EXPERIMENTAL INVESTIGATION OF FLOW BOILING HEAT TRANSFER OF HFO1234YF AND R32 REFRIGERANT MIXTURE IN A SMOOTH HORIZONTAL TUBE

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Abstract: HFO1234yf has been proposed as a promising candidate to mobile air conditioner due to its low GWP and comparable performance to R134a. However its performance is inferior to that of R410A. That makes it difficult to be applied into residential air conditioners. In order to apply the low GWP refrigerant to residential air conditioners, refrigerant mixtures of HFO1234yf + R32 are proposed and their flow boiling heat transfer performances at two mass fractions (80/20 and 50/50 by mass%) in a smooth horizontal tube with ID 2 mm were investigated. The experiments were conducted under heat fluxes from 6kW/m^2 to 24kW/m^2 and mass fluxes from 100kg/m^{2}s to 400kg/m^{2}s at evaporating temperature of 15^{o}C. The measured heat transfer coefficients were compared with those of pure R32 and pure HFO1234yf, respectively. The results showed that the heat transfer coefficients of the mixture at R32 mass fraction of 20% are 10% ~ 30% lower than those of pure HFO1234yf at different mass fluxes and heat fluxes. But results of the mixture are 10%-20% higher than those of pure HFO1234yf at a high heat flux and high mass flux condition when the mass fraction of R32 increases to 50%. Heat transfer coefficients of the mixture are about 20%-50% lower than that of pure R32. It is indicated that mass diffusion and the temperature glide of the mixture influence the heat transfer significantly. A correlation was proposed to predict heat transfer coefficients of the mixture HFO1234yf+R32, pure R32 and pure HFO1234yf. The deviation was confirmed be within ±20% for fitting over 80% data.

Key Words: HFO1234yf, R32, Refrigerant Mixture, Heat Transfer Coefficient, Low GWP refrigerant

1 INTRODUCTION

The release of MAC direct of EU, which bans the use of refrigerants with a GWP (Global Warming Potential) above 150 in new type of mobile air conditioning from 2011 in the EU market, has triggered the research and development of new refrigerants for mobile air conditioners. HFO1234yf, a newly developed refrigerant with GWP as low as 4, is proposed to be a drop-in solution of the current mobile air conditioner. At the same time, increasing concern on the environmental protection also leads to the reconsideration of the refrigerants in other applications. As for the stationary conditioner, either HFCs with a high GWP or even HCFCs are used, transition from these refrigerants to low GWP refrigerants is a crucial issue globally, however, there is no an available complete solution at present since this transition should balance the environmental protection and system performance.

Because HFO1234yf has a smaller latent heat compared to R410A currently being used, COP would decrease when HFO1234yf is dropped directly into stationary heat pump systems. One approach to obtain a higher system COP is to use refrigerant mixtures of HFO1234yf + R32. However, due to the relatively high GWP of R32, the trade-off between system performance and GWP of the refrigerant mixture must be considered. Therefore, detailed

information of the thermodynamic and heat transfer characteristics of the refrigerant mixture with the mixing ratio of R32 as parameter is required.
Several drop-in experiments of the system performance using either pure HFO1234yf or HFO1234yf+R32 mixtures have been conducted. 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 HFO1234yf is significantly lower than that of R410A. The performance of the mixture HFO1234yf+R32 was improved as the R32 concentration increases. The COPs of HFO1234yf+R32 (50/50) under the cooling and heating conditions are 95% and 94% of those of R410A, respectively. Hara *et al.* (2010) tested the HFO1234yf in room air conditioners in two different models. The improved model enabled the capacity and COP of HFO1234yf to be almost same to that of R410A. Okazaki et al. (2010) tested HFO1234yf and HFO1234yf+R32 mixtures in modified room air conditioners. The modified unit with HFO1234yf can reach 95% APF ratio of R410A. When mass fraction of R32 reaches 60%, APF ratio of the mixture is 93.3% of R410A. Thermodynamic properties of HFO1234yf+R32 mixture, including vapor-Liquid Equilibrium and dynamic viscosity, were experimentally measured at various R32 mass fractions (Arakawa *et al.* 2010), The temperature glide of the mixture was found about 8^{o}C at 22% R32 in mass fraction at a temperature of 15 ^{o}C. Flow boiling heat transfer characteristics of different zeotropic mixtures have been studied by many researchers (Aprea et al.2000, Jung et al.1989, Zhang et al. 1997). However, there is no experimental study on heat transfer characteristics of HFO1234yf+R32 mixture available. Van Wijk et al. (1956) investigated the heat transfer of mixtures and explained that the temperature glide was caused by the different boiling points of components of fluids. Fraction ratio of the mixture around the bubble changed continually because the more volatile component evaporated faster than the other component during the bubble growth process. The inhomogeneity of consistency in the fluid leads to the mass diffusion and influences the heat transfer coefficient of the mixture thereby.
In this paper, the variation of heat transfer coefficient of the mixture HFO1234yf+R32 (80/20 and 50/50 by mass fraction) were studied experimentally. The heat transfer characteristics of refrigerant mixtures are compared with those of pure HFO1234yf and pure R32 under the same mass flux and heat flux conditions. Based on experimental results, a correlation is proposed to predict the heat transfer coefficients of the pure R32, pure HFO1234yf and the mixtures. Effects of the mixture on heat transfer coefficient are also discussed.

2 PROPERTIES OF MIXTURES

The properties of mixtures at 15^{o}C saturated temperature are listed in Table 1. Considering the GWP limit in F-gas regulation of 150, refrigerant mixtures with R32 mass fraction of 20% and 50% were tested; GWPs of mixtures are 138 and 340, respectively. From Table 1 it also can be seen that the specific heat and conductivity of the mixture increase in comparison with pure HFO1234yf. That can improve the heat transfer of fluids.

Table 1 Properties of refrigerants

Parameters	**Unit**	**R32 100%**	**HFO1234yf:R32=50%:50%**	**HFO1234yf:R32=80%:20%**	**HFO1234yf 100%**
Molecular weight	kg/kmol	52	71	92	114
GWP(100 year)	----	675	340*	138*	4
Density of Liquid	kg/m^3	1000.9	1048	1063	1127
Density of Vapor	kg/m^3	35.19	35.89	44	28.25
Thermal Conductivity of LD	mW/mK	133.54	82	74	71.13
Specific heat	kJ/kg	1.843	1.296	1.259	1.366
Surface tension	mN/m	8.41	8.09	7.75	7.39
Latent heat	kJ/kg	290	223	175	153.05
Temperature glide	^{o}C	----	4.55	7.65	----

Note: * Cited from Akira Fujitaka et al.(2010)

The properties of mixtures are acquired based on Peng-Robinson type state equation (Arakawa et al.2010) and the properties of pure refrigerants are calculated using Refrprop Ver.8.0. The surface tension of the binary mixture is computed from the surface tension of each component by the following formula.

$$\sigma_m = \tilde{x}_1\sigma_1 + \tilde{x}_2\sigma_2 \qquad (1)$$

where, $\tilde{x}_1$ is the mole fraction of component one.

3 EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus used in heat transfer performance measurement and flow pattern observation of the refrigerant mixture is shown in Figure 1. The test loop contained a Coriolis-type flowmeter, a condenser, a flow control valve, a test tube (evaporator), a sight glass and a gear pump. The test section is a smooth horizontal stainless tube with ID 2-mm.
The flow rate and inlet pressure of the measured fluid were controlled by adjusting the frequency of the magnetic gear pump and the opening of the flow control valve. The mass flow rate was measured by using a Coriolis-type flowmeter with an accuracy of ±0.2 %. The inlet vapor quality of the test section is kept to be about 0.2 by adjusting the amount of heat supplied to pre-heater located upstream of the test section. The input electrical power was measured by using a voltmeter and an ammeter. The energy required for evaporation was supplied by directly heating the test tube using direct current.
Outer wall temperature of the test tube was measured at midway between the top and bottom of the tube along the axis by using a 0.1-mm-OD T-type thermocouples, and temperature of the inner wall of the tube were calculated from the measured outer wall temperatures by using the Fourier's law. An 8-μm-thick Teflon sheet was inserted between each thermocouple and the test tube to eliminate the influence of current on the thermocouples. All the thermocouples were calibrated by using a high precise platinum resistance thermometer sensor with an accuracy of ±0.03 K. The accuracy of the calibrated thermocouples was within ±0.1 K. The pressure points were installed in test section. Pressure can be recorded through a pressure sensor with an accuracy of ±1KPa. To reduce the heat loss from the test tube to the environment, the entire test tube was placed inside an air channel. The air temperature is controlled and equals to the outer surface temperature of the test tube.

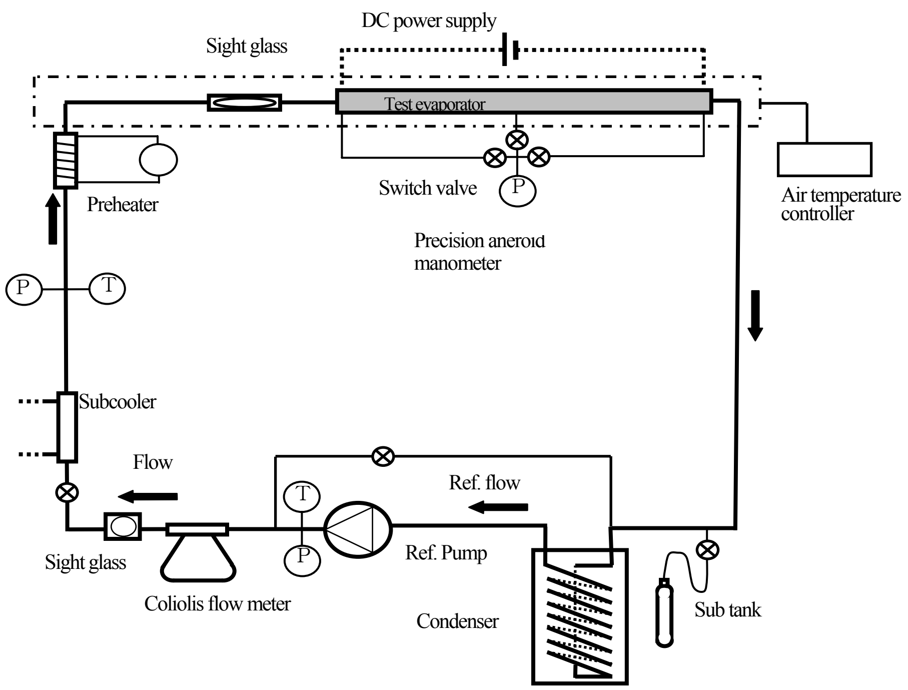


Figure 1: Schematic of experimental system used to measure flow boiling heat transfer.

The purity of the refrigerant HFO1234yf was 99% and that of R32 was 99.9%. HFO1234yf and R32 were mixed at a desired mass fraction in advance and charged into the system in liquid. The concentration of the mixture in the system was calculated base on measured parameters of the fluid at the inlet and outlet of pre-heater by using the Peng-Robinson type state equation proposed in our lab (Arakawa, *et al.* 2010). In order to confirm the concentration of the mixture further, a gas chromatography was used to test the component of superheat vapor at the outlet of the test section. The deviation of the two values is within 2%. The concentrations calculated through the measured parameters were applied to derive the final results.
The experimental conditions are summarized in Table 2. Saturation temperature of the mixture at vapor quality of 0.5 was set to be 15°C during experiments. The local heat transfer coefficient h_{exp} in the test tube was defined as:

$$h_{\mathrm{exp}} = \frac{q}{T_{\mathrm{wall}} - T_{\mathrm{m,sat}}} \tag{2}$$

where T_{wall} is the temperature of inner wall, and $T_{m,sat}$ is the saturation temperature of the mixture deduced from a local refrigerant pressure calculated by interpolation between the inlet and outlet pressures and the vapor quality at the location. All experimental data were collected after steady state of temperature, pressure and refrigerant flow was achieved.

Table 2 Experimental conditions

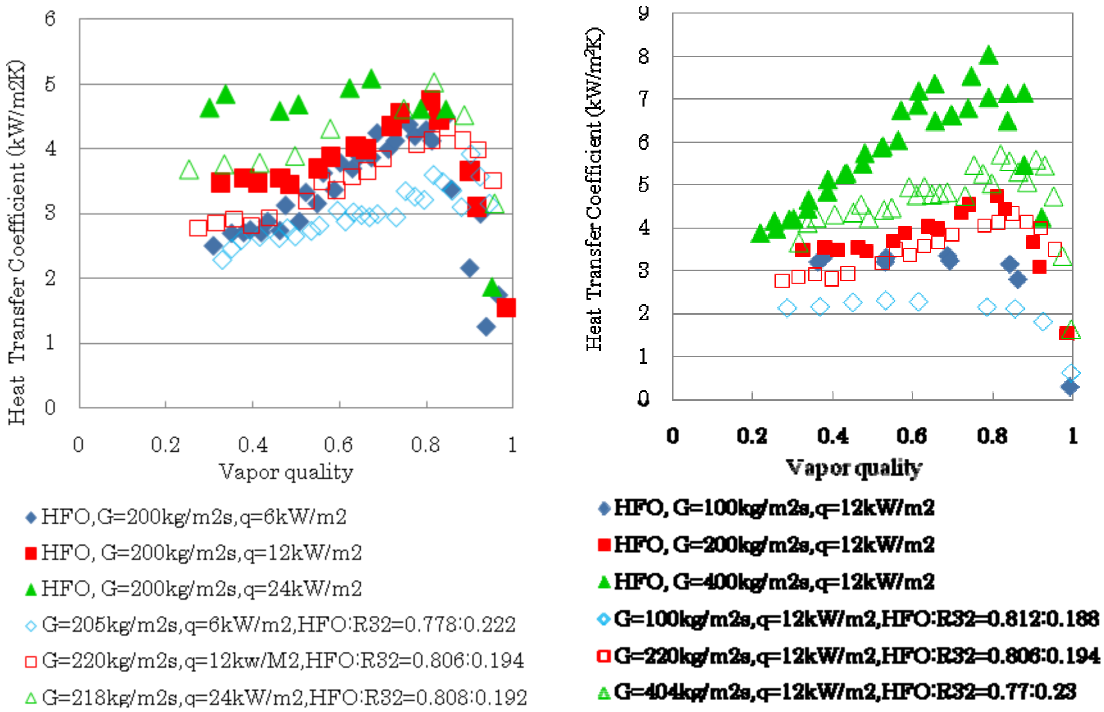
Refrigerant	HFO1234yf + R32
Concentration wt%	HFO1234yf:R32=80:20;HFO1234yf:R32=50:50
Quality	0.2-1.0
Heat flux [kW/m^2]	6,12,24
Mass flux [kg/m^2 s]	100,200,400

4 RESULTS AND DISCUSSIONS

4.1 Comparison of heat transfer coefficients of mixtures with pure HFO1234yf

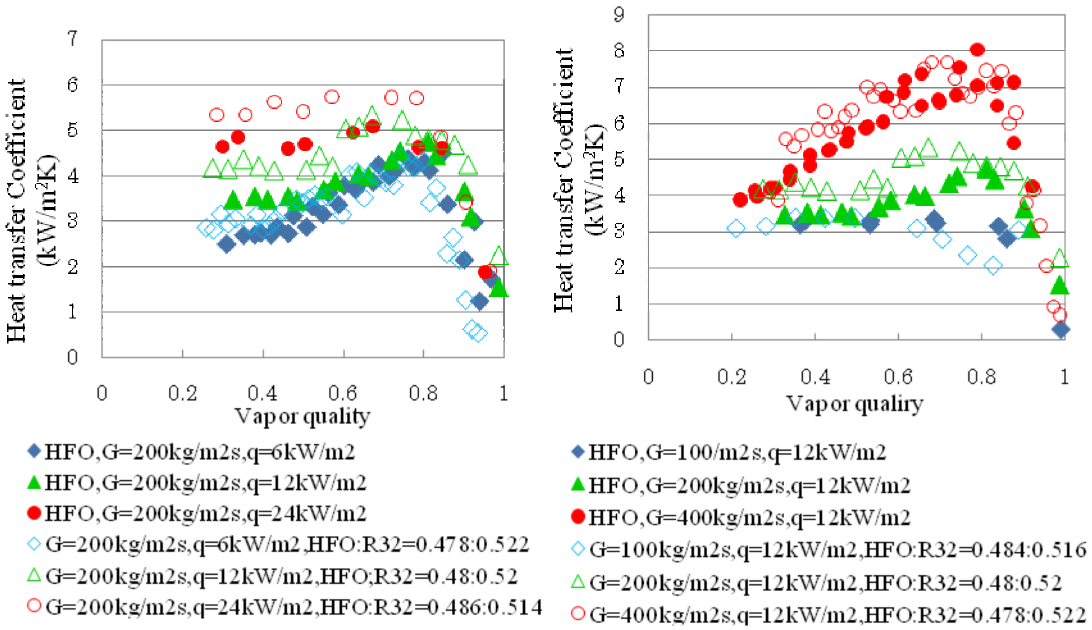
The comparison of heat transfer coefficient of the mixture HFO1234yf+R32 (80/20 and 50/50 by mass%) with that of pure HFO1234yf is presented in Figures 2 and 3. From Figure 2(a) and Figure2(b), it can be seen that the heat transfer coefficient of mixture at R32 mass fraction of 20% is 10% ~ 30% lower than that of pure HFO1234yf at different mass fluxes and heat fluxes. In Figure 2(a), at heat fluxes of 12kW/m^2 and 24kW/m^2, heat transfer coefficients of the mixture are lower than that of pure HFO1234yf at lower vapor quality but closing to that of pure HFO1234yf at a high vapor quality. It seems that nucleate boiling of the mixture at low vapour quality is suppressed. The reason is that high heat flux causes a large composition difference between the interface of bubble and the liquid bulk at low vapour quality. With the increasing of vapour quality, the velocity of the flow increases and the disturbance of the fluid become large to decrease the composition gradient around the bubble. The effect of mass diffusion on the nucleate boiling is moderated. The nucleate boiling is suppressed mainly by the convective heat transfer at high vapour quality.
In case of low heat flux of 6kW/m^2, heat transfer coefficients of the mixture are close to that of pure HFO1234yf at a low vapour quality and the heat transfer of the mixture is suppressed greatly at a high vapour quality. The same tendency occurs at a mass flux of 400kg/m^{2}s and a heat flux of 24kW/m^2 as shown in Figure2(b) when the two conditions have the same low Bo

number. It can be explained that at a low heat flux, the bubble growth rate is low and the composition difference of the bulk and the interface of bubble is not so large. Then the heat transfer coefficients of the mixture approaches that of pure HFO1234yf at low quality.



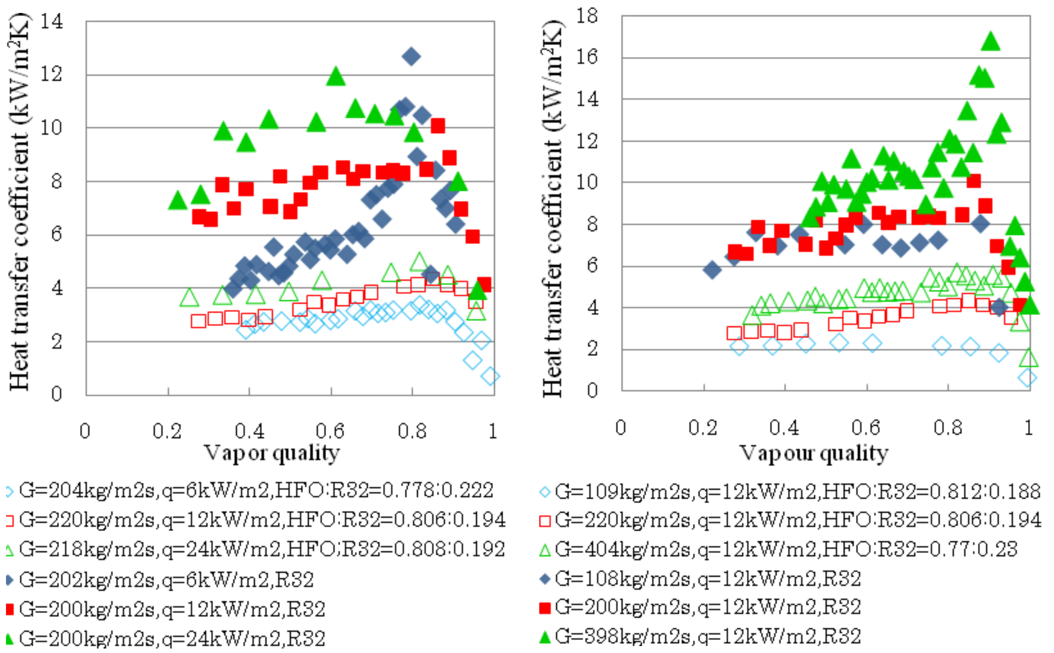
(a) (b)

Figure 2: Measured heat transfer coefficient of pure HFO1234yf and the mixture of HFO1234yf+R32 at R32 mass fraction of 20%



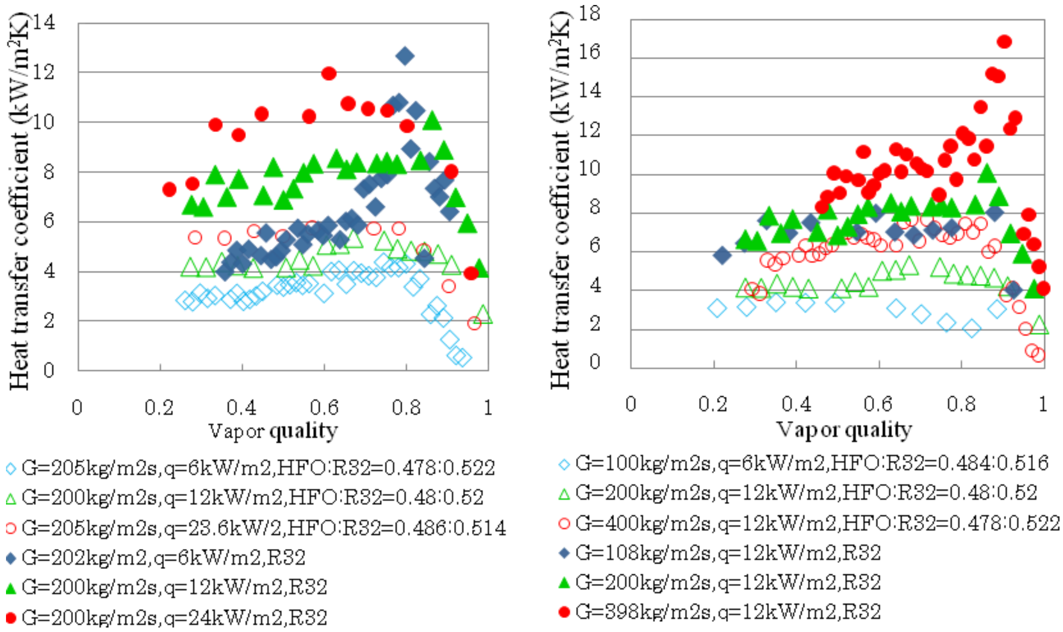
(a) (b)

Figure 3: Measured heat transfer coefficient of pure HFO1234yf and the mixture of HFO1234yf+R32 at R32 mass fraction of 50%



(a) (b)

Figure 4: Measured heat transfer coefficient of pure R32 and the mixture of HFO1234yf+R32 at R32 mass fraction of 20%



(a) (b)

Figure 5: Measured heat transfer coefficient of pure R32 and the mixture of HFO1234yf+R32 at R32 mass fraction of 50%

Figure 3 shows the comparing results of heat transfer coefficient of HFO1234yf + R32 mixture and that of pure HFO1234yf at R32 mass fraction of 50%. It is indicated from these two figures that the heat transfer coefficient of the mixture is higher than that of pure HFO1234yf at a relatively higher R32 mass fraction R32 of 50%, especially at a large mass flux and a high heat flux. Because of the increased mass ratio of R32, the thermodynamic properties of R32 play a positive contribution on heat transfer coefficients of the mixture. Due to a moderate temperature glide of 4.55^{o}C at R32 mass fraction of 50%, composition difference between the interface of bubble and the liquid bulk is smaller than that at R32 mass fraction of 20%. The mass diffusion can be mitigated effectively by the perturbation caused by the high heat flux or mass flux. At a low heat flux and a low mass flux, the effects of mass diffusion on heat transfer appear obviously. Therefore the mass diffusion influences the heat transfer of the mixture significantly.

4.2 Comparison of heat transfer coefficients of mixtures with pure R32

Results of the mixture HFO1234yf + R32 also are compared with that of pure R32 as shown in Figures 4 and 5. When the mass fraction of R32 is 20%, the heat transfer coefficient of the mixture is 20%-50% lower than that of R32. When the concentration of R32 in the mixture is 50%, the heat transfer coefficient of the mixture is about 20%-40% lower than that of pure R32. From above results, it is indicated that R32 has very good heat transfer characteristics.

4.3 Effects of the mass flux and heat flux

The effects of mass fluxes and heat fluxes on the heat transfer coefficients of mixtures can be observed from Figure 2 to Figure 5. Figures 2(a) and 3(a) show the variety of heat transfer coefficients of the mixtures against vapor quality at three heat fluxes when the mass flux of refrigerant is 200kg/m^{2}. The heat transfer coefficients of the pure refrigerants approaches same values at a high vapour quality at different heat flux when the mass flux keeps the same. That implies that the forced convective heat transfer dominates the heat transfer process when the vapor quality is high. In the case of zeotropic mixture HFO1234yf+R32, the same phenomenon can be observed when the heat flux is large as shown in Figures 2(a) and 3(a). High heat flux can help improving the heat transfer of the mixture.
In contrast to Figures 2(a) and 3(a), Figures 2(b) and 3(b) present heat transfer characteristics of mixtures at three different mass fluxes at the same heat flux of 12kW/m^{2}. When the heat flux keeps constant and the mass flux is changed, heat transfer coefficients of the pure refrigerants are close at low vapour quality. For instant the heat transfer coefficients of pure HFO1234yf and pure R32 shown in Figures 2(b) and 4(b) both observed this regulation. That means the nucleate boiling dominates the heat transfer at low vapour quality. However, for the mixture of HFO1234yf+R32, this phenomenon did not occur. It can be seen in Figures 2(b) and 3(b) that the larger the mass flux, the higher heat transfer coefficients are obtained. From the Figures 2(b) and 3(b), it can be concluded that the heat transfer coefficient of the mixture at low mass flux is suppressed significantly. A high mass flux can cause turbulent of the flow and decrease the inhomogeneity of the consistence and increase the heat transfer coefficient of the mixture.

5 PREDICTIONS OF PRE-DRYOUT HEAT TRANSFER

Based on the measured pre-dryout heat transfer coefficient for both pure refrigerants and refrigerant mixtures, a new correlation is proposed. The correlation shown in Equation (3) includes two parts - nucleate boiling heat transfer and forced convective heat transfer. The nucleate boiling heat transfer form is the correlation proposed by Cooper (Cooper 1984) because it can predict the heat transfer coefficient of the Freon fluid widely with high accuracy. The forced convective heat transfer correlation is the Dittus-Boelter Equation, equation (5). The factor F is a function of Martineli-number. Referred the Weber number of vapor phase in F factor proposed by Saitoh[2], Weber number is also introduced into the F equation based on the Chen's type in equation (6). Suppression factor S is revised based on the suppression factor S proposed by Yoshida (Yoshida 1994). In the case of the mixture fluid, two suppression factors F_{mix} and S_{mix} are introduced into the Chen's form as shown in equation (8). The difference in mole fraction Y-X is an important factor which influences not only the nucleate boiling but also the forced convection. Many previous studies applied C|Y - X |(Shin *et al.* 1989) or 1 - C|Y - X |^n (Sami *et al.*1992) to correct the heat transfer coefficient of the mixture. Y-X is related to the difference temperature of bulk temperature and bubble temperature of the fluid. In this paper, the difference temperature is used to correct the forced convective heat transfer coefficient. The formula of F_{mix} is similar to the equation of Palen and Small correlation. But the definition of the difference temperature is different. The S_{mix} is formula presented by Scriven (Scriven 1959) who investigated the influence of mass transfer on the growth of a spherical bubble in a binary mixture. The growth of bubble is related to the superheat of fluid. Bennet and Chen (1980) considered that the heat transfer coefficient during the nucleate boiling is related to the effective liquid superheat which is equal to ideal superheat multiplying Scriven equation which is shown in Equation (7). In this equation, the mass diffusion coefficient is difficult to obtain. Then the method of estimation has to be used. Kenneth J.C. *et al.* (1975) proposed a hard sphere model of diffusion coefficients in binary solution of components.

$$h_{tp} = Fh_l + Sh_n \tag{3}$$

$$h_n = 55\,\mathrm{Pr}^{0.12}\left(-\log \mathrm{Pr}\right)^{-0.55} M^{-0.5} q^{0.67} \tag{4}$$

$$h_l = 0.023\frac{\lambda_l}{D}\left[\frac{G(1-x)D}{\mu_l}\right]^{0.8}\mathrm{Pr}^{0.4} \tag{5}$$

$$F = 1.0 + 1.8\cdot\left(0.3+\frac{1}{X_{tt}}\right)^{0.88} / \left(1+Wev^{-0.4}\right) \tag{6}$$

$$S = \frac{1}{0.5+0.5\dfrac{\left(\mathrm{Re}_{tp}\times 10^{-3}\right)^{0.3}}{\left(Bo\times 10^{3}\right)^{0.23}}} \tag{7}$$

$$h_{tpm} = F_{mix}Fh_l + S_{mix}Sh_n \tag{8}$$

$$F_{mix} = \exp\left(-0.027\left(T_{msat}-T_b\right)\right) \tag{9}$$

$$S_{mix} = \frac{\Delta T_m}{\Delta T_{id}} = \left[1-\left(y-x\right)\left(\frac{dT}{dx}\right)\left(\frac{C_p}{\Delta h}\right)\left(\frac{a_c}{D}\right)^{0.5}\right]^{-1} \tag{10}$$

In the calculating process, the activity coefficient and fugacity of the mixture are required, which are calculated by Refprop. The predicted mass diffusion coefficients of HFO1234yf+R32 are about 2 x10^{-5} cm^2/s ~ 4 x 10^{-5} cm^2/s.

Figure 6 depicts the predicted and the measured results of pure HFO1234yf, pure R32 and refrigerant mixture HFO1234yf + R32 (80/20 and 50/50 by mass%) by using the proposed correlation. The figures show that the deviation limits for two pure refrigerants is less than ±20% for 90% data in Figure 6(a) and 6(b). When calculating the heat transfer coefficient of the mixture, the factors for the mixture Fmix and Smix were taken into account. The predicted results of the mixtures HFO1234yf + R32 (80/20 and 50/50 by mass%) by the proposed correlations have a good agreement to experimental results as shown in Figure 6(c) and Figure 6(d). The deviation limits in two Figures can enclose 80% of the data.

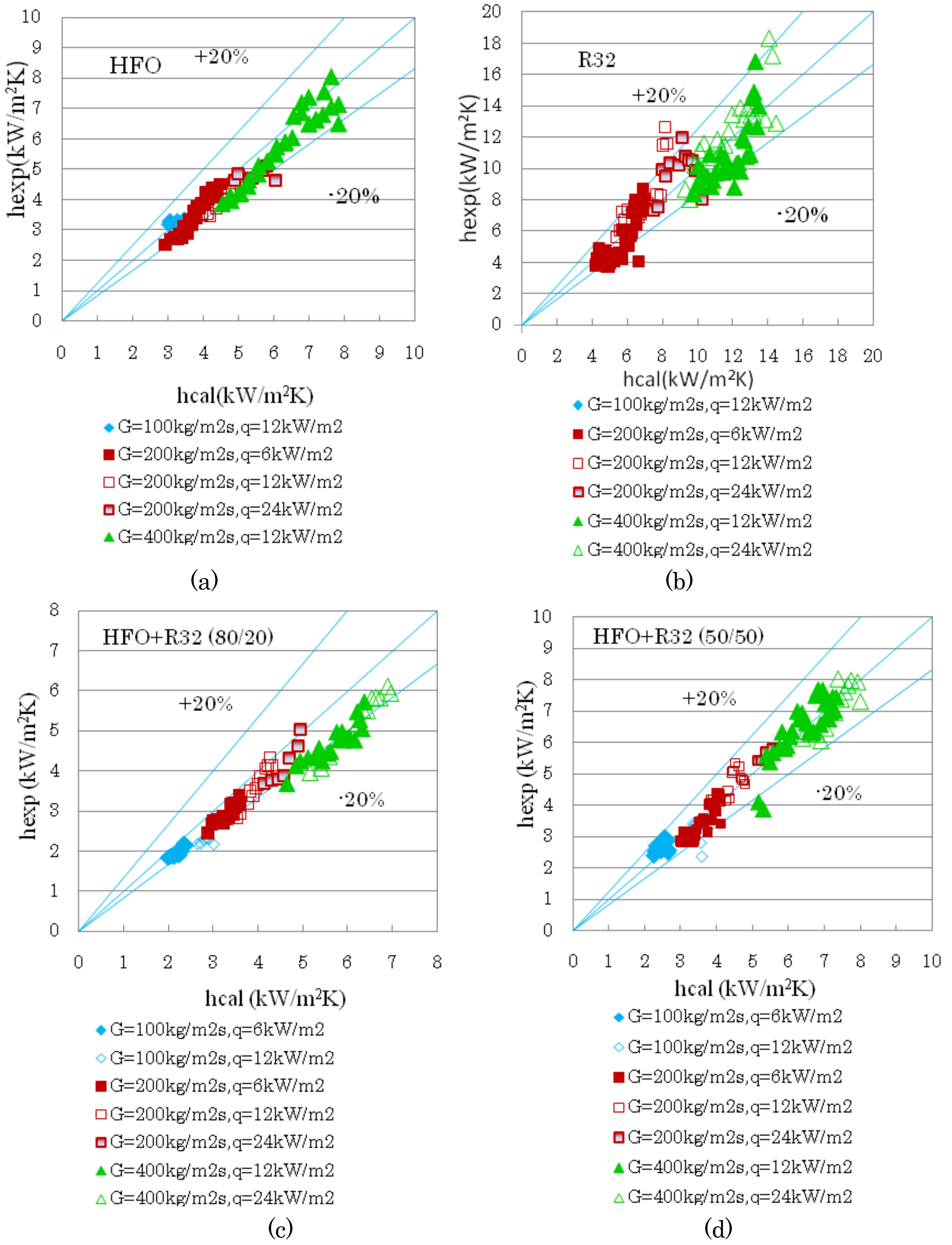


Figure 6: Comparison of the theroretical and experimental heat transfer coefficients.

6 PRESSURE DROP OF MIXTURES

Two-Phase pressure drop (Δp) was predicted by using Lockhart - Martinelli correlation (Ghiaasiaan 2008) and compared with the measured results. The correlations are defined as following.

$$-\left(\frac{dp}{dz}\right)_{tp} = -\left(\frac{dp}{dz}\right)_{l}\phi_l^2 = -\left(\frac{dp}{dz}\right)_{v}\phi_v^2 \quad (11)$$

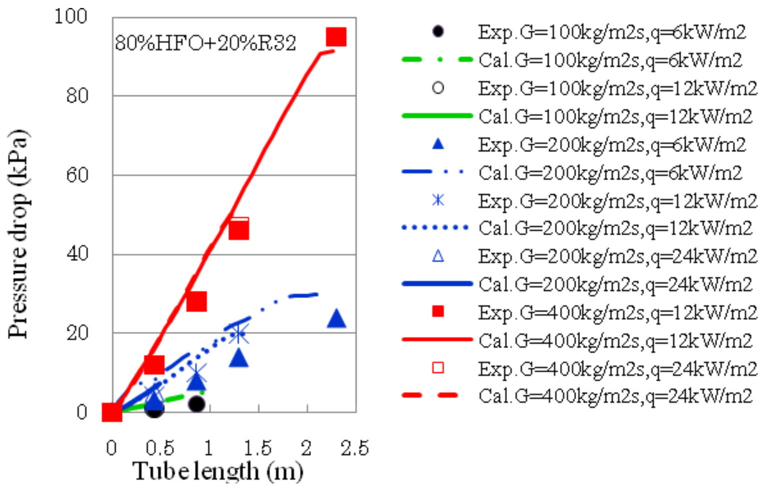
$$\left(-\frac{dp}{dz}\right)_l = f_l \frac{G_l^2}{2D\rho_l} \qquad (12)$$

$$\left(-\frac{dp}{dz}\right)_v = f_v \frac{G_v^2}{2D\rho_v} \qquad (13)$$

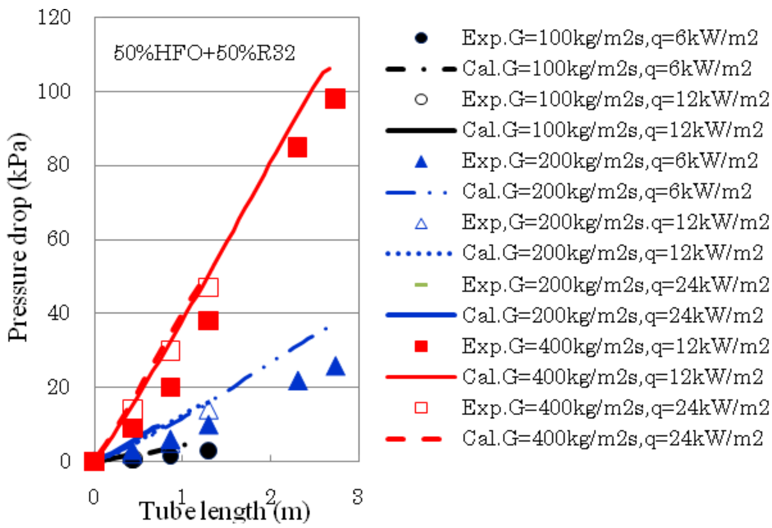
$$\phi_l^2 = 1 + C/X + 1/X^2 \qquad (14)$$

$$\phi_v^2 = 1 + CX + X^2 \qquad (15)$$

where, Φ_l and Φ_v are the two-phase multipliers in the liquid and gas phases, respectively. f_v and f_l are the friction factors of vapor and liquid. Figures 7 show the measured pressure drops of the mixture HFO1234yf+R32 (80/20 and 50/50 by mass%) and those predicted using the Lockhart-Martinelli correlation. The measured pressure drops agreed well with that predicted using the Lockhart-Martinelli correlation.



(a)



(b)

Figure 7: The pressure drop of mixtures

7 CONCLUSIONS

The flow boiling heat transfer of the refrigerant mixture HFO1234yf+R32 under two concentrations was experimentally investigated. The local heat transfer coefficients were measured when the mass fraction of R32 is 20% and 50%, respectively with the mass flux ranging from 100 to 400 kg/ m^2s and heat flux ranging from 6 to 24 kW/m^2. The inner diameter of the test tube is 2 mm and the evaporating temperature is set 15°C at vapor quality of 0.5. The results are summarized as follows.

1) Heat transfer coefficients of the refrigerant mixture HFO1234yf + R32 at R32 mass fraction of 20% are lower than that pure HFO1234yf. The heat transfer coefficient of the mixture at a higher mass fraction of 50% is higher than that of pure HFO1234yf at high heat fluxes and mass fluxes.
2) Heat transfer coefficients of the mixtures under two concentrations are 20%-50% lower than that of pure R32.
3) Effects of mass diffusion on heat transfer of the mixture are significant
4) A new correlation was proposed to predict the heat transfer coefficients of pure R32, pure HFO1234yf and the mixture. The proposed correlation can predict 80% heat transfer coefficients of both the pure refrigerant and refrigerant mixtures in pre-dryout region with average deviation less than ±20%.
5) Lockhart-Martinelli correlation was proposed to predict the pressure drop of the mixture. The predicting results can agree well with the measured pressure drops.

NOMENCLATURES

Bo	boiling number
c_{pl}	specific heat at constant pressure in liquid phase, J/kg K
D	inner diameter of a tube, m
G	mass flux, kg/m^2s
h	boiling heat transfer coefficient, kW/ m^2 K
p	pressure, Pa
q	heat flux, kW/m^2
Re	Reynolds number
T_{wall}	inside-wall temperature, K
T_{msat}	saturation temperature of the mixture, K
We	Weber number
x	vapor quality
X	Lockhart-Martinelli parameter
z	coordinate along the tube direction, m
Greek symbols	
λ	thermal conductivity, W/mK
μ	viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension, N/m
Φ	two-phase flow multiplier
Subscripts	
v	gas-phase, vapor-phase
L,l	liquid-phase
tp	two-phase
exp	experimental
cal	calculated
m,mix	mixture

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