The CO_2 Heat Pump Water Heater as a New Countermeasure Against Global Warming: Drastic Improvement in Energy Efficiency in Three Years Since Its Debut

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ABSTRACT

The CO_2 heat pump water heater (CO2HPWH) for residential use was brought to the Japanese market in 2001. It is composed of a heat pump with CO_2 as the working fluid and a hot-water storage tank. The use of natural refrigerant CO_2 and an annual total efficiency higher than that of combustion boilers are the main features. It has been widely alleged that the annual total efficiency, including heat loss from the storage tank, achieves 3.0. In order to verify its performance *in situ*, we carried out field performance tests for the units in 2004-2005.

Units manufactured in 2004 and installed in six homes demonstrated that the annual total efficiency exceeded 3.0 and the primary energy efficiency was no less than 1.0, with a fuel-to-electric conversion factor of 0.366.

In this paper, the market growth of the CO2HPWH in Japan and its performance improvement is described. Results from the field test which we carried out are also reported in detail. The paper concludes with a discussion about the potential for further improvement.

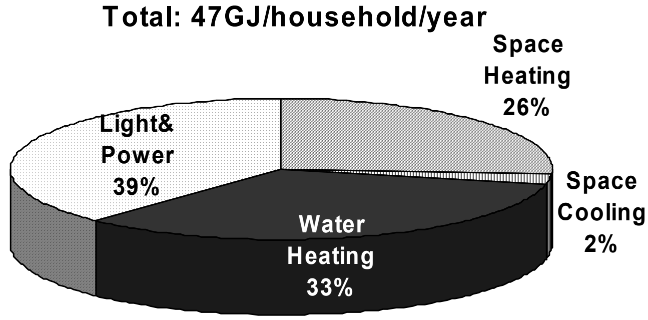
Introduction

Residential energy consumption of hot water accounts for about 30% of all residential energy consumption in Japan (Figure 1). Though energy savings in air conditioning and light and power use have been tackled over the past decade through improvement in efficiency of appliances, energy saving in domestic water heating from a technological point of view stalled with the development of the condensing boiler, which was commercialized in 2002 in Japan. Further improvements in combustion boiler efficiency are not expected due to performance already nearing theoretical maximum.

In the United States, the fluorocarbon heat pump water heater has been on the residential market for twenty years (ORNL 2004). To improve the energy efficiency of hot-water use in homes, the Japanese manufacturer developed and commercialized the CO_2 heat pump water heater (CO2HPWH) in 2001. Since then, electric power companies have strenuously promoted them. The Japanese government also created a subsidy program aimed at realizing a market penetration rate up to 10% by 2010 (5.2 million units out of 52 million households). (Figure 2)

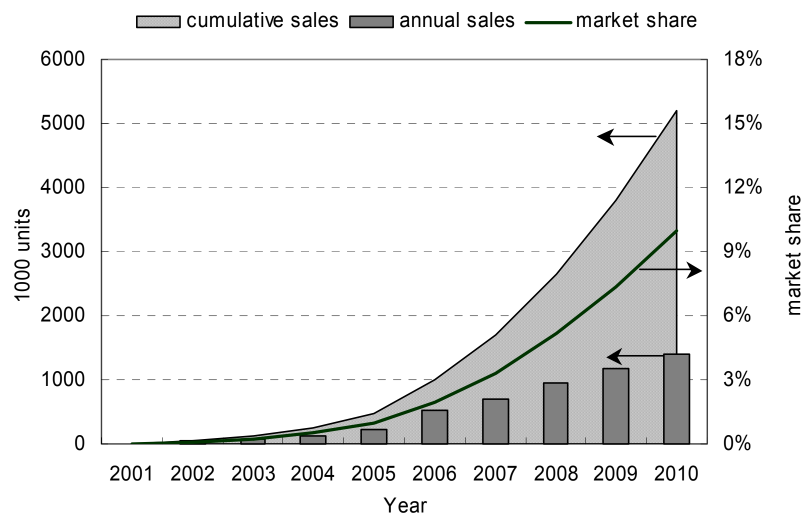
It is generally understood that the annual total efficiency of energy consumption equipment is lower than the standard rating efficiency (Shibata et al. 2004). Therefore, it is very important to figure out the real performance to estimate the macroscopic energy saving potential of this equipment. In order to verify CO2HPWH performance *in situ*, we carried out field performance tests for the units in 2004-2005.

Figure 1. Share of Residential Energy Consumption by Type of End-Use in Japan



Source: Jyukankyo Research Institute, *Residential Energy Statistics Yearbook 2004*

Figure 2. Japanese Government Target for Diffusion of CO_2 Heat Pump Water Heater



Note: Estimated from the 2010 value in *Outlook on Energy Supply and Demand 2030*, Subcommittee for Energy Supply and Demand, Advisory Committee for Energy and Resource, Ministry of Economy, Trade and Industry (METI), Japan

Characteristics of the CO_2 Heat Pump Water Heater

The CO2HPWH for residential use (Figure 3) is composed of a heat pump with CO_2 as the working fluid and a hot-water storage tank. The use of natural refrigerant CO_2 and an annual total efficiency higher than that of combustion boiler are the main features.

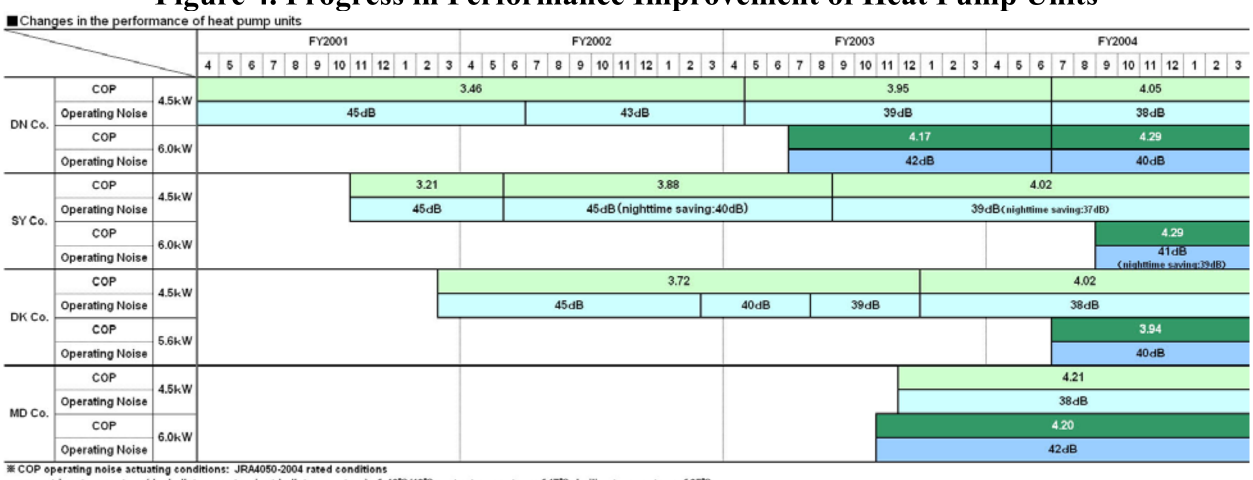
The fluorocarbon heat pump offers a higher coefficient of performance (COP) when the temperature of air or water is raised by several degrees, such as air conditioning use. However, its COP falls for residential hot water applications that require temperature elevations from 15°C of feed water to 65°C. Moreover, fluorocarbon use is restricted from a viewpoint of preservation of the ozone layer.

On the other hand, CO_2 has no impact on the ozone layer and has calorific characteristics superior to fluorocarbon gases at higher temperatures. The calorific capacity of CO_2 is eight times greater than HFC134a; the critical point temperature is 31°C (at 7.34MPa), and CO_2 does not change its phase at the condenser in the critical state, resulting in an effective heat transfer to elevate the water temperature up to 90°C.

Figure 3. CO_2 Heat Pump Water Heater

The CO2HPWH is produced by more than ten manufacturers in Japan. The cost is US$6000~7000 including installation, and the amount of subsidy is about US$400 for a newly-built house, US$700 for a replacement water heater. The CO2HPWH is generally installed by plumbers and electricians, jointly.

Figure 4. Progress in Performance Improvement of Heat Pump Units



As the market for CO2HPWH grows, competition among the manufacturers is getting fierce, which has led to a rapid improvement of the heat pump unit performance and the reduction of operating noises. The HPCOP of the model (heating capacity of 4.5kW) first introduced into the markets under the JRA (The Japan Refrigeration and Air-Conditioning

Industry Association) rated heating condition was improved from 3.46 to 4 or more, and operating noise levels were reduced from 45 dB to 40 dB or less (Figure 4).

Field Performance Test

To verify the performance *in situ* of the latest type of the CO2HPWH, we carried out field performance tests for the units manufactured in 2004 by DN. Co. (Figure 4), which were installed in six residences; their performance was monitored from November 2004 to October 2005.

Site Specifics

Five of the six houses had two adults, with the number of children ranging from none to three. One house (C) has three adults. The average number of occupants is 4.2. All houses are located in a metropolitan or suburban area in Japan at a latitude of about 35 degrees north. The annual average outdoor temperature of B, C and D, which are situated close to the Pacific coast, is about 1 degree warmer than that of E and F, which are situated inland and at a higher elevation (Table 1).

Table 1. Period of Field Test and Household Attributes

Monitoring Period	11/2004~10/2005					
ID	A	B	C	D	E	F
Number of occupants	2 2 adults	4 2 adults, 2 children	6 3 adults, 3 children	5 2 adults, 3 children	5 2 adults, 3 children	3 2 adults, 1 child
Annual average outdoor temperature °C	16.0	16.3	16.9	16.7	15.3	15.5
Annual average feed water temperature °C	19.3	20.0	21.9	19.9	19.6	19.9

Specification of CO2HPWH for Field Test

Table 2 shows the manufacturer's specifications of CO2HPWH with a tank volume of 460 L (105 gallons) that was installed in all six residences. The heat pump with an output capacity of 4.5~6.0 kW is able to produce hot water at 65°C to 90°C. The heat pump outlet temperature is automatically controlled everyday depending on customer's hot-water usage (profile and quantity) in the previous week.

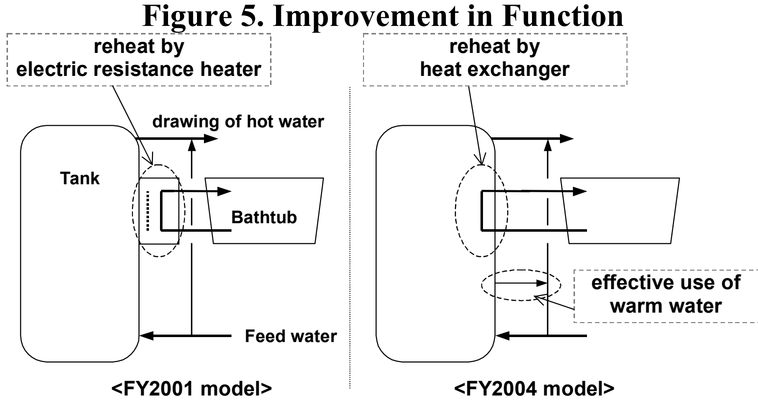
Table 2. Manufacturer's Specification of CO_2 HP Water Heater

Year of manufacture: 2004 Tank Volume: 460L Reheat function: heat exchange in tank			HPCOP conditions		
			Ambient temperature	HP inlet water temperature	HP outlet water temperature
	mode	COP (output/input)			
HPCOP	Rated point	4.29 (6.0/1.4 kW)	16°C	17°C	65°C
	Summer	4.64 (4.5/0.97 kW)	25°C	24°C	65°C
	Winter1	3.66 (6.0/1.64 kW)	7°C	9°C	65°C
	Winter2	3.02 (6.0/1.99 kW)	7°C	9°C	90°C

Improvement in performance. The CO2HPWH has improved its performance in the last three years. The principal points are:

- HPCOP elevation: The rated HPCOP (for output capacity 4.5kW), which was 3.5 in 2001, has exceeded 4.0 in 2004. The greatest contributor is adoption of an ejector cycle that realized an increase in compressor suction pressure leading to a decrease in compressor input power. Furthermore, compressor mechanical efficiency, heat exchange efficiency and operation control are also improved.
- Reheat function[1] without electric resistance heater: Though the FY2001 type uses an electric heater to reheat lukewarm water in a bathtub, the FY2004 type equips a heat exchanger in the storage tank to reheat, making the total efficiency higher (Figure 5).
- Utilization of water at middle temperature in the storage tank: Hot water from the storage tank is commonly mixed with the feed water to be low enough for the demand temperature, even though there remains warm water around the middle of the storage tank. Instead of this, FY2004 type mixes the warm water situated around the middle of the storage tank with the storage output hot water, leading to effective use of warm water (Figure 5).
- Suspension of heat pump operation: The FY2002 type is connected to a power line full-time and the heat pump operates almost everyday even though no hot water is drawn due, for instance, to all residents' being on vacation. The FY2004 type can prevent this unnecessary operation of the heat pump by turning off its power when there is no need for hot water use for long periods.

Figure 5. Improvement in Function



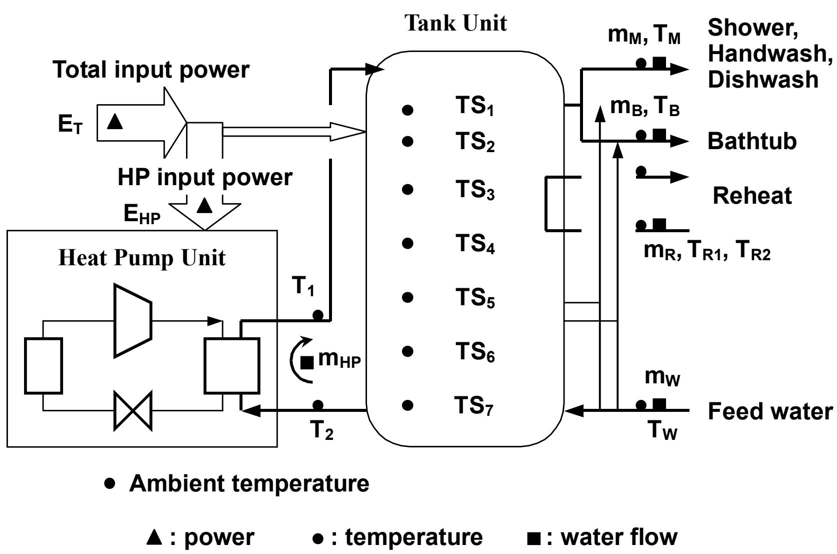
[1] The hot water in the bathtub gets tepid during bathing. To reheat the tepid water, water is piped between the bathtub and water heater, where the bathtub water circulates to receive heat from the water heater.

Parameters Monitored

Figure 6 shows measurement points for a CO2HPWH. Data were recorded at 3 second intervals. The electric power is monitored at the total input for the water heater (E_T) and only for the heat pump unit (E_{HP}); the difference represents auxiliary power (water circulation motors and stand-by power). The heat provided by the heat pump to the tank (Q_{HP}) is calculated using the HP inlet and outlet water temperatures (T_2, T_1) and the flow rate circulating between the heat pump and the tank (m_{HP}). Heat demand for the bathtub and miscellaneous uses are calculated by water flow (m_B, m_M), hot-water temperature (T_B, T_M) and feed water temperature (T_W). Heat demand for the bathtub reheat is calculated from the circulating flow rate (m_R) and water temperatures to and from the bathtub (T_{R1}, T_{R2}). The summation of these three types of heat demand is called the total heat demand (Q_T). The ambient temperature is monitored near the heat pump unit. In addition, storage tank surface temperatures (TS_1~TS_7) are sensed at several points.

This paper deals with two efficiencies: actual HPCOP, which is calculated by dividing the heat provided by the heat pump by the electrical energy consumed in the heat pump ($HPCOP=Q_{HP}/E_{HP}$) and; actual total efficiency which is calculated by dividing total heat demand by the total electrical energy consumed by the system ($\eta_T=Q_T/E_T$).

Figure 6. Schematic of CO2HPWH and Measurement Points



Results of Monitoring

Heat Demand

Figure 7 shows the comparison of the monitored total heat demand for hot water use in six homes (A~F and av.) and three references (R2, R3 and R4). The number below each label presents the number of occupants in the house during the monitoring period. R2 (Jyukankyo Research Institute 2004) is a nationwide average of hot water heat demand estimated from energy consumption for hot water use in statistical data multiplied by 0.8, the efficiency of a gas combustion boiler that is commonly used in Japan. R3 (Ukaji et al. 2004) and R4 (Institute for Building Environment and Energy Conservation 2002) are hot-water heat demand postulated in a project of the Ministry of Land Infrastructure and Transport (MLIT) and a project of the Institute for Building Environment and Energy Conservation (IBEC), respectively.

As shown in Figure 7, there is some variation among the six monitored homes, but the average heat demand of 15.9 kWh/day and average number of occupants of 4.2 is similar to those in studies R3 and R4.

Figure 7. Comparison of Total Hot-Water Heat Demand

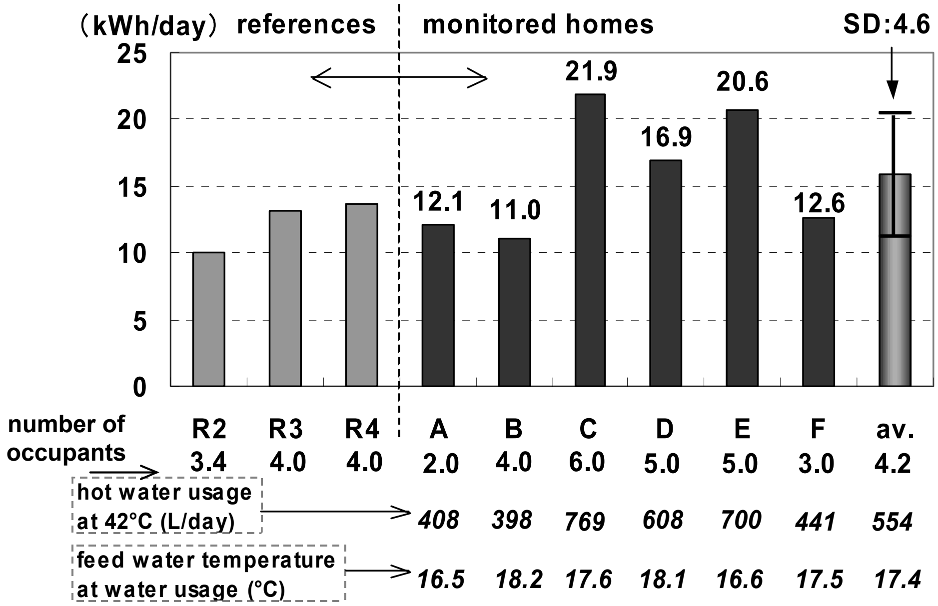
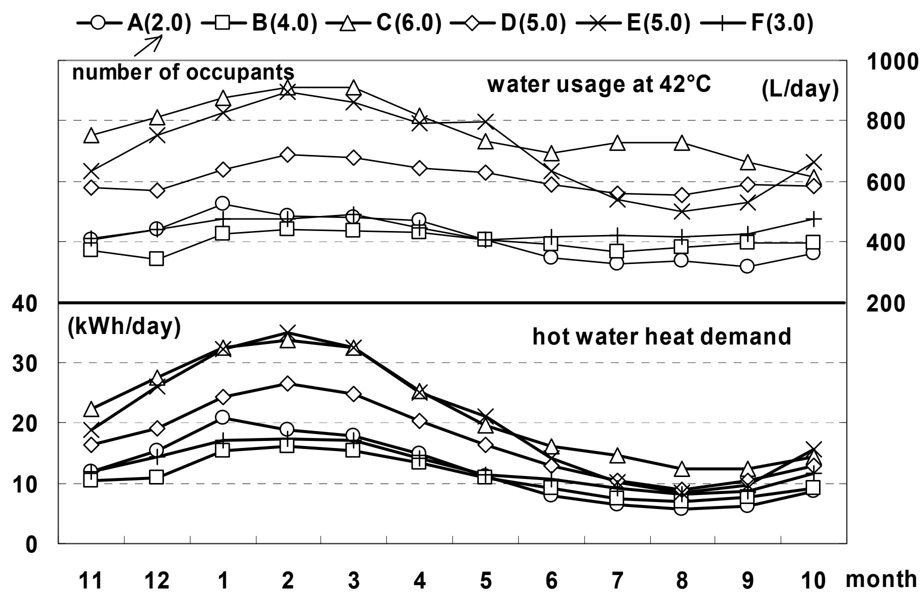


Figure 8. Monthly Total Hot-Water Heat Demand and Water Usage at 42°C



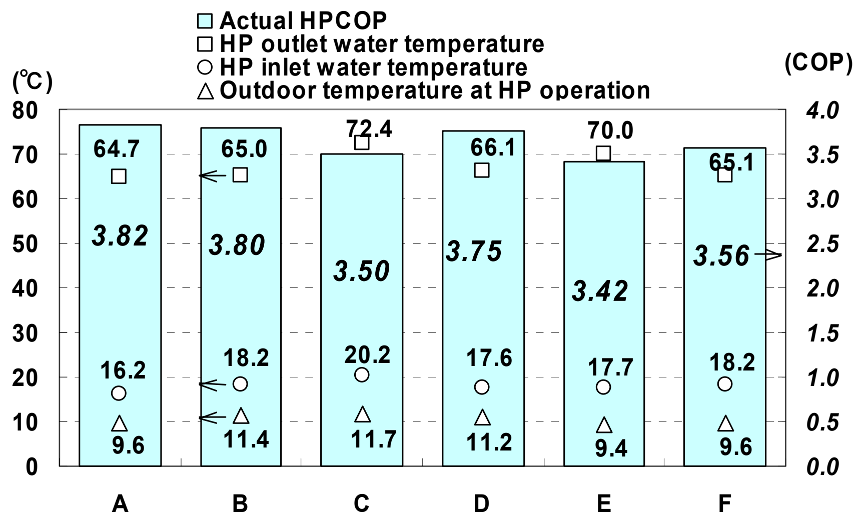
Among the six homes, C and E consume much more hot water than the other homes due to the large number of occupants. D has the same number of occupants as E and consumes relatively more hot water. On the other hand, A, B and F consume less than the C, D and E due to the smaller number of occupants.

Figure 8 shows monthly heat demand for all six homes. The heat demand in February, when peak occurs, is two to three times larger than in August, when demand is at a minimum.

Actual HPCOP

Figure 9 shows the annual average of actual HPCOP along with the factors that would have an effect on HPCOP, HP outlet water temperature, HP inlet water temperature, and outdoor temperature. The HP outlet and inlet water temperatures are the average weighted values by HP water flow. The outdoor temperature is averaged only when HP is in operation. Theoretically, the higher the HP outlet water temperature and inlet water temperature, the lower the outdoor temperature, the lower the HPCOP. Figure 10 presents these three temperatures on a monthly basis. Figure 11 presents monthly actual HPCOP and actual total efficiency.

Figure 9. Annual Average of Actual HPCOP



A and B have less heat demand (Figure 7), and hence, the HP outlet temperature is constantly controlled at around the lowest temperature (i.e., 65°C) year-round, leading to a higher HPCOP of about 3.8. Although F also has less heat demand, HP outlet water temperature is 65.1°C, HPCOP is not so high (3.56). This number can be attributed to the lower outdoor temperature and relatively higher HP inlet water temperature. On the other hand, C and E have much more heat demand than A, B, and F and the HP outlet water temperatures are 72.4°C and 70.0°C, respectively. The higher HP outlet temperature causes lower HPCOP 3.50 and 3.42, respectively. D’s heat demand is situated between A, B, F and C, E and HP outlet water temperature is 66°C, a little higher than A, B and F. This number leads to a relatively higher HPCOP of 3.75.

The upper cluster in Figure 11 shows that actual HPCOP was in the range of 4.5~5.0 in summer and 2.5 ~ 3.0 in winter.

As described above, HPCOP varies with the heat demand. However, in spite of the fact that the HP inlet temperature is higher and the outdoor temperature is lower than the standard rating points in the manufacturer’s specification (Table 2), the annual average of the actual

HPCOP lies between rating point (4.29) and winter2 condition (3.02). This leads to a conclusion that actual HPCOP is almost the same as the manufacturer's specified performance.

Figure 10. Monthly Temperatures Having Impact on HPCOP

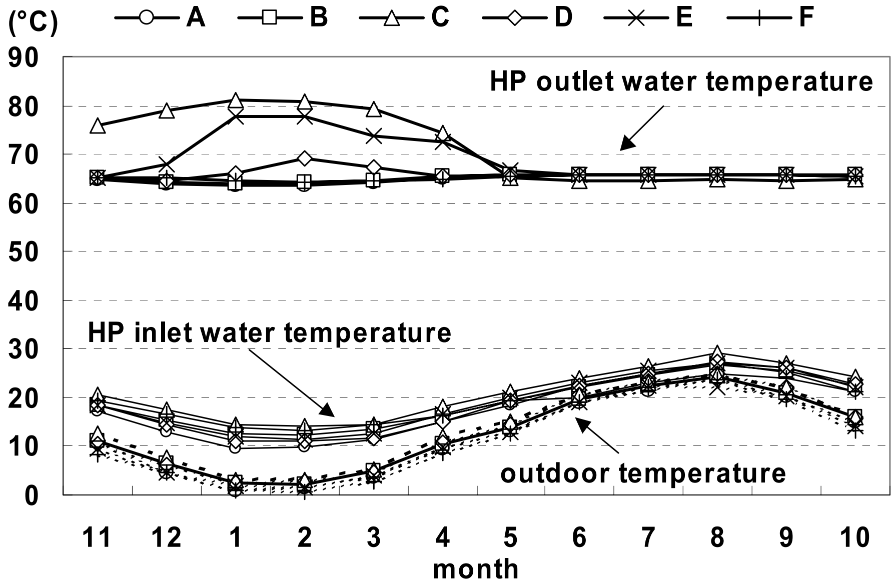
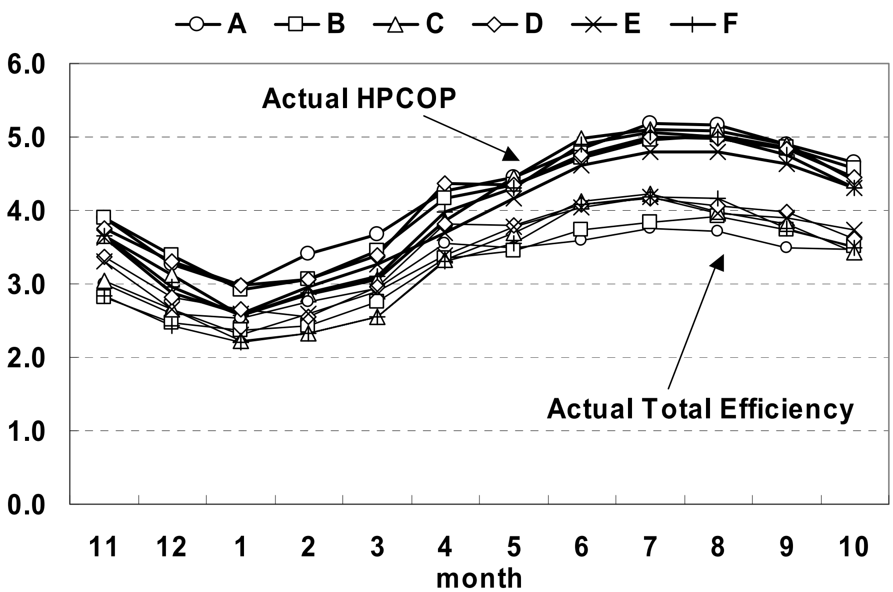


Figure 11. Monthly Actual HPCOP and Actual Total Efficiency



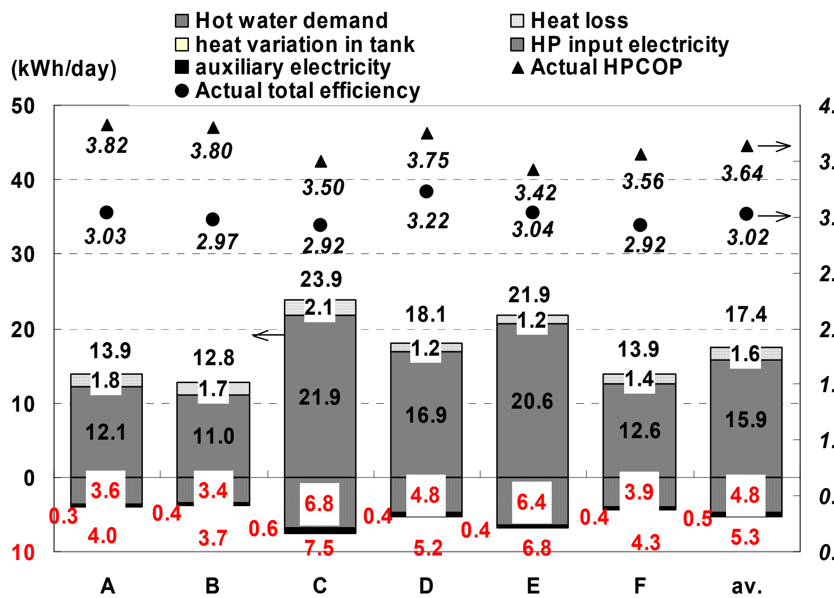
Actual Total Efficiency

Finally, we discuss the actual total efficiency. Figure 12 shows annual average of energy balance and efficiencies for each home. The plus domain in the bar chart represents the total heat demand and the heat standby loss from the tank. The minus domain represents electrical energy input in total and only for HP. Although there exists variation in the heat demand, the annual total efficiency lies in a narrow range between 2.9 and 3.2, and the average for six homes exceeds 3.0, leading to a primary energy efficiency of no less than 1.0 (Table 3) with a conversion factor of 0.366. This conversion factor represents the electricity delivered to the heat pump as a fraction of energy in the fuel consumed at the power plant which generates that electricity.

C and E have lower HPCOP due to larger heat demand, but the fraction of tank heat losses in the heat delivered from the HP is less. On the other hand, A and B have higher HPCOP due to smaller heat demand, but the fraction of tank heat loss is larger. D has a medium level of heat demand among the six homes and a relatively higher HPCOP and a relatively lower fraction of the tank heat loss, resulting in the highest actual total efficiency.

As for the seasonal variation, the lower cluster in Figure 11 shows the actual total efficiency was 3.5 ~ 4.0 in summer and 2.0 ~ 2.5 in winter.

Figure 12. Energy Balance and Efficiency



Note: Heat variation in the tank means the difference in the heat value of the storage water at the beginning of the day and at the end of the day

Table 3. Annual Actual Performances

	A	B	C	D	E	F	**av.**
Actual total efficiency in primary energy	1.11	1.09	1.07	1.18	1.11	1.07	**1.11**
CO_2 emission (kg-CO_2/year)	551	512	1034	722	937	594	**725**

Note: Primary energy conversion factor for electricity is 9830 kJ/kWh (Ministry of Economy, Trade and Industry). CO_2 emission coefficient of grid electricity is 0.378 kg- CO_2/kWh (Ministry of Environment)

Conclusions

This research evaluated the performance of the latest type of CO2HPWH through field testing of six homes in Japan. The actual HPCOP in 2004 was 3.4 ~ 3.8 and the actual total efficiency was 2.9 ~ 3.2. The actual total efficiency for the primary energy was 1.07 ~ 1.18. Each manufacturer is tackling the improvement in efficiency on the JRA standard, which is at singlepoint conditions; Manufacturers are also tackling simultaneously improvement in total efficiency on an *in situ* annual basis as well. They are not just focused on the rating condition performance.

The manufacturer's specification for the 2005 model claims the HPCOP is about 4.5. The CO2HPWH for hot water use combined with floor heating use is also commercialized. In addition, the "instant CO2HPWH," which has 23 kW of output capacity and a 45 L of storage tank, is also being developed. The requirement on installation space has almost limited CO2HPWH introduction into the market to detached houses. However, the downsized CO2HPWH for attached housing has recently been developed and commercialized.

If the latest model of CO2HPWH was introduced into 10% of all households in Japan by 2010 as the government aims, energy consumption for water heating is estimated to be reduced 7%, which corresponds to 2% of the entire residential sector energy consumption. The CO2HPWH can be expected to make significant contributions towards energy savings.

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