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Theoretical and Experimental Study on High-Temperature Heat Pumps Using a Low GWP Refrigerant

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Abstract

This paper describes the theoretical and experimental study on high temperature heat pumps using a low GWP refrigerant. An HFO refrigerant R1234yf is selected to heat water or air to the temperature range from 65 °C to 80 °C while the temperature of source water or air is in the range from 7 °C to 25 °C. Sub-critical heat pump cycles with smaller degree of sub-cooling than 10 °C are discussed for low temperature-rise heating to reheat circulating hot water or circulating hot air, returning with temperature drop ranged lower than 10 °C. Further, sub-critical heat pump cycles with larger degree of sub-cooling than 40 °C were discussed and tested for high temperature-rise heating to supply hot water or air. An experimental apparatus and experimental results were presented. Regarding the sub-critical heat pump cycles with larger degree of sub-cooling than 40 °C, the experimental results have been obtained, which the heating COP reaches 4.0 when the hot water temperature is 80 °C and the source water temperature is 26 °C, and the heating COP reaches 4.0 when the hot water temperature is 65 °C and the source water temperature is 8 °C.

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keywords: High Temperature Heat Pump, Hot Water Supply, Hot Air Supply, HFO, R1234yf, Sub-cooling

1. Introduction

Heat pump technology is important to boost the reduction of CO_2 emissions, reduce primary energy consumption and increase the amount of renewable energy usage due to high energy efficiency of heat pumps. To further enhance these effects, the development and spread of high temperature heat pumps for hot water supply, hot air supply, re-heating of circulating hot water and re-heating of circulating hot air must be supported.

The low GWP refrigerants, hydrofluoroolefins (HFOs) are expected as the next generation refrigerants for air-conditioners, refrigerators and heat pumps. As representative HFOs, R1234yf has been originally developed for mobile air conditioners, and R1234ze (E) has been originally developed as a blowing agent, respectively. Both have low GWP_{100} values less than 1. R1234yf and R1234ze(E) are mildly flammable refrigerants. Risk assessment of mildly flammable refrigerants was promoted for the application to mini-split air conditioners, variable refrigerant flow systems, and chillers by JSRAE [1].

There are three previous studies [2-4] on thermodynamic cycles related to this paper. The first is a study on optimal heat source temperature for thermodynamic optimization of sub-critical organic Rankine cycles, using R227 for a single cycle or R227 and R245fa for a dual cycle [2]. The second is a literature review of multi-temperature heat pumps including two interesting heat pump cycles. One is a three-stage compressor cycle with three condensers, two sub-coolers and an evaporator using R123/R134a for water heating at a sink water temperature of 85 °C and a heat source temperature of 50 °C. The other is a separated gas cooler cycle with a de-super-heater and a condenser using R410A for a target domestic hot water temperature of 65 °C and space heating temperature of 35 °C, supplied by a ground inlet temperature of 5 °C, the highest COP measured was 4.5

[3]. The third is a study on a heat pump water heater with two-stage heating for a great rise of water temperature with a two-stage compressor [4].

In this paper, we aim at single-stage compressor cycles to realize high-temperature heat pumps using a low GWP refrigerant. An HFO refrigerant R1234yf is selected to heat water or air in the temperature range from 65 °C to 80 °C while the temperature of heat source water or air is in the range from 7 °C to 25 °C. In comparison to CO_2, there are two merits of R1234yf as a refrigerant. One is lower pressure than CO_2 to realize high temperature heating, and then, use of common parts for air-conditioners or refrigerators are enabled. The other is that both low temperature-rise heating and high temperature-rise heating are enabled.

Two subcritical cycle heat pumps are investigated. One is a sub-critical cycle heat pump with smaller degree of sub-cooling than 10 °C, which is discussed for low temperature-rise heating to reheat circulating hot water or circulating hot air, returning with lower temperature drop than 10 °C. The other is a sub-critical cycle heat pump with larger degree of sub-cooling than 40 °C, which is discussed and tested for higher temperature-rise heating than 40 °C to supply hot water or hot air. Also, the experimental results of the sub-critical cycle heat pump with larger degree of sub-cooling than 40 °C are presented.

2. Selection of a refrigerant

Properties of refrigerants, which are R744, R290 and R600a as natural refrigerants, R32, R410A and R134a as HFCs and R1234yf and R1234ze(E) as HFOs, are shown in Table 1. GWP_{100}, safety, critical pressure, critical temperature and boiling point temperature of each refrigerant are described in the table. When we select a refrigerant in this paper, we think the refrigerants to be removed, whose GWP_{100} is higher than 100, or whose flammability is high (3). And we also think the refrigerants to be removed, whose critical temperature is lower than 60 °C because a sub-critical cycle is adopted and heating temperature is needed to be higher than 60 °C. Further, we think the refrigerants to be removed, whose boiling point temperature is higher than -25 °C because the lowest evaporation temperature of a sub-critical cycle is -25 °C, assumed that the lowest temperature of heat source air is -15 °C and the lowest evaporation temperature is lower by 10 °C than the temperature of heat source air. Only R1234yf is selected because it is not removed.

Table 1. Properties of refrigerants

Classification	Refrigerant number	Chemical formula	GWP_{100} *	Safety **	Critical pressure (M Pa)	Critical temperature (°C)	Boiling point*** (°C)
Natural refrigerant	R744 (Carbon dioxide)	CO_2	1	A1	7.38	31.0	-78.0
Natural refrigerant	R290 (Propane)	C_3H_8	3	A3	4.24	106	-42.1
Natural refrigerant	R600a (Isobutane)	C_4H_{10}	3	A3	3.66	135	-11.8
HFC	R32	CH_2F_2	677	A2L	5.78	78.1	-51.7
HFC	R410A	R32 (50 wt. %) + R125 (50 wt. %)	1,923	A1	4.81	70.5	-51.4
HFC	R134a	CF_3CH_2F	1,300	A1	4.06	101.1	-26.1
HFO	**R1234yf**	**$CF_3CF=CH_2$**	**<1**	**A2L**	**3.38**	**94.7**	**-29.4**
HFO	R1234ze(E)	Trans-$CHF=CHCF_3$	<1	A2L	3.64	109.4	-19.0

*) GWP_{100} values of hydrocarbons: IPCC Fourth Assessment Report, Table 2.15.
GWP_{100} values of all others: IPCC Fifth Assessment Report, Table 8.A.1.
GWP_{100} values of blends: calculated using weighted average of components.

**) A: lower toxicity, B: higher toxicity, 1: no flame propagation, 2L: lower flammability with a maximum burning velocity of ≤10 cm/s, 2: lower flammability with a maximum burning velocity of >10 cm/s, 3: higher flammability, ISO 817:2014.

***) Boiling temperature under standard atmosphere, 0.1013 MPa.

3. Simulation of heat pump cycles

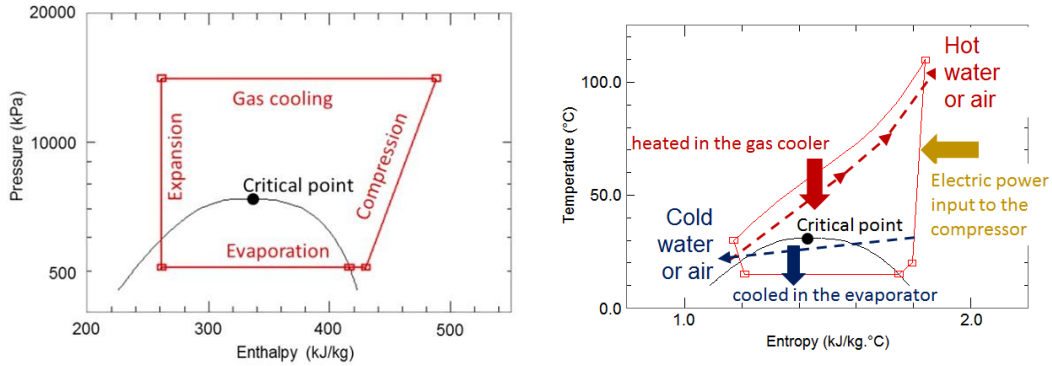
Three heat pump cycles, which are a CO_2 trans-critical cycle, an R1234yf sub-critical cycle heat pump with smaller degree of sub-cooling than 10 °C, and an R1234yf sub-critical cycle heat pump with larger degree of sub-cooling than 40 °C, are simulated and discussed.

3.1. A CO_2 trans-critical cycle

Since CO_2 trans-critical cycle heat pumps operate in the supercritical region of refrigerants, they enable high temperature-rise (40-90 °C) heating of air or water efficiently. The CO_2 trans-critical cycle heat pump consists of a gas cooler, an expansion valve, an evaporator and a compressor. Table 2 shows the conditions and results of the heat pump cycle analysis using a calculation program of a compressor manufacturer and CYCLE_D (NIST vapor compression cycle design program) [5]. The compressor for basic experiments is a semi-hermetic reciprocating type and selected as the smallest capacity product in the manufacturer line-up. Fig. 1 shows the pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of a CO_2 trans-critical cycle.

Table 2. Conditions and results of the heat pump cycle analysis (a CO_2 trans-critical cycle heat pump)

Refrigerant	CO_2	Refrigerant super heat	5 °C
Hot water or air temperature	from 20 °C to 100 °C	Compressor isentropic efficiency	0.70
Cold water or air Temperature	from 30 °C to 25 °C	Compressor motor efficiency	0.90
Refrigerant condensation temperature	14 MPa	Heating COP	3.5
Refrigerant sub-cooling	30 °C	Cooling COP	2.5
Refrigerant evaporation temperature	15 °C	Total COP	6.0



Pressure-enthalpy diagram Temperature-entropy diagram

Fig. 1. The pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of a CO_2 trans-critical cycle and energy flow

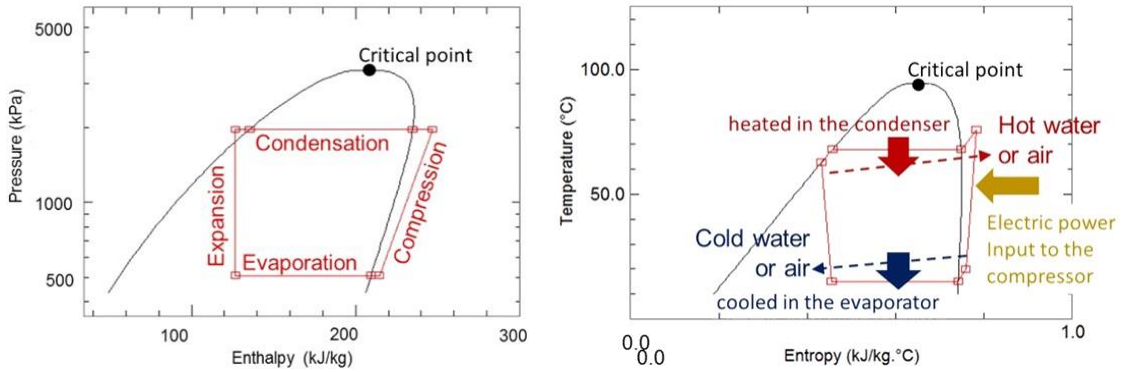
3.2. An R1234yf sub-critical cycle with smaller degree of sub-cooling than 10 °C

An R1234yf sub-critical cycle with smaller degree of sub-cooling than 10 °C can be used for low temperature-rise heating to reheat circulating hot water or circulating hot air, returning with lower temperature drop than 10 °C, such as circulation heating of washing baths or recycle air conditioning in the drying chambers.

Table 3 shows the conditions and results of the heat pump cycle analysis using a calculation program of a compressor manufacturer and CYCLE_D (NIST vapor compression cycle design program) [5]. The compressor for basic experiments is a semi-hermetic reciprocating type and selected as the smallest capacity product in the manufacturer line-up. Fig. 2 shows the pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of the R1234yf sub-critical cycle with smaller sub-cooling than 10 °C and energy flow. Water or air is heated from 60 °C to 65 °C by utilizing the heat source at a temperature of 25 °C. The heating COP is 3.6; the cooling COP is 2.6; and then, total COP is 6.2.

Table 3 Conditions and results of the heat pump cycle analysis (the R1234yf sub-critical cycle heat pump with smaller degree of sub-cooling than 10 °C)

Refrigerant	R1234yf	Refrigerant super heat	5 °C
Hot water or air temperature	from 60 °C to 65 °C	Compressor isentropic efficiency	0.74
Cold water or air Temperature	from 25 °C to 20 °C	Compressor motor efficiency	0.95
Refrigerant condensation temperature	68 °C	Heating COP	3.6
Refrigerant sub-cooling	5 °C	Cooling COP	2.6
Refrigerant evaporation temperature	15 °C	Total COP	6.2



Pressure-enthalpy diagram Temperature-entropy diagram

Fig. 2. The pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of the R1234yf sub-critical cycle with smaller degree of sub-cooling than 10 °C

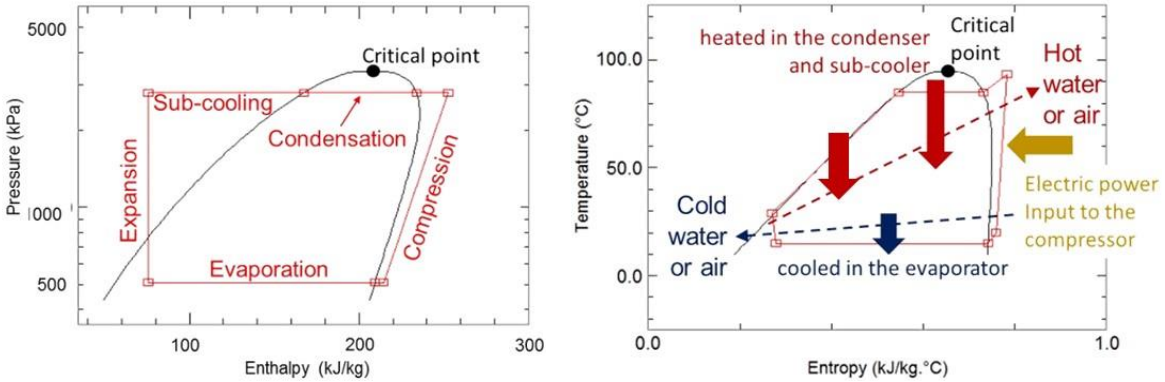
3.3. An R1234yf sub-critical cycle with larger degree of sub-cooling than 40 °C

An R1234yf sub-critical cycle with larger degree of sub-cooling than 40 °C can be used for higher temperature-rise heating of water or air than 40 °C to supply fresh hot air in the drying process, such as fresh hot water supply to washing baths or fresh hot air supply to drying chambers.

Table 4 shows the conditions and results of the heat pump cycle analysis using a calculation program of a compressor manufacturer and CYCLE_D (NIST vapor compression cycle design program) [5]. The compressor for basic experiments is a semi-hermetic reciprocating type and selected as the smallest capacity product in the manufacturer line-up. Fig. 3 shows the pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of the R1234yf sub-critical cycle with larger sub-cooling than 40 °C and energy flow. Water or air is heated from 25 °C to 80 °C by utilizing the heat source at a temperature of 25 °C. The heating COP is 4.4; the cooling COP is 3.4; and then, total COP is 7.8.

Table 4 Conditions and results of the heat pump cycle analysis (the R1234yf sub-critical cycle heat pump with larger degree of sub-cooling than 40 °C)

Refrigerant	R1234yf	Refrigerant super heat	5 °C
Hot water or air temperature	from 25 °C to 80 °C	Compressor isentropic efficiency	0.77
Cold water or air Temperature	from 25 °C to 20 °C	Compressor motor efficiency	0.95
Refrigerant condensation temperature	85 °C	Heating COP	4.4
Refrigerant sub-cooling	56 °C	Cooling COP	3.4
Refrigerant evaporation temperature	15 °C	Total COP	7.8



Pressure-enthalpy diagram Temperature-entropy diagram

Fig. 3. The pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of the R1234yf sub-critical cycle with larger sub-cooling than 40 °C and energy flow

3.4. Comparison between the CO_2 trans-critical cycle and the R1234yf sub-critical cycles

While the highest pressure of the CO_2 trans-cycle is over 10 MPa for 80 °C heating, the highest pressure of the R1234yf sub-critical cycles is under 3 MPa for 80 °C heating. While the CO_2 trans-cycle enables only higher temperature-rise heating than 40 °C efficiently, the R1234yf sub-critical cycles enable both lower temperature-rise heating than 10 °C efficiently without the sub-cooler and higher temperature-rise heating than 40 °C efficiently with the sub-cooler.

4. Experimental apparatus of the heat pump cycle

Fig. 4 shows the outside view of the apparatus. Fig. 5 shows the schematic drawing of an experimental apparatus and measure points. The apparatus consists of a refrigerant circuit of a heat pump cycle and two water circuits to measure heating and cooling capacity.

The refrigerant circuit consists of a compressor, a condenser, a receiver, a sub-cooler, an expansion valve, an evaporator, an accumulator and sight glasses. The receiver is arranged between the condenser and the sub-cooler to cool only liquid refrigerant in the sub-cooler. The semi-hermetic reciprocating compressor 2KES-05Y made by Bitzer was adopted. The compressor has two cylinders, a bore diameter of 30 mm, a stroke of 33 mm and a displacement volume of 490 m^3/h when the frequency of power source is 60 Hz. The maximum discharge pressure is 3.2 MPa, and the maximum suction pressure is 1.9 MPa. The compressor has a 3-phase 200V induction motor, which has a maximum output of 1.8 kW. The commercial automatic temperature expansion valve for R134a is adopted conveniently.

The water circuit of heat sink water consists of a water tank, an auxiliary chiller, a water pump driven by an inverter and a fan coil unit. And the water circuit of heat source water consists of a water tank and a water pump driven by an inverter. Both inner volume of the heat source water tank and that of the heat sink water tank are 0.035 m^3. Heat sink water heated in the condenser and sub-cooler and heat source water cooled in the evaporator exchange heat in a water-to-water heat exchanger. The heat equivalent to electric power input is dissipated to ambient air in the fan coil unit. The condenser, sub-cooler, evaporator and water-to-water heat exchanger are all copper-brazed stainless steel plate type heat exchangers made by SWEP.

Refrigerant pressure is measured with piezo-resistance pressure transducers. Refrigerant temperature is measured with copper-constantan thermo-couples attached on outside surfaces of copper tubes in which refrigerant flows. Water temperature is measured with platinum resistor temperature sensors inserted in the water pipe. Both flow rate of heat sink water and that of heat source water are measured with electromagnetic flowmeters.

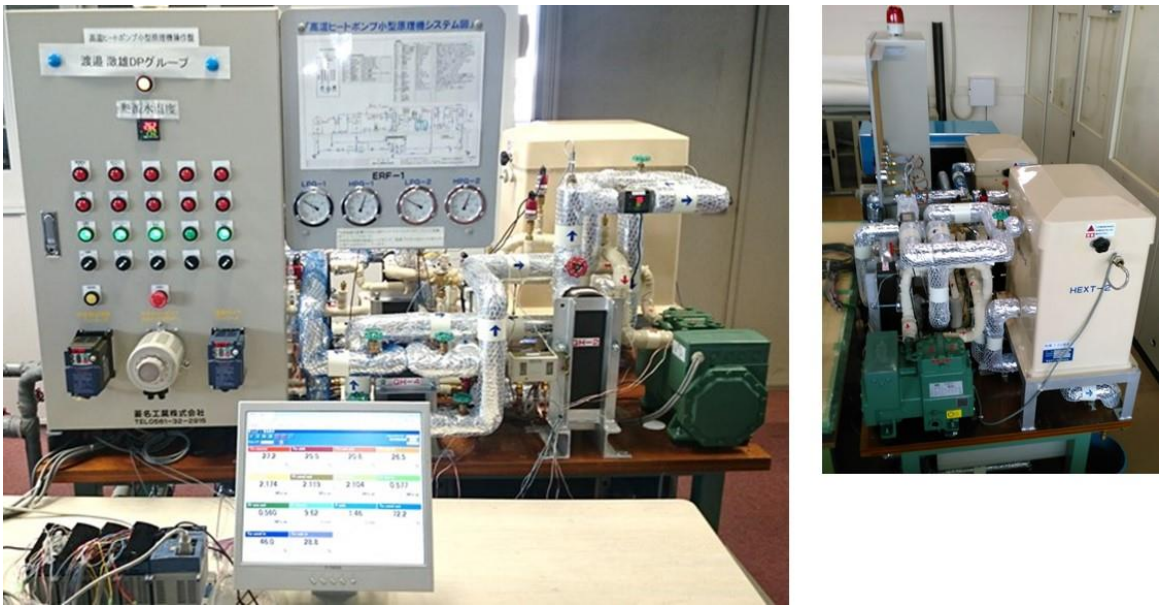


Fig. 4. Outside view of the experimental apparatus

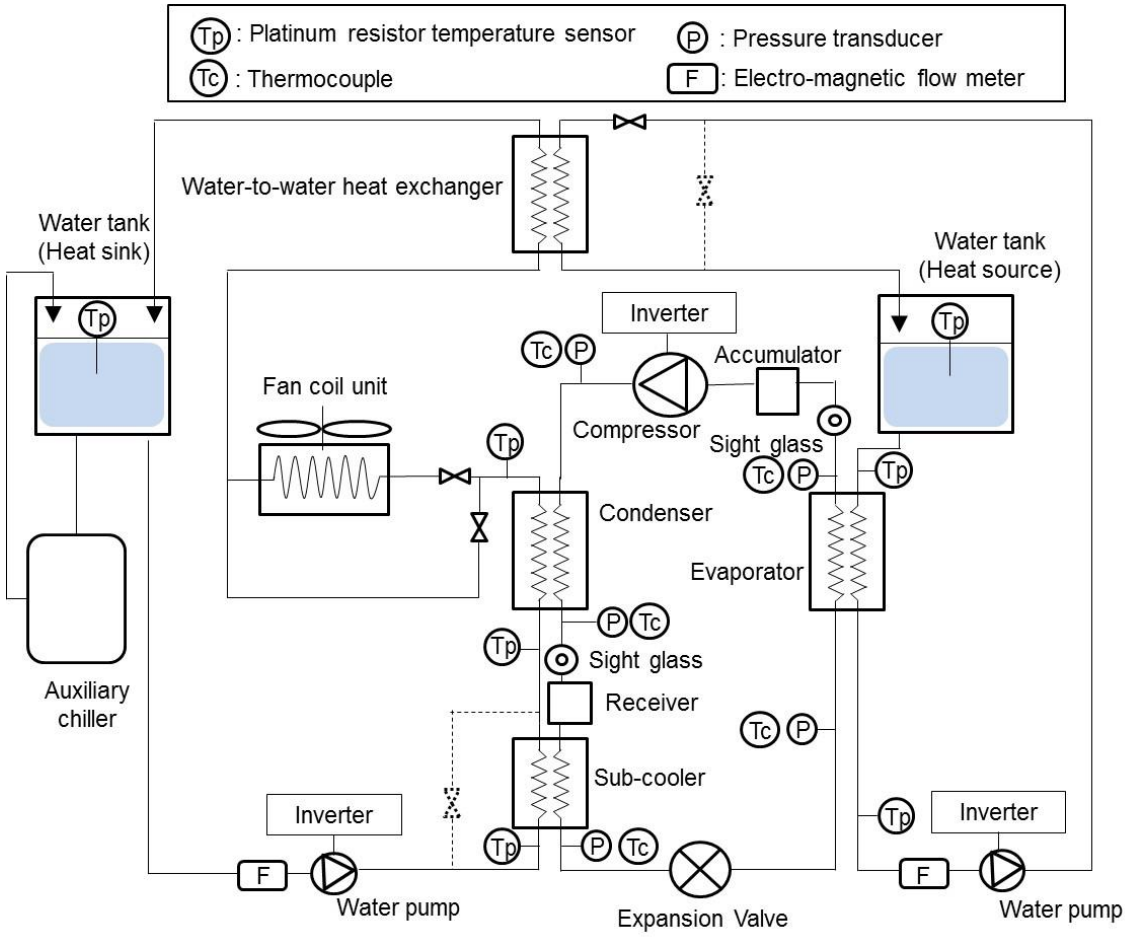


Fig. 5. Schematic drawing of the apparatus and measure points

5. Experimental results

Experimental results are shown in Table 5. Nominal temperature of heat source water corresponds to the water temperature at the inlet of the evaporator. Nominal temperature of heat source water is 25 °C in the table column of test No. 1 and test No. 2, being equivalent to average outside air temperature in the summer period in Japan. Nominal temperature of heat source water is 17 °C in the table column of test No. 3 and test No. 4, being equivalent to average outside air temperature in the intermediate period in Japan. Nominal temperature of heat source water is 7 °C in the table column of test No. 5 and test No. 6, being equivalent to average outside air temperature in the winter period in Japan. But the water temperature at the inlet of the evaporator in the test No. 5 and test No. 6 is unsuccessfully controlled, and then, became 7.7 °C in the test No. 5 and 8.7 °C in the test No. 6. The precise temperature control will be made the next task.

Nominal temperature of hot water corresponding to the water temperature at the inlet of the sub-cooler. Nominal temperature of hot water is 65 °C in the table column of test No. 1, test No.3 and test No. 5. Nominal temperature of hot water is 80 °C in the table column of test No. 2, test No.4 and test No. 6.

Fig. 6 shows heating capacity and heating COP when nominal temperature of hot water is 65 °C, and Fig. 7 shows heating capacity and heating COP when nominal temperature of hot water is 80 °C. Heating COP is defined as the ratio of heating capacity to electric power input to the compressor.

Fig. 8 shows the pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of the refrigerant cycle corresponding to the test No. 2. In the test No. 2, heating capacity is 4.75 kW; electric power input to the compressor is 1.18 kW; heating COP is 4.02; heat sink water temperature at the outlet of the condenser is 79.8 °C; heat sink water temperature at the inlet of the sub-cooler is 23.5 °C; heat source water temperature at the inlet of the evaporator is 25.5 °C; heat source water temperature at the outlet of the evaporator is 19.8 °C. Refrigerant pressure at the inlet of the condenser is 2.39 MPa; Refrigerant pressure at the outlet of the sub-cooler is 2.30 MPa; Refrigerant pressure at the inlet of the evaporator is 0.54 MPa; Refrigerant pressure at the outlet of the evaporator is 0.52 MPa; and then, the compression ratio of the compressor is 4.6. The degree of sub-cooling is 47 °C.

Fig. 9 shows the pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of the refrigerant cycle corresponding to the test No. 3. In the test No. 3, heating capacity is 4.16 kW; electric power input to the compressor is 0.97 kW; heating COP is 4.29; heat sink water temperature at the outlet of the condenser is 64.9 °C; heat sink water temperature at the inlet of the sub-cooler is 15.1 °C; heat source water temperature at the inlet of the evaporator is 15.8 °C; heat source water temperature at the outlet of the evaporator is 10.8 °C. Refrigerant pressure at the inlet of the condenser is 1.71 MPa; Refrigerant pressure at the outlet of the sub-cooler is 1.65 MPa; Refrigerant pressure at the inlet of the evaporator is 0.41 MPa; Refrigerant pressure at the outlet of the evaporator is 0.39 MPa; and then, the compression ratio of the compressor is 4.4. The degree of sub-cooling is 42 °C.

Fig. 10 shows the pressure-enthalpy diagram (left) and the temperature-entropy diagram (right) of the refrigerant cycle corresponding to the test No. 5. In the test No. 5, heating capacity is 3.55 kW; electric power input to the compressor is 0.88 kW; heating COP is 4.03; when heat sink water temperature at the outlet of the condenser is 65.0 °C; heat sink water temperature at the inlet of the sub-cooler is 8.4 °C; heat source water temperature at the inlet of the evaporator is 7.7 °C; heat source water temperature at the outlet of the evaporator is 3.2 °C. Refrigerant pressure at the inlet of the condenser is 1.65 MPa; Refrigerant pressure at the outlet of the sub-cooler is 1.60 MPa; Refrigerant pressure at the inlet of the evaporator is 0.33 MPa; Refrigerant pressure at the outlet of the evaporator is 0.32 MPa; and then, the compression ratio of the compressor is 5.2. The degree of sub-cooling is 48 °C.

Table 5. Experimental results of the sub-critical cycle heat pump with larger degree of sub-cooling than 40 °C

Test No.			1	2	3	4	5	6
Nominal temperature of heat source water (°C)			25	25	16	16	7	7
Nominal temperature of hot water (°C)			65	80	65	80	65	80
Condenser and Sub-cooler	Water temperature (°C)	Outlet of condenser	65.1	79.8	64.9	80.3	65.0	80.1
		Inlet of condenser	35.8	47.1	31.3	40.7	27.6	36.6
		Inlet of sub-cooler	23.6	23.5	15.1	16.6	8.4	9.5
	Refrigerant Temperature (°C)	Inlet of condenser	74.7	83.9	73.9	87.0	76.2	86.6
		Outlet of condenser	58	72.4	56.5	69.2	54.6	66.6
		Outlet of sub-cooler	26.3	28.6	18.1	21.3	11.8	14.2
	Refrigerant pressure (MPa)	Inlet of condenser	1.76	2.39	1.71	2.30	1.65	2.26
		Outlet of condenser	1.70	2.33	1.66	2.24	1.61	2.21
		Outlet of sub-cooler	1.68	2.30	1.65	2.23	1.60	2.19
Evaporator	Water Temperature (°C)	Inlet of evaporator	25.1	25.5	15.8	16.0	7.7	8.7
		Outlet of evaporator	18.5	19.8	10.8	11.1	3.2	4.6
	Refrigerant temperature (°C)	Outlet of evaporator	14.4	16.1	7.2	8.3	1.3	3.2
		Inlet of evaporator	14.9	16.6	7.9	8.9	2	3.7
	Refrigerant Pressure (MPa)	Outlet of evaporator	0.49	0.52	0.39	0.41	0.32	0.35
		Inlet of evaporator	0.51	0.54	0.41	0.42	0.33	0.36

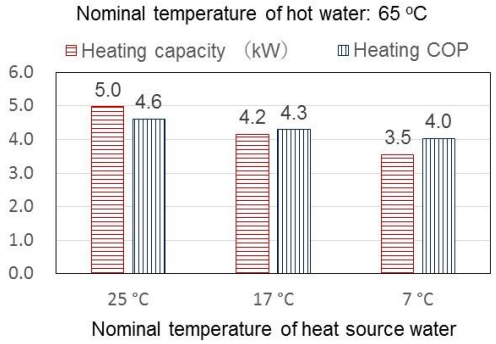


Fig. 6. Heating capacity and heating COP (Nominal temperature of hot water 65 °C)

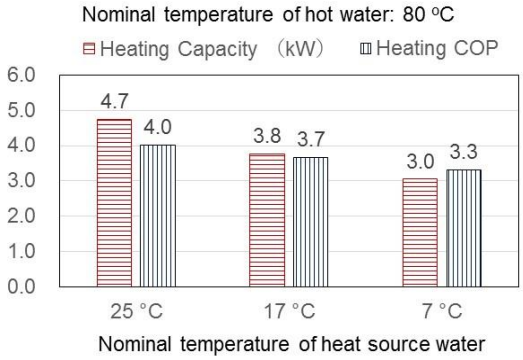
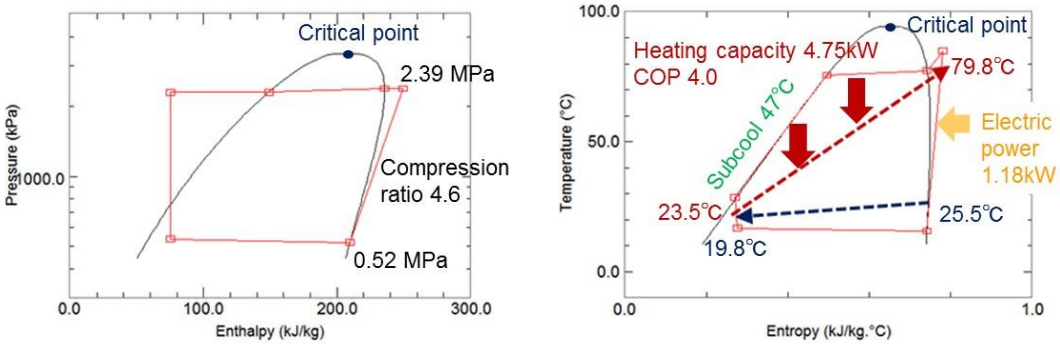
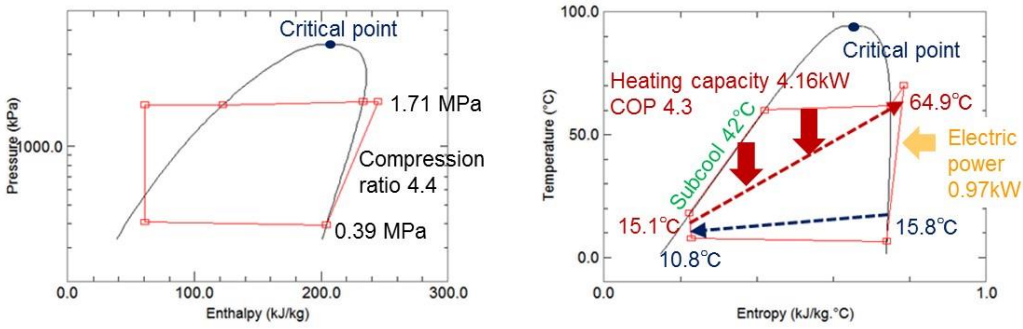


Fig. 7. Heating capacity and heating COP (Nominal temperature of hot water 80 °C)



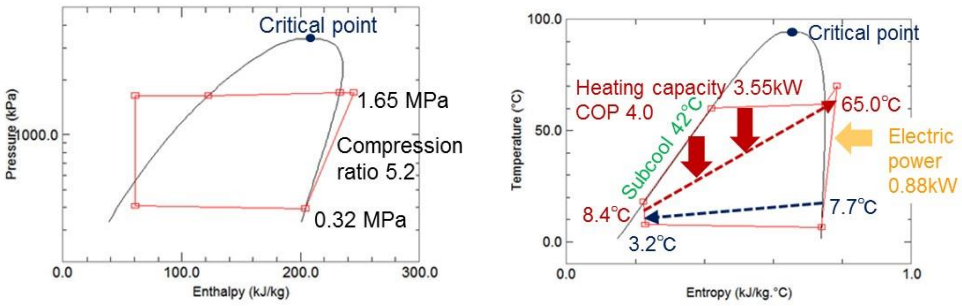
Pressure-enthalpy diagram Temperature-entropy diagram

Fig. 8. The R1234yf sub-critical cycle with larger degree of sub-cooling than 40 °C (Test No. 2)



Pressure-enthalpy diagram Temperature-entropy diagram

Fig. 9. The R1234yf sub-critical cycle with larger degree of sub-cooling than 40 °C (Test No. 3)



Pressure-enthalpy diagram Temperature-entropy diagram

Fig. 10. The R1234yf sub-critical cycle with larger degree of sub-cooling than 40 °C (Test No. 5)

6. Conclusion

An HFO refrigerant R1234yf is selected to heat water or air to the temperature range from 65 °C to 80 °C while the temperature of heat source water or air is in the range from 8 °C to 25 °C. Since the highest pressure of the R1234yf sub-critical cycles is under 3 MPa for 80 °C heating, use of common parts for air-conditioner or refrigerators are enabled. The R1234yf sub-critical cycles enable both lower temperature-rise heating than 10 °C efficiently without the sub-cooler and higher temperature-rise heating than 40 °C efficiently with the sub-cooler.

Sub-critical heat pump cycles with larger degree of sub-cooling than 40 °C were discussed and tested for high temperature-rise heating to supply hot water or hot air. An experimental apparatus and experimental results were

presented. Regarding the sub-critical heat pump cycles with larger degree of sub-cooling than 40 °C, the experimental results have been obtained, which the heating COP reaches 4.0 when the hot water temperature is 80 °C and the source water temperature is 26 °C, and the heating COP reaches 4.0 when the hot water temperature is 65 °C and the source water temperature is 8 °C.

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