

Evaporation Heat Transfer Characteristics of Hydrocarbon Refrigerants R-290 and R-600a in the Horizontal Tubes

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Abstract : This paper presents the experimental results of evaporation heat transfer coefficients of HC refrigerants (e.g. R290 and R600a), R-22 as a HCFCs refrigerant and R-134a as a HFCs refrigerant in horizontal double pipe heat exchangers, having four different inner diameters of 10.07, 7.73, 6.54 and 5.80 mm respectively. The experiments of the evaporation process were conducted at mass flux of 35.5~210.4 kg/m²s and cooling capacity of 0.95~10.1 kW. The main results were summarized as follows : The average evaporation heat transfer coefficient of hydrocarbon refrigerants(R-290 and R-600a) was higher than the refrigerants, R-22 and R-134a. In comparison with R-22, the evaporation heat transfer coefficient of R-134a is approximately -11~8.1 % higher, R-290 is 56.7~70.1 % higher and R-600a is 46.9~59.7 % higher, respectively. In comparison with experimental data and some correlations, the evaporation heat transfer coefficients are well predicted with the Kandlikar's correlation regardless of a type of refrigerants and tube diameters.

Key words : HC refrigerant(탄화수소계 냉매), Natural refrigerant(자연냉매), R290(프로판), R600a(이소부탄), Evaporation heat transfer coefficient(증발 열전달계수)

	Symbols	
	Q : heat capacity	[kW]
	q : heat flux	[kW/m ²]
c_p : specific heat	[kJ/kgK]	T : temperature
d : diameter of tube	[m]	x : quality
G : mass flux	[kg/m ² s]	z : tube length
h : heat transfer coefficient	[kW/m ² K]	
ID : inner diameter	[m]	Dimensionless Numbers
i_{fg} : latent heat	[kJ/kg]	Bo : Boiling number
κ : thermal conductivity	[kW/mK]	Co : Convection number
M : mass flow rate	[kg/h]	

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Re : Reynolds number [-]

Subscripts

avg : average

E : evaporation

es : cooling water of evaporator

eq : equivalent

ID : inner diameter

in : inlet

L : liquid

loc : local

OD : outer diameter

out : outlet

R : refrigerant

V : vapour

w : wall

wi : inside wall

wo : outside wall

1. Introduction

The regulation prohibiting the use of CFCs as refrigerants is currently in effect, and guidelines for phasing out HCFCs as refrigerants in the future have already been agreed upon by many nations. This has prompted researchers worldwide to investigate the feasibility of natural refrigerants in novel refrigeration cycles.

The description 'natural' implies their presence in the environment from biological and geological sources. In other words, the natural refrigerants are naturally occurring substances, namely, hydrocarbons(HCs), nitrogen(N_2) and water(H_2O) represent a further 'natural' alternative. Among these natural refrigerants, HCs refrigerants are

examined positively as an alternative refrigerant for (H)CFC because it is easily available and its GWP and ODP are almost close to zero. But, the developed countries like US and Japan have not adapted them except for Europe due to flammability of HCs. However, according to James⁽¹⁾, in case of the household refrigerators, the possibility of explosion by flammability can be negligible since the HCs charge quantity is about half of general CFC refrigerant's one. Besides, if some simple safety device is installed, it can overcome that problem in the large size air conditioning and refrigeration system. But, the researches for performance of the refrigeration and air-conditioning system using the HCs as a refrigerant are not enough, especially, the study on characteristics of evaporation heat transfer is the one of those.

This study aims to concentrate in the hydrocarbon refrigerants R-290, R-600a, in order to develop the technology and expand the knowledge based on natural working fluids in compression heat pumping systems. Especially, focusing on the characteristics of evaporation, which is the basis for the optimum evaporator design for heat pump cycles using a natural refrigerant. For the purpose of the study, a basic heat pump apparatus with a horizontal tube-in-tube type evaporators was made. It will confirm applicability of natural refrigerants to regulate refrigerant R-22, support presentation of alternative refrigerant data for optimum design in the refrigeration and air-conditioning systems.

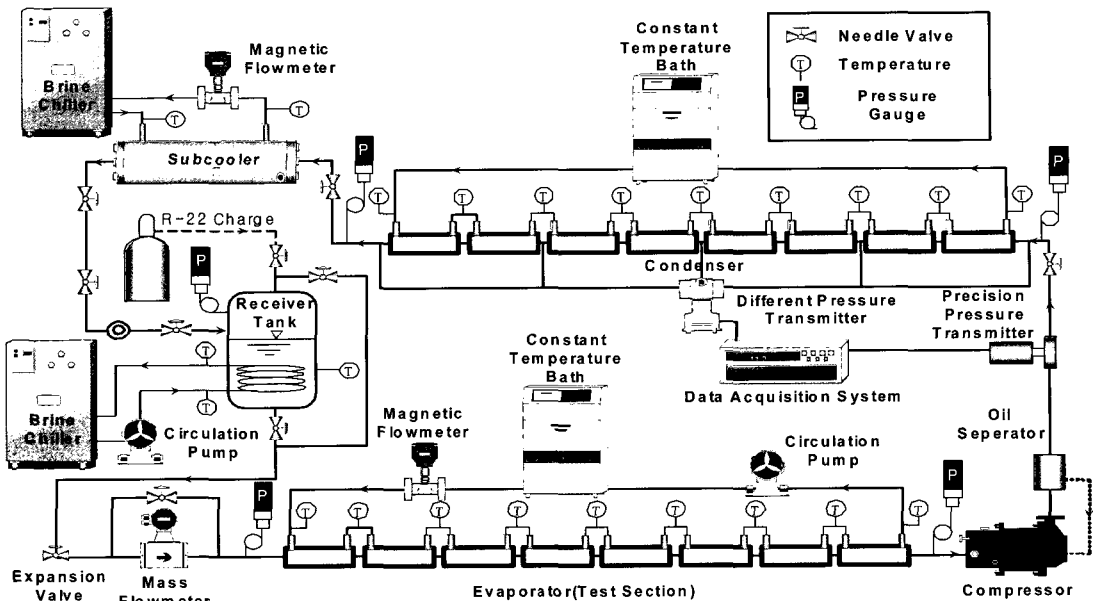


Fig. 1 Schematic diagram of experimental apparatus for evaporation heat transfer

2. Experimental Apparatus and Procedures

2.1 Test facility

Fig. 1 shows the experimental apparatus including basic refrigerating system consisting of a compressor, an evaporator, an condenser, an expansion valve, a receiver, an accumulator and so on. The system also consists of two main flow loops: a refrigerant loop and a secondary heat source water circuit involving either evaporation or evaporation loop. In the test section of the experiment, the evaporator is a double-tube type heat exchanger divided into two sections, which are inner tube and annular region.

The detail of heat exchanger (test section) is shown in Fig. 2. The inner diameters of the inner copper tubes are

respectively 10.07 mm, 7.73 mm, 6.54 mm and 5.80mm. The heat exchanger consists of ten subsections of 500 mm length. The shape of the refrigerant tube through the U-bend is double-tube type with identical bending to avoid a detour. As shown in Fig. 2, water flows counter-currently in the annulus test section of the double-tube heat exchanger, while refrigerant is condensed inside the test tube. Fig. 2 shows the temperature measurement locations of the refrigerant, cooling water and inner wall of heat exchanger. All thermocouples are calibrated with a standard thermometer. The wall surface temperatures of copper tubes are measured at three points (top, bottom and side). Channel output signals from instrumentation points are fed to a data acquisition and control unit, and processed by a desktop computer. Test facility is

allowed to come to steady state before the data acquisition. The summary of experimental conditions is given in Table 1.

Table 1 Experimental conditions for evaporation heat transfer

Parameters	R-22	R-134a	R-290	R-600a
Test section	Horizontal smooth tube			
I.D of test section (mm)	10.07, 7.73, 6.54, 5.80			
Mass flow rate (kg/h)	4.3 ~ 49.3	4.0 ~ 48.8	4.7 ~ 36.2	4.6 ~ 32.6
Mass flux (kg/m ² s)	50.0 ~ 210.4	37.1 ~ 160.4	35.5 ~ 165.1	35.5 ~ 178.8
Evaporating temperature (K)	263 ~ 283			

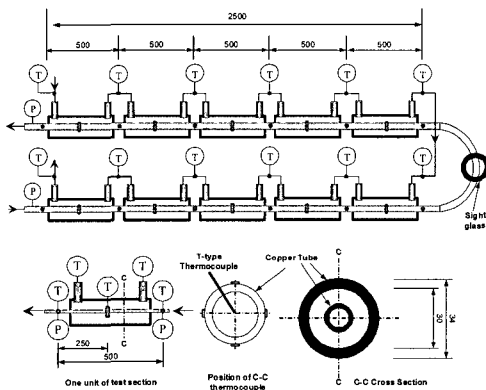


Fig. 2 Test section for evaporating heat transfer

In this paper, four refrigerants, namely R-290 (propane, purity 99.5%), R-600a (iso-butane, purity 99.5%), R-22 and R-134a were investigated to evaluate their evaporation heat transfer characteristics. Here, R-600a has a small mass flux range due to the larger specific volume than other refrigerants.

2.2 Data Reduction

The thermo-physical properties of R-22,

R-134a, R-290 and R-600a were calculated using REFPROP (version 6.01)⁽²⁾ by NIST. Raw data from the data acquisition system were analyzed for each run to determine the heat transfer rate and quality. The main equations used in processing the raw data were based on energy balances.

The amount of heat exchanged in the evaporator can be given by:

$$Q_{ew} = M_{ew} \cdot c_{p,ew} \cdot (T_{E,out} - T_{E,in}) \quad (1)$$

$$Q_{E,R} = M_{E,R} \cdot r(i_{E,in} - i_{E,out}) \quad (2)$$

where, Q_{ew} is the heat amount from water to refrigerant and $Q_{E,R}$ is the heat amount from refrigerant to water. M_{ew} and $M_{E,R}$ are the cooling water flow rate [kg/h] and refrigerant mass flow rate [kg/h] separately. $T_{E,in}$ and $T_{E,out}$ are the temperature [K] of heat source water at the inlet and outlet of the evaporator. $i_{E,in}$ and $i_{E,out}$ are the inlet and outlet enthalpy of refrigerant. $c_{p,ew}$ is the specific heat capacity of chilled water [kJ/kgK].

The local heat transfer coefficient at the subsection of the evaporator, $h_{E,loc}$ is calculated as follows:

$$h_{E,loc} = \frac{q_E}{T_{E,wi} - T_{E,R}} \quad (3)$$

where q_E is heat flux [kW/m²] shown in Eq. (4). $T_{E,R}$ and $T_{E,wi}$ are refrigerant temperature [K] and the inner wall temperature of the inner tube.

$$q_E = \frac{Q_{ew}}{\pi \cdot d_{ID} \cdot dz} \quad (4)$$

$$T_{E,wi} = T_w - Q_{E,sub} \cdot \frac{\ln(d_{OD}/d_{ID})}{(2 \cdot \pi \cdot dz \cdot \kappa_w)} \quad (5)$$

Where d_{ID} and dz are the inner diameter (m) of inner tube and the length (m) of subsection. $T_{E,wi}$ is the average temperature (K) measured from one at the top, two at the side and one at the bottom, at outer wall of inner tube. $Q_{E,sub}$ measured by the experiment is the exchange heat amount (kW) at the subsection of the evaporator. d_{OD} and k_w are the outer diameter (m) of inner tube and the thermal conductivity (kW/mK) of copper tube separately.

The average evaporation heat transfer coefficient $h_{E,avg}$ can be expressed as Eq. (6)

$$h_{E,avg} = \frac{1}{x_{in} - x_{out}} \int_{x_{out}}^{x_{in}} h_{E,loc} dx = \sum \frac{h_{E,loc}}{n} \quad (6)$$

where x_{in} and x_{out} are the quality at the inlet and outlet of the evaporator subsection, n is the number of the subsection. The refrigerant quality x is given to Eq. (7), the quality $x_{E,out}$ is the outlet (quality) of the evaporator subsection.

$$\Delta x = \frac{\Delta i_{sub}}{i_{fg}} \quad (7)$$

$$x_{E,out} = x_{in} + \frac{\pi \cdot d_{ID}}{M_{E,R} \cdot i_{fg}} \int_{z_{in}}^{z_{out}} q_E dz \quad (8)$$

where Δi_{sub} is the enthalpy difference between inlet and outlet of the subsection, i_{fg} is the latent heat of refrigerant. z_{in} and z_{out} are the inlet and outlet of a section, respectively.

3. Results and Discussion

3.1 Local heat transfer

Fig. 3 show the variation of the local

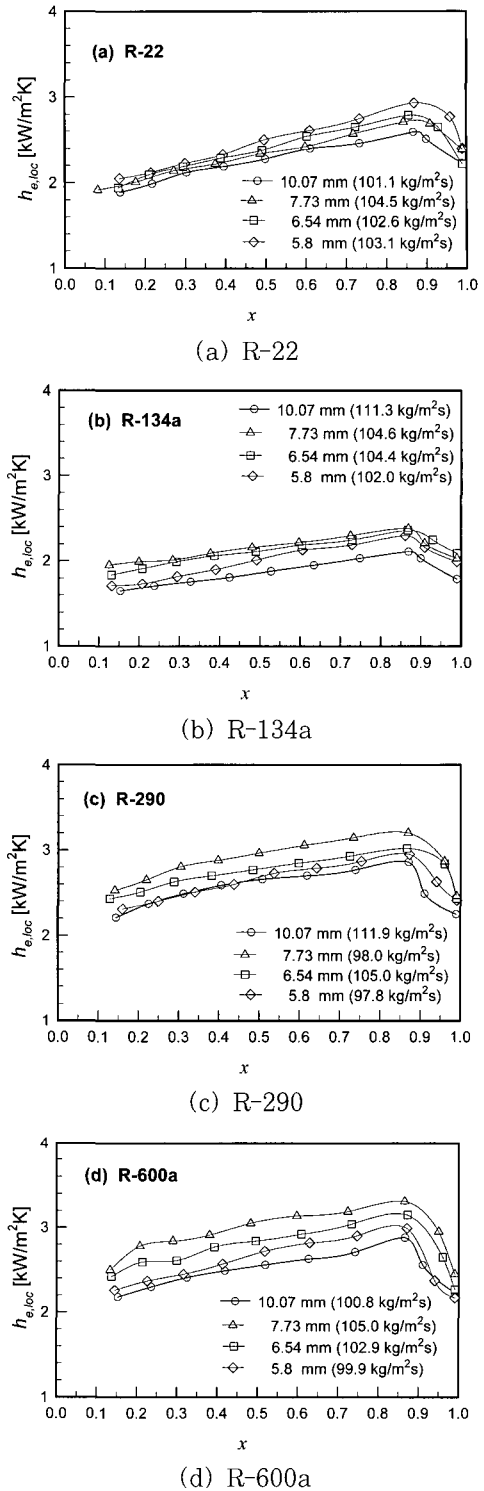


Fig. 3 Local evaporation heat transfer coefficients of R-22, R-134a, R-290 and R-600a

evaporation heat transfer coefficient with respect to refrigerant qualities and inner diameter tubes. At high quality of $x > 0.8$, the liquid film surrounding the inside wall of the tube in annular flow is easily broken into pieces and the wall is essentially dry. The wall temperature of inside tube increases suddenly and the heat transfer coefficient decreases.

The local evaporation heat transfer coefficients of all refrigerants increase slightly as inner diameter tube decreases. It is predicted that this resulted from diminishing of liquid film of annular flow and fast transition from stratified flow or wavy flow to annular flow in small diameter tubes. Fig. 3 (a) represents the local evaporation heat transfer coefficients of R-22 with respect to quality.

The variation of local evaporation heat transfer coefficients in decrease of inner diameter tube is almost identical except for the quality region of $0.73 < x < 0.87$. In Fig. 3(b), the local evaporation heat transfer coefficients of R-134a with quality are almost identical for all diameter tubes except for 10.07mm. As can be seen in Fig. 3(c), the local evaporation heat transfer coefficients of R-290 are almost identical for all tubes except for 5.80 mm. As shown in Fig. 3(d), the local evaporation heat transfer coefficients of R-600a increases slightly with the decrease of inner diameter tube.

3.2 Average heat transfer

Fig. 4 ~ 5 show the average evaporation heat transfer coefficients of four refrigerants (R-22, R-134a, R-600a and R-290)

with respect to varying mass fluxes and diameter tubes. The some lines in Fig. 4 ~5 represents the fit curving lines of the experimental data.

As shown in Fig. 4, the average evaporation heat transfer coefficients of R-290 in diameter tube of 7.73 mm are the highest values in four refrigerants. In comparison to R-22, the average evaporation heat transfer coefficient for R-134a is 11.0% lower for 7.73 mm diameter tube.

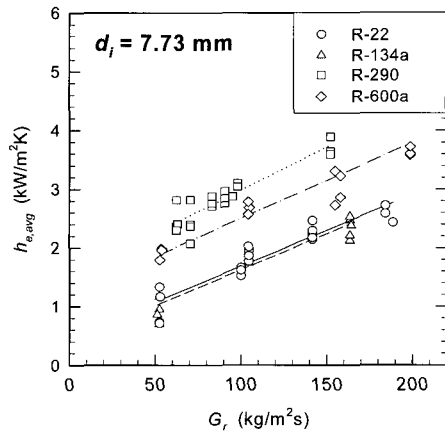


Fig. 4 Average evaporation heat transfer coefficients of ID 7.73mm

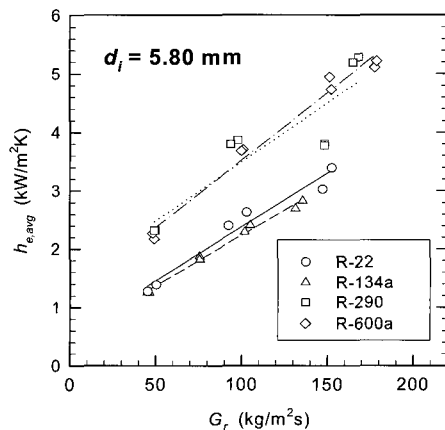


Fig. 5 Average evaporation heat transfer coefficients of ID of 5.80mm.

However, the average evaporation heat transfer coefficient for R-290 and R-600a is respectively 64.0% and 46.93% higher for 7.73 mm diameter tube. Fig. 5 shows the average evaporation heat transfer coefficients for inner diameter tube of 5.80 mm with respect to mass fluxes. In comparison to R-22, the average evaporation heat transfer coefficient for R-134a is 10.0% lower for 5.80 mm diameter tube. However, the average evaporation heat transfer coefficient for R-290 and R600a is respectively 56.7% and 50.3% higher for 5.80 mm diameter tube.

As shown in Fig. 4~5, the average evaporation heat transfer coefficients of four refrigerants in decreasing inner diameter tube of 10.07 mm to 5.80 mm were summarized as follows : the average evaporation heat transfer coefficient of R-22 is approximately 13.5% higher, R-134a is 6.1% higher, R-290 is 11.5% higher and R-600a is 10.07% higher, respectively. Therefore, the enhancement of the average evaporation heat transfer coefficients in decrease of diameter tube is almost identical to the four refrigerants. The average evaporation heat transfer coefficients of R-600a and R-290 for all diameter tubes are higher than R-22 and R-134a.

3.3 Comparison with other correlations

Several correlations available in research literature have been verified for use with various refrigerants. Some of these correlations are described in this study. They are the correlation by Shah⁽³⁾, Jung et al.⁽⁴⁾, Gungor-Winterton⁽⁵⁾ and Kandlikar⁽⁶⁾.

Here, Kandlikar correlation is given to Eq. (9)~(14).

$$h_{TP} = \text{the larger of } h_{NBD} \text{ and } h_{CBD} \quad (9)$$

$$h_{NBD} = (0.6683 \cdot Co^{-0.2} + 1058.0 \cdot Bo^{0.7} F_{fl}) h_L \quad (10)$$

$$h_{CBD} = (1.1360 \cdot Co^{-0.9} + 667.2 \cdot Bo^{0.7} F_{fl}) h_L \quad (11)$$

where the Dittus-Boelter correlation⁽⁷⁾ is used to calculate the heat transfer coefficient h_L for the single-phase liquid only. The variable F_{fl} is a fluid-dependent parameter. The magnitude of F_{fl} for hydrocarbon refrigerants is not available in the literature. Hence, we used Frost-Zuber correlation⁽⁸⁾ to find out pool boiling data of experimental fluid with suppression factor S , defined in Eq. (12). This is the reflection of the fact that as flooded convection effect grows and thickness of thermal boundary decreases, distribution of nucleate boiling is greatly restricted. This concept, at first, was proposed by Chen⁽⁹⁾, and was developed by Collier and Thome⁽¹⁰⁾ for practical use later on.

$$s = \frac{1}{1 + 2.56 \times 10^{-6} \cdot Re_{eq}^{1.17}} \quad (12)$$

where Re_{eq} is equivalent Reynolds number that can be calculated through Eq. (13).

$$Re_{eq} = \frac{G_{eq} \cdot d_{ID}}{\mu_L} \quad (13)$$

where G_{eq} is equivalent mass flux that can be calculated through Eq. (14).

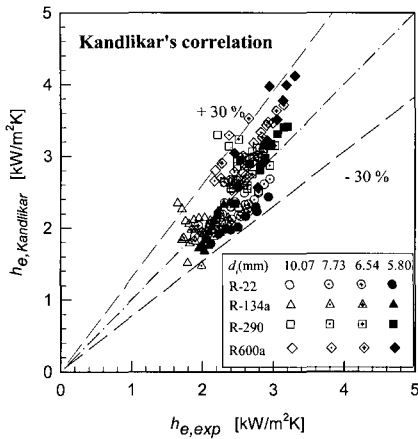


Fig. 6 Comparison of experimental heat transfer coefficient with Kandlikar's correlation

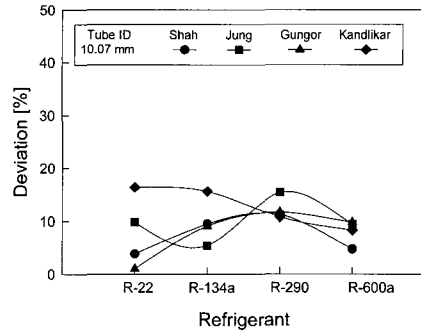
$$G_{eq} = G \cdot [(1-x) + x \cdot (\rho_L/\rho_V)^{1/2}] \quad (14)$$

Fig. 6 show the comparison of Kandlikar's correlation described above with the experimental data. As shown in Fig. 6, Kandlikar's correlation agrees quite well with the experimental data within $\pm 30\%$ for all diameter tubes and refrigerants.

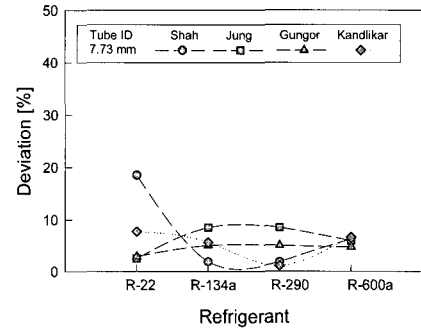
Fig. 7 shows the average deviation of experimental data and some correlations. As shown in Fig. 7, the deviation of experimental data and some correlations is large for all refrigerants and diameter tubes. Among the correlations, Kandlikar's correlation agrees quite well with the experimental data within $\pm 30\%$ for all diameter tubes and refrigerants.

4. Conclusion

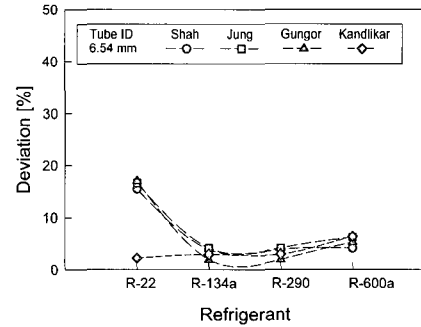
The fundamental study on the evaporation heat transfer was conducted to produce basic data for the design of that



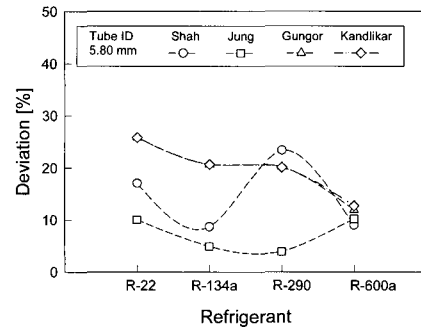
(a) Tube ID=10.07 mm



(b) Tube ID=7.73 mm



(c) Tube ID=6.54 mm



(d) Tube ID=5.80 mm

Fig. 7 Average deviation of experimental data and some correlations

uses HC's refrigerants. Conclusions of the present study include:

The local evaporation heat transfer coefficients of all refrigerants increase at the vapor quality of $x < 0.9$, and decrease rapidly over vapor quality of 0.9. The average evaporation heat transfer coefficient of the refrigerants (R-22, R-134a, R-290, and R-600a) increased according to the increase of the flow rate, and it was obtained the higher value in hydrocarbon refrigerants, R-290 and R-600a than the Freon refrigerants, R-22 and R-134a. The evaporation heat transfer coefficients of four refrigerants are not almost influenced by the effect of decrease of diameter tubes. In comparison with R-22, the evaporation heat transfer coefficient of R-134a is approximately -11~8.1% higher, R-290 is 56.7~70.1% higher and R-600a is 46.9~59.7% higher, respectively. In comparison with the experimental results and some correlations, the Kandlikar's correlation highly seemed to conform to the obtained experimental data in the all test tubes and refrigerants.

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