Characteristics of Hydrocarbon Refrigerants on Evaporating Heat Transfer and Pressure Drop

Ho-Saeng Lee[†], Thanh Tong Phan, Jung-In Yoon[*]

Graduate School, Refrigeration and Air-Conditioning Engineering, School of Mechanical Engineering, Pukyong National University, Busan 608-739, Korea

[*]School of Mechanical Engineering, Pukyong National University, Busan 608-739, Korea

Key words: Heat transfer coefficient, Hydrocarbon, Pressure drop, Natural refrigerant, Evaporator

ABSTRACT: Experimental results for heat transfer characteristics and pressure gradients of HCs refrigerants R-290, R-600a, R-1270 and HCFC refrigerant R-22 during evaporating inside horizontal double pipe heat exchangers are presented. The test sections which has one tube diameter of 12.70 mm with 0.89 mm wall thickness, another tube diameter of 9.52 mm with 0.76 mm wall thickness are used for this investigation. The local evaporating heat transfer coefficients of hydrocarbon refrigerants were higher than that of R-22. The average evaporating heat transfer coefficient increased with the increase of the mass flux, with the higher values in hydrocarbon refrigerants than R-22. Hydrocarbon refrigerants have higher pressure drop than R-22. Those results from the investigation can be used in the design of heat exchangers using hydrocarbons as the refrigerant for the air-conditioning systems.

Nomenclature

c_p : specific heat [kJ/kgK]
d : tube diameter [m]
h : heat transfer coefficient [kW/m^{2}K]
i : enthalpy [kJ/kg]
m : mass flow rate [kg/s]
n : number
P : pressure [Pa]
Q : heat transfer rate [kw]
q : heat flux [kW/m^2]
T : temperature [℃]
x : quality

Greek symbols

μ : viscosity
ρ : density
ϕ : two phase flow parameter
X_{tt} : Martinelli parameter

Subscripts

avg : average
cw : chilled water
e : evaporator
in : inlet
loc : local
out : outlet
r : refrigerant
sat : saturation
w : water
wi : inside tube wall

† Corresponding author
Tel.: +82-51-620-1506; fax: +82-51-611-8818
E-mail address: purger77@pknu.ac.kr

1. Introduction

Due to the environmental problems by CFCs and HCFCs, the development of new alternative refrigerants with the high efficient machine which can reduce energy consumption has been becoming an urgent issue.[1,2] HFCs or Non-azeotropic Refrigerant Mixtures[3] has been being regarded as alternative refrigerants. However, HFC's can make acids and toxic substances when they are resolved from a compound into their forming elements by sunlight,[4] and though they have zero ODP (ozone depletion potential), they have high GWP (global warming potential). Besides of those facts, it is hard to treat Non-azeotropic Refrigerant Mixtures efficiently and it is difficult to reproduce the primary constant composition due to its variation caused by leakage or repairing. So, new alternative refrigerants having no poisonous characteristics, no flammability and should be similar to conventional refrigerant in terms of thermodynamic property are required.

Under these circumstances, additional and active studies regarding the so-called "natural refrigerants" have been under way. Especially those 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 U.S and Japan except Europe have not adapted them due to flammability of HC's. However, according to James,[5] in case of the household refrigerators, the possibility of explosion by flammability can be negligible since the HC's charge quantity is about a half of general CFC refrigerant's one. Besides, if some simple safety device (e.g. ventilation system or leakage detector) is installed, it can overcome that problem in the large size air-conditioning and refrigerating systems. But the researches for performance of the refrigeration and air-conditioning systems using the HC's as a refrigerant are not enough, especially, the study on characteristics of evaporating heat transfer is the one of those.

Kandlikar[6] introduced a general correlation about fluid boiling in the vertical · horizontal tube. Kwon[7] experimented regarding the characteristics of evaporating heat transfer using R-290, R-410A and compared with those of R-22. According to his report, evaporating heat transfer coefficient of R-290 was higher than that of R-22 or R-410A, but the research on evaporating heat transfer of natural refrigerants is still rare.

In this scenarios, the purpose of this paper is to obtain basic data for the purpose of designing the evaporator that uses HC's refrigerants and is to compare experimentally, the evaporating heat transfer characteristic and the pressure drop of R-1270 (propylene), R-290 (propane), R-600a (iso-butane), taking R-22 as base at the smooth tube.

2. Experimental apparatus and test procedure

2.1 Experimental apparatus

Figure 1 shows the schematic of the experimental apparatus including basic air-conditioning and refrigerating system, consisted of compressor, condenser, expansion valve, evaporator and peripheral devices. The system also consists of two main flow loops: a refrigerant loop and a heat source water loop for evaporating or condensing. In the test section of the experiment, the evaporator is a double-tube type heat exchanger divided into three sections, which are inner tube, outer tube and annular section.

The heat exchanger (test section) is shown in Fig. 2. The inner diameter of the inner tube (copper) is 10.92 mm, 8 mm, and outer and inner diameters of the outer tube (copper) are 19.94 and 22.22 mm, respectively. The heat exchanger is divided into 8 small subsections with identical length, each has 675 mm length, and the shape of a refrigerant tube through the U-bend is double-tube type with identical bending used to avoid a detour. As seen from Fig.

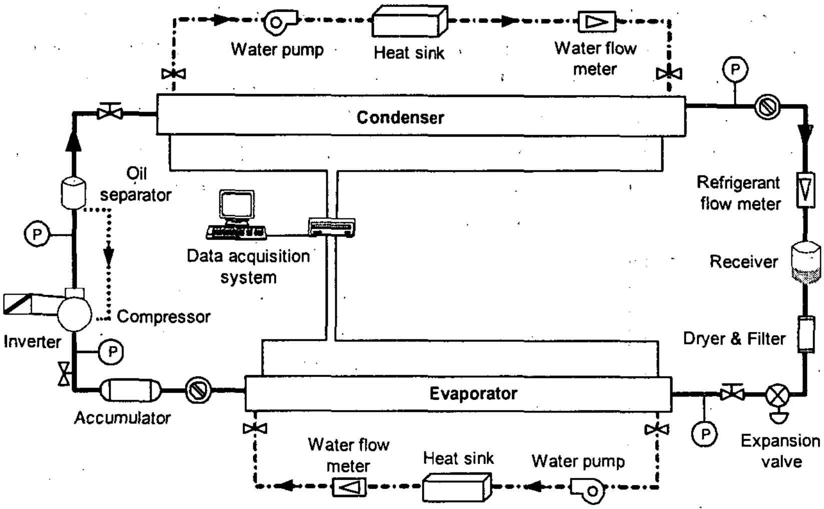


Fig. 1 Schematic diagram of experimental apparatus.

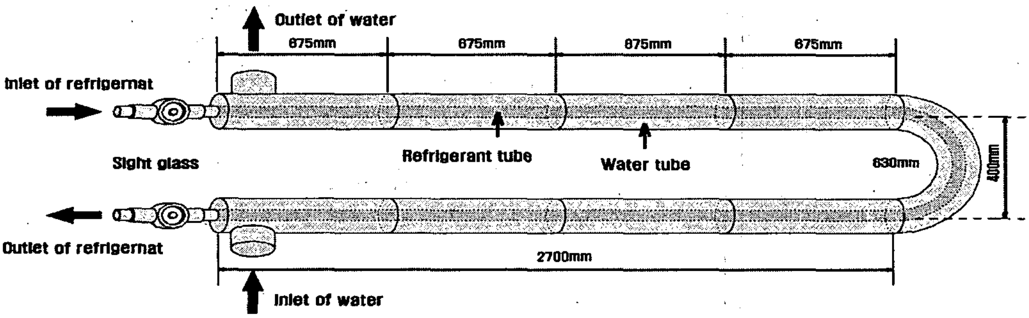


Fig. 2 Test section of the evaporator.

2, inside the double-tube heat exchanger, water flows counter-currently in the test section annulus, while refrigerant is evaporated inside the test tube.

The temperatures of the refrigerant, cooling water and inner wall of heat exchanger are measured in the heat exchanger as stated above. Each of these subsections is instrumented with

Table 1 Experimental conditions

Refrigerant	R22	R290	R1270	R600a
P_{sat} [kPa]	292~753	352~700	381~845	148~244
Evaporating temperature [K]	258~286	264~285	260~286	272~286
Mass flux [kg/m^2·s]	150~250			63~150
Tube diameter (ID) [mm]	10.92, 8			
Quality	0.11~1			
Chilled water				
Temp. of eva. inlet [K]	287			
Mass flow rate [kg/h]	240			

four insulated type T thermocouples of 0.3 mm diameter, one at the top, two at the both sides and one at the bottom. With pressure gages installed at the inlet and outlet of the heat exchanger, we can measure the pressure drop of the refrigerant in the inner tube.

The test conditions are summarized in Table 1.

2.2 Experimental method

In this paper, we use R-22, R-290 (propane, purity 99.5%), R-600a (iso-butane, purity 99.5%) and R-1270 (propylene, purity 99.5%) as working fluids. To examine the evaporating heat transfer characteristics, the data (temperatures of refrigerant, source water and outer wall) are collected at the heat exchanger.

The refrigerant, secondary fluid and tube wall temperatures at the heat exchanger, also, the flow rates of refrigerant and secondary fluid of heat exchanger are measured as well. From these data, condensing and evaporating heat transfer characteristics are investigated.

The pressure of each subsection and the pressure between inlet and outlet of the heat exchanger are measured for examining pressure drops in condenser and evaporator. The measurement of absolute pressure is done by differential pressure gauge (DPI 420, ±0.2 kPa) and the pressure gauge was installed at an interval of 1.35 mm.

All the temperatures are measured by T-type thermocouple that has ±0.1℃ error range, and we use Bourdon-type pressure gauges installed 12 pieces throughout all sections for checking the pressure. The mass flow meter is installed at the outlet of condenser, and an orifice flow-meter is set to measure heat source water flow rate at the inlets of evaporator and condenser, respectively.

The data are obtained at least 30 minutes in a stationary state of the system after regulating temperature and flow rates of the refrigerant and secondary fluid and that time, all test parameters like temperature, pressure, flow rate and many other variables are prepared over 2 hours on standard condition. After the experiment is completed under the first test condition, it is conducted with the same method with the first time. Measured data are stored in the computer through the data logger (MX100, Yokogawa Company).

2.3 Data reduction

Signals for checking data are processed with the computer through the data logger. The thermo-physical properties of R-22, R-1270, R-290 and R-600a are calculated by REFPROP (version 6.0), a thermo-physical property calculation program developed by NIST (National Institute of Standards and Technology). We used the following equations to analyze the test data, using the above mentioned properties.

The heat exchange rate at the evaporator is given as:

$$Q_w = m_{ew} \cdot c_{p,ew} \cdot (T_{in} - T_{out}) \tag{1}$$

$$Q_r = m_{er} \cdot (i_{e,out} - i_{e,in}) \tag{2}$$

where Q_w is the heat transfer rate from water to refrigerant, Q_r is the heat transfer rate from refrigerant to water, m_{ew} and m_{er} are the heat source water mass flow rate [kg/s] and the refrigerant mass flow rate [kg/s] respectively. $T_{e,in}$ and $T_{e,out}$ are the temperatures [K] of heat source water at the inlet and outlet on the evaporator, $i_{e,in}$ and $i_{e,out}$ are enthalpy [kJ/kg] of inlet and outlet and $c_{p,ew}$ is the specific heat [kJ/kgK] of chilled water.

In case of the evaporating process, we calculated a heat transfer coefficient along circumferential direction of the tube, since it has many influences on the system, and is defined as follows:

$$h_{e,loc} = \frac{q_e}{T_{e,wi} - T_{er}} \tag{3}$$

where $h_{e,loc}$ is the local heat transfer coefficient [kW/m^{2}K] at the subsection of the evaporator and q_e is heat flux [kW/m^2] shown in Eq. (3). T_{er} and $T_{e,wi}$ are refrigerant temperature [K] and inner wall temperature at the inner tube.

The average evaporating heat transfer coefficient, $h_{e,avg}$ [kW/m^{2}K], was written:

$$h_{e,avg} = \frac{1}{x_{out} - x_{in}} \int_{x_{in}}^{x_{out}} h_{e,loc} dx = \sum \frac{h_{e,loc}}{n} \quad (4)$$

3. Results and discussion

3.1 Heat transfer characteristics

To scrutinize the reliability of the experimental set-up, we examined the heat balance between refrigerant and heat source water in the evaporator and the result is shown in Fig. 3. Figure 3 reveals that the heat transfer rate Q_w calculated by Eq. (1) is given in X-direction and the heat transfer rate Q_r calculated by Eq. (2) is in Y-direction.

In case of HC's refrigerants, the range of error is produced almost equal values of around ±10% regardless of refrigerant types and tube diameter used in the experiment.

Figure 4 shows the local evaporating heat transfer coefficient with respect to the change of quality on refrigerant types. It increases continuously with refrigerant quality. Besides, it decreases rapidly for the identical mass-flux, but over 0.85 quality. This means that the increased gaseous refrigerant comes out with the completion of evaporation of liquidized refrigeration over 0.85 quality and causes the drop of heat transfer. It is reported that the local heat transfer rate of HC's refrigerants is almost identical with that of R-22 in a qualitative tendency, but is 13.4% higher in an average than that with a diameter of 12.70 mm and is 13.7% also higher for 9.52 mm outer diameter in a quantitative difference.

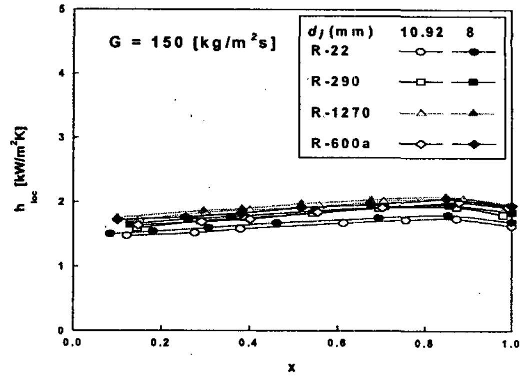


Fig. 4 Local evaporating heat transfer coefficients vs. quality.

The average evaporating heat transfer coefficient is shown in Fig. 5 with respect to the refrigerant mass flux. It increases as the mass

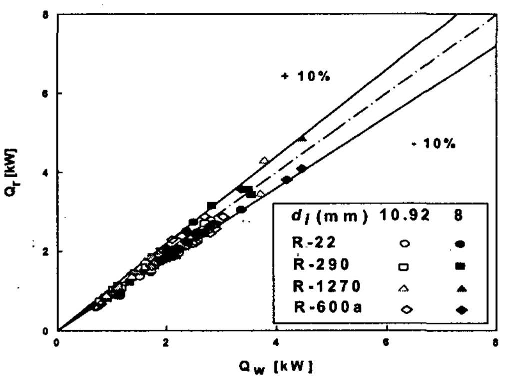


Fig. 3 Heat balance in the evaporator.

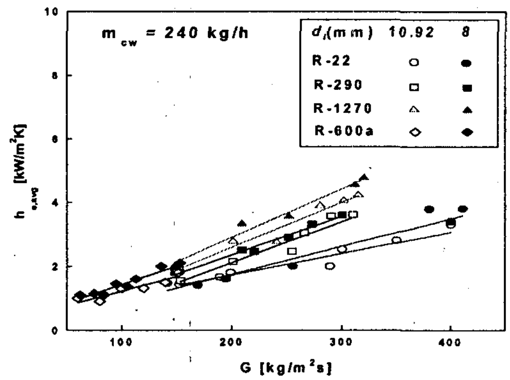


Fig. 5 Average evaporating heat transfer coefficient.

flux increases irrespective of refrigerant type. If we observe the data in terms of refrigerant classification, the average evaporating heat transfer coefficients of HC's refrigerants are higher than those of CFCs, and appeared in the order of R-1270, R-600a, R-290 with respect to the approaching of the high-mass flow velocity. Turbulence happens more often for 9.52 mm outer diameter than 12.70 mm. That's why the evaporating heat transfer coefficient shows higher value for 9.52 mm. In comparison with R-22, the average evaporating heat transfer coefficient for R-290 is approximately 19.0% higher, R-600a is 18.3% higher and R-1270 is 32.4% higher, respectively for 12.70 mm inner tube. In case of 9.52 mm inner tube, R-290 is approximately 20.0% higher, R-600a is 18.6% higher and R-1270 is 34.2% higher, respectively.

3.2 Pressure drop characteristics

3.2.1 Pressure drop

In Fig. 6, the average pressure drops of R-22, R-290, R-600a and R-1270 are compared with respect to the quality for 150 [kg/m^{2}s] mass flux. The highest value of pressure drop is shown at 0.6 quality point at which the bent pipe section (at the evaporator) is located. After 0.8 quality point, pressure drop decreased gradually and it seemed that the friction loss caused by thinned liquid film is diminished at the annular flow section. In comparison with R-22, the average pressure drop of HC's refrigerants is approximately 67.7% higher. The vapor density of R-22 is higher than that of the hydrocarbon refrigerant. The greater the density, the smaller the pressure drop refrigerant experiences. The results are similar with the studies of Wijaya and Spatz,[8] Torikoshi et al.[9]

Figure 7 shows the change of pressure drop for 50~250 [kg/m^{2}s] mass flux, and in comparison with R-22, the average pressure drop of HC's refrigerants is approximately 47.2% and 45.4% higher for 12.70 mm and 9.52 mm outer diameter, respectively.

3.2.2 Two-phase flow parameter

Chisholm[10] presented the new pressure drop correlation correcting the proposed correlation in 1963 and the new correlation proposed by Chisholm can be depicted as a function of the parameter X_{tt}.

$$\Phi^2 = 1 + \frac{5}{X_{tt}} + \frac{1}{X_{tt}^2} \tag{5}$$

where X_{tt} is Martinelli parameter. It assumes different values, depending upon whether the type of flow in the two phases is laminar or turbulent. In the two-phase flow in a horizontal tube, the vapor and liquid flow are all tur-

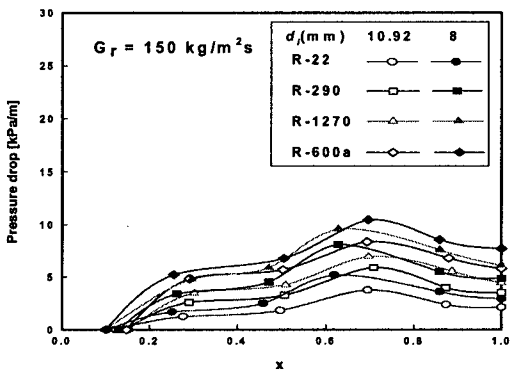


Fig. 6 Pressure drop vs. quality.

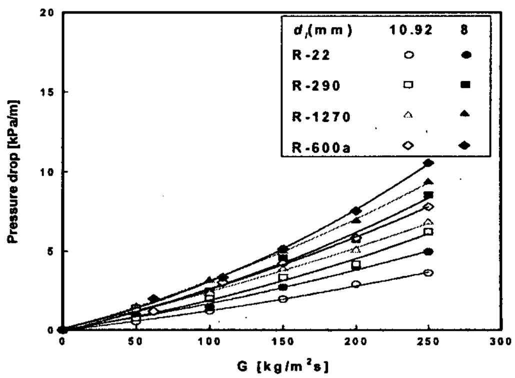
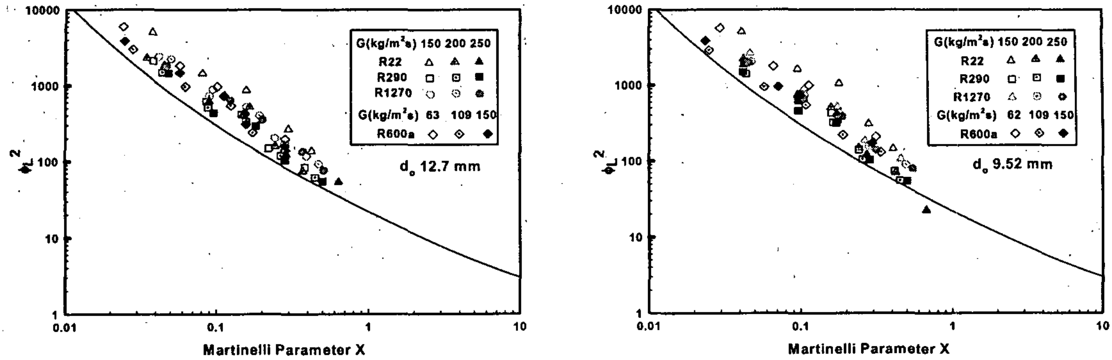


Fig. 7 Average pressure drop vs. mass flux.



(a) Tube diameter 12.70 mm (b) Tube diameter 9.52 mm

Fig. 8 Frictional multiplier vs. Martinelli parameter for the experimental data.

bulent flow due to the high Reynolds number. Accordingly, Martinelli parameter X_{tt} follows becomes

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\mu_l}{\mu_v}\right)^{0.1}\left(\frac{\rho_v}{\rho_l}\right)^{0.5} \tag{6}$$

Figure 8 shows the comparison between the experimental data and the predicted data using Chisholm's correlation. The X-direction means the friction loss parameter and Y-direction indicates Lockhart-Martinelli parameter. As shown in this figure, we can know that the evaporation progresses as the X_{tt} decreases which means the quality increase. The ϕ^2 of the hydrocarbon refrigerant showed higher values than that of R-22. The experimental data presented more or less higher values than the predicted data, but the values showed a totally similar tendency.

4. Conclusions

In connection with the above results, we have projected the following conclusions for natural refrigerant on HC's that is expected to be the alternative refrigerant of R-22 with environment friendly vision.

The local evaporating heat transfer coefficient of HC's is higher than that of conventional R-22. R-1270 showed the highest average evaporating heat transfer coefficient among all the HC's refrigerants.

In comparison to R-22, HC's refrigerants have similar or better ability and are also environmentally friendly other than flammability. Hence, we can claim that they can be used as the new alternative refrigerants (naturally) of R-22 in the future.

It turned out that the pressure drop of HC's refrigerants is greater than that of R-22 through our experiment. Accordingly, we need further study to reduce the loss caused by pressure drop and to get more accurate results.

Acknowledgement

This research was partially supported by the Pukyong National University in 2006.

References

1. Molina, M. J. and Rowland, F. S., 1974, Stratospheric sink for chlorofluoromethanes: chlorine atom catalyzed destruction of ozone, Nature, Vol. 249, pp. 810-814.
2. Kurylo, M. J., 1990, The chemistry of stratospheric ozone: its response to natural and anthropogenic influences, International Journal of Refrigeration, Vol. 13, pp. 62-72.

3. Didion, D. A. and Bivens, D. B., 1990, Role of refrigerant mixtures as alternatives to CFCs, International Journal of Refrigeration, Vol. 13, pp. 163-175.
4. Ebner, T. and Halozan, H., 1994, Testing the available alternative-an examination of R-134a, R-152a and R-290, IEA HPC Newsletter, Vol. 12, No. 1.
5. James, R. W. and Missenden, J. F., 1992, The use of propane in domestic refrigerators, International Journal of Refrigeration, Vol. 15, No. 2, pp. 95-100.
6. Kandlikar, S. G., 1990, A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes, Journal of Heat Transfer, Vol. 112, pp. 219-228.
7. Kwon, O. B., 1997, Performance characteristics of water sources heat pump using HCFC22 alternative refrigerants, PhD thesis, Pukyong National University, Korea.
8. Wijaya, H. and Spatz, M. W., 1995, Two-phase flow heat transfer and pressure drop characteristics of R-22 and R-32/125, ASHRAE Transaction 101, Part 2, pp. 1020-1026.
9. Torikoshi, K. and Ebisu, T., 1993, Heat transfer characteristics and pressure drop characteristics of R-134a, R-32 and a mixture of R-32/R-134a inside a horizontal tube, ASHRAE Transaction Research, Vol. 99, No. 2, pp. 90-96.
10. Chisholm, D., 1983, Two-Phase Flow in Pipelines and Heat Exchangers, Longman.