RESEARCH AND DEVELOPMENT OF NEXT-GENERATION HEAT PUMP WATER HEATER SYSTEM

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Abstract: In recently years, the energy conservation equipment and the heat pump water heater system bathe in attention as a response of the low carbonization society. It is important to advance the energy saving and carbon dioxide (CO2) emission reduction in the field of hot water supply which requires 1/3 of total energy consumption by households in Japan.

Therefore, reducing CO_2 emissions from the energy use from this source is one of the top priorities for Japan in order to mitigate climate change.

However, the introduction of heat pump water heater is facing a difficulty due to Japanese housing situation. Typical Japanese houses in urban area are either apartment complex or small houses proximately situated next to each other.

In an attempt to further diffusion of the heat pump water heaters, this paper describes the research on the element components for the next generation heat pump water heater system and the development of compact residential CO2 heat pump system.

Key Words: heat pump water heater, element equipment,refrigerant,CO2

1 INTRODUCTION

Recently, there has been a move towards energy saving design and the use of natural refrigerants over fluorocarbons in refrigeration, air-conditioning and water heating equipment in order to protect the ozone layer and address global warming. Regarding refrigerants, in particular, research has been actively underway in Europe to use natural substances (e.g., ammonia, hydrocarbons, CO_2) to replace HFC refrigerants, which contribute to global warming.

In Japan, roughly one-third of the energy consumed by households is used for water heating. More than 90 percent of this total is accounted for by combustion type water heaters. Hence, increasing the energy-efficiency of water heaters is an important measure to reduce CO_2 emissions from this source, and a key priority for the Japanese government, power companies, manufacturers and others.

Power generation systems tend to generate excess power at night. Therefore, to reduce energy consumption in Japan, power companies promote the use of electricity at night for power load equalization. An efficient thermal storage system using night-time electric power is ideal for this situation, and a high-efficiency heat pump has the potential to fill this role. They must not only be efficient in their energy use, they must also move away from reliance on HFCs—a key refrigerant used in the air conditioning and refrigeration sector. CO_2 refrigerant used for water heating has the possibility to offer performance equal to or greater than that of HFCs. That is why the Japanese government has provided subsidies since September 2002 for introducing CO_2 refrigerant heat pump water heaters. At the same time, power companies are involved in the development and promotion of high-efficiency electric water heaters

designed to improve electric power load equalization by operation at night. Against such a background, we have developed a swing compressor design to match the characteristics of CO_2 refrigerant, as well as a residential CO_2 heat pump water heater (hereafter referred to as a CO_2 water heater) that includes a water heat exchanger. We have worked on the development of compact water heater to take advantage of new technology further. This paper describes these new products and a CO_2 water heater with a compact design.

2 REFRIGERANT CHARACTERISTICS

Studies were conducted to compare the performance of non-fluorocarbon refrigerants (e.g., CO_2) to HFC refrigerants, namely R-410A (HFC32/125=50/50wt%) and R-407C (HFC32/125/134a=23/25/52wt%) for use in residential heat pump water heaters. Table 1 presents the characteristics of the HFCs and R-744 (CO_2). As shown, R-410A and R-407C have somewhat higher COP but far higher GWP than R-744. As Table 1 shows, suitable refrigerants must be selected for different applications, i.e., HFCs are suitable for residential air conditioners and packaged air conditioners, while CO_2 is suitable for water heaters.

Table 1：Refrigerant Characteristics

Refrigerant	HFC		Natural refrigerant
	R410A	R407C	R744(CO_2)
Practical examples of commercialization	RAC PAC Commercial Water Heater	PAC Chiller Commercial Water Heater	Residential Water Heater (Eco Cute) & Commercial Water Heater
ODP[1]	0	0	0
GWP[2]	1975	1652.5	1
Combustible	No	No	No
Toxic	Low	Low	Low
Pressure (MPa) (low/ high)	2.7/3.0	1.8/2.0	9.5/11
COP(compared to R410A) (low/high)	100	95/100	60/80

Note: RAC= residential air-conditioning; PAC= packaged air-conditioning.
[1] Ozone depletion potential
[2] Global warming potentials are based on IPCC 2001.

The CO_2 water heater systems consist of three-unit components: the heat pump unit, the hot water storage unit and the remote controller. The heat pump unit draws heat from the atmosphere, compresses the heated refrigerant to heat it further, and transfers the heat to water to make it hot. The storage unit stores the hot water. The remote controllers installed in the kitchen and the bathroom enable the user to draw hot water when needed. The advantages of the CO_2 water heater are that: the ODP of the refrigerant is 0 and GWP of that is 1; it can heat water up to 90°C without a heater; the heat pump method offers energy saving and safety; and it is of the night-time thermal storage type, contributing to electric power load equalization in Japan [1]. In addition, a CO_2 heat pump water heater can boil additional water more efficiently than traditional electric water heaters of night-time thermal storage type.

3 DEVELOPMENT BACKGROUNDS

Hot water is typically used differently by Japanese households compared to other countries. The Japanese are the fondest of bathing in the world. Given this, they need a large amount of

hot water at one time to fill a bath almost everyday. The quantity used for this purpose is double that in Western countries. On the other hand, the hourly water heating capacity of most CO_2 water heaters is lower than that of combustion type water heaters due to cost considerations. Accordingly, it is hard to heat a large amount of water at one time using a CO_2 water heater. This means that, if a large amount of hot water is required at one time, it is more cost-effective to heat water in advance. Considering these conditions, in order to achieve a system favorable to both consumers and electric power companies, and to compensate for the drawbacks of a heat pump, the heat pump unit is run at night, In Japan, in order to promote the use of electricity at night for power load equalization, electric power is cheaper at night.

Thanks to these efforts, the spread of CO_2 water heater in Japan is definitely in progress. Figure 1 shows CO_2 water heater development activities in Japan. Currently, the center of the spread is mainly detached houses, the spread of CO_2 water heater to residential housing in narrow space or to apartment houses has not been established yet due to space constraints. To improve this situation, there was a need to address CO_2 water heater compact. To achieve compactification, eliminates concerns of hot water out of the tank, it is necessary to ensure that there is no problem to use. In order to resolve these issues, studies were performed jointly by manufacturer and power companies.

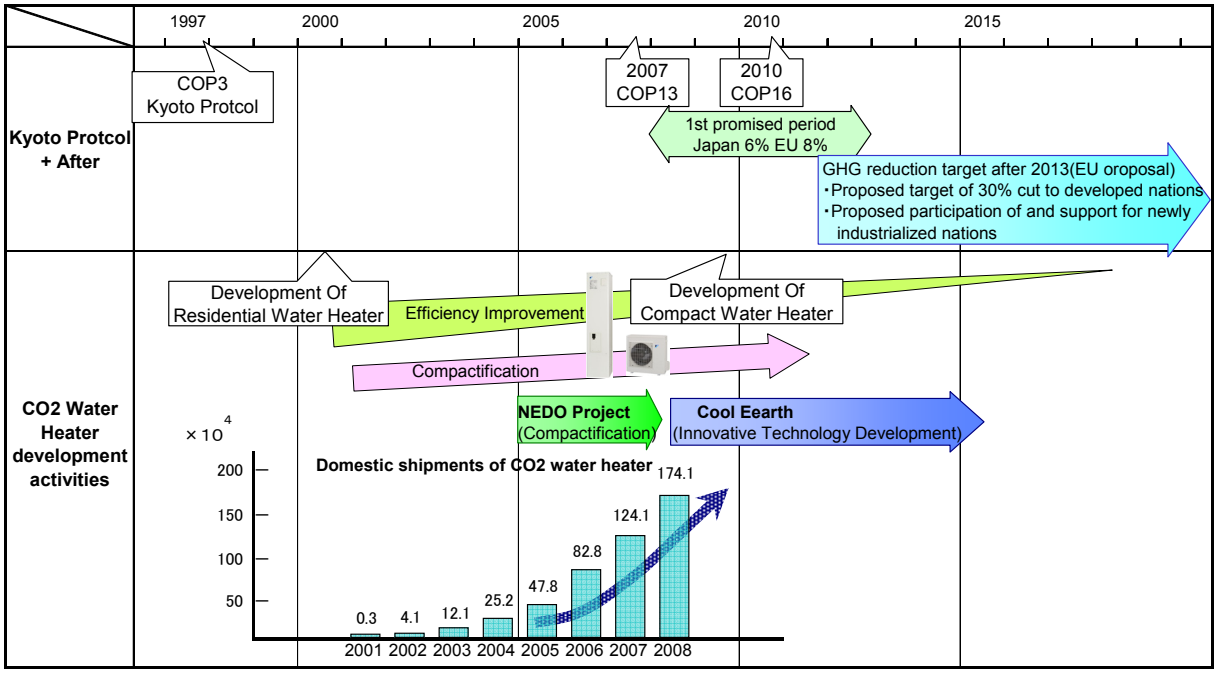


Figure 1：Development Activities Of CO_2 Water Heater

4 TECHNOLOGICAL DEVELOPMEN OF MAJOR COMPONENTS

New compressors and water heat exchangers were the major components developed for heat pump units of CO_2 water heaters. These components are outlined below.

4.1 Optimization of Swing Compressor

To compact water heater ie storage tank, it is necessary to increase the amount of circulating of compressor in heat pump unit. Therefore, we investigated for use in high speed rotation compressor. In a conventional rotary compressor, in high speed rotation, internal

leaking and the reliability of the sliding area on high differential pressure are concerns. We developed a swing compressor, to improve reliability.

Figure 2 shows the structure of a conventional rotary compressor and our developed swing compressor. With a rotary compressor, imposing a vane on the roller by pressure difference (between high pressure and the pressure in the compressor chamber) results in areas of high and low pressure, as shown in Figure 2. Because the differential pressure is several times larger in a CO_2 water heater, wear or burning at the tip of the vane causes problems; due to the increase in differential pressure and the speed of sound, internal gas leakage across the vane from the high to low pressure areas increases. To address this, the Daikin swing compressor combines a vane and roller. With the swing compressor, there is no sliding between the vane and roller, so they do not wear, thereby eliminating gas leakage through the gap. Due to these characteristics, a swing compressor can perform superbly with CO_2.

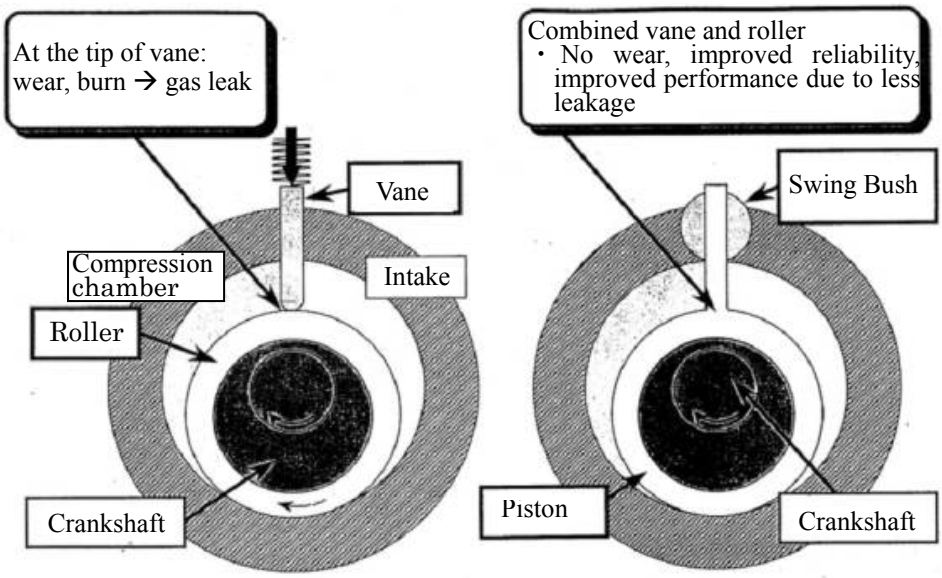


Figure 2：Comparison of conventional rotary and swing compressors

In addition to the above, enhance the strength around the discharge valve, and elastic bearing was used to withstand the compressive load and high-speed rotation. Through these measures, the output of the compressor can be increased to 10kW, the swing compressor has excellent performance.

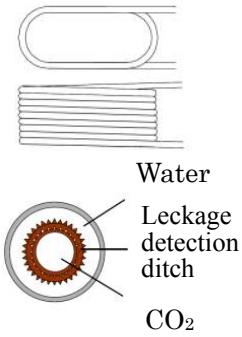
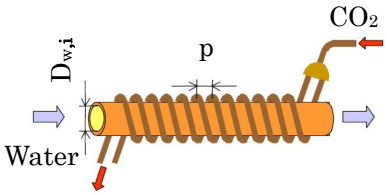
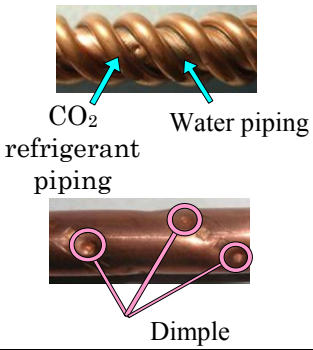
4.2 Improvement of Water Heat Exchanger

Generally, a double tube construction is used in water heat exchanger. When this is applied to heat pump water heater, a leakage detection ditch is added to prevent mixture of refrigerant or oil and water in the event of refrigerant leakage (see double tube shown in Table 2).

However, this type of double tube has the drawbacks of being heavy, expensive, and difficult to reduce in size because the bending R cannot be reduced. To address this, Daikin developed a new heat exchanger with a capillary tube acting as a flow channel for CO_2 (see smooth tube shown in the Table 2), wound around the core pipe as water flow and both brazed. The shape of the water heat exchanger is presented in Figure 3.As shown, the core pipe is wound on a plane surface, and the wound pipe is arranged to produce a double layer.

Therefore, the weight and volume of the water heat exchanger is about 10 to 30% less than those of a double-tube exchanger. For further energy conservation, a water heat exchanger using an innovative dimple water tube was developed. As Figure 3 shows, water in the dimpled tube is stirred, which results in efficient mixing of high temperature and low temperature water compared with conventional heat exchangers to heat water, in which the water flow is straight.

Table 2：Comparison of water heat exchanger

	Former type	New type	
Spec	Double tube	Smooth tube（initial time）	Dimple tube（latest）
Outline of shape			
Capacity ratio	1.00	0.89	0.89
Weight ratio	1.00	0.74	0.64
Performance	1.00	1.00	1.00

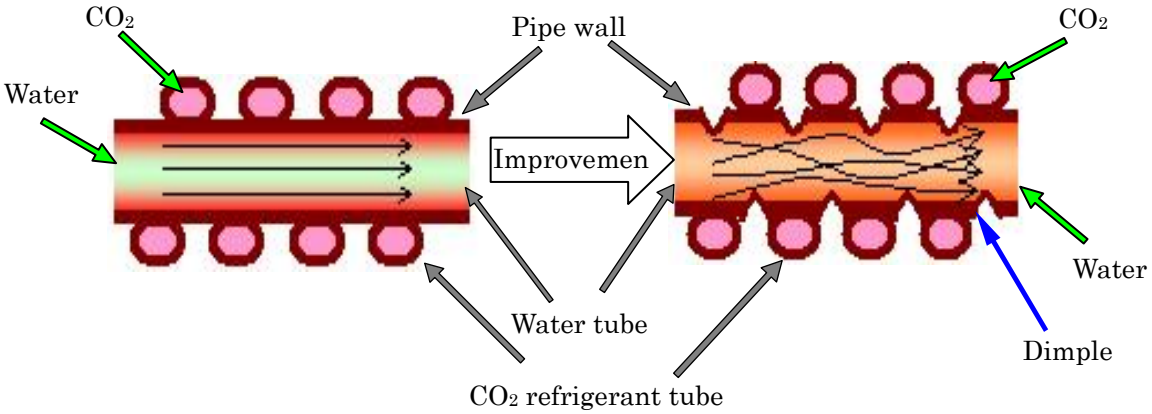
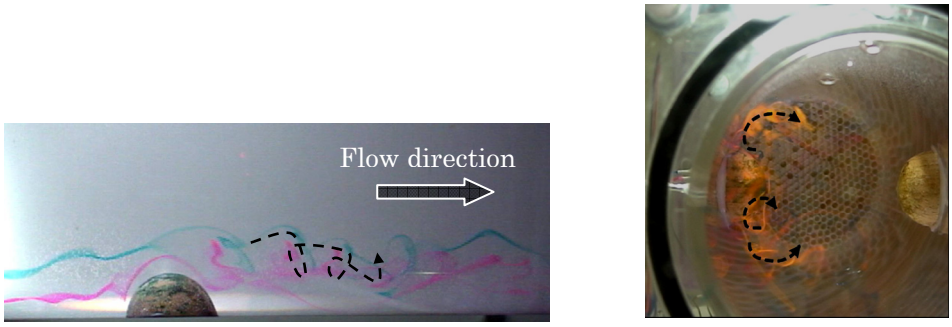


Figure 3：Improvement of a heat transfer rate of a water heat exchanger

The improvement in performance was proven by the image of the dimple tube. Figure 4-(a) shows an image of the dimple tube. The image of the protrusion captured from the side of the acrylic tube shows the detailed flow around the protrusion. Figure 4-(b) shows the downstream whirlpool structure around the protrusion. The flow near the wall continuously forms a small vertical vortex after passing the protrusion; the vortex has with its central axis along the tube axis, and is about the size of the radius of the protrusion. Along with this vortex, the flow of the main flow side forms a similar vortex as if it is induced, and both are then mixed as shown in Figure 4-(a). As shown by the dashed arrow in Figure 4-(b), a small vertical vortex is formed after the protrusion, which reaches to the tube center on both sides. The improvement in performance was proven by the time-series images of the dimple tube. By using the dimple tube, the heat transfer performance is doubled compared to a smooth tube.

The accelerated heat transmission can be seen especially in the low Reynolds number field as shown in Figure 5 [2].



(a)Flow pattern (b)Vortex structure

Figure 4 : Images around the dimple

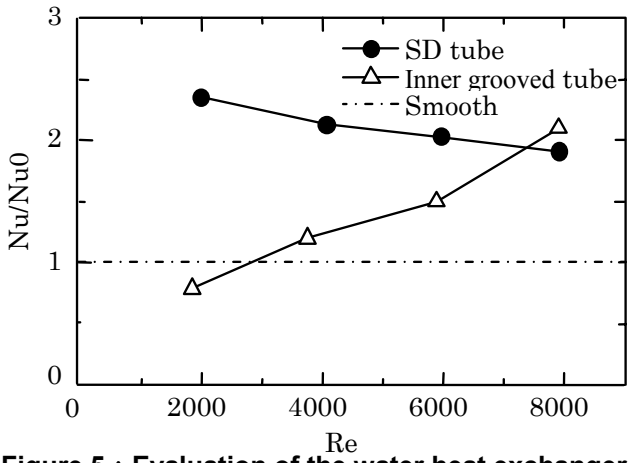


Figure 5 : Evaluation of the water heat exchanger

4.3 Compactification of Hot Water Storage Tank Unit

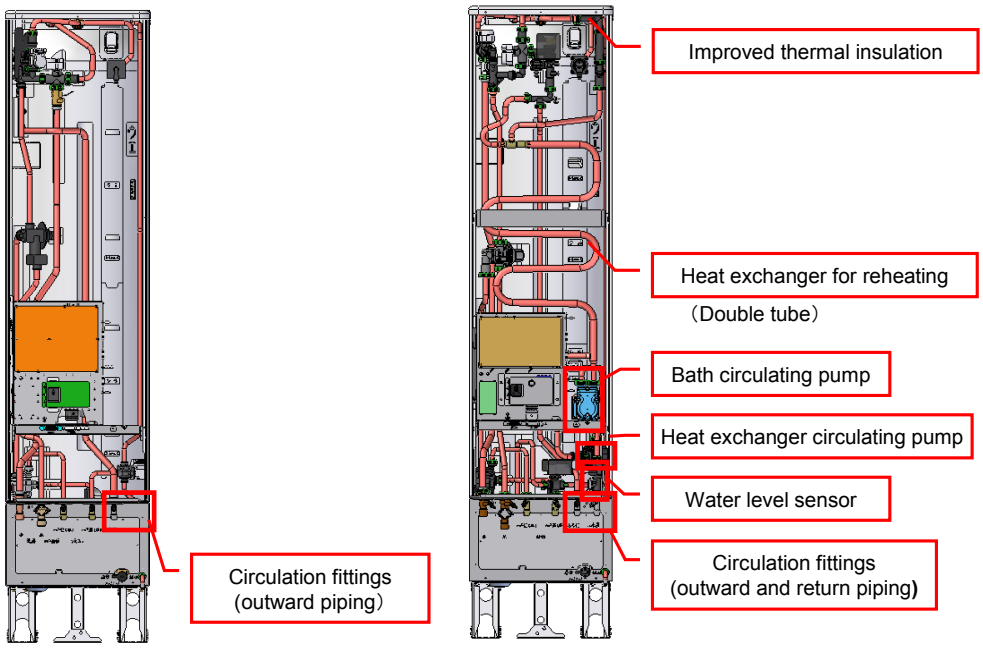
As to enable the establishment of residential housing in narrow space or apartment houses, half of the conventional hot water storage tank (180L) suppressed to less than half the footprint. In the tank unit, which is equipped with components such as pumps and heat exchanger for reheating. These components are arranged properly inside the slim container.

We have developed a new double-tube heat exchanger for reheating.It has been designed to reinforcement of the unit cover and support material for valves and other components. This compact equipment has an automatic type and the fully automatic type. Figure 6 shows the structure of the hot water storage tank unit. The hot water storage tank unit was produced in smaller size designed to account for proper placement of components. It has a width 430mm, depth 560mm, height 1,890 mm.

5 DEVELOPMENT OF NEW TYPE CO_2 WATER HEATER SYSTEM

5.1 Development Overview

In Japan, residential housing complex and small houses are not popular using CO_2 water heaters. To improve this situation, for further dissemination to the small houses, we developed a compact CO_2 water heater footprint by half a unit from a conventional hot water storage tank.



(a) Automatic Type (b) Fully Automatic Type

Figure 6：Structure Of Tank Unit

5.2 The Contents of the Development

By halving the size of the hot water storage tank to 180L, the required installing area for the equipment was reduced to less than half of the conventional ones. At the same time, water boiling capability was improved by increasing the output of heat pump system from 6kW to 10kW. In order to realize conpactification of the equipment, the above mentioned new compressor and water heat exchanger were employed while the structural design and system control of tank were optimized. Automatic and full automatic tanks come with the same size.

The Figure 7 indicates the developed equipment. For full automatic type, the height of heat pump unit was reduced by 100mm by using compactified motor for compressor, heat transfer tube with narrower diameter, and high performance fin. The specific size is 825mm (W) x 300mm (D) x 635(H). The Table 3 describes the main specifications.



Figure 7：Outward of system performance

Table 3：Main Specifications of the Equipment

Item			automatic type	fully automatic type
System	Operational range	℃	- 10 ~ 43	- 10 ~ 43
	Annual Performance Factor(APF)	※1	3.0	3.1
tank unit	Dimension (W×D×H)	mm	430×560×1,890	430×560×1,890
	Capacity	L	180	180
	Weight	kg	49	52
Heat pump unit	Heating capability	kW	4.5 ~ 10	4.5 ~ 10
	Dimension (W×D×H)	mm	825×300×735	825×300×635

※1：kWh when standard mode is used / the value converted to heat energy consumption (Based on JRA4050-2007R: standard condition)

When executing automatic heat-retention for bath water, the bath water is heated by high temperature water at around 80℃ which is kept at the upper part of the tank. Then the bath water is cooled down to 45℃ and circulated to the bottom part. It warms up the water at the bottom to decrease the efficiency of the equipment. In order to address the problem, we optimized the system control of tank for the case of automatic heat-retention or reheating of bath water.

5.3 Field Tests

Development equipment tank is half the size of a conventional tank capacity. In order to take into account the actual use of this developed equipment, such as anxiety run out of hot water during use, it is necessary to avoid problems. From this perspective, after the development of element technologies, field tests were conducted using the six "Automatic mode" where all the 165 days were used in all, the average hot water prototypes.
usage 590L / day in all areas. The maximum amount is 1,200 L / day or more there, but did not occur out of hot water. So there was no hot water supply capacity problem. Table 4 shows the results of the field tests. In the field testing, the actual usage of different families, using a large amount of hot water was found to be functioning well and delicate control by adding boiling with learning capabilities. In addition, we confirmed that the new equipment is superior running costs compared to when using combustion type water heaters.

Table 4 : Field Test Results

Item		average
Family size	Persons	3.7
Outside air temperature (HP-operating)	℃	8.6
Hot water consumption (in terms 42℃)	L/day	590
Total heat load on hot water	MJ/day	80.6
Hot water supply	MJ/day	37.5
Covering hot water bath	MJ/day	27.1
Adding hot water bath	MJ/day	5.8
Hot water circulation	MJ/day	10.2

6 CONCLUSIONS

The following is the summery of the “Research and Development of next-generation Eco-Cute, compactified heat pump water heater using CO2 refrigerant.

- In order to realize high performance to make reduce tank size, the structure of the compressor was optimized to ensure reliability under high speed operation mode.
- By using dimple tube, the performance of water heat exchanger was doubled in comparison to the conventional smooth tube.
- The mechanism of performance improvement of the water heater exchanger was verified through a visualization test.
- The improved water heat exchanger is 10-30% lighter than the conventional double tube type, contributing to achieve smaller and lighter equipment.
- The tank size was reduced from 370L to 180L through modification of system control. As a result, the size of automatic and full automatic tank units can become the same.
- Improvement in element components such as compressor, water heat exchanger, and tank structure and system control has achieved conpactification of equipment. It indicates the possibility for future development of CO2 residential hot water heater.

The improvement in components and system technology of heat pump will significantly contribute to global warming mitigation effort.

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