Nonmiscible refrigerant R1234ze(E)/R32 の水平平滑管内凝縮伝熱特性の解析

Analysis of condensation heat transfer characteristics of zeotropic refrigerant mixture R1234ze/E inside a Horizontal Smooth tube

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Experimental data and mathematical model have been used in the present analysis to understand the condensation characteristics, especially the heat transfer degradation of binary zeotropic mixtures of R1234ze(E) and R32 inside a horizontal smooth tube of which inside diameter is 4.35 mm. The variations in the mass fractions of mixtures R1234ze(E)/R32 are 0.25/0.75, 0.55/0.45, 0.75/0.25 and the variations of mass fluxes of refrigerants are 50–400 kg m⁻² s⁻¹. The temperatures and concentrations at the bulk and interface regions are obtained to understand the heat transfer degradation due to the mass transfer resistance of both the vapor-side and liquid-side. Considering the heat transfer degradation effect, the experimental local heat transfer coefficients are predicted by the obtained interface temperatures and correlation of pure refrigerant condensation.

Key Words: Mixture refrigerant, Heat transfer degradation, Condensation, Interface temperature

1. Introduction

Increasing concerns regarding the environmental impact of HFCs used in residential air conditioners have led to the reconsideration of refrigerants in these applications. Nonzeotropic refrigerant mixtures of HFOs and R32 might be good alternatives of the existing HFCs. The drop-in experiments on heat pump cycle using mixtures of R1234ze(E)/R32 show that these mixtures are strong candidates for replacing R410a from residential air conditioning systems [1]. However, only limited information is available regarding the heat transfer characteristics of this mixture.

In this analysis, existing experimental data [2] of R1234ze(E)/R32 inside a horizontal smooth tube and a mathematical model have been used to understand the condensation characteristics, especially the heat transfer degradation of that zeotropic mixture.

2. Physical Model

2.1 Assumptions

Fig. 1 shows the physical model employed in the present analysis. The following assumptions were made in this model similar to Jin et al. [3]. (1) The phase equilibrium is established at the vapor-liquid interface; i.e., the bulk vapor is in a saturated state and the bulk liquid is subcooled, as shown in Fig. 2. (2) The heat transfer behavior in the liquid film is same as that of the condensation of a pure refrigerant, and the liquid film heat transfer coefficient is estimated using the correlations developed for pure refrigerant condensation. (3) The flow is annular with uniform film thickness along the tube circumference. (4) The convective heat transfer in the vapor phase is negligible.

\[ h = \frac{q_w}{T_b - T_w} \]  

where \( q_w \) is the heat flux at the inside wall of the tube, \( T_b \) is the thermodynamic equilibrium temperature of the refrigerant, and \( T_w \) is the temperature at the inside wall.

2.3 Heat transfer in the liquid film

From the heat balance of refrigerant, the inside wall heat flux is expressed as

\[ q_w = h_L(T_i - T_w) \]  

where \( T_i \) is the liquid-vapor interface temperature and \( h_L \) is the liquid film heat transfer coefficient. In this study, we used the correlations of Haraguchi [4] to obtain \( h_L \).

2.4 Mass transfer

The total condensation molar flux \( N_i \) and the condensation molar flux of the more volatile component \( N_1 \) are obtained from the vapor-side molar conservation:

\[ N_i = -\frac{V}{m_d} \frac{dX}{dz} \]  

\[ N_1 = -\frac{V}{m_d} \frac{d(XY_{vhl})}{dz} \]  

Where, \( V \) is the refrigerant molar flow rate, \( X \) is the molar quality, \( Y \) is the mole fraction of R32.

The condensation molar flux of the more volatile component is made up of diffusive and convective contribution:

\[ N_1 = N_1 V_i - J_v \]  

\[ N_1 = N_1 Y_{vL} - J_L \]  

where the diffusion fluxes in each phases are given by

\[ J_v = k_v(Y_{vl} - Y_{vb}) \]  

\[ J_L = k_L(Y_{vL} - Y_{vL}) \]  

Where the vapor-side mass transfer coefficient \( k_v \) and the liquid-side mass transfer coefficient \( k_L \) are estimated similar to Jin et al. [3]

3. Calculation procedure

Considering a control volume between \( z \) and \( z + \Delta z \) in the condenser, the above mentioned mass transfer equations are solved to obtain the interface temperatures and concentrations.
In this calculation, the inlet refrigeration conditions, the molar quality and pressure at the inlet and out let of the control volume are known parameters.

The calculation procedure can be summarized as follows:

(i) Specify the control volume length $\Delta z$ similar to experiment, (ii) Assume $V_{L_z}$ and $X_{z+\Delta z}$, (iii) Calculate $Y_{L_z}$ using $V_b$ and $X_{z+\Delta z}$, (iv) Calculate $T_b$, $Y_{LB}$, and $P$ at the reference point (middle of the control volume) by interpolation, (v) From REFPROP (SATP, TRNPTR, and THERM subroutines) obtain reference thermodynamics and transport properties of the vapor side, (vi) Reference liquid side density is assumed, (vii) Calculate $K_v$, (viii) From equations (5) and (7) calculate $Y_{L_z}$, (ix) From REFPROP (SATP subroutine) obtain $Y_{L_z}$ and $T_L$ of, (x) Calculate the reference liquid bulk temperature using $T_{LB} = T_w + \frac{1}{3}(T_l - T_w)$, (xi) From REFPROP (TRPHO, TRNPTR, THERM, SURF subroutines) thermodynamics and transport properties of liquid side at the reference point are obtained, (xii) Considering $T_{LB_z+\Delta z} = T_{LB_{reference}}$, thermodynamics and transport properties at point $z + \Delta z$ are obtained from REFPROP, (xiii) Calculate $k_L$, (xiv) From equations (6) and (8) calculate $Y_{L_z}$, (xv) Check the values of $Y_{L_z}$ from step (9) and step (14). If they are not equal then return to step (2) and repeat the process until they are equal. (xvi) Continue the above procedure until the end of the condensation.

4. Results and discussion

Fig. 3 shows the interface and bulk temperatures variations along the condenser that are obtained from the above calculation procedure. Mass transfer resistance causes the interface temperature to always be lower than that of the bulk vapor. However, the difference gradually vanishes on approaching the end of the condensation process. Fig. 4 shows the variation of the molar fraction of the more volatile component (R32) with changing the mass quality. The bulk and the interface concentrations of the more volatile component increase towards the downstream. During condensation of zeotropic mixture the less volatile component condenses more readily than the more volatile component accumulates at the vapor interface. For this reason, the molar fraction of the more volatile component at the vapor-side and liquid-side interface become larger than that of the bulk vapor and liquid, respectively.

From equation (1) and (2), the local heat transfer coefficient of the mixture can be expressed as

$$h = \frac{T_I - T_w}{T_b - T_w}$$

where, $(T_I - T_w)/(T_b - T_w)$ represents gradient contribution to the heat transfer degradation. The gradient contribution includes the effects of concentration and temperature variations as mentioned in the explanation of Figs. 3 and 4. $(T_I - T_w)/(T_b - T_w)$ = 1 means no heat transfer degradation. Lower value of that term represents higher heat transfer degradation due to gradient contribution. Fig. 5 shows the gradient contribution to the heat transfer degradation along the condensation. This degradation is lower at high mass flow and at low temperature glide. At high mass flow the flow turbulence reduces the temperature and concentration variation. This variation is also low at low temperature glide. At the beginning and at the end of the condensation process the heat transfer degradations are high due to higher difference between the interface and bulk temperature and concentration at those positions as shown in the Figs 3 and 4.

The validity check of the present analysis is done by the comparison between the calculated condensation heat transfer coefficients and the experimental ones as shown in the Fig. 6. The heat transfer coefficients are calculated by the Eq. (9) where $h_0$ is the Haraguchi’s correlation [4] and $T_l$ are obtained from the present model and koyama’s model [5]. Inclusion of both the vapor-side and liquid-side mass transfer resistance in the present model shows better prediction than the Koyama's model in which they did not consider the liquid-side mass transfer resistance. On the other hand, Thome’s correlation [6] shows under prediction at the beginning of the condensation.

5. Conclusions

(i) The heat transfer degradation at the beginning of the condensation is dominated by the vapor-side gradient contribution while the liquid-side gradient contribution dominates in the downstream region.

(ii) This degradation is lower at high mass flow and at low temperature glide.

(iii) Inclusion of both the vapor-side and liquid-side mass transfer resistance in the present model shows well prediction of the local heat transfer coefficient.

References