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Flow Boiling Heat Transfer of Binary Mixtures HFO1234yf/R32 in a Smooth Horizontal Tube

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Investigation of flow boiling heat transfer of binary mixtures (HFO1234yf/R32) at two concentrations in a smooth horizontal tube

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ABSTRACT

HFO1234yf is a promising alternative for automobile air conditioners because of its low GWP of 4 and thermophysical properties similar to those of R134a. However, its performance is inferior to R410A. This makes it difficult to be applied to residential air-conditioners. A mixture of HFO1234yf and R32 is expected to balance both the GWP and COP requirement when applied to residential air-conditioning systems. In this study, flow boiling heat transfer coefficients of HFO1234yf and R32 (80:20 and 50:50 by wt%) were measured in a smooth horizontal tube at a saturation temperature of 15°C. The inner diameter (ID) of the test section is 4 mm. The mass flux ranges from 100 to 300 $kg/m^2{\cdot}s$, and the heat flux changes from 6 to 24 kW/m^2. Heat transfer coefficients of the mixtures and pure HFO1234yf were summarized at three Bo numbers. The influence of Bo on mass discussion was observed and discussed. It is found that there is notable influence of mass diffusion on heat transfer when Bo is large. When Bo is small, the convective heat transfer at high vapor qualities seems to be suppressed due to the effects of mass diffusion. Results show that the heat transfer coefficient of the 50:50 wt% mixture of HFO1234yf and R32 is higher than that of the 80:20 wt% mixture and is also the same or even higher than that of pure HFO1234yf. A theoretical model was proposed to predict the heat transfer coefficients of the mixtures HFO1234yf and R32 under two concentrations. The prediction model can catch 80% of the data within deviation of ±20%.

1. INTRODUCTION

Increasing concern on the environmental protection has led to the reconsideration of the refrigerant in air conditioners. Although HFCs does not deplete ozone, which are currently used to replace HCFCs, they usually have a notable global warming potential. Transition from these refrigerants to low GWP refrigerants is a crucial issue globally. Owing to its low global warming potential (GWP = 4), HFO1234yf is proposed as a promising alternative to HFC134a (GWP = 1450) in automobile air conditioners. In addition, the application of HFO1234yf to residential air conditioners is expected. However, its performance is inferior to that of R410A mainly due to its small latent heat. Some Experimental results (Fujitaka *et al*., 2010, Hara *et al*., 2010, Okazaki *et al*., 2010) show that the coefficient of performance of the HFO1234yf system is lower than that of the R410A system when HFO1234yf is dropped directly into stationary heat pump systems. This makes it difficult to be applied to residential air-conditioners. One of the proposed solutions is to use mixtures of HFO1234yf and R32 to improve the performance of the air conditioner. Fujitaka *et al.* (2010) compared system performance of pure HFO1234yf and HFO1234yf/R32 mixtures to that of R410A in room air conditioners. The system performance of the mixture HFO1234yf/R32 was improved as R32 concentration increases. The COPs of HFO1234yf/R32 (50/50 wt%) under the cooling and heating conditions are 95% and 94% of those of R410A, respectively. Okazaki *et al*. (2010) tested HFO1234yf/R32 mixtures in modified room air conditioners. When the concentration of R32 reaches 60%, the APF ratio of the mixture is 93.3% of R410A. In the study of Kamiaka *et al.* (2011), the analysis shows that the mixture of HFO1234yf and R32 can help to improve the COP of system. Therefore, detailed information of the thermodynamic and heat transfer characteristics of the refrigerant mixture with the mixing ratio of R32 as parameter is required in order to carry out the further study. Authors (Li *et al*. 2012) have investigated the flow boiling heat transfer characteristics of HFO1234yf/R32 in a horizontal smooth tube with an inner diameter of 2 mm. It is found that the mixture with 50% of R32 can be higher than that of pure HFO1234yf at large heat flux and mass flux. In this study, the characteristics of the flow boiling heat transfer of HFO1234yf/R32 at two concentrations in a horizontal smooth tube with an inner diameter (ID) of 4 mm are investigated.

2. TEST APPARATUS

Figure 1 shows the experimental system, which includes a Coriolis-type flow meter, condenser, flow control valve, test tube (evaporator), sight glass, and gear pump. The devices of this system were described in detail by Li *et al*. (2012). The test section was a smooth stainless steel tube with a 4-mm ID in this study. The heat needed for evaporation was supplied by DC power.

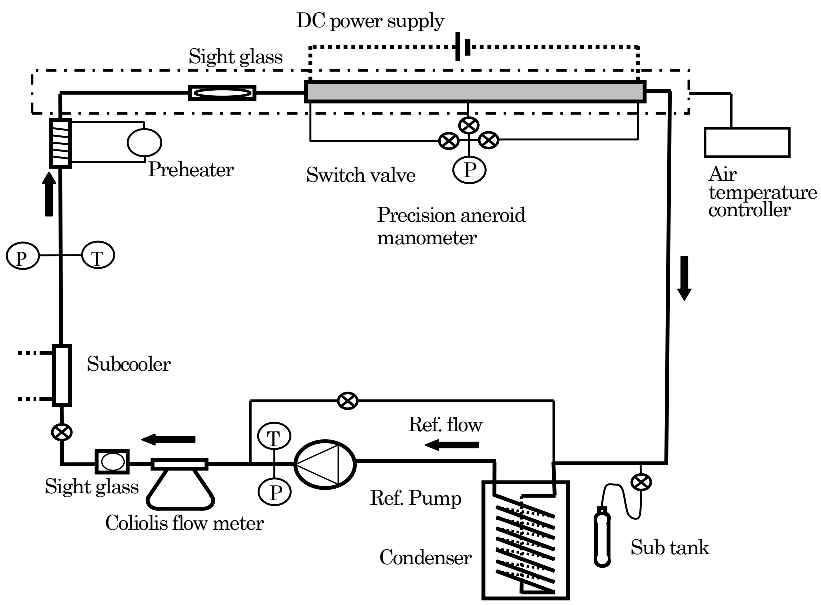


Figure1 Schematic of experimental system

The wall temperatures at the top, side, and bottom of the tube surface at each location were measured by thermocouples with an outer diameter of 0.1 mm. An 8-μm-thick Teflon sheet was inserted between each thermocouple and the test tube to eliminate the influence of electric current on the thermocouples. All the thermocouples were calibrated using a high-precision platinum resistance thermometer sensor with an accuracy of ±0.03 K. The accuracy of the calibrated thermocouples was ±0.1 K within the range of 0～50^{o}C. The local heat transfer coefficient, $h_{\mathrm{exp,i}}$, was defined as Eq. (1). The local heat transfer coefficient at each cross section, h_{exp}, was determined by averaging the measured heat transfer coefficients at the top, bottom, and side, as shown in Eq. (2).

$$h_{\mathrm{exp,i}} = \frac{q}{T_{\mathrm{wall,i}} - T_{\mathrm{m,sat,i}}} \quad (\mathrm{i} = 1, 2, 3\ldots) \tag{1}$$

$$h_{\mathrm{exp}} = \frac{h_{\mathrm{exp,t}} + 2 \cdot h_{\mathrm{exp,s}} + h_{\mathrm{exp,b}}}{4} \tag{2}$$

where T_{wall} is the temperature of the inner wall, and $T_{m,sat}$ is the saturation temperature of the mixture. The purity of the refrigerant HFO1234yf was 99.7% and that of R32 was 99.9%. Heat transfer coefficients of the two concentrations of HFO1234yf/R32 mixtures were measured. The properties of the mixtures are acquired based on a Peng-Robinson-type state equation (Kamiaka *et al*., 2011, Arakawa *et al*., 2010). The properties of pure refrigerants are from REFPROP 8.0 (Lemnon *et al*.). Test conditions are listed in Table 1. The saturation temperature of the mixture is set to 15°C at a vapor quality of 0.5.

In the study, the heat transfer coefficients of the mixture are compared with the data of HFO1234yf which are cited from Saitoh *et al*. (2011).

Table 1 Experimental conditions

Refrigerant	HFO1234yf + R32
Concentration HFO1234yf:R32 [wt%]	80:20,50:50
Inner diameter [mm]	4
Vapor quality	0.2–1.0
Heat flux [kW/m^2]	6, 12, 24
Mass flux [kg/m^2·s]	100, 200, 300, 400
Heating method	Joule Heating

3. INFLUENCE OF Bo ON MASS DIFFUSION

Bo depicts the relative importance of nucleate boiling against convective heat transfer on the flow boiling heat transfer and the interaction between them, and is defined as

$$\text{Bo} = q/(h_{fg}G) \tag{3}$$

where h_{fg} is the latent heat. Bo is introduced to discuss the influence of mass flux and heat flux on mass diffusion. Table 2 lists the Bo values of mixtures at two concentrations and pure HFO1234yf at different heat fluxes and mass fluxes. On the basis of the test conditions listed in Table 2, three degrees of comparison are obtained for Bo.

Table 2 Boiling numbers under different experimental conditions

Heat flux (kW/m^2)/Mass flux (kg/m^2·s)	HFO1234yf	HFO1234yf + R32 (80/20 by wt%)	HFO1234yf + R32 (50/50 by wt%)	Degree of comparison
6/200	1.96×10^{-4}	1.98×10^{-4}	1.50×10^{-4}	Small
12/300	2.61×10^{-4}	2.67×10^{-4}	2.16×10^{-4}	Moderate
12/100, 24/200	7.84×10^{-4}	7.45×10^{-4}	5.91×10^{-4}	Large

Note: The saturation temperature is 15°C

Figure 2 shows the variation in the heat transfer coefficients of HFO1234yf/R32 (80/20 by wt%) and the pure HFO1234yf when the degrees of Bo are small and moderate. Figure 3 shows the results of the mixture at a high Bo. The heat transfer coefficients of HFO1234yf/R32 (80/20 by wt%) are lower than those of pure HFO1234yf at different Bo. As shown in Figure 2, at a low Bo, the heat transfer coefficient of the mixture at a low quality is close to the heat transfer coefficient of HFO1234yf. However, with an increase in the vapor quality, the results decrease below that of the heat transfer coefficient of HFO1234yf. Compared with Figures 2 and 3, the altitude difference between the heat transfer coefficients of HFO1234yf/R32 (80/20 by wt%) and the pure HFO1234yf increased with an increase in Bo. It seems that the suppression of heat transfer of the mixture at a high Bo is greater than that at a low Bo.

Figure 4 shows the experimental results of HFO1234yf/R32 (50/50 by wt%) and the pure HFO1234yf against the vapor quality when the degrees of Bo are small and moderate. Figure 5 shows the heat transfer coefficient of HFO1234yf/R32 (50/50 by wt%) at a high Bo. At small and moderate degrees of Bo, heat transfer coefficients of mixtures HFO1234yf/R32 (50/50 by wt%) are higher than that of pure HFO1234yf. The reason is that thermodynamic properties of R32 positively contribute to heat transfer coefficients of the mixture when the mass fraction of R32 is 50%. The temperature glide becomes moderate, decreasing from 7.7°C to 4.55°C, and the influence of mass diffusion is less obvious when the concentration of R32 increases from 20% to 50%. At a low Bo, the heat transfer coefficient of the mixture is higher than that of pure HFO1234yf at a low vapor quality but is close to that of pure HFO1234yf at high vapor quality. It is surmised that the convective heat transfer is suppressed at a high vapor quality at a small Bo, which is similar to the phenomenon occurring at a small Bo in Figure 2 when the mass fraction of R32 is 20% in the mixture. The results in Figure 5 show that the heat transfer coefficient of the mixture is lower than that of pure HFO1234yf when Bo increases. It seems that the influence of mass diffusion on suppression of heat transfer becomes significant.

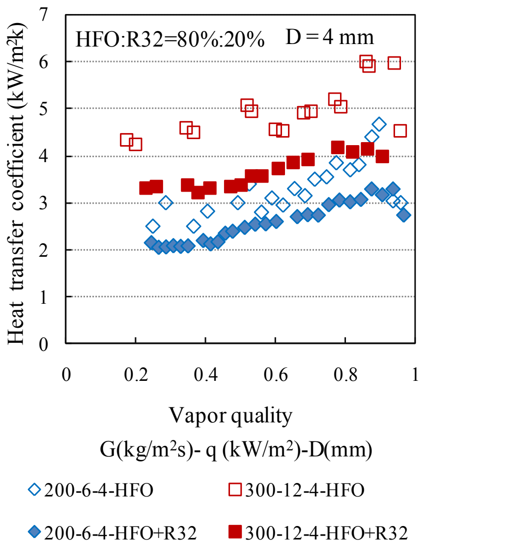


Figure 2 Measured heat transfer coefficients of pure HFO1234yf and the mixture of HFO1234yf+R32 at R32 mass fraction of 20% at small and moderate Bo numbers

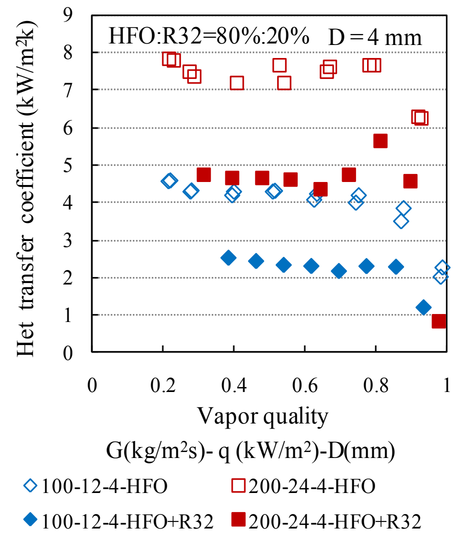


Figure 3 Measured heat transfer coefficients of mixtures of HFO1234yf+R32 at R32 mass fraction of 20% at a high Bo number

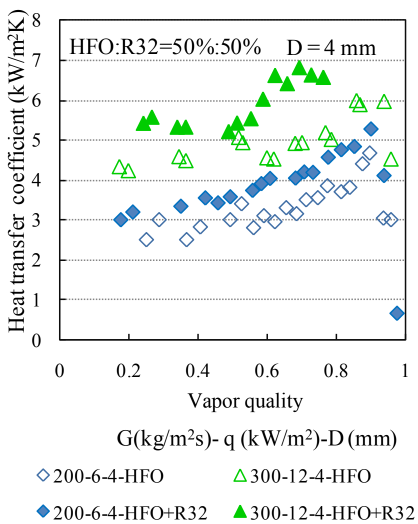


Figure 4 Measured heat transfer coefficients of mixtures of HFO1234yf+R32 at R32 mass fraction of 50% at small and moderate Bo numbers

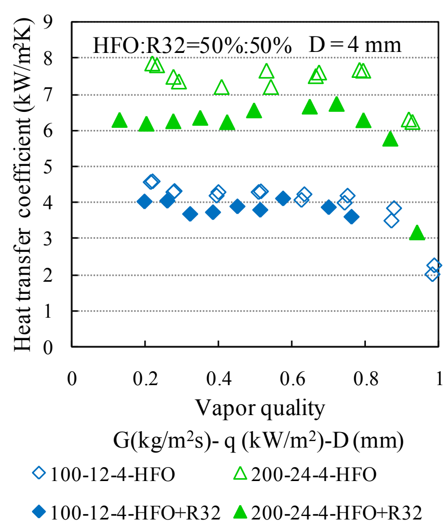
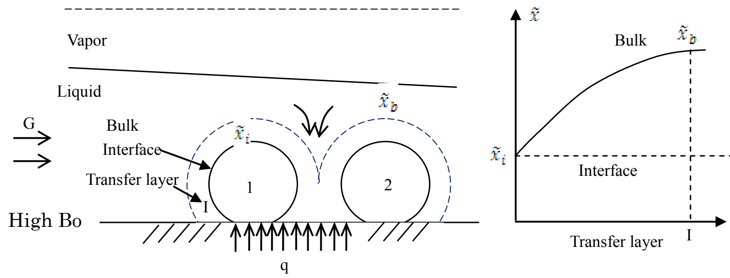
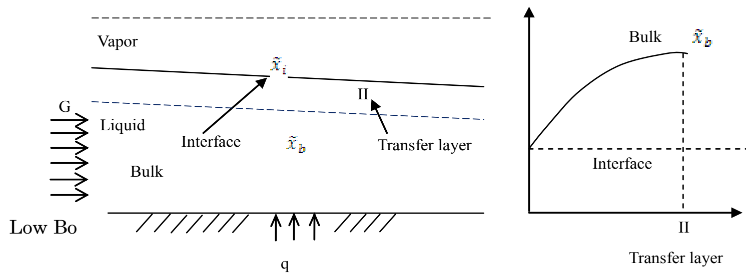


Figure 5 Measured heat transfer coefficients of mixtures of HFO1234yf+R32 at R32 mass fraction of 50% at a high Bo number

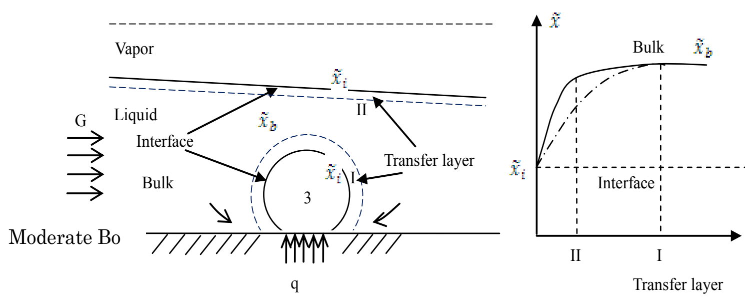
As can be seen in Figure 2 to 5, some relationships exist between the heat transfer coefficients of the mixtures and that of the pure HFO1234yf with a change in Bo. When Bo is large, there is greater influence of mass diffusion on heat transfer. When Bo is small, the convective heat transfer at high vapor qualities seems to be suppressed. In a study by Li *et al*. (2012), the same tendency was seen when the fluid HFO1234yf/R32 (80/20 by wt%) flows and evaporates inside a 2-mm ID tube.



(a) Flow boiling situation at high Bo



(b) Flow boiling situation at low Bo



(c) Flow boiling situation at moderate of Bo

Figure 6 The flow boiling situation at three kinds of Bo

The evaporation process of mixtures is different from that of pure refrigerants. The volatile component evaporates firstly because of low boiling points compared to the other component. In the evaporation process, the less volatile component accumulates continually around the bubble and forms a shell with a concentration gradient. The volatile component in the bulk has to overcome this shell to reach the interface of liquid bulk and bubble. At a high Bo, nucleate boiling dominates the entire heat transfer. A high heat flux causes violent boiling. Owing to a high density of bubbles on the surface, the boundary layers of two bubbles may overlap each other as shown in Figure 6 (a), it is more difficult for the volatile component to reach the interface and a larger compositional inhomogeneity forms in the interface around the bubble. Therefore, mass diffusion causes greater suppression of the heat transfer. The disturbances of the fluid caused by the mass flux are relatively weak to decrease mass diffusion.

When Bo is small, at a high vapor quality, convective heat transfer is prevailing to the entire heat transfer. Owing to acceleration of the vapor phase, the velocity of the liquid phase increases. The nucleate boiling is suppressed completely. Subsequently, evaporation occurs violently at the interface of the liquid and vapor phases, not the surface of the bubble. According to the same principle of evaporation, the volatile component evaporates firstly through the interface. The less volatile component accumulates near the liquid and vapor phase interface as shown in Figure 6(b). The layer of the concentration gradient forms near the interface. The volatile component in the bulk has to pass through the layer to complement the content of the volatile component attributable to the concentration gradient. Although a large mass flux can help to eliminate the concentration gradient, the mass diffusion still affects the convective heat transfer owing to the strong compositional inhomogeneity during the intense evaporation process.

At moderate Bo, because of both nucleate boiling and convective heat transfer, the concentration gradient layer exits at not only the surface of the bubble but also at the liquid and vapor phase interface, as shown in Figure 6(c). The density of bubbles is low. It is easy to complement the volatile component from the bulk to the interface, and the compositional inhomogeneity is decreased in comparison to that at a large Bo. The component gradient near the interface of evaporation is low because the evaporating process is less vigorous. Moreover, a bubble transitioning from the liquid to the vapor phase can cause agitation that decreases the effect of the mass diffusion.

Through Figure 6, effects of Bo on mass diffusion can be used to explain the relationship between heat transfer coefficient of mixtures and pure that of HFO1234yf at different Bo.

4. PREDICTION OF MIXTURES

The correlation proposed by Li *et al*. (2011) was used to predict the heat transfer coefficients of mixtures. The suppression factor S and enhancement factor F for nucleate boiling and convection heat transfer were introduced into the correlations. Meanwhile, considering the mass diffusion existing in the mixture, suppression factors of F_{mix} and S_{mix} were also used in the correlations. The correlations were used to predict the heat transfer coefficient of the mixture HFO1234yf/R32 (80/20 by wt%) and captured 75% of data including HFO1234yf, R32 and HFO1234yf/R32 (80/20, 50/50 by wt%) in a 2-mm ID tube within ±20% (Li *et al*., 2011).

$$h_{tp} = Fh_l + Sh_n \tag{4}$$

$$h_n = 55\,\mathrm{Pr}^{0.12}\left(-\log \mathrm{Pr}\right)^{-0.55} M^{-0.5} q^{0.67} \tag{5}$$

$$h_l = 0.023\frac{\lambda_l}{D}\left[\frac{G(1-x)D}{\mu_l}\right]^{0.8}\mathrm{Pr}^{0.4} \tag{6}$$

$$F = 1.0 + 1.8\cdot\left(0.3 + \frac{1}{X_{tt}}\right)^{0.88} / \left(1 + Wev^{-0.4}\right) \tag{7}$$

$$S = \frac{1}{0.5 + 0.5\dfrac{\left(\mathrm{Re}_{tp}\times 10^{-3}\right)^{0.3}}{\left(Bo\times 10^{3}\right)^{0.23}}} \tag{8}$$

$$h_{tpm} = F_{mix}Fh_l + S_{mix}Sh_n \tag{9}$$

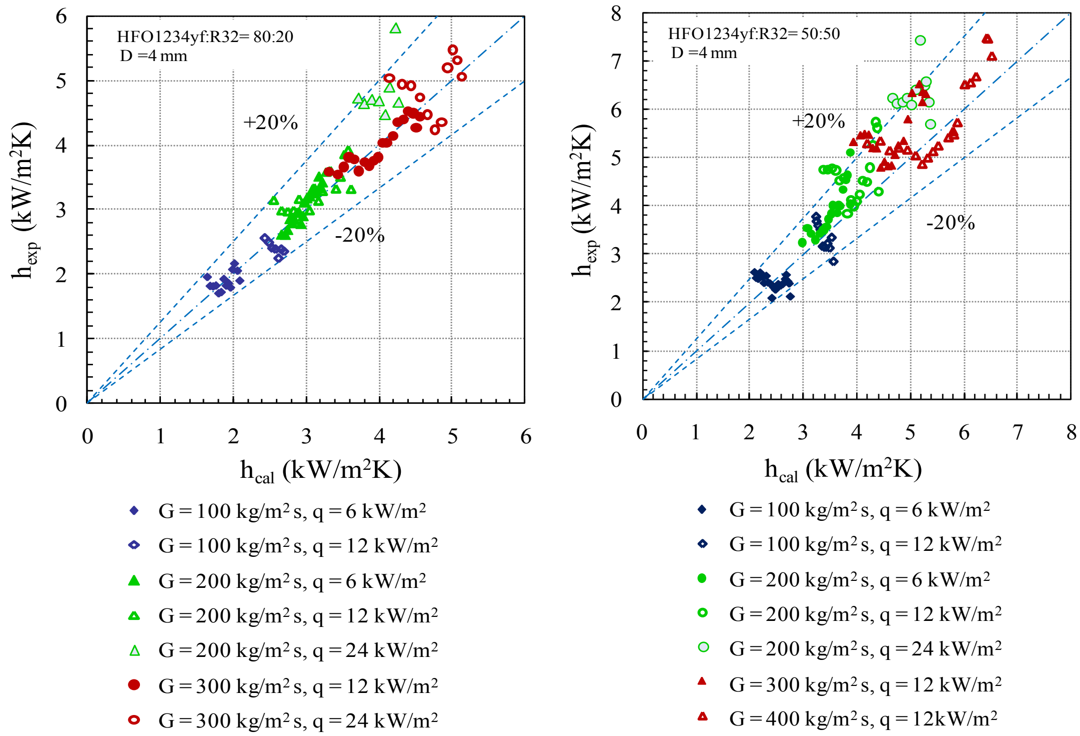
$$F_{mix} = \exp\left(-0.027\left(T_{msat} - T_b\right)\right) \tag{10}$$

$$S_{mix} = \frac{\Delta T_m}{\Delta T_{id}} = \left[1 - (\tilde{y} - \tilde{x})\left(\frac{dT}{d\tilde{x}}\right)\left(\frac{c_p}{\Delta h}\right)\left(\frac{a_c}{D_m}\right)^{0.5}\right]^{-1} \tag{11}$$

where D_m is the mass diffusion coefficient, a_c is the thermal diffusion factor, and $dT/d\tilde{x}$ is the slope of the bubble point line. D_{kin} is the kinetic diffusion coefficient, and γ is the activity coefficient.

Figure 7 depicts the predicted and measured results of HFO1234yf + R32 refrigerant mixtures at two concentrations (80/20, 50/50 by wt%) using the proposed correlation in a 4-mm ID tube. The deviation limits for the mixture refrigerant are less than ±20% for 90% of the data in Figure 7 (a) for an R32 mass fraction of 20%. In case of the mixture with an R32 mass fraction of 50%, the proposed correlations enclose 86% of experimental data within ±20%, as shown in Figure 7 (b).

Although the effect of Bo on mass diffusion is discussed in section 3, this value is not introduced into the factors of F_{mix} and S_{mix}. Bo is considered to reflect the influence of heat flux and mass flux on mass diffusion and needs to be taken into account in the prediction correlation in subsequent studies.



(a) (b)

Figure 7 Comparison of measured and theoretical results of mixtures of HFO1234yf+R32 at two contentrations

5. CONCLUSIONS

1) The heat transfer coefficients of HFO1234yf/R32 (50:50 by wt%) can be higher than those of pure HFO1234yf at low and moderate Bo and those of HFO1234yf/R32 (80:20 by wt%) in a 4-mm ID tube.
2) The heat transfer coefficients of HFO1234yf/R32 (80:20 by wt%) are lower than those of pure HFO1234yf at various Bo.
3) At a high Bo, there is greater suppression of nucleate boiling of the mixture than that at a low Bo because of greater mass diffusion. The convective heat transfer at a high vapor quality is deteriorated by the effect of mass diffusion at a low Bo.
4) The predicted heat transfer coefficients by the proposed correlation agree well with the experimental results of the mixtures at two concentrations.

NOMENCLATURE

				Subscripts
Bo	boiling number	(–)		
We	Weber number	(–)	bp	bubble point
Re	Reynolds number	(–)	b	bottom
c_p	specific heat at constant pressure	(J/kg·K)	cal	calculated
D	inner diameter of a tube	(m)	exp	experimental
D_m	mass diffusion coefficient	(cm^2/s)	id	ideal
G	mass flux	($kg/m^2{\cdot}s$)	L, l	liquid-phase
h	heat transfer coefficient	($kW/m^2{\cdot}K$)	m, mix	mixture
q	heat flux	(kW/m^2)	n	nucleate boiling
P_r	P/P_{cri}	(–)	s	side
T	temperature	(K)	tp	two-phase
X_{tt}	Lockhart-Martinelli parameter	(–)	t	top

x	vapor quality	(–)	sat	saturation
Δh	latent heat	(kJ/kg)	v	vapor phase
$\tilde{x}$	mole fraction of volatile component in liquid phase	(–)	wall	inside wall
$\tilde{y}$	mole fraction of volatile component in vapor phase	(–)		
p	pressure	(Pa)		
μ	viscosity	(Pa·s)		
λ	thermal conductivity	(W/m·K)		

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