

DEVELOPMENT AND FIELD TESTS OF 75kW CLASS CO₂ REFRIGERANT HEAT PUMP

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Abstract: We have developed the air-source CO₂ refrigerant heat pump for hot water supply with a heating power of 75 kW class. The developed heat pump has the largest heating power as the air-source CO₂ refrigerant heat pump in Japan. The performance tests of the developed heat pump were conducted in the climatic environmental testing room. Heating power for hot water supply and COPs was measured. The field test of the developed heat pump was conducted at a tourist hotel with public baths in a semi-cold district, and the seasonal energy efficiency of the developed heat pump was evaluated. On the basis of the results, the CO₂ emission due to the energy consumption of the developed heat pump in the semi-cold district is estimated to be 39.9% lower than that of the heavy oil boiler and 16.0% lower than that of the natural gas boiler. The performance and reliability of the developed heat pump were verified and the developed heat pump was improved for its commercialization. Furthermore, the energy measurement of the six commercialized heat pumps installed in the public bathhouse in a warm district was conducted and the annual energy efficiency of the commercialized heat pumps was evaluated. On the basis of the results, the CO₂ emission due to the energy consumption of the commercialized heat pumps in the warm district is estimated to be 45.4% lower than that of the heavy oil boilers and 23.6% lower than that of the natural gas boilers.

Key Words: CO₂ Refrigerant, Heat Pump, 75kW Class, Heating Power

1 INTRODUCTION

Air-source CO₂ refrigerant heat pumps in the heating power range 4 to 28 kW, which supply hot water to residences, food service stores, etc., have been developed in Japan. However,

heat pumps with more heating power are required for hot water supply to public bathhouses, tourist hotels, hospitals and welfare facilities for the aged.

We have developed the air-source CO₂ refrigerant heat pump for hot water supply with a heating power of 75 kW class. The developed heat pump has the largest heating power as the air-source CO₂ refrigerant heat pump in Japan. It is very important to verify the performance and reliability of the developed heat pump and improve the developed heat pump. The performance tests in the climatic environmental testing room and the field tests at a tourist hotel with public baths in a semi-cold district were conducted. Furthermore, the energy measurement of the improved and commercialized heat pumps installed in the public bathhouse in a warm district was conducted and the annual energy efficiency of the developed heat pump was evaluated.

2 OUTLINE OF 75kW CLASS CO₂ REFRIGERANT HEAT PUMP

The outside appearance of the 75kW class CO₂ refrigerant heat pump is shown in Figure 1 and the specifications are shown in Table 1. The highest temperature of leaving water was determined as 90°C for heat storage in the hot water tank mainly in use of inexpensive electric power in the night time. The multiple capillary tube system was adapted as the mechanism of CO₂ gas expansion in order to enable rapid supply of hot water. The semi-hermetic 2-cylinder reciprocating compressor developed by Mayekawa Mfg. Co., Ltd., shown in Table 2, was adopted in order that CO₂ gas discharge pressure may be higher enough to supply hot water at a temperature of 90°C.



Figure 1: Outside Appearance of the 75kW Class CO₂ Refrigerant Heat Pump

Table 1; Specifications of the 75kW Class CO₂ Refrigerant Heat Pump

Heating Power (kW)	75	78
Leaving Water Temperature (°C)	90	65
Entering Water Temperature (°C)	17	17
Hot Water Flow Rate (l/h)	833	1398
Ambient Temperature (°C)	16 (DB), 12 (WB)	16 (DB), 12 (WB)
Electric power input (kW)	23.4	20.5
Electric Power Supply	200 V - 3 Phase - 60 Hz	
Refrigerant	CO ₂	
CO ₂ Gas Cooler	Copper Double Tube Heat Exchanger	
CO ₂ Liquid Evaporator	Copper Tube and Aluminum Plate Fin Heat Exchanger	
Mechanism of CO ₂ Gas Expansion	Multiple Capillary Tube System	
Dimension (mm)	1140 (Width) X 2085 (Length) X 2070 (Height)	
Weight (kg)	1,525 (Running 1,550)	

Note; DB: Dry Bulb Temperature, WB: Wet Bulb Temperature

Table 2; Specifications of the Adapted Compressor

Model	2HT
Type	Semi-Hermetic 2-Cylinder Reciprocating
Refrigerant	CO ₂
Speed (rpm)	900 (Minimum), 1,800 (Maximum)
Type of Motor	3 Phase Induction Motor
Displacement Volume (m³/h)	12.5 at 1,450 rpm
Suction Pressure (MPa)	7.0 (Maximum)
Discharge Pressure (MPa)	15.0 (Maximum)

3 PERFORMANCE TESTS OF THE CO₂ REFRIGERANT HEAT PUMP

The performance tests of the developed heat pump were conducted in the climatic environmental testing room in the research and development division of Chubu Electric Power Co., Inc. Heating power for hot water supply and COPs (heating power divided by electric power input) were measured. The conditions for the measurement of heating power and COPs were as follows; ambient temperature range: -10 to 43°C, entering water temperature range: 5 to 50°C, leaving water temperature range: 65 to 90°C.



Figure 2: the Developed Heat Pump Tested in the Climatic Environmental Testing Room

3.1 Rated Performance Tests

The performance test standard of the heat pump water heater for business use is not established. Consequently, rated performance tests were conducted on the basis of The Japan Refrigeration and Air Conditioning Industry Association (JRAIA) Standard (JRA4050: 2001); "Performance and Rating Criteria for Residential Heat Pump Water Heater". The conditions for the rated performance tests are shown in Table 3.

Table 3; Conditions for Rated Performance Tests (JRA4050: 2001)

	Ambient Temperature (°C)	Entering Water Temperature (°C)	Leaving Water Temperature (°C)
(a) Rated Heating Test	16 (DB), 12 (WB)	17	65
(b) High Temperature Heating Test during Winter	7 (DB), 6 (WB)	9	90
(c) Defrosting Test during Winter	2 (DB), 1 (WB)	5	90
(d) Overload Test	43 (DB), 26 (WB)	29	90

The results of the rated performance tests are shown in Table 4. The measured values of heating power are more than 95% of target values and measured values of COPs are more than 90% of target values.

Table 4; Results of Rated Performance Tests

	Heating Power (kW)		COP	
	Target Value	Measured Value	Target Value	Measured Value
(a) Rated Heating Test	78.0	74.4 (95.4%)	3.80	3.48 (91.6%)
(b) High Temperature Heating Test during Winter	66.0	68.4 (103.6%)	3.00	2.96 (98.7%)
(c) Defrosting Test during Winter	-	41.5	-	2.10
(d) Overload Test	70.7	72.5 (102.5%)	2.80	2.83 (101.1%)

The trend curves of leaving water temperature, heating power and COPs are shown in Fig. 3. The trend curves in (a) rated heating test, (b) high temperature heating test during winter and (d) overload test are stable. However, the trend curves in (c) defrosting test during winter are varied periodically because the frosting and defrosting of the aluminium plate fin evaporator is repeated.

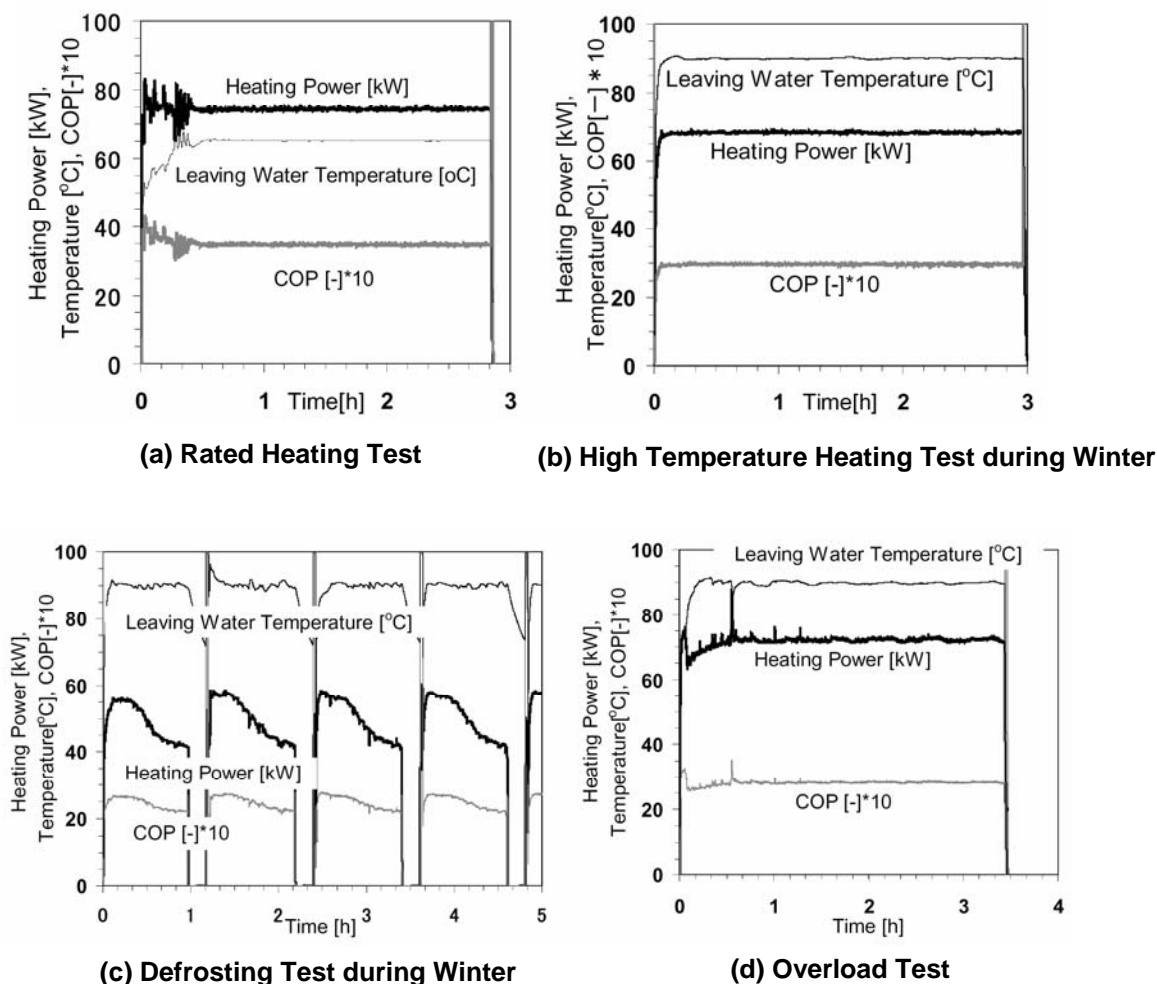


Figure 3: Trend Curves of Leaving Water Temperature, Heating power and COPs (Rated Performance Tests)

3.2 High Temperature Heating Test during Mid-season

High temperature heating test during mid-season (i.e. autumn or spring) was conducted in order to confirm specified values in Table 1. The conditions for the test are shown in Table 5 and the results of the test are shown in Table 6.

Table 5; Conditions for High Temperature Heating Test during Mid-season

	Ambient Temperature (°C)	Entering Water Temperature (°C)	Leaving Water Temperature (°C)
(e) High Temperature Heating Test during Mid-season	16 (DB), 12 (WB)	17	90

Table 6; Results of High Temperature Heating Test during Mid-season

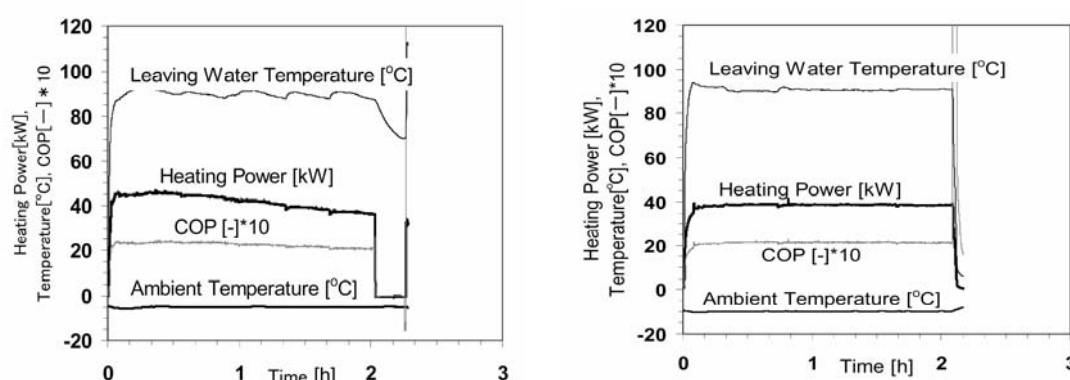
	Heating power (kW)		COP	
	Target Value	Measured Value	Target Value	Measured Value
(e) High Temperature Heating Test during Mid-season	75.0	73.2 (97.6%)	3.20	3.02 (94.4%)

3.3 High Temperature Heating Tests during winter in Semi-cold Districts

High temperature heating tests during winter in semi-cold districts were conducted. The conditions for the tests are shown in Table 7 and the results of the tests are shown in Table 8. In Figure 4, the trend curves of (f) low temperature (-5°CDB) ambient test and (g) low temperature (-10°CDB) ambient test show the one cycle of frosting and defrosting. The frosting and defrosting cycle time of (f) low temperature (-5°CDB) ambient test and (g) low temperature (-10°CDB) ambient test in Figure 4 are nearly 2 hours and nearly double as long as that of (c) defrosting test during winter (Ambient 2°CDB) in Figure 3. This is due to the reduction of absolute water volume in ambient air with decreasing temperature.

Table 7; Conditions of High Temperature Heating Tests during Winter in Semi-cold Districts

	Ambient Temperature (°C)	Entering Water Temperature (°C)	Leaving Water Temperature (°C)
(f) Low Temperature (-5°CDB) Ambient Test	-5 (DB), -6 (WB)	5	90
(g) Low Temperature (-10°CDB) Ambient Test	-10 (DB), -11 (WB)	5	90



(f) Low Temperature (-5°CDB) Ambient Test

(g) Low Temperature (-10°CDB) Ambient Test

**Figure 4: Trend Curves of Water Temperature, Heating power and COPs
(High Temperature Heating Tests during Winter in Semi-cold Districts)**

Table 8; Results of High Temperature Heating Tests during Winter in Semi-cold Districts

Type of Test	Heating power (kW)	COP
	Measured Value	Measured Value
(f) Low Temperature (-5°CDB) Ambient Test	47.8	2.36
(g) Low Temperature (-10°CDB) Ambient Test	38.9	2.14

3.4 High Temperature Entering Water Tests

High temperature entering water tests during summer, mid-season and winter were conducted in order to confirm the performance for re-heating of hot water returned from the hot water storage tank. The conditions for the tests are shown in Table 9 and the results of the test are shown in Table 10.

Table 9; Conditions for High Temperature Entering Water Tests

Type of Test	Ambient Temperature (°C)	Entering Water Temperature (°C)	Leaving Water Temperature (°C)
(h) High Temperature Entering Water Test during Summer	25 (DB), 21 (WB)	50	90
(i) High Temperature Entering Water Test during Mid-season	16(DB), 12 (WB)	50	90
(j) High Temperature Entering Water Test during Winter	7 (DB), 6(WB)	50	90

Table 10; Results of High Temperature Entering Water Tests

Type of Test	Heating power (kW)	COP
	Measured Value	Measured Value
(h) High Temperature Entering Water Test during Summer	48.5	1.84
(i) High Temperature Entering Water Test during Mid-season	47.5	1.85
(j) High Temperature Entering Water Test during Winter	46.9	1.88

3.5 Leaving Water Temperature Rise Rate Tests

The rising rate of the leaving water temperature in the rated heating condition was measured. The trend curve of the leaving water temperature is shown in Figure 5. It took only 26 seconds for the leaving water temperature to reach 65°C from 17°C. This high rising rate is attributed to the simplified piping system by the multiple capillary tube system adapted as the mechanism of CO₂ gas expansion.

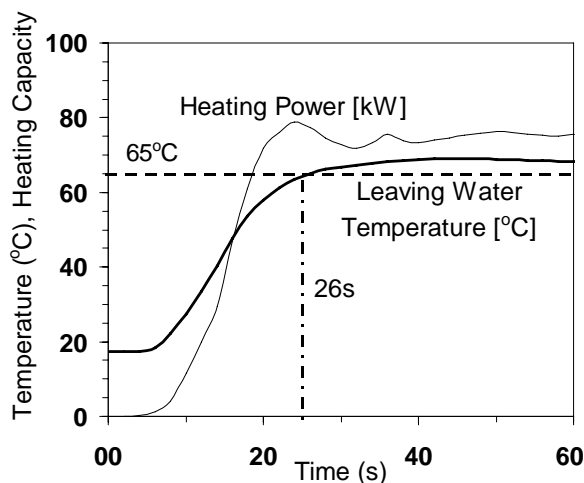


Figure 5: Trend Curve of Leaving Water Temperature

4 FIELD TEST AT A HOTEL WITH PUBLIC BATHS IN A SEMI-COLD DISTRICT

Field test of the developed heat pump was conducted at a tourist hotel with public baths at highlands near Mt. Fuji in Shizuoka Pref. in February to July 2005. The developed heat pump installed at the hotel is shown in Figure 6. Snow hoods were set at the inlet and outlet of air. The flow of the hot water supply system including the developed heat pump, the existing heavy oil boiler, and hot water tanks is shown in Figure 7.



Figure 6: the Developed Heat Pump Installed at a Tourist Hotel

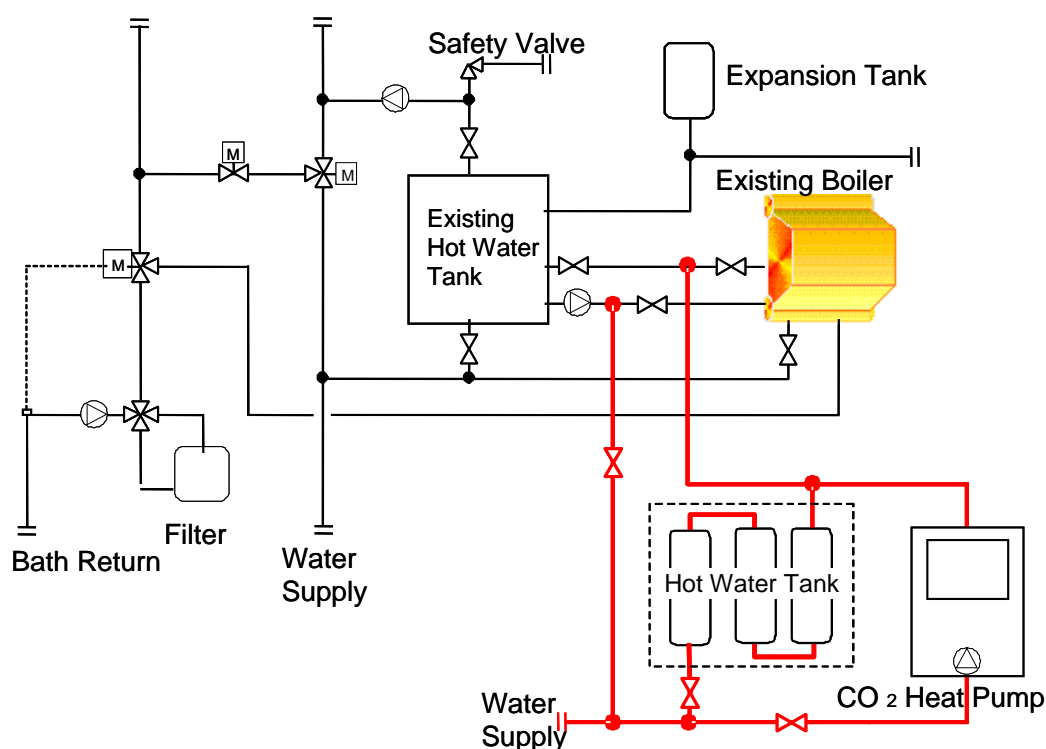


Figure 7: Flow of Hot Water Supply System

The temperature ranges of the field test are shown in Table 11. Monthly average values of the field test results are shown in Table 12. The annual average or total values, shown in Table 13, were estimated from the half-year values shown in Table 12. The average COP as the seasonal energy efficiency of the developed heat pump was 2.73. The CO₂ emissions due to the energy consumption of the developed heat pump, the heavy oil boiler and the natural gas boiler are shown in Table 14. The CO₂ emission of the developed heat pump is estimated to be 39.9% lower than that of the heavy oil boiler and 16.0% lower than that of the natural gas boiler. The operation results of the winter days 24 to 25 February are shown in Figure 8.

Table 11 Temperature Ranges of Field Test

Ambient Temperature (°C)	-2.8~23.8
Entering Water Temperature (°C)	10.8~50.2

Table 12; Monthly Average Values of Field Test Results

Month	Ambient Temperature (°C)	Entering Water Temperature (°C)	Leaving Water Temperature (°C)	Heating Capacity (kW)	COP
February	0.3	11.9	87.2	49.0	2.60
March	3.8	19.1	91.9	51.3	2.53
April	6.9	16.5	88.8	57.1	2.71
May	11.0	18.1	89.9	58.3	2.95
Jun	17.3	28.4	90.5	62.5	2.67
July	20.0	24.1	90.5	67.2	2.88

Table 13; Annual Average or Total Values Estimated from Table 12

Average Ambient Temperature (°C)	Average Entering Water Temperature (°C)	Average Leaving Water Temperature (°C)
9.9	19.7	89.8

Total Amount of Electric Power Input (MWh/Y)	Total Heat Supplied (GJ/Y)	Average COP
57.0	560	2.73

Table 14; Annual Primary Energy Consumption and CO₂ Emissions

	Primary Energy Consumption (GJ/Y)	CO ₂ Emission (Ton- CO ₂ /Y)		
CO ₂ Refrigerant Heat Pump	557 ^{*1}	27.4 ^{*3}	(84.0%)	(60.1%)
Natural Gas Boiler	659 ^{*2}	32.6 ^{*4}	(100%)	-
Heavy Oil Boiler	659 ^{*2}	45.6 ^{*5}	-	(100%)

*1: Primary Energy Efficiency of Thermal Power Plant at the Demand Side in Japan: 0.369 (1 kWh of electric power generation is considered to need 9,760 kJ of primary energy.)

*2: Boiler Efficiency: 85%

*3: CO₂ Emission Coefficient for Electric Power: 0.481kg- CO₂/kWh (Chubu Electric Power, 2006)

*4: CO₂ Emission Coefficient for Liquefied Natural Gas: 49.5 kg-CO₂/GJ (Ministry of the Environment, Government of Japan, 2006)

*5: CO₂ Emission Coefficient for Heavy Oil: 69.3 kg-CO₂/GJ (Ministry of the Environment, Government of Japan, 2006)

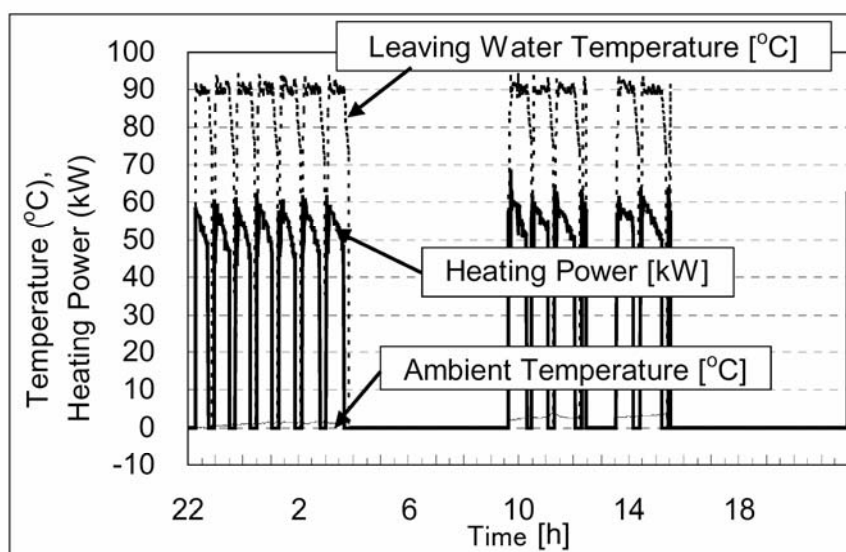


Figure 8: Operation Results of Winter Days

5 IMPROVEMENT AND COMMERCIALIZATION OF THE DEVELOPED HEAT PUMP

The developed heat pump has been improved considering productivity and commercialized. The rated performance tests of the commercialized heat pump were conducted in the climatic environmental testing room in the Higashihiroshima factory of Mayekawa Mfg. Co., Ltd. The results of the tests are shown in Table 15.

Table 15; Results of Rated Performance Tests (Commercialized Heat Pump)

Type of Test	Heating power (kW)		COP	
	Target Value	Measured Value	Target Value	Measured Value
(a) Rated Heating Test	78.0	79.7 (102.1%)	3.80	3.45 (90.7%)
(b) High Temperature Heating Test during Winter	66.0	70.1 (103.6%)	3.00	3.03 (101.0%)
(c) Defrosting Test during Winter	-	54.1	-	2.40
(d) Overload Test	70.7	92.8 (131.3%)	2.80	3.44 (122.9%)

6 ENERGY MEASUREMENT OF THE COMMERCIALIZED HEAT PUMP AT A PUBLIC BATHHOUSE IN A WARM DISTRICT

The energy measurement of the improved and commercialized heat pump was conducted at a public bathhouse in Okazaki city in Aichi Prefecture in May 2006 to April 2007. The outside appearance of the public bathhouse and six heat pumps installed are shown in Figure 9. Monthly average values of the energy measurement are shown in Table 16. The average COP as the seasonal energy efficiency of the developed heat pump was 3.0. On the basis of the results, the CO₂ emission due to the energy consumption of the developed heat pumps in the warm district is estimated to be 45.4% lower than that of the heavy oil boilers and 20.6% lower than that of the natural gas boilers.

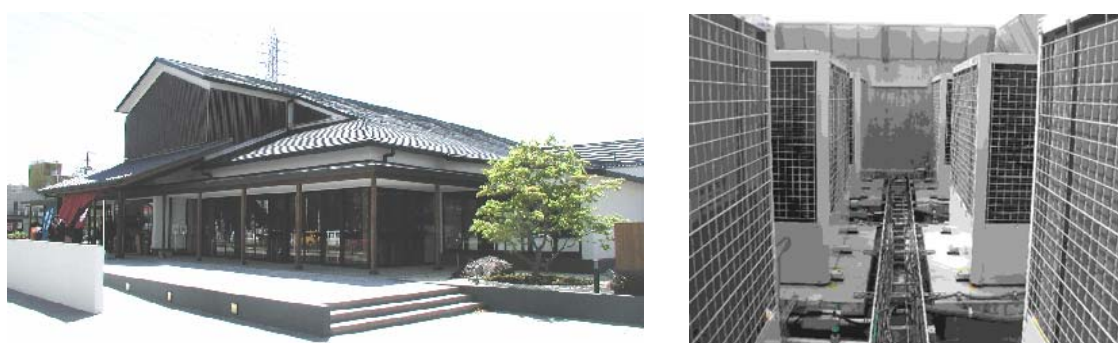


Figure 9: Photograph of a Public Bathhouse (Left) and Six CO₂ Heat Pumps (Right)

Table 16; Monthly Average Values of Energy Measurement

	Ambient Temperature (°C)	Entering Water Temperature (°C)	Leaving Water Temperature (°C)	Total Running Time of Six Heat Pumps (h)	Heat Supplied (GJ)	Amount of Electric Power Input (MWh)	COP
May '06	17.0	18.0	91.8	1,255	360	31.80	3.1
Jun. '06	20.7	21.8	90.6	1,063	319	27.70	3.2
Jul. '06	23.9	24.2	90.6	1,008	304	26.56	3.2
Aug. '06	26.0	27.7	90.2	888	266	23.57	3.1
Sep. '06	20.5	24.8	91.0	990	316	26.45	3.3
Oct. '06	15.5	20.9	91.7	1,272	428	34.04	3.5
Nov. '06	12.4	15.8	91.5	1,385	379	34.22	3.1
Dec. '06	5.9	10.7	89.9	1,680	363	37.96	2.7
Jan. '07	4.4	8.4	87.3	1,702	355	37.65	2.6
Feb. '07	5.5	9.4	86.9	1,536	336	34.46	2.7
Mar. '07	6.8	10.8	86.3	1,575	373	36.85	2.8
Apr. '07	10.5	15.0	85.0	1,254	351	32.69	3.0

Table 17; Annual Average Values of Energy Measurement

Ambient Temperature (°C)	Entering Water Temperature (°C)	Leaving Water Temperature (°C)	Total Running Time of Six Heat Pumps (h)	Heat Supplied (GJ/Y)	Amount of Electric Power Input (MWh/Y)	COP
14.1	17.3	89.4	15,608	4,149	383.95	3.0

Table 18; Primary Energy Consumption and CO₂ Emissions

	Primary Energy Consumption (GJ/Y)	CO ₂ Emissions (Ton- CO ₂ /Y)		
CO2 Refrigerant Heat Pump	3,746* ¹	184.6* ³	(79.4%)	(54.6%)
Natural Gas Boiler	4,878* ²	232.5* ⁴	(100%)	-
Heavy Oil Boiler	4,878* ²	338.1* ⁵	-	(100%)

*¹: Primary Energy Efficiency of Thermal Power Plant at the Demand Side in Japan: 0.369 (1 kWh of electric power generation is considered to need 9,760 kJ of primary energy.)

*²: Boiler Efficiency: 85%

*³: CO₂ Emission Coefficient for Electric Power: 0.481kg- CO₂/kWh (Chubu Electric Power, 2006)

*⁴: CO₂ Emission Coefficient for Liquefied Natural Gas: 49.5 kg-CO₂/GJ (Ministry of the Environment, Government of Japan, 2006)

*⁵: CO₂ Emission Coefficient for Heavy Oil: 69.3 kg-CO₂/GJ (Ministry of the Environment, Government of Japan, 2006)

7 CONCLUSION

We have developed the air-source CO₂ refrigerant heat pump for hot water supply with a heating power of 75 kW class. The developed heat pump has the largest heating power as the air-source CO₂ refrigerant heat pump in Japan.

- (1) The performance tests of the developed heat pump were conducted in the climatic environmental testing room, and heating power and COPs were measured.
The conditions for the measurement were as follows; ambient temperature range: -10 to 43 °C, entering water temperature range: 5 to 50°C, leaving water temperature range: 65 to 90 °C.
- (2) It took only 26 seconds for the leaving water temperature to reach 65°C from 17°C. The high rising rate is attributed to the simplified piping system by the multiple capillary tube system adapted as the mechanism of CO₂ gas expansion.
- (3) The field test results of the developed heat pump in a semi-cold district during a half year were as follows; average ambient temperature: 9.9°C, average entering water temperature: 19.7°C, average leaving water temperature: 89.8°C, average COP 2.73.
On the basis of the results, the CO₂ emission due to the energy consumption of the developed heat pumps in the semi-cold district is estimated to be 39.9% lower than that of heavy oil boilers and 16.0% lower than that of natural gas boilers.
- (4) The energy measurement results of the commercialized heat pumps in a warm district during one year were as follows; average ambient temperature: 14.1°C, average entering water temperature: 17.3°C, average leaving water temperature: 89.4°C, average COP 3.0.
On the basis of the results, the CO₂ emission due to the energy consumption of the commercialized heat pumps in the warm district is estimated to be 45.4% lower than that of heavy oil boilers and 23.6% lower than that of natural gas boilers.

The commercialized heat pump has been further improved by Mayekawa Mfg. Co., Ltd.
The latest specified COPs are as follows:

COP 3.9 for 200V - 3Phase - 60Hz in the rated heating condition shown in Table 3 (a),
COP 4.1 for 200V - 3Phase - 50Hz in the rated heating condition shown in Table 3 (a).

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