The Development of Heat Pump Water Heaters Using CO_2 Refrigerant

○ Shigeharu TAIRA*

* DAIKIN Industries, Ltd., 1000-2 Aza-Ohtani, Okamoto-cho, Kusatsu, Shiga 525-8526

Abstract

Water heating consumes about one-third of total residential energy in Japan. Therefore, addressing the carbon dioxide (CO_2) emissions from this energy use is one of the top priorities for Japan in order to mitigate climate change. Further, heat pumps that rely on HFCs pose another problem in the form of direct greenhouse gas emissions, due to their high GWPs. To reduce energy and minimize emissions of both greenhouse gases and ozone depleting substances, CO_2 was chosen as a refrigerant. This paper describes how the properties of CO_2 are not only suitable for hot water heaters, but why CO_2 is actually preferred because of the electric power generating composition and resulting charge rate structure in Japan. It also discusses the latest product development and describes Japanese national policy to expand the use of this type of product in order to reduce climate emissions.

Key words: heat pump water heater, natural refrigerant, CO_2, COP

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, as shown in Figure 1. 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 (including the New Energy and Industrial Technology Development Organization [NEDO]), power companies, manufacturers, and others towards reducing emissions by 2010.

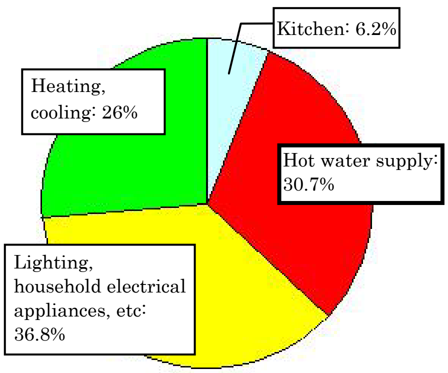


Figure 1. Household energy consumption in Japan
(Extract from a catalogue of Daikin of Feb. 2008)

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. However, for heat pumps to be most effective in reducing greenhouse gas emissions, 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. Although research into CO_2 refrigerant is currently underway (especially in Europe), it is not yet considered to be practical; mass production of CO_2 in air conditioning units has not yet become a reality. However, 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, as its national policy, has provided subsidies since September 2002 for introducing CO_2 refrigerant heat pump water heaters, with the goal of expanding the market in Japan.
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, Daikin has developed a swing compressor design to match the characteristics of CO_2 natural 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. This paper describes these new products.

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.

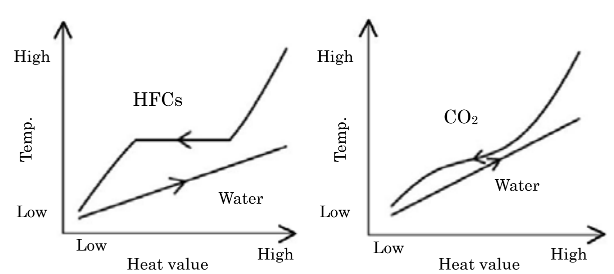
Table 1. Refrigerant characteristics

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.

Standard electric water heaters in Japan heat water from 10°C to 65°C in a single-pass system. Figure 2 (a) and (b) are temperature-heat (T-Q) lines showing the relationship of heat value and temperature of a heat pump water heater. As shown in Figure 2 (a), HFCs heat low-temperature water by high condensing temperature, so irreversible heat loss is unavoidable and the theoretical performance is low[1]. A heat pump cycle with a multistage compressor can reduce the loss, but cost increases due to complications of the cycle and other technical problems must be addressed.

Conversely, as shown in Figure 2 (b), a CO_2 heat pump that heats water using supercritical CO_2 efficiently heats water from low to high temperatures in the most basic single-stage compressor cycle. Fluid in a supercritical condition does not undergo a phase change, so the temperature of CO_2 drops gradually as the water is heated; the temperature difference between water and CO_2 is almost unchanged while heat is exchanged. This means a smaller irreversible loss in the water heat exchanger that exchanges heat between water and refrigerant.



(a) 1-Stage Cycle using HFCs. (b) Trans-Critical Cycle using CO_2

Figure 2. T-Q Diagram about Heat Pump Water Heating

This is the main reason why CO_2 refrigerant is suitable for water heaters and other single-pass heating applications with large temperature differences, which heat water from low- to high temperatures. 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.

3. Advantages of CO_2 water heater

Figure 3 presents CO_2 water heaters. The 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: (1) both the ODP and GWP of the refrigerant are 0; (2) it can heat water up to 90℃ without a heater (see Figure 4); (3) the heat pump method offers energy saving and safety; and (4) it is of the night-time thermal storage type, contributing to electric power load equalization in Japan[2]. 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. Based on design requirements, the size of the tank can be reduced, so the 370 L tank has grown to be more popular than the 460 L tanks of most traditional electric water heaters.

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, when electric power is cheaper to pool hot water in the tank and provide it in the daytime[3]. Figure 5 shows the typical electricity usage of Japanese homes. The CO_2 water heater has been designed to maximize the benefit of this kind of rate system, which promotes the use of electricity at night for power load equalization.

Figure 3. CO_2 water heaters

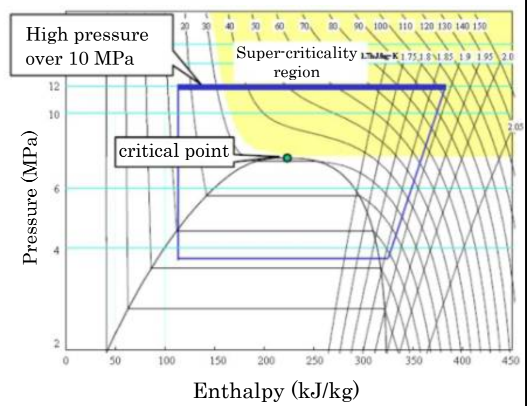


Figure 4. P-h lines of CO_2 refrigerant

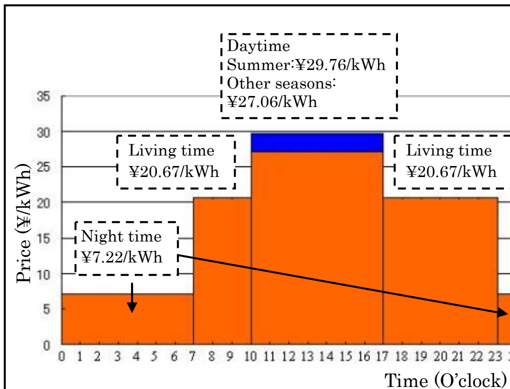


Figure 5. Electricity rates by season and time (KANSAI ELECTRIC POWER CO.)

4. Technological development 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 Swing compressor

In a CO_2 water heater that is heating water to a high temperature, the pressure on the high pressure side of the refrigeration cycle is typically more than three times that of R-410A used in an air conditioner. Therefore, when a conventional rotary compressor is used, the reduction in compressor efficiency caused by internal leaking and the reliability of the sliding area on high differential pressure become concerns. Figure 6 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 6. 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, as shown in Figure 6. 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.

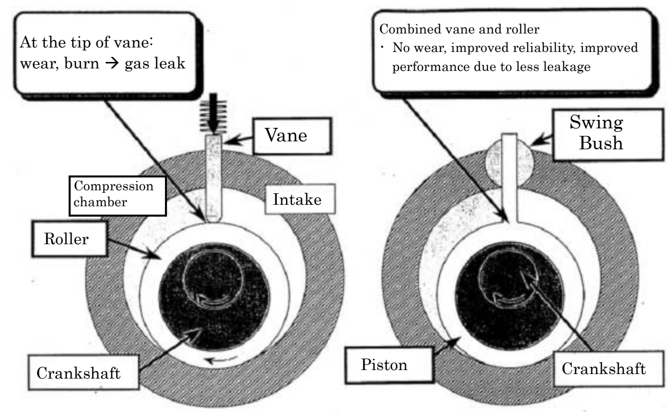
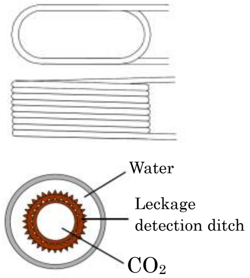
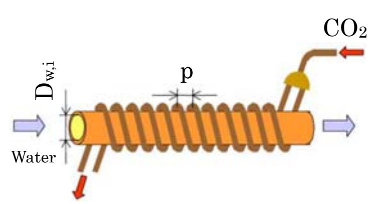
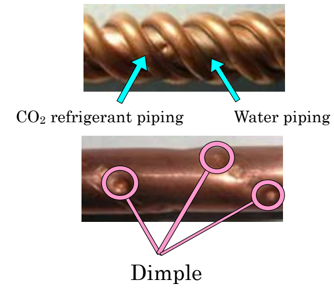


Figure 6. Comparison of conventional rotary and swing compressors

4.2 Water heat exchanger

Generally, a double tube construction is used in water heat exchangers. When this is applied to heat pump water heaters, a leakage detection ditch is added to prevent mixture of refrigerants 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 7. 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

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

water heat exchanger using an innovative dimple water tube was developed. 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[4].

Figure 7. Photo of appearance of water heat exchanger

5. Steps for the next generation CO_2 water heater

A number of technological challenges still need to be resolved for water heaters. Two characteristics in particular—the use of ambient air as a heat source, and the storage of hot water—are problematic when larger capacity is required. In Japan's high density urban areas, space is at a premium. The development of compact products to fit tight space will be critical for future expansion of the CO_2 water heater market. In addition, in order to improve performance of CO_2 water heaters, Daikin is developing an expander to recover energy in the process of expansion of refrigerant, which is currently believed to be the most effective way to improve the efficiency of the CO_2 cycle.[5] Figure 8 shows that the expander recovers the energy of expansion, which was historically used only for expanding using the expansion valve. Typically, the expansion of isoenthalp is driven by using an expansion valve wherein refrigerant cooled by a gas air conditioner expands from the high to low pressure. However, using an expander can lead to recovery of power produced in the process of expansion. When the recovered power is utilized as compression energy, the power consumption of the refrigerant cycle is reduced. Figure 9 shows how the efficiency of CO_2 water heat systems is improved by expander-compressor coupling. Comparing the existing cycle with the expander's recovery of power, the figure also shows that recovery of energy loss due to restriction during decompression process is improved. Figure 10 shows the schematic drawing and the actual appearance of the hermetically sealed expander-compressor unit. Daikin developed this prototype for a CO_2 water heater where the expander is connected with the compressor in one line, and conducted testing. The results showed that energy requirements for the compressor were reduced. The engineering development work for this CO_2 water heater, expected to be complete in March 2008, has been carried out by Daikin

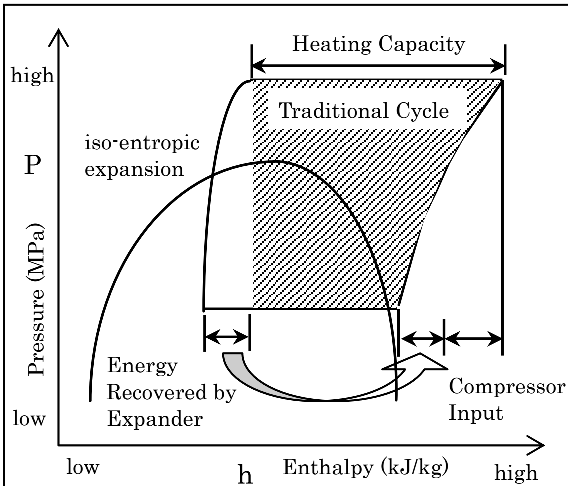


Figure 8. Principle of expander-compressor

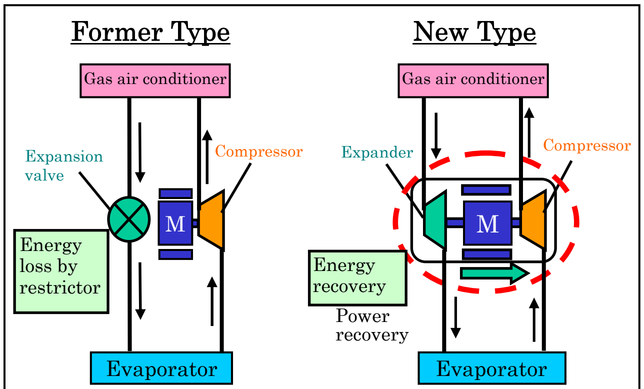


Figure 9. Outline of improvement of efficiency by expander compressor

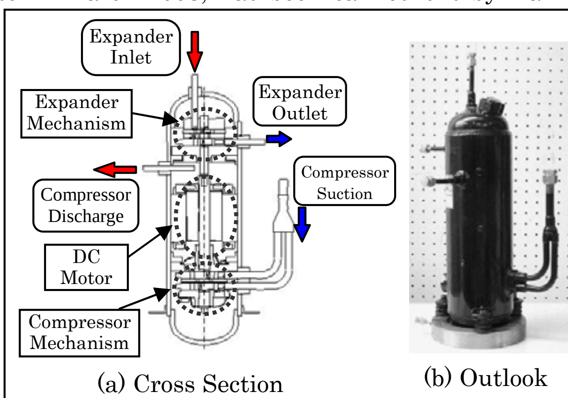


Figure 10. Structure of hermetic prototype of Expander-Compressor Unit

together with NEDO since June 2005. Work has focused on downsizing the water heater for the purpose of expanding its use in high density urban areas, and on improving system efficiency. However, as there are still cost barriers, more advanced development of this system is needed for market-oriented commercialization.

6. Conclusion

The development of heat pump water heaters using CO_2 natural refrigerant can be summarized as follows:

- CO_2 is suitable for home water heaters because it excels in environmental performance and can heat water to temperatures up to 90℃ without a heater.
- For domestic use, both the user and the electric power company can benefit from operation of a CO_2 heat pump unit at night. The user can reduce the operating cost and the power company can equalize electric power load.
- In Japan, commercialization of residential water heaters using CO_2 refrigerant began in 2001.
- Thanks to development of water heat exchangers, expander-compressors, and other key components and improvement of system technologies, heat pumps may contribute significantly in future to addressing the challenge of global warming.

Acknowledgement

I'd like to express many thanks to the staff of Central Research Institute of Electric Power Industry, the Federation of Electric Power Companies of Japan, Tokyo Electric Power Company, Kansai Electric Power Co Inc, Chubu Electric Power, Kyushu Electric Power Company, and NEDO, New Energy and Industrial Technology Development Organization who have provided me with materials in preparing this paper.

References

1) Katsumi HASHIMOTO, et al.: Trend report of development of residential CO_2 heat pump hot water heater in Japan. Lectures at the 9th Power and Energy Technology Symposium (2004)

2) Hirosi NAKAYAMA, et al.: The development of heat pump water heater system with a carbon dioxide hermetic swing rotary compressor, the 9th Power and Energy Technology Symposium (2004)

3) Hirofumi IDA: The development trend and future view of the CO_2 refrigerant heat pump water heater, *Reito*, September 2007, vol. 82, No. 959.

4) Mitsuharu NUMATA, et al.: Heat transfer enhancement of water- CO_2 heat exchanger for CO_2 heat-pump water heaters, JSRAE (2006).

5) Katsumi SAKITANI, et al.: Development of two-phase flow expander for CO_2 air-conditioners, 8th IEA Heat Pump Conference 2005.

Contact: shigeharu.taira@daikin.co.jp