PERFORMANCE PREDICTION OF A R744 TRANSCRITICAL CYCLE FOR AIR CONDITIONING

J. Xue, Student, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University,
Kasuga, Fukuoka, 816-8580, Japan
S. Koyama, Professor, Faculty of Engineering Sciences, Kyushu University,
Kasuga, Fukuoka, 816-8580, Japan
K. Kuwahara, Assistant Professor, Faculty of Engineering Sciences, Kyushu University,
Kasuga, Fukuoka, 816-8580, Japan

Abstract: From the viewpoint of global environmental protection and energy-saving, the research and development on high-efficiency heat pump systems using environment-friendly refrigerants have become one of the most important issues in the air-conditioning and refrigeration sector. Carbon dioxide (R744) is regarded as a candidate for alternative refrigerant, and R744 heat pump water heater has already been commercialized. However, due to its low critical temperature and high operating pressure, there are still many problems that remain to be solved. One of the agenda is the prediction method for cycle performance when R744 is used as the working fluid of air conditioning equipment. In the present study, a steady-state model of the R744 transcritical cycle for air conditioning has been developed to estimate the cooling and heating performance. This cycle consists of a rotary compressor, a fin-tube gas cooler, a fin-tube evaporator, an expansion valve and connecting tubes. The cycle performance has been examined by varying the specifications of heat exchangers and the degree of refrigerant superheat.

Key Words: R744, Prediction method, Performance

1 INTRODUCTION

From the viewpoint of global environmental protection and energy-saving, the research and development on high-efficiency heat pump systems using environment-friendly refrigerants have become one of the most important issues in the air-conditioning and refrigeration sector. R744 is regarded as a candidate for alternative refrigerant, and R744 heat pump water heater has already been commercialized. However, due to its low critical temperature and high operating pressure, the R744 transcritical cycle is greatly different from the conventional subcritical cycle. There are still many problems that remain to be solved, and one of the agenda is prediction method for cycle performance.

Although some simulation studies on the R744 cycle (Kim [1], Sarkar [2], Kato [3], etc) have been carried out, most of them focused on the water heating application. There is only a limited number of studies concerning the air conditioning heat pump. In the present study, a steady-state model of the R744 transcritical cycle for air conditioning has been developed. The cooling and heating performance has been examined by varying the specifications of heat exchangers (HEX), as well as the degree of refrigerant superheat at evaporator outlet.

2 DESCRIPTION OF THE MODEL

Figure 1 shows the schematic diagram of the R744 transcritical cycle for air conditioning. This cycle consists of a rotary compressor, a cross-counter flow fin-tube gas cooler, an expansion valve, a cross-parallel flow fin-tube evaporator and connecting tubes.

The compressor model is developed by Yanagisawa *et al*. (Yanagisawa [4]). In the HEX model, the finite volume method is used. That is, the HEX is equally divided into several computational elements,

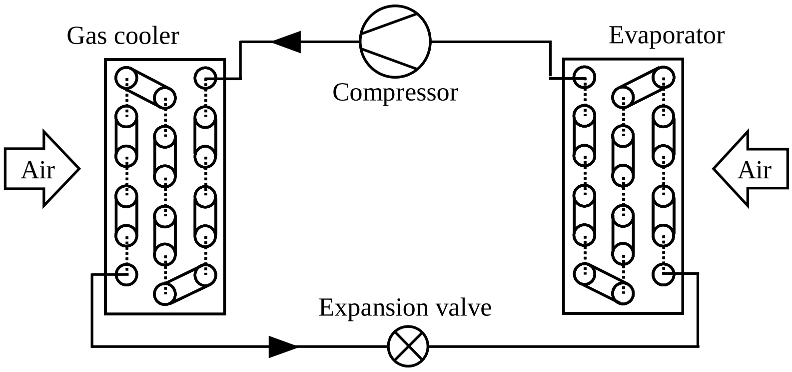


Figure 1. R744 transcritical cycle

and local heat transfer and flow characteristics are evaluated. The following assumptions have been introduced: (1) air is in homogeneous distribution on the inlet face, which means the velocity, dry-bulb temperature and wet-bulb temperature are the same; (2) the heat transfer coefficient (HTC) on the air side is constant; (3) the flow loss on the air side is neglected; (4) the effects of the return bends are not taken into account; (5) the gravitational effect is neglected; and (6) the refrigerant flowing into each bifurcated branch is under the same condition when HEX has more than one path. The thermodynamic and transport properties of R744 are calculated by REFPROP ver. 8.0. As for the estimation of inside tube HTC, the Dang-Hihara correlation (Dang [5]) is used for supercritical R744; the Gnielinski correlation (Gnielinski [6]) is applied to single-phase flow; the correlation proposed by Yu *et al.* (Yu [7]) is utilized for two-phase flow with a quality of up to 0.8; and an empirical correlation cited by Fujii *et al.* ([8]) is employed for two-phase flow with a quality of above 0.8. The frictional pressure drop of two-phase flow is calculated by the Friedel correlation (Friedel [9]). The friction factor of single-phase flow and supercritical R744 is estimated by the Blasius equation. The properties of air are calculated by prediction expressions (JAR [10]). The outside tube HTC is supplied as an input parameter, which is based on the outer surface area of heat transfer tube. In the evaporator model, the effect of dew condensation generated on the cooling surface is considered, and the mass transfer coefficient is calculated on the assumption that Lewis number equals 1. Moreover, the expansion process is assumed to be isenthalpic.

In the program, the cooling or heating capacity, compressor discharge pressure, degree of refrigerant superheat at evaporator outlet, inlet air conditions (dry-bulb temperature, wet-bulb temperature and velocity) and specifications of each component (compressor, gas cooler, evaporator and connecting tubes) are given as input data. The details are described by Koyama *et al.* (Koyama [11], [12]).

3. RESULTS AND DISCUSSIONS

The calculation conditions are shown in Table 1. In the present study, the investigation on the R744 cycle performance has been carried out under the typical operating conditions in Japan. In both operating conditions, the face velocity and HTC of indoor air, as well as those of outdoor air, are remained the same. The degree of refrigerant superheat at evaporator outlet is kept at 3 K, except for section 3.1. In addition, the cooling and heating capacity are 2.8 kW and 3.6 kW, respectively.

Table 2 shows the specifications of the standard HEXs, that is, all of the performance comparisons are made based on the cycle with these HEXs. It is noted that for the commercial air conditioning equipment, the indoor HEX works as evaporator in cooling mode, while it works as gas cooler in heating mode. The following discussions have taken the HEXs switching into account.

3.1 The influence of refrigerant superheat at evaporator outlet

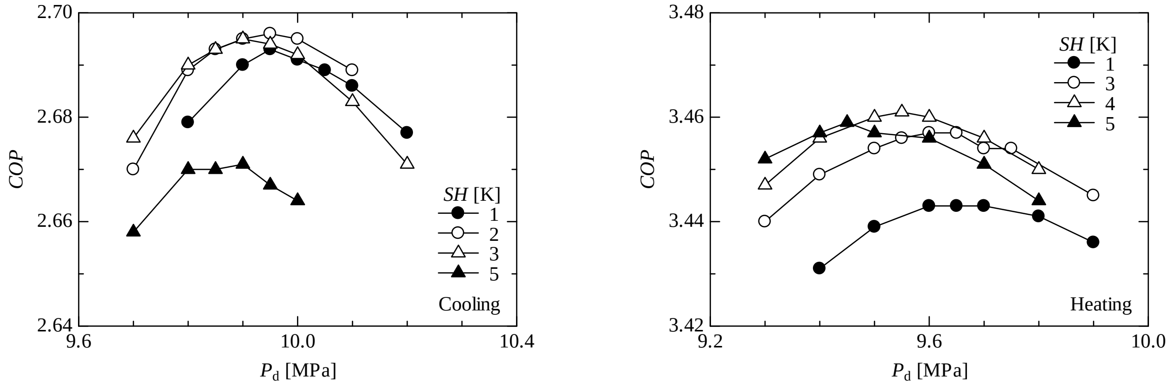
Figure 2 shows the variations of COP with respect to compressor discharge pressure when the degree of refrigerant superheat at evaporator outlet changed. The results show that in both operating conditions, the maximum COP increases with the increase in refrigerant superheat until a certain value, and then starts to decrease. Meanwhile, the compressor discharge pressure at which the COP reaches a maximum (the optimal discharge pressure) falls as the refrigerant superheat increases. However, the refrigerant superheat has little influences on both COP and the optimal discharge pressure.

Table 1: Calculation conditions

		Cooling Mode	Heating Mode
Capacity [kW]		2.8	3.6
Degree of superheat [K]		3.0	3.0
Indoor Air	Dry-bulb temperature [℃]	27.0	20.0
	Wet-bulb temperature [℃]	19.0	15.0
	Velocity [m/s]	1.2	1.2
	HTC [kW/(m^2 K)]	1.0	1.0
Outdoor Air	Dry-bulb temperature [℃]	35.0	7.0
	Wet-bulb temperature [℃]	24.0	6.0
	Velocity [m/s]	1.5	1.5
	HTC [kW/(m^2 K)]	0.8	0.8

Table 2: Specifications of heat exchangers

	Indoor HEX	Outdoor HEX
Tube outer diameter [mm]	6.35	6.35
Tube inner diameter [mm]	4.75	4.75
Number of columns	10	20
Column pitch [mm]	18.0	18.0
Number of rows	2	2
Row pitch [mm]	15.6	15.6
Width [m]	0.66	0.90
Number of paths	1	1



(a) Cooling mode **(b) Heating mode**

Figure 2. The influence of refrigerant superheat at evaporator outlet on COP

3.2 The influence of the arrangement of heat transfer tubes of HEX

Figure 3 shows the influence of the arrangement of heat transfer tubes on COP, on the assumption that the outside tube HTCs are the same regardless of tube arrangement. The results show that compared to the in-line arrangement, the staggered arrangement brings about higher COPs. And the tube arrangement of the indoor HEX has a greater impact than that of the outdoor HEX. However, there is little change in the optimal discharge pressure.

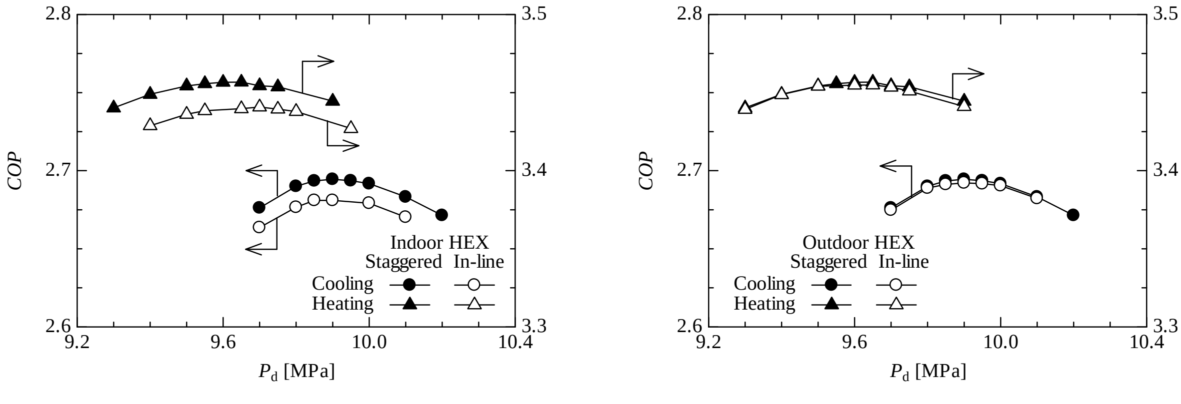
3.3 The influence of the total length of heat transfer tubes of HEX

Figure 5 shows the variations of COP with respect to compressor discharge pressure when the number of HEX rows changed. As the tube length per row remains unchanged, the total length of heat transfer tubes increases with the increase in rows. In both cases, COP shows a substantial increase when HEX has longer heat transfer tubes. In the case of indoor HEX, the rise of heating COP is greater than that of cooling COP. Meanwhile, cooling COP rises far more than heating COP in the case of outdoor HEX. It indicates that the tube length of gas cooler has a stronger impact on COP than that of evaporator. Furthermore, the optimal discharge pressure shows a significant drop with the increase in tube length of gas cooler, while it changes slightly as the tube length of evaporator varies.

The R744 cycles with different indoor HEXs of tube length under respective optimal discharge pressure are shown in Figure 6. The R744 state changes in HEXs are represented using local values and the air inlet and outlet temperatures of the corresponding computational element are also plotted on the T-h diagram. Figure 6 (a) shows that with the increase in tube length of indoor HEX, which works as evaporator in cooling mode, the R744 evaporating pressure becomes higher due to the reduction of temperature difference between R744 and air. Consequently, the R744 enthalpy change in compressor decreases while the enthalpy change in evaporator remains virtually unchanged, which result in an improvement in cooling COP. Figure 6 (b) shows that the increase in tube length of indoor HEX, which works as gas cooler in heating mode, causes a considerable reduction in gas cooling pressure, while the evaporating pressure remains almost the same. Thus the R744 enthalpy change in compressor reduces. Meanwhile, the R744 temperature at gas cooler outlet gets closer to the air inlet temperature, and consequently the R744 enthalpy change in gas cooler increases. As a result, the heating COP is improved.

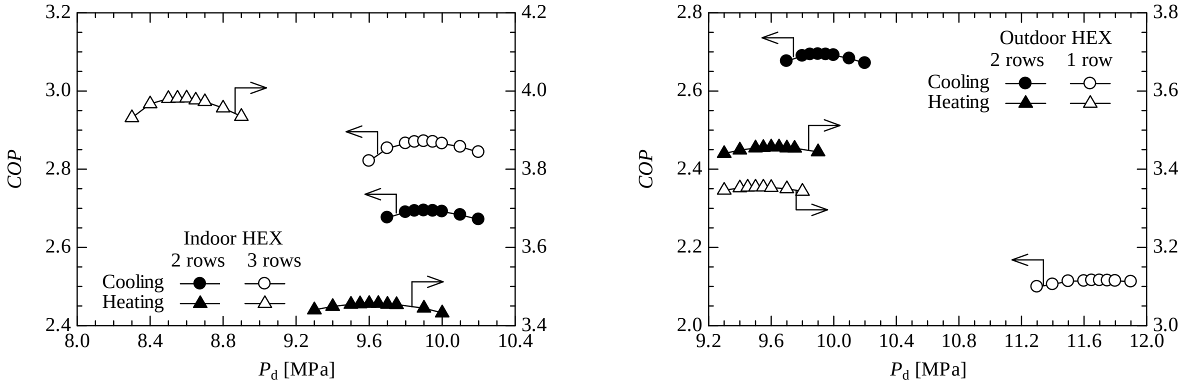
3.4 The influence of refrigerant distribution

Figure 7 shows the influence of refrigerant distribution on COP when R744 is separated into 2 paths by dividing the HEX columns equally. The results show that the refrigerant distribution in indoor HEX causes decrease in both cooling COP and heating COP. As for the distribution in outdoor HEX, the



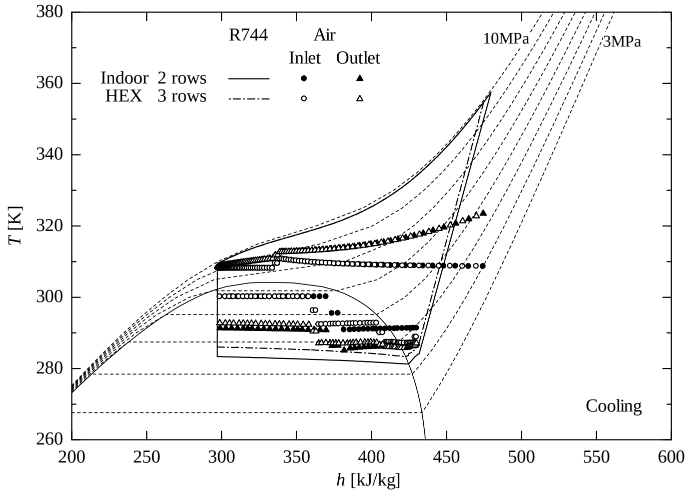
(a) Indoor HEX **(b) Outdoor HEX**

Figure 3. The influence of the arrangement of heat transfer tubes on COP

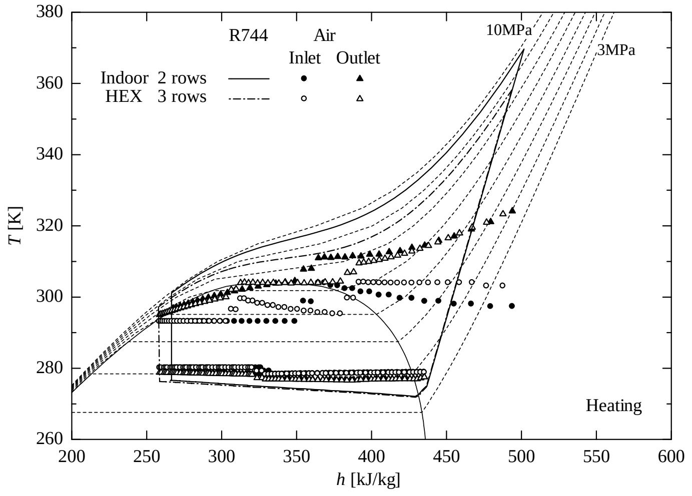


(a) Indoor HEX **(b) Outdoor HEX**

Figure 5. The influence of the total length of heat transfer tubes on COP



(a) Cooling mode



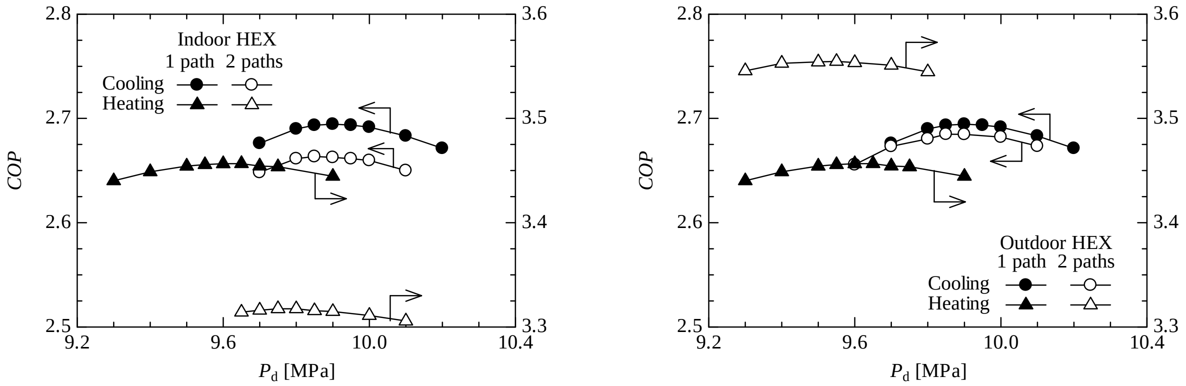
(b) Heating mode

Figure 6. Comparison of cycles with different indoor HEXs of length on T-h diagram

cooling COP drops slightly while the heating COP rises.

The R744 cycles with different indoor HEXs of path under respective optimal discharge pressure are shown in Figure 8. Figure 8 (a) indicates that the main cause of cooling COP decrease is the reduction of evaporating pressure. Although the flow reduction due to refrigerant distribution reduces the pressure drop, it also leads to degradation of heat transfer performance. Consequently, the R744 evaporating temperature falls to complete the specified cooling capacity. Figure 8 (b) indicates that the main cause of heating COP decrease is the reduction of R744 enthalpy at gas cooler outlet, which is caused by the increase in temperature difference between R744 and air at gas cooler outlet due to the degradation of heat transfer performance.

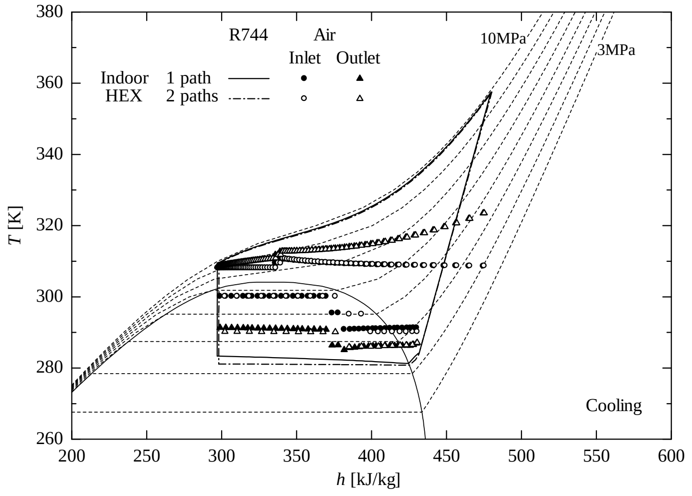
When HEX serves as evaporator, the refrigerant distribution sometimes improves COP and sometimes worsens the cycle performance, as mentioned above. The reason for difference in the influence of refrigerant distribution in evaporator is shown in Figure 9 and Figure 10. Figure 9 shows that unlike in cooling mode as shown in Figure 8 (a), in heating mode although the R744 pressure at evaporator inlet is lower when refrigerant is separated into 2 paths, the outlet pressure is higher which contributes to improving COP. The cumulative rates of heat exchange in evaporator under respective optimal discharge pressure are shown in Figure 10. Figure 10 (a) shows that in cooling mode, the sensible heat ratio is higher in the case of 2 paths, that is, the latent heat exchange due to dew condensation is less and the cycle works with a greater temperature difference between R744 and air. However, there is not



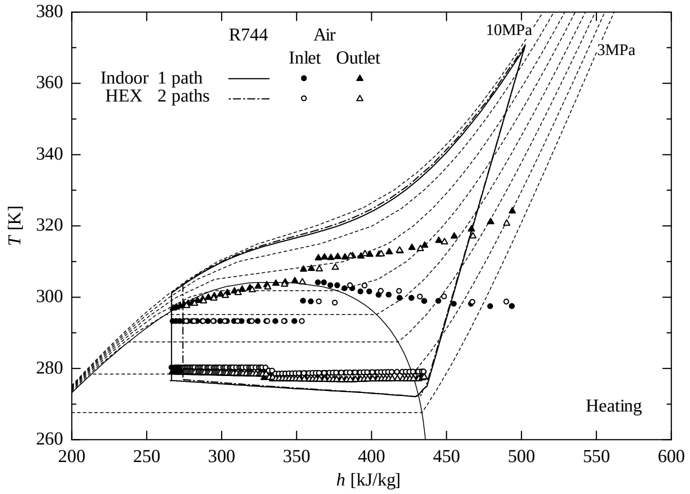
(a) Indoor HEX

(b) Outdoor HEX

Figure 7. The influence of refrigerant distribution on COP



(a) Cooling mode



(b) Heating mode

Figure 8. Comparison of cycles with different indoor HEXs of path on T-h diagram

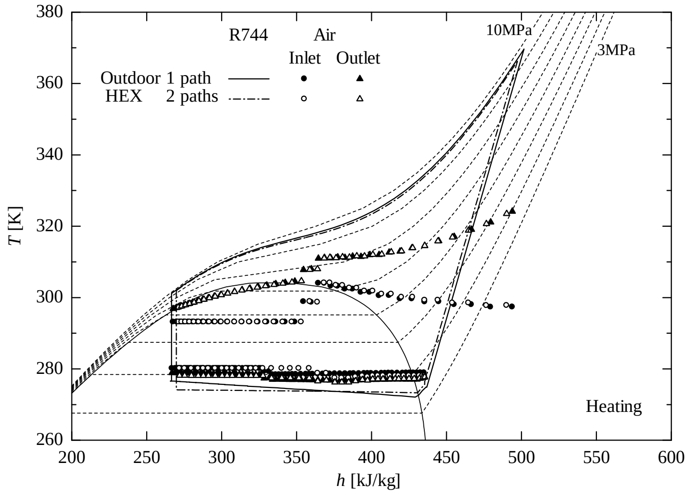
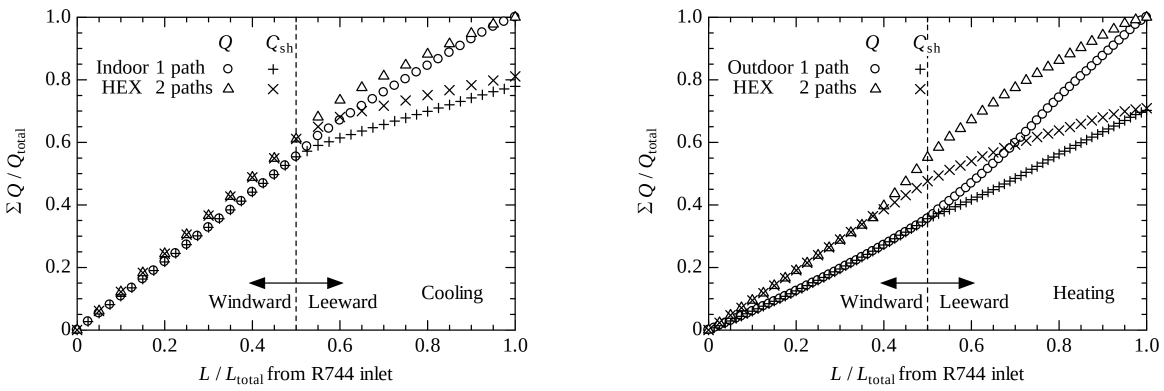


Figure 9. Comparison of cycles with different outdoor HEXs of path in heating mode on T-h diagram



(a) Cooling mode

(c) Heating mode

Figure 10. Cumulative rates of total heat exchange and sensible heat exchange in evaporator

much difference in the sensible heat ratio between two cases as shown in Figure 10 (b). The results suggest that the influence of refrigerant distribution in evaporator depends on the reduction of pressure drop, the degradation of heat transfer performance and dew condensation occurrence.

4. CONCLUSIONS

In the present study, the cooling and heating performance of a R744 transcritical cycle for air conditioning has been examined by a steady-state model. The calculation results show that the degree of refrigerant superheat at evaporator outlet has little influence on both COP and the optimal compressor discharge pressure. The staggered arrangement of heat transfer tubes brings about higher COPs compared to the in-line arrangement even if the outside tube HTCs are the same. The increase in heat transfer tube length of HEX leads to an improvement in COP. The primary causes are the reduction in gas cooling pressure and R744 enthalpy at gas cooler outlet in the case of gas cooler, and the rise in evaporating pressure in the case of evaporator. The refrigerant distribution in gas cooler causes a reduction of COP, mainly due to the decrease in R744 enthalpy at gas cooler outlet. However, the refrigerant distribution in evaporator sometimes improves COP and sometimes worsens cycle performance, which depends on the reduction of pressure drop, the degradation of heat transfer performance and dew condensation occurrence.

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