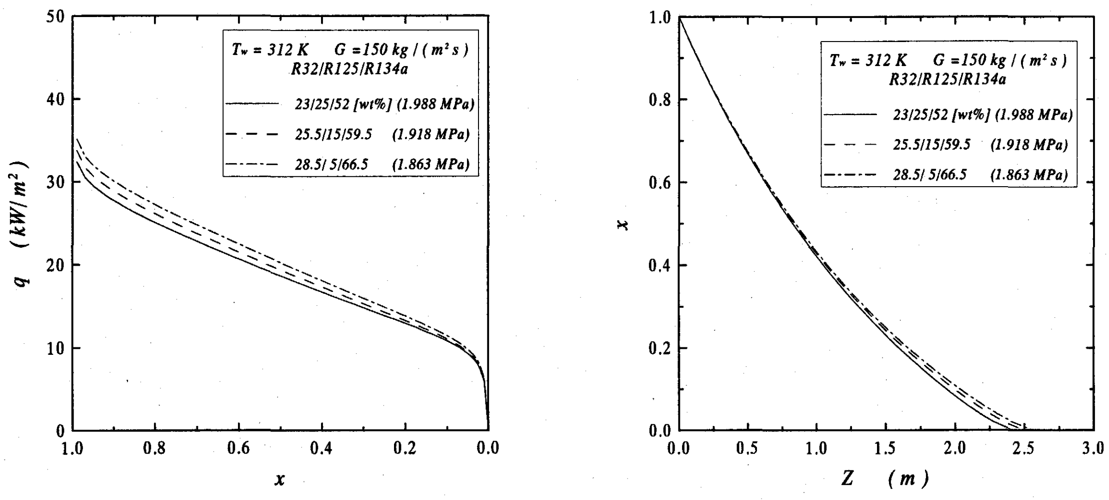

Figure 5 Effect of HFC125-composition on q_w and x

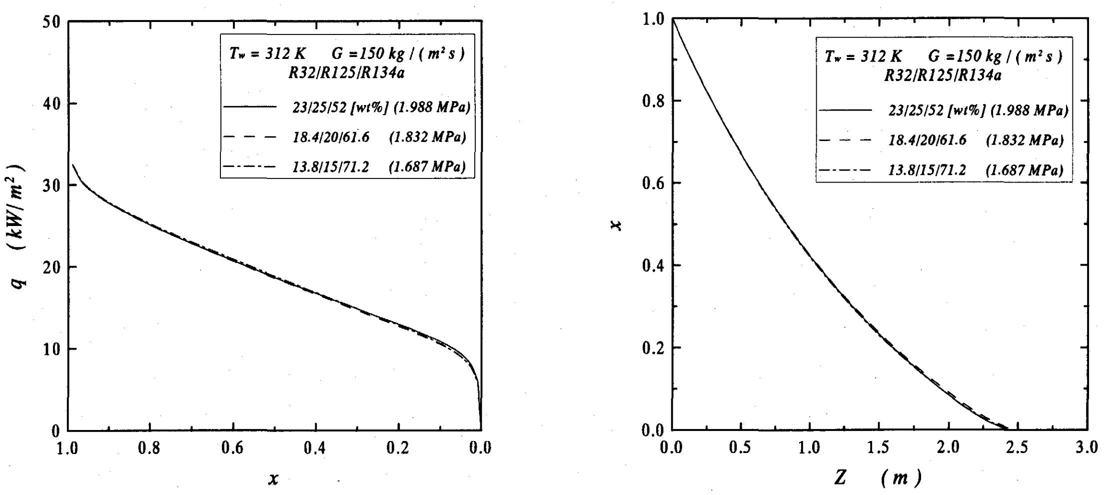

Figure 6 Effect of HFC32/125 leakage on q_w and x

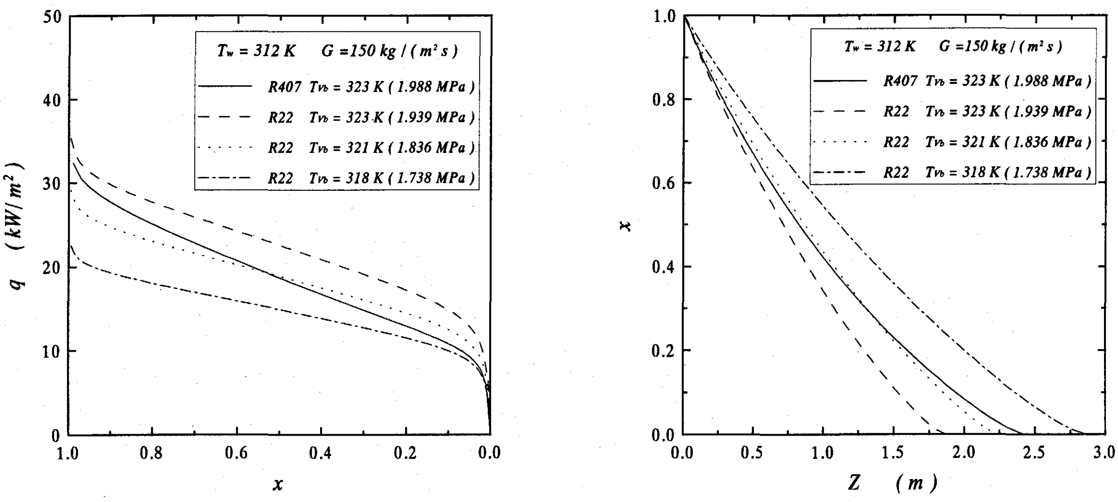

Figure 7 Comparison of condensation characteristics between R407C and R22

(2) When the concentration of HFC125 decreases, the condensing tube length and the heat transfer rate increase.
(3) The heat transfer characteristics is little affected by the leakage of volatile components of HFC32 and HFC125.
(4) The result of R407C is the closest to that of R22 in case that the saturation temperature of R22 equals to the arithmetic mean of the dew and bubble point temperature of R407C at the refrigerant inlet.

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