AN OVERVIEW OF NATIONAL R&D PROJECTS IN HEAT PUMP TECHNOLOGY IN JAPAN

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ABSTRACT

Heat pump technology in Japan has developed as the core technology of the national "Moonlight Program/Energy Conservation Project" as illustrated by the "Super Heat Pump Energy Accumulation Project" (1984-1992). Recently, for the purpose of reducing greenhouse gas emissions, CO_2 working fluids have become the focus, and several combinations based on CO_2 working fluids have been developed and introduced.

Key Words: ***heat pump technology, national R&D projects, CO_2 working fluid, super heat pump, triple-effect absorption chiller-heater.***

1 INTRODUCTION

In Japan, the Moonlight Program started in 1976, and within the program a "Waste Heat Utilization Project" was executed. Starting in 1984, another project, "Super Heat Pump Energy Accumulation Project," followed. This project was very important because it doubled the COP value of earlier heat pumps in the 1000kw class for hot water supply. Subsequently, in 1993, the "Eco-Energy City Project" followed as part of "The New Sunshine Program." After that, the focus moved to reducing greenhouse gas emissions, and CO_2 was designated as a natural working fluid. Today, several applications for heat pump systems using CO_2 as the working fluid are being developed. This paper shows some example of Japanese national R&D in heat pump technology.

2 HISTORY

Figure 1 shows the sequential development of national R&D programs in Japan related to heat pump technology. Heat pump technology had been developed as the key technology of major national energy conservation projects until FY2000. Subsequently, each R&D project concentrated on more concrete subjects that have been executed under the National Strategic R&D Program for Energy Conservation.

2.1 Waste Heat Utilization Project (NEDO 1995)

This project is so called “target-driven development.” In order to utilize the waste heat exhaust from cities and industries, heat pump technology was developed. The outline is shown in Table 1.

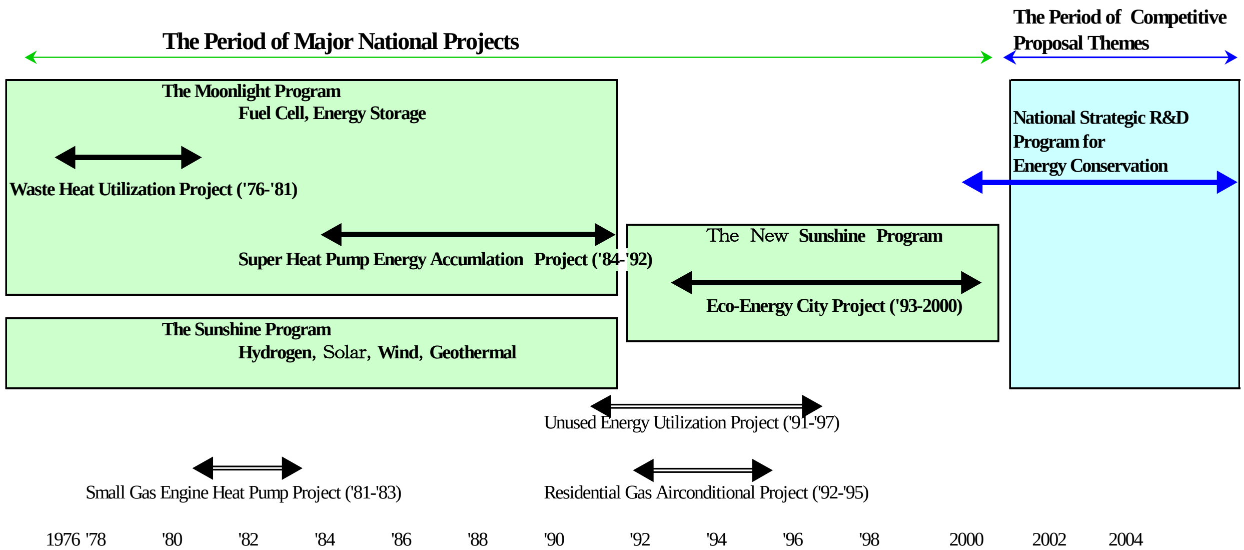


Fig. 1 Heat Pump Technology Development in National R&D Programs in Japan

Table 1. The outline of heat pump technology in Waste Heat Utilization Project

Theme	Object	COP	Inlet Temp.	Outlet Temp.	Application
Heat source duty corresponding	Heating	3.8	10℃	45℃	Regional air conditioning,
heat pump systems	Cooling	3.4	25℃	-	Industry
Low temperature heat sorce	Heating	3	5/2℃	60℃	Regional air conditioning
heat pump system	-	-	-	-	using sea water
Heat source duty corresponding	Heating	3.2	12/5℃	50/70℃	Regional air conditioning,
& cool temp utilize systems	Cooling	5	27/37℃	12/5℃	Buildings
Heat source duty corresponding	Heating	3.8	15/10℃	55/60℃	Regional air conditioning,
high-efficient heat pump systems	Cooling	6	25/30℃	12/7℃	Buildings
Natural heat source corresponding	Heating	1.4	7℃	42/47℃	Regional air conditioning,
absorption heat pump systems	Cooling	1.3	25℃	12/7℃	Buildings
Waste heat of city corresponding	Heating	1.8	15℃	42/47℃	Regional air conditioning,
heat pump systems	Cooling	1.5	25℃	12/7℃	Buildings
Waste heat derived	-	-	-	-	Waste heat from garbage
absorption heat pump systems	Cooling	0.53	60℃	7℃	Incineration

2.2 Super Heat Pump Energy Accumulation Project (NEDO 1997)

The Moonlight Program aimed to establish an energy conservation process combining a highly efficient heat pump and chemical heat reservoir. The main objectives were as follows:

(1) High energy conservation: Doubling of COP level
(2) High temperature output: 150℃～300℃
(3) Compact chemical heat reservoir
(4) CFC, HCFC-free working fluid

2.2.1 General results

General results of the project are shown in Table 2.

2.2.2 Sample results of high efficiency heating and cooling pump.

Specifications are as follows:

(1) Two stage economizer system (Fig. 2)
(2) Cog-shaped screw compressor
(3) Non-azeotrope medium as a working material
(4) Plate-fin type counter flow heat exchanger
(5) Out put Capacity: 1050kw

Table 2. Outline of Heat Pump Technology in Super Heat Pump Energy Accumulation Project

Category	Type	Object	COP	Inlet Temp.	Outlet Temp.
Compressive heat pump	High efficiency	Heating	8.1	50	85
			8.2	35	65
		Heating & cooling	6.2	10	45
			7.1	32	7
	High temperature output	For lower temp. heat source	3	50	150
			5	95	150
		For higher temp. heat source	3	150	300
			5.8	200	300

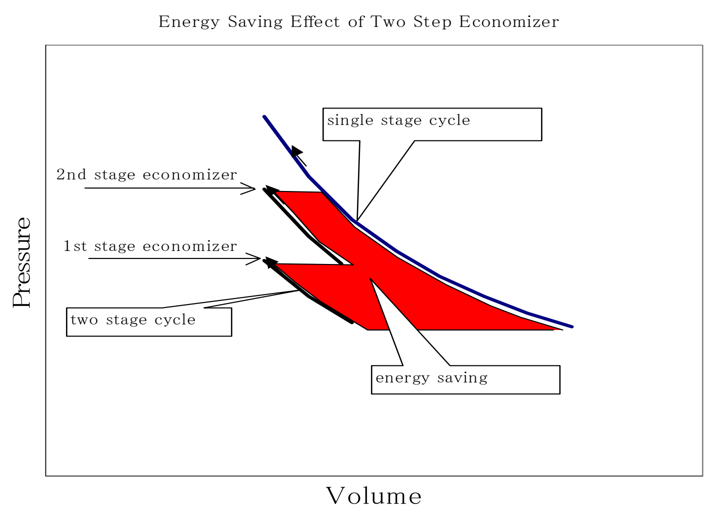


Fig. 2. Energy Saving Effect of Two Step Economizer

2.3 Eco-Energy City Project (A Heat Supply Incorporating an Efficient Heat Pump Complying with Multiple Fuels) (NEDO 2001)

2.3.1 Concept

The Eco-Energy City Project was aimed at constructing efficient wide-area energy networks to enable the utilization of energy in cascade style, such as to make effective use of untapped waste heat emitted by industrial plants at temperatures under 200℃.

2.3.2 Typical example of heat pump as key technology of Eco-Energy City Project

1) A heat supply system incorporating an efficient heat pump complying with multiple fuels

・A heat pump system using helium as the working gas, operated by a gas engine complying with multiple fuels, was developed to supply heat over a wide range of temperatures for refrigeration, cooling, heating, and hot water supply.

・Total COP=2.5 (fuel reformed gas, cold water: 7℃, hot water: 45℃, hot water supply: 80℃)

2) An electric, energy-saving heat pump system using natural refrigerants

・Absorption cycle using a natural working fluid for the heating and air-cooling system.

・COP Cooling: 0.83, Heating: 1.25

3 INTRODUCTION OF RECENT ACTIVITIES (THE PERIOD OF COMPETITIVE PROPOSAL THEMES)

3.1 CO_2 Two-Phase Flow Expand / Compressor

3.1.1 Purpose

To develop a more energy efficient, environment-friendly heat pump system for heating, suitable to cold climate regions.

3.1.2 Outline

CO_2 was used as the working fluid for the purpose of reducing greenhouse gas emissions.

By combining a two-phase flow expander and compressor by a common rotating shaft, energy recovery can be achieved.

3.1.3 Main item of development

Evaluation for the type of expander concerning the mechanisms of pumps and compressors was done in the first stage. A swing mechanism was selected because the estimated performance and reliability are high.

The expander was designed, and evaluation and a test trial were conducted in the second stage. Simulation was executed and mechanical and sealing technology were contrived for the new type of expander.

The third stage was to develop the expander-compressor unit in which the expander, motor, and compressor are connected with a single shaft.

3.1.4 Results

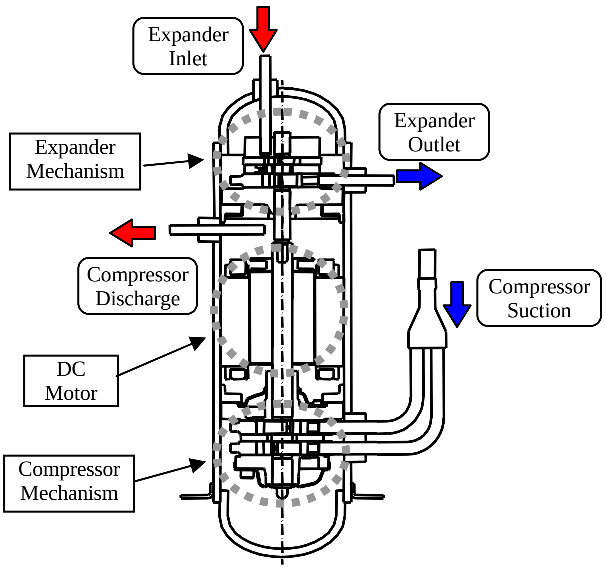
The following tables, 3 and 4, show the specifications and results of development, respectively. The values of COP for the CO_2 working fluid are approximate.

Table 3 Specifications

Category	Heating
Working fluid	CO_2
Room temperature	20 ^{0}**C**
Supply air temperature	45 ^{0}**C**
Capacity	14kW
COP result	3.7

Table 4 Results of development

Items	Results
Primary energy equivalent efficiency	139%
Efficiency of expander	59%
Average COP for heating season	2.85



(a) Cross Section

(b) Outlook

Fig. 3 Structure of hermetic prototype of Expander-Compressor Unit

3.2 Triple-Effect Absorption Chiller-Heater

3.2.1 Purpose

Recently the COP for a double-effect absorption chiller-heater was improved from 1.35 to 1.4, achieving the maximum level for a double-effect. In order to improve the COP to G.E. 1.6, the temperature of the re-generator must be raised, necessitating a triple-effect absorption chiller-heater, the objective of this project.

3.2.2 Outline

Multiple combination patterns of HTG, MTG, and LTG were concurrently developed by several companies, as shown in Fig. 4.

3.2.3 Main item of development

As HTG’s maximum temperature reaches 200℃, it is necessary to solve a corrosion problem and safety problem.

3.2.4 Result

The Japan Gas Association, aiming to acquire basic information, conducted various corrosion evaluations. As a result, it was clear that the combination of carbon steel and lithium molybdenum inhibiter could be utilized for the triple-effect absorption chiller-heater and is effective for temperatures up to 220℃.

Figure 6 shows the measured COP chart for trial products. It indicates a COP G.E. 1.6 for the rating load. A COP up to 1.8 is achieved at partial load.

A field test began in January 2003 under actual load conditions to confirm durability, load compliance and other performance factors of the 150RT test model. Total working time has now exceeded ten thousand hours, without serious trouble.

Table5. Target of development

Item	Target	Double-effect absorption
Efficiency of the triple-effect	Cooling COP: G.E. 1.6 (HHV Standard) Fuel consumption reduction	1.07 (current type)
Compactness	Chiller-heater volume: within 120% of double-effect	100%
Exhaust heat utilization	Fuel consumption reducing ratio utilizing the exhaust heat:	15%

Table 6. Specification of trial products

Category	Absorption chiller-heater
Working fluid	Water with lithium molybdenum inhibitor
Chilled water inlet temp.	12 or 15(deg)
Chilled water outlet temp.	7(deg)
Capacity	100～300RT
COP	G.E. 1.6

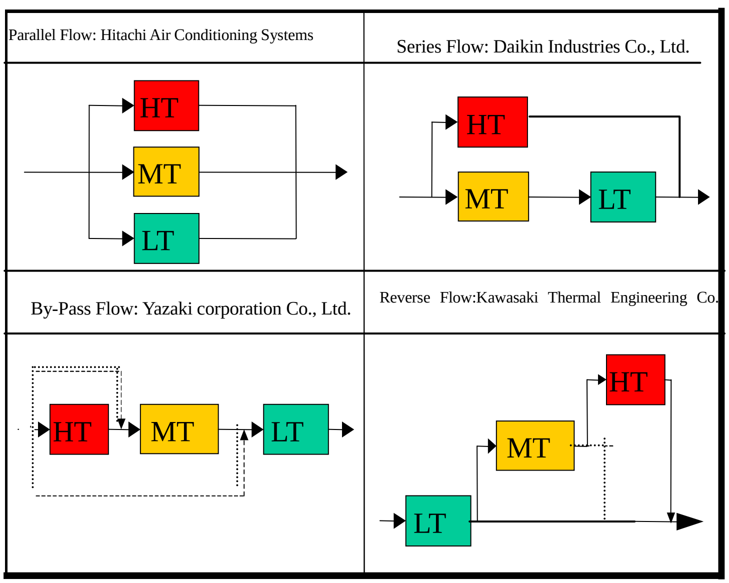


Fig. 4. Cycle type

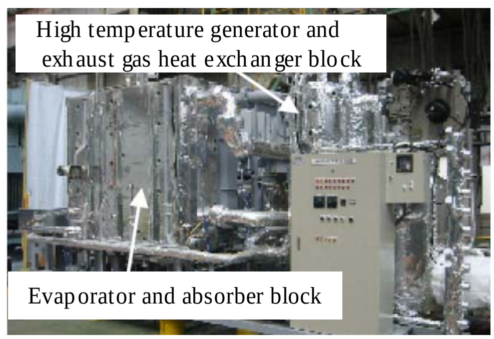


Fig. 5 The outside view of the developed absorption chiller heater

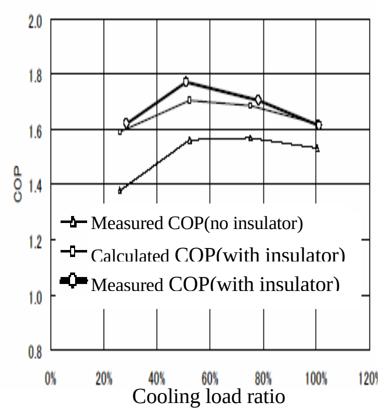


Fig. 6 Load ratio-COP relation

3.3 Hybrid System

3.3.1 Purpose

To develop a hybrid air-conditioning system to utilize the waste heat (60℃) from office buildings and commercial facilities.

3.3.2 Outline

Absorption Chiller utilizing waste heat (60℃) aiming for a cycle COP of 0.42. Variable compression ratio heat pump using natural working fluid aims for a cycle COP of 17.4. The combination of the two methods enables a system COP of 7.0.

3.3.3 Main item of development

The first step was to design a generator utilizing waste heat to improve efficiency in order to achieve an absorption chiller system. The second step was to enable the variable compression ratio and to improve heat exchange. The third stage was to develop a hybrid cycle and to achieve a total system.

3.3.4 Result

Table 7 shows the results of development and COP value for the hybrid air-conditioning system.

Table 7 the results of development

Items	
Total system	System COP=7.0
Absorption Chiller (Evaporating Temp.=10　Coolant Temp.=30　,Waste heat Temp.=60　)	Cycle COP=0.42
Variable compression ratio heat pump (Evaporating Temp.=7　Condensing Temp.=15　)	Cycle COP=17.4

Fig. 7. Outline of Machine

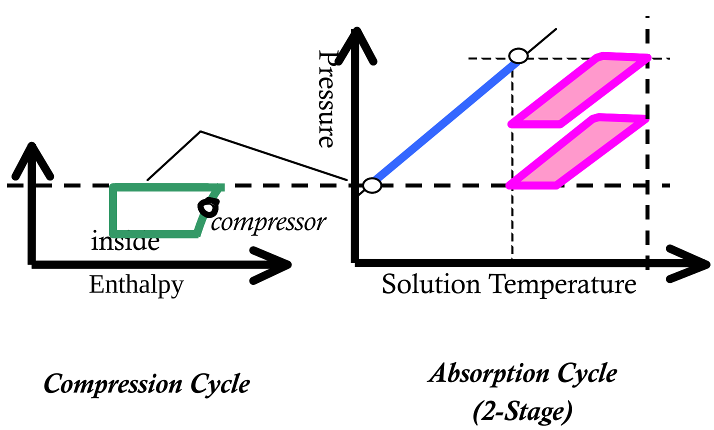


Fig. 8. PH & PT diagram

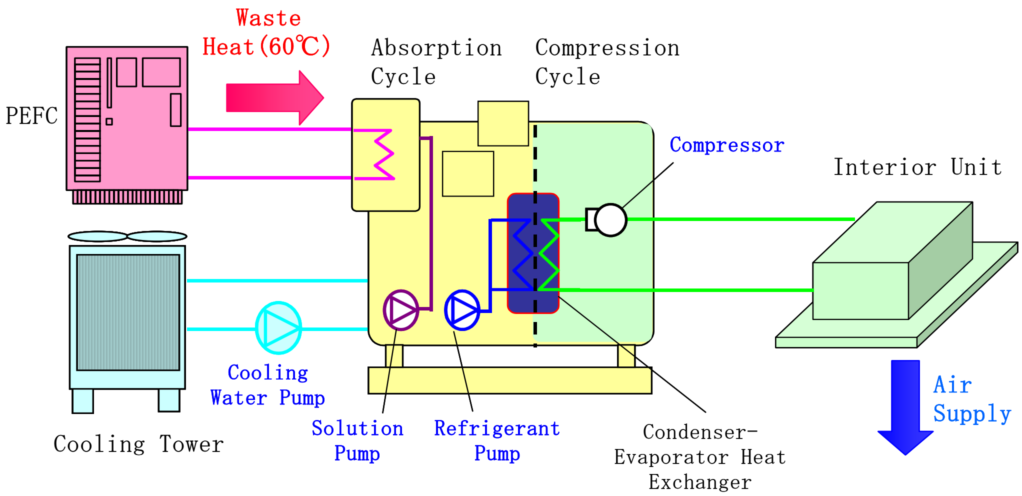


Fig. 9 Schematic diagram of systems

3.4 Air-Conditioning System for Cold Climate Area

3.4.1 Purpose

To develop a heat pump for recovering heat exhaust from houses, particularly in cold regions, as well as hybrid heat pumps for exhaust heat and ground heat.

3.4.2 Outline

Figure 10 shows the schematic illustration of the ground heat extraction system. Table 8 shows the specifications of the total system. Figure 11 shows the outline of the total system. Exhaust temperature is 22℃ and target COP is 2.5.

3.4.3 Main item of development

In order to recover the exhaust heat of a house, the heat exchanger was improved. From outside of the house, the heat exchanger is transferred to the exhaust air duct. Instead of a fan convector air heating system, recovery heat is converted to circulating hot water. Radiant heating is introduced to utilize the converted heat.

3.4.4 Result

Table 9 shows the results of the COP. Attained values exceeded targeted values.

Table 10 shows the effect of the hybrid heat pump on energy conservation.

Table 8 Specification

Category	Working fluid	Entrance circumstance temp.	Exit supply temp.	Capacity	COP result
Heating	R410	-12℃	37℃	2.25kW	3.75

Table 9 Total target of COP

	Targets	Results
Recovery of exhaust heat	2.5	2.4
Hybrid heat pump	3.5	3.75

Table 10 The Effect of hybrid heat pump on the energy conservation

	Targets	Results
to electric heating	1.7kl/house	1.8 kl/house
to oil heating	0.3 kl/house	0.5 kl/house

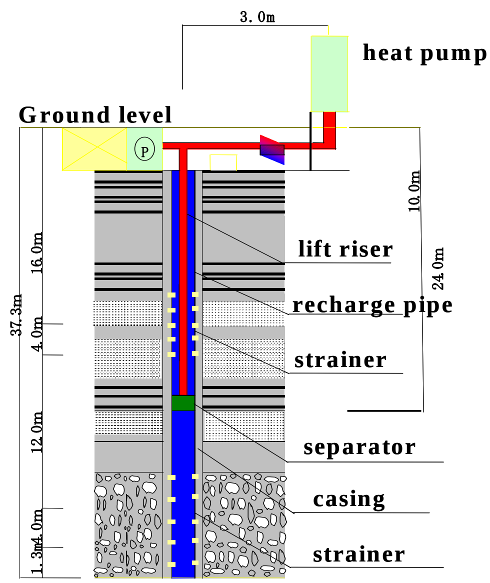


Fig. 10 Schematic illustration of ground heat extraction system

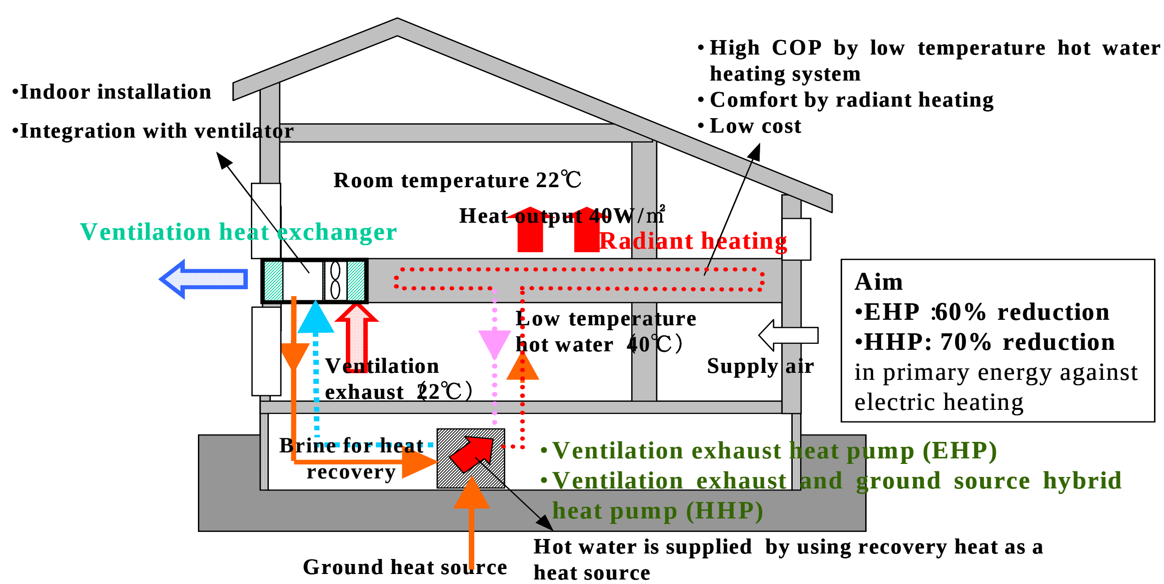


Fig. 11 The outline of total system

4 CONSIDERATION

4.1 Aim of Analysis

As mentioned until Chapter 2, several conditions such as temperature and mechanical conditions differ, respectively. It is not so easy to clear the phenomena of the heat pump and indicate the solution to improve the COP, here the trial is carried out by calibrating the temperature conditions and working fluid, and after that the remaining tasks are shown.

4.2 Method of Analysis

4.2.1 Effect of temperature

(1) Commercialized Products

Figure 13 shows the actual results of the temperature dependence of COP. The factors are very complicated, but can be simulated as follows;

(2) Model study

Calibration of working fluid was more difficult, because each working fluid has a specific P-H diagram and there are many courses of process for application categories (e.g., cooling, heating, and water heating). Therefore, calibration was carried out in each application under typical conditions
Using these conditions, specifications of working fluids were calculated and are shown in Table 11.

Table 11 Calculated COP Values of Various Working Fluids by P-H diagram

	Evaporator inlet	Compressor inlet	Compressor outlet	Compressor efficiency	COP
	Kj/kg	Kj/kg	Kj/kg		
CO2	257.4	433.6	461	0.6	4.46
R-410A	239.2	435	471.2	0.6	3.85
R-407C	313.7	422	460.3	0.6	2.30
HCFC22	292.6	414.2	457.4	0.6	2.29
Non-azeotrope medium (HCFC22-HCFC-142b)	419	632	652	0.6	6.99

Here compressor efficiency must be determined for the calculations. Such efficiency is determined by mechanical factors, which are shown in Fig. 12, as a function of the pressure ratio. Here an assumption is introduced that the machines can be adjusted to the value of 0.6, the value adopted for calculation in Table11.

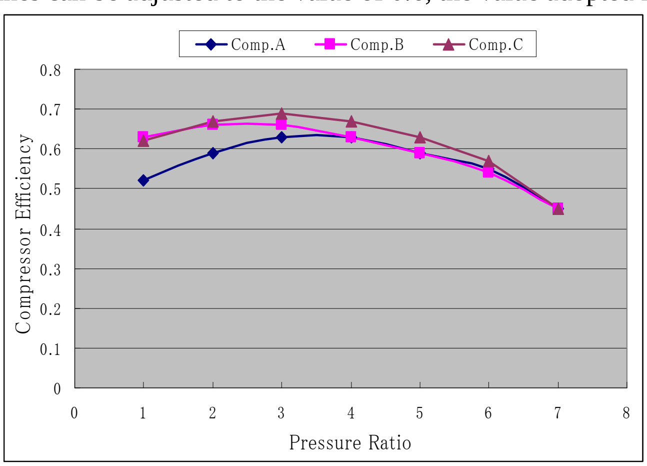


Fig. 12 Pressure dependency of compressor efficiency

Fig.14 shows one example of the calculated results. This COP temperature coefficient is used for calibration.

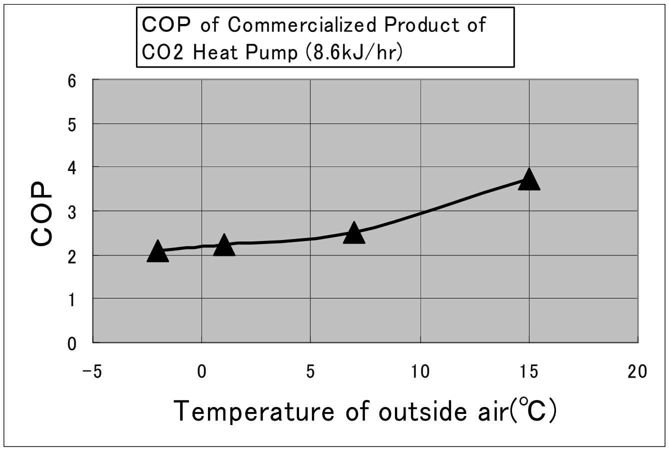


Fig. 13 Temperature dependency of COP of commercialized product

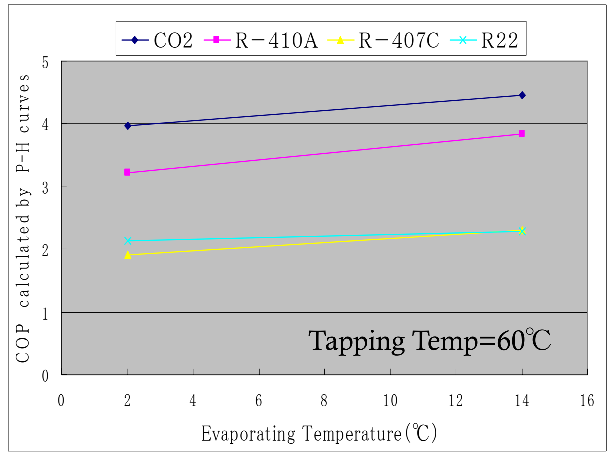


Fig. 14 Calculated temperature dependency of COP

4.2.2 Effect of working fluid

As mentioned in 3-2-1, actual COP results of various working fluids can be compared by considering the differences of working fluids and temperatures. Here a relative COP ratio was used for calibration and COP data was calibrated for the case of CO_2 working fluid.

4.3 General Overview

Table 12 shows the overall results. The results of the COP and COP temperature calibrated, as well as COP Temp.+working fluid calibrated, are also shown in Table 12. Figure 15 shows the results of COP and COP calibrated. The results of the super heat pump for heating water indicates a high value which is mainly because of the non-aerotrope medium working fluid and the two-stage economizer system. If this date were calibrated to the CO_2 heat pump condition, the value would be approximately 3.7.

The CO_2 heat pump has made progress and recently achieved a 4.2. This value approaches 4.4, which is the calculated value from the P-H diagram.

At the end of Table 12, the level of direct tapping technology, 4.6, is shown as the actual result. The COP value calibrated for standard conditions is relatively low because of the large tapping rate for direct tapping.

4.4 Remaining Task

Figure 16 shows the difference between the temperature dependence of COP actual and calculated by P-H diagram. In cooler regions, the COP is lower than calculated, meaning there is a heat transfer problem in the heat exchanger. Figure 17 shows the tapping rate dependence of COP and this figure also shows the problem of heat transfer. There certainly must be some technology that improves the heat transfer coefficient on the surface of the heat exchanger.

Table 12 Results of COP

Case	Category	Working fluid	Entrance temp.	Exit supply temp.	Standard entrance temp.	Standard exit supply temp.	Capacity	COP result	COP Temp. callibrated	COP Economizer calibration	COP Temp+ working fluid
Waste heat utilization	heating	R22	12	50	7	35	0	3.2	2.70		2.66
Super heat pump	hot water	Non-azeotrope medium	10	45	16	65	1000	6.2	6.20	5.83	3.72
Double phase expand/compressor	heating	CO_2	7	30	7	35	14	3.68	3.68		3.68
Air conditioning system for cold cilmate area	heating	R410	-12	37	7	35	2.25	3.75	5.65		4.39
Hot water reserver (spring & fall) ; tapping rate<3liter/min	hot water	CO_2	16	65	16	65	6	4.2	4.20		4.20
Direct tapping (spring & fall) ; tapping rate>10liter/min	hot water	CO_2	16	42	16	65	26	4.6	3.45		3.45

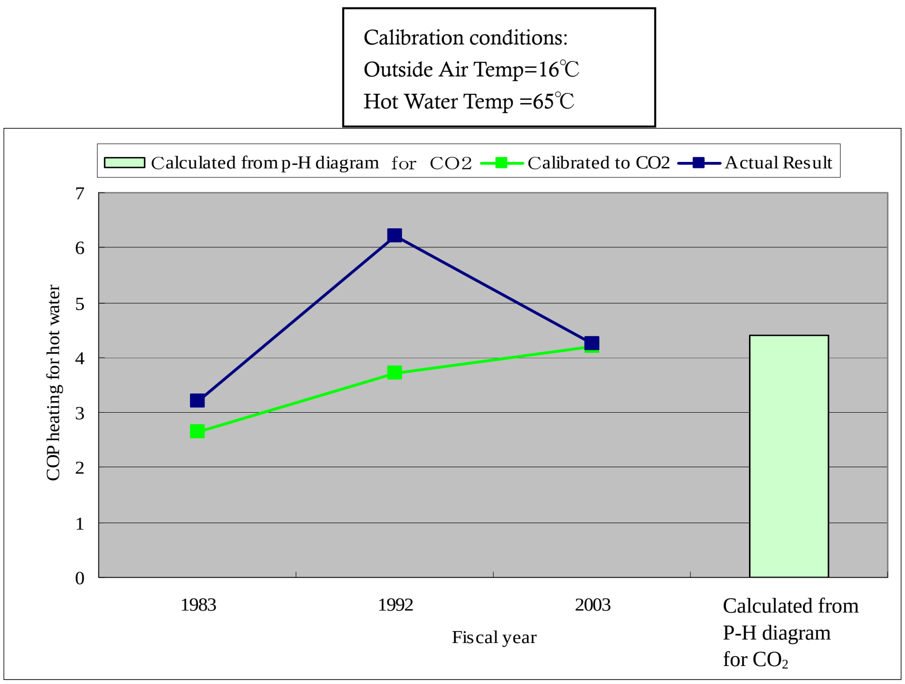


Fig. 15 Actual Results and Calibrated to CO_2 data of COP $_{\text{heating for hot water}}$

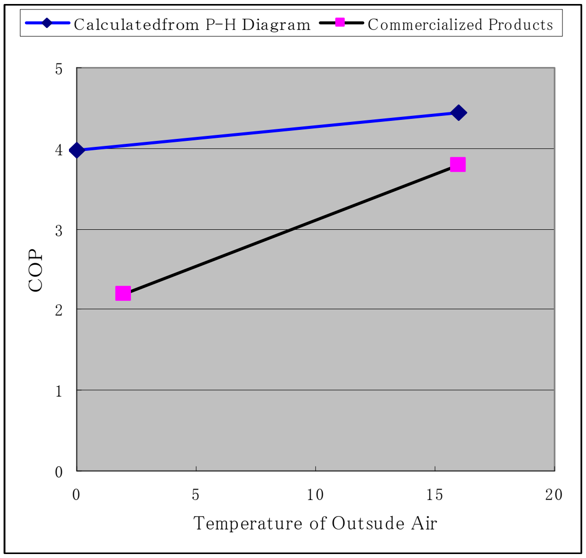


Fig. 16 Temperature Dependence of COP Actual &Calculated

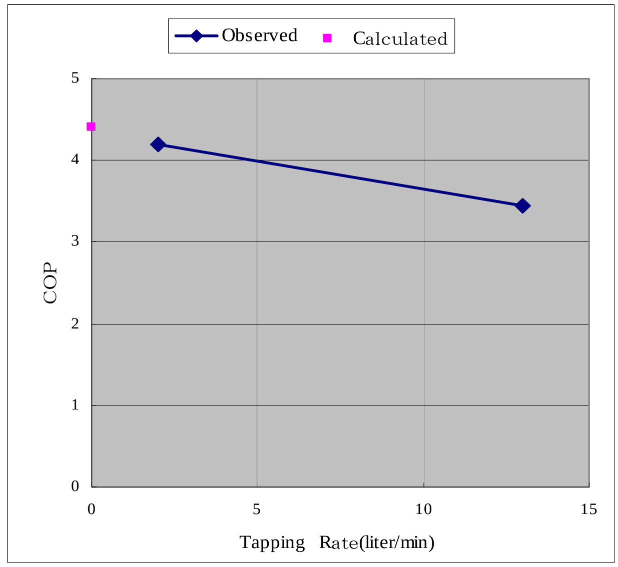


Fig. 17 Tapping Rate Dependence of COP

5 CONCLUSIONS

5.1Transition of Working Fluid to Natural Medium

For greenhouse gas reduction, a CO_2-based heat pump has been developed, mechanical improvement has been executed, and the COP improved to 4.2 under standard conditions, nearly the theoretical level of 4.4.

5.2 Other Improvement for Diversity

Based on the CO_2 heat pump, the variation has designed as mentioned in Chapter 2. On the other hand, the value of the absorption chiller, COP 1.6, is almost the same level as the CO_2 heat pump when one considers the generating efficiency of 0.4 (0.4*4=1.6). The probability of a hybrid heat pump is also recognized.

5.3 To Disseminate the Technology

In order to realize the revolutionary spread of the CO_2 heat pump system, it is important to improve the heat exchange equipment, as that greatly influences both the COP values and the cost.

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