HIGH-EFFICIENCY HEAT-PUMP WATER HEATER FOR COMMERCIAL FIELD

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Abstract: Japan is now striving to attain the lower greenhouse gas emission target set in the Kyoto Protocol. Doing so promptly requires a significant reduction in CO_2 emission levels in transportation, commercial, and residential applications because increasing CO_2 emission levels are seen in these three areas. Water heating accounts for 20% of energy consumption in commercial use. Japan has difficulty in substantially reducing the CO_2 emission level resulting from water heating, because most water heaters in Japan are combustion-based water heaters, which employ gas, petroleum, or other similar resources as heat sources. In order to meet end-user demands, such as lower CO_2 emission levels, ensured safety, and lower costs, we have developed a high-efficiency heat-pump water heater for commercial use. Beginning initial research towards commercialisation in 2004, we strove to increase the capacity of the prototype, and in 2007 finally succeeded in commercializing a large-capacity water heating system that can supply 40 tons of hot water each day. Compared with gas-fueled water-heating systems, the heat-pump water heater is capable of reducing the primary energy consumption by approximately 40% and the CO_2 emission level by approximately 50%. We describe an overview of our product and report its features, in the hope that this type of product will spark global adoption of heat-pump water heaters.

Key Words: ***heat-pump water heater, COP, CO_2 emission, commercial use***

1 INTRODUCTION

Japan is committed to reduce the greenhouse gas emission level by 6% by 2008 through 2012, relative to the reference year 1990. On the other hand, however, the greenhouse gas emission level is continuing to increase, requiring Japan to reduce the greenhouse gas emission level by 14% by the target years mentioned above. The CO_2 emission levels were on a rising trend in all applications except industrial applications. There were significant increases particularly in transportation, commercial, and residential applications. Reduction in CO_2 emission in these applications is therefore challenging. Water heating accounts for 20% of energy consumption. Most water heaters are combustion-based water heaters which employ gas or petroleum as heat sources. Since combustion-based water heaters have a combustion efficiency of 1 or less, a significant reduction in the CO_2 emission level and dramatic energy conservation can be achieved by replacing these combustion-based water heaters with high-efficiency heat-pump water heaters.

In order to reduce the CO_2 emission level and help users save energy and money, we have developed a heat-pump water heater for commercial use that takes full advantage of developments in energy-saving technology, control technology, and cost-saving technology that have been achieved in the manufacture of air conditioners. For commercialisation of heat-pump water heaters, the amount of hot water that can be supplied per day was gradually increased in three steps, as shown in Fig. 1, in order to expand the potential market:

Step 1: Heat-pump water heaters that can supply 2 to 3 tons of hot water per day
— for restaurants, grocery stores, etc.

Step 2: Heat-pump water heaters that can supply 10 to 12 tons of hot water per day
— for small-scale social welfare facilities for the elderly, feeding centres, etc.

Step 3: Heat-pump water-heating systems that can supply a maximum of 40 tons of hot water per day
— for hotels, social welfare facilities for the elderly, hospitals, factories, etc.

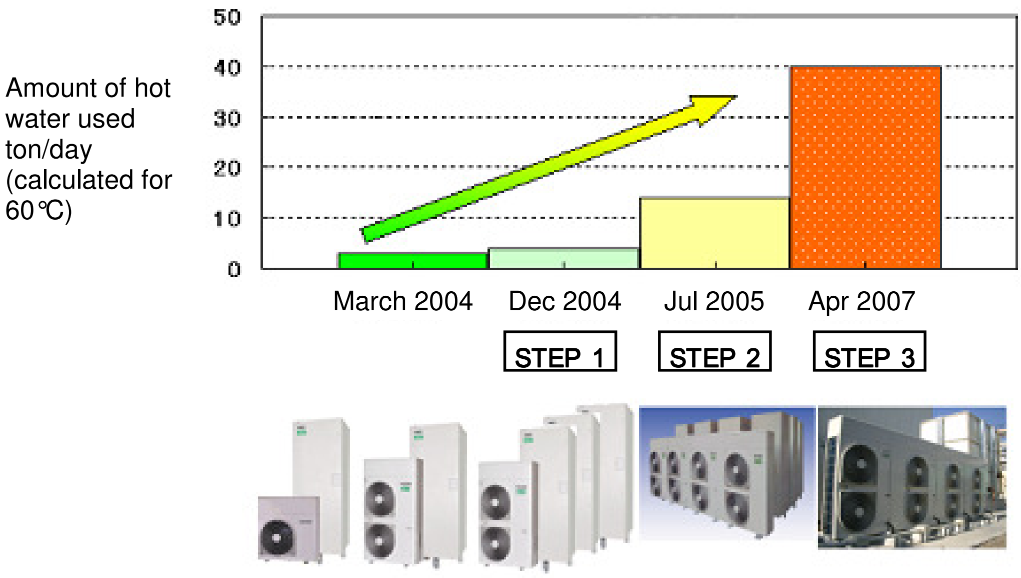


Fig: 1 Steps for commercialization.

2 REFRIGERANT USED

Refrigerant for transferring heat in a heat pump is necessary to change cold water into hot water by the power of the heat pump. In developing heat-pump water heaters for commercial use, we conducted a comparative evaluation of market appeal of HFC refrigerant (R410A) and CO_2 refrigerant, from the user's viewpoint. Based on results of the comparative evaluation, which are summarised in Table 1, we decided to employ the HFC refrigerant (R410A), which is also used in air conditioners for residential and commercial use, in order to accelerate widespread adoption of high-efficiency, low-price, heat-pump water heaters. Since the R410A refrigerant has the drawback of high global warming potential, we employed a refrigeration cycle configuration in the heat-pump water heater (no refrigerant operation is needed at the time of installation), as in window air conditioners, in order to prevent the R410A refrigerant from escaping into the atmosphere. To this end, stringent refrigerant recovery must be observed when the heat-pump water heater is disposed of. In future, it will be necessary to find a natural refrigerant that is superior to R410A in terms of TEWI evaluation.

Table 1; Comparison of refrigerants in the heat-pump water heater

	Refrigerant	HFC (R410A)	CO_2
Comparison of market appeal	Efficiency	◎ High COP can be achieved. The highest-COP product in the current Japanese market	○ High COP can be achieved.
	Environmental friendliness	◎ Substantial advantage over gas water heater △ Refrigerant recovery is needed at the time of disposal.	◎ Substantial advantage over gas water heaters
	Safety	◎ Almost same refrigeration cycle pressure as that of an air conditioner	○ The refrigeration cycle pressure is three times higher than that with the HFC refrigerant. Some measures need to be taken.
	Temperature of tapped hot water	○ Max. 70℃ for the current product (Max. 90℃ for products for residential use) Since the temperature of hot water in practice is 50℃ or less, it is beneficial to prepare a large amount of hot water efficiently.	◎ Max. 90℃ When a large amount of hot water is used, storage of high-temperature water is problematic in terms of efficiency and heat loss from the tank.
	Serviceability in the market	◎ On-site repair associated with refrigeration cycle can be performed as easily as for air conditioners.	△ On-site repair is difficult due to high pressure. The unit needs to be returned to the factory for repair.
	Product price	◎ Relatively low because components can be shared with air conditioners	△ Relatively high because many dedicated components are required
	Ease of expansion of the product	◎ Timely commercialization in response to market needs is easy. - High-capacity heat pump unit - Split-type product - Hybrid product of air conditioner and water heater Cooling by waste heat released while hot water is stored (Storage of hot water by waste heat during cooling) - Floor heating + water heating	△ Timely commercialization is difficult. - Development of dedicated components - The bottleneck is high pressure. - The efficiency when high-temperature water is to be reheated, such as during space heating, is low.
	Overall evaluation	The keys to widespread use of heat-pump water heaters are the efficiency, product price, and market serviceability. For commercialization, the HFC (R410A) refrigerant, which is advantageous in the above-described key points, has been adopted. Extreme care needs to be exercised to prevent refrigerant from being emitted into the atmosphere. The heat-pump water heater is designed so that the refrigerant circuit does not need to be operated when it is installed or disposed of in the field (same structure as that of a window air conditioner).	

3 STEP 1: DEVELOPMENT OF HEAT-PUMP WATER HEATERS WITH HEATING CAPACITIES OF 8 AND 14 kW

3.1 Overview of the product

The heat-pump water heater is constructed as shown in Fig. 2. More specifically, it includes a heat pump unit that absorbs heat from outside air to transform cold water into hot water, a closed hot-water storage tank unit that stores the hot water, and a remote controller that controls the water heater. For the heat pump unit, two types of units are available: one has an hourly heating capacity of 8 kW and the other 14 kW. For the tank unit, fives types of units with hot-water storage capacities of 370 L to 1680 L are available so that customers can benefit from a wide variety of options according to their need for hot water and intended usage scenarios. In summary, eight different combinations of heat pump unit and tank unit are available, as shown in Fig. 3.

3.2 Operating mechanism

The basic system, shown in Fig. 6, is operated in accordance with the following procedure:

(1) Tap water is supplied to the hot-water storage tank via the pressure release valve.
(2) Cold water is introduced from the lower part of the hot-water storage tank into the heat pump unit through the pump.
(3) The operation of the heat pump causes the cold water to be transformed into hot water, which is then returned to the upper part of the hot-water storage tank.
(4) When the hot-water storage tank is filled with hot water, the heat pump stops operating.
(5) When the customer uses hot water, that amount of cold water is drawn into the lower part of the hot-water storage tank. Tapped hot water is supplied at the water supply pressure.
(6) When the hot-water storage tank is filled with a predetermined amount of cold water, the cold water is transferred to the heat pump unit, where it is transformed into hot water.

3.3 Features

This product achieves a top-level high COP among water heaters for commercial use marketed in Japan and exhibits the following features based on this high COP:

(1) High efficiency: Spring and fall COP: 4.45 (14-kW heating-capacity model)
* Measurement conditions: In accordance with Standard JRA-4050 of the Japan Refrigeration and Air Conditioning Industry Association

Outside air-temperature conditions: 16/12 ℃
Inlet water temperature: 17 ℃
Outlet hot-water temperature: 65 ℃

(2) High environmental friendliness: 50% reduction in CO_2 emission level (compared with gas water heater)
(3) High energy-conservation: 40% reduction in primary energy (compared with gas water heater)
(4) Highly economical: 60% reduction in operating costs (compared with gas water heater)
(5) Ease of maintenance: Field service of refrigeration cycle can be performed as easily as for air conditioners.

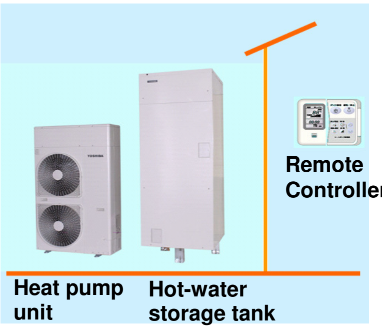


Fig: 2 Basic configuration of the heat-pump water heater

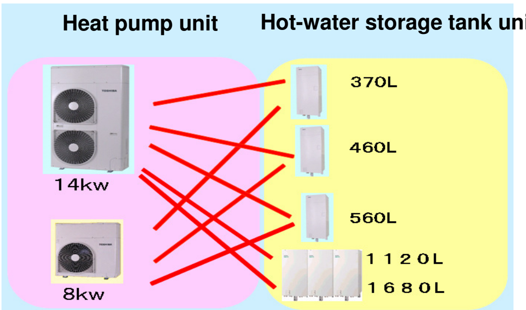


Fig: 3 Hot Power Eco BIG lineup

4 STEP 2: DEVELOPMENT OF HEAT-PUMP WATER HEATERS WITH HEATING CAPACITIES OF 28 TO 56 kW

This system is a water-heating system where two to four of the water heaters commercialised in STEP 1 (each water heater including a heat pump unit with a heating capacity of 14 kW and a tank unit with a hot-water storage capacity of 560 to 1680 L) are used in combination, each constituting a module, so that the heating capacity and the hot-water tapping capacity can be increased by up to four times those of a single water heater. As shown in Fig. 4, multiple heat pump units and tank units, one system controller, and one system remote controller are connected on-site to construct the system.

Fig. 5 External appearance of the quad-coupling system

The external appearance of such a quad-coupled system is shown in Fig. 5. This system has a heating capacity of 56 kW and a hot-water storage capacity of 6720 L. Since multiple tanks are coupled together, with a 560-L tank serving as a basic unit, the full-fledged system includes four heat pump units and twelve 560-L tanks.

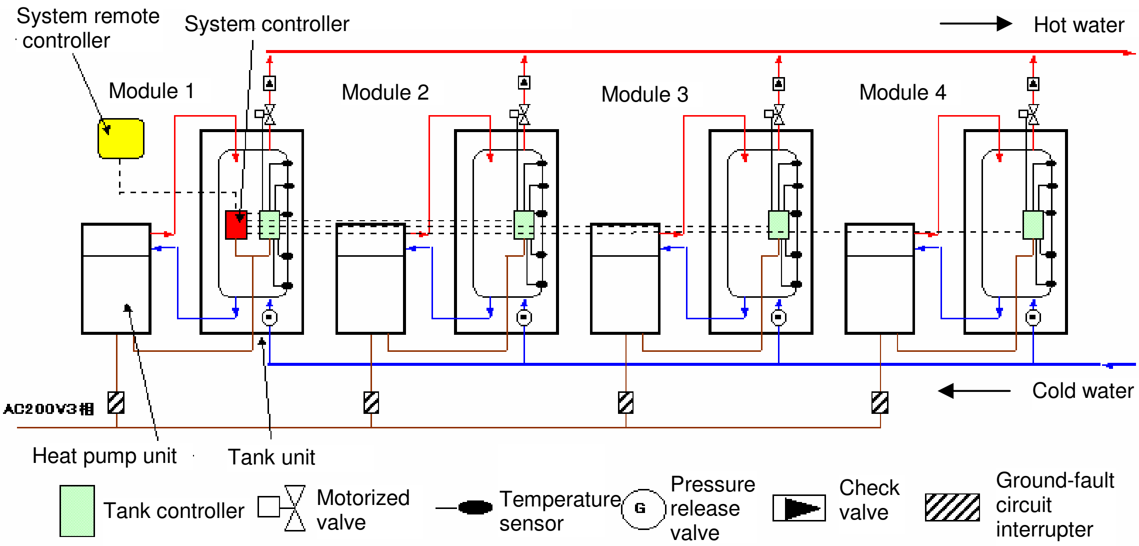


Fig. 4 Basic configuration of the quad-coupling system

5 STEP 3: DEVELOPMENT OF LARGE-CAPACITY WATER-HEATING SYSTEMS

5.1 Overview of the system

This product is a high-efficiency heat-pump water-heating system that can be used in facilities requiring a large amount of hot water (6 to 40 tons of hot water per day), such as facilities for social welfare for the aged, hotels, and factories. The basic configuration of the system is shown in Fig. 6. This system has superior energy conservation due to the provision of a function for supplying hot water as soon as the faucet is turned. This function is achieved by realizing heat retention in a water-heating secondary circulation circuit using a heat pump system instead of the conventional heater system.

Water stored in the water-receiving tank is drawn in via the system tank unit into two or more heat pump units, where hot water is prepared. The hot water is then stored in the open hot-water storage tank via the system tank unit. The pump is operated upon the customer's request to supply hot water from the open hot-water storage tank. Two to twelve heat pump units and up to four reheating heat pump units can be connected.

5.2 Features of the system

The system has the following features:

(1) The optimal system configuration can be achieved according to the amount of hot water used. (The heating cap acity can be adjusted from 28 to 168 kW in 14 kW increments.)

(2) Highest efficiency in the industry. Heat pump unit: Spring and fall COP of 4.45

(3) Reheating heat pump unit for energy-efficient heat retenti on of the circulation circuit is employed for the first time in Japan.

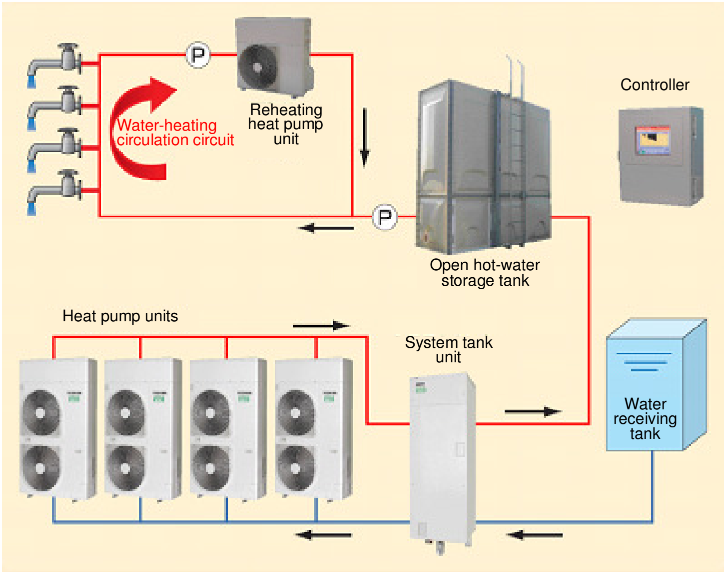


Fig. 6: Basic configuration of the Ultra BIG system

(4) A liquid-crystal touch-panel system control unit that allows various operation settings is employed. By monitoring the past history of the amount of hot water remaining in the hot-water storage tank, it is possible to provide an energy-saving setting, which is both economical while preventing running out of hot water, for the amount of remaining hot water in accordance with the user's demands.

(5) The system can respond to a sudden request for a large amount of hot water, supplying both downstairs and upstairs hot water, by employing a variable water-level open tank.

(6) Field service in the event of a problem in a heat pump unit can be performed without risk while ensuring uninterrupted operation by employing a design in which multiple heat pump units are coupled.

5.3 Evaluation of energy-conservation performance

For evaluation, the system shown in Fig. 7 was set up in our factory and operated for three consecutive days in winter, where the amount of hot water to be used was specified for every hour of the day, assuming that the system would be used in a social welfare facility for the elderly.

5.3.1 Basic system evaluated

The basic system we evaluated had the following components:

- Heat pump units: 8 units
(the temperature of tapped hot water was set at 70℃)
- System tank unit: 1 unit
- Open tank unit: 18 ton

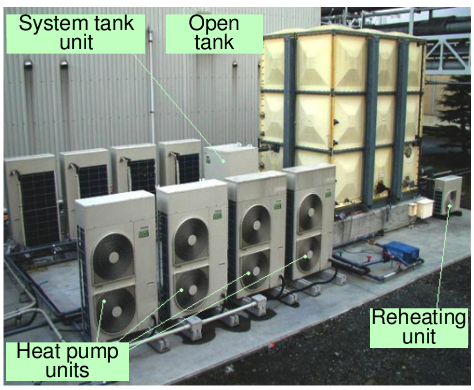


Fig. 7: Evaluation system

5.3.2 Amount of tapped hot water specified hour by hour

As shown in Table 2, the system was operated for evaluation by specifying the amount of tapped hot water to be used, which was obtained from an actual usage scenario in a social welfare facility for the elderly.

5.3.3 Results of measurements for the three days

Results of measurements for the three days are shown in Table 3. The system COP at the open tank outlet over the three days in winter was 3.32. The COP during continuous operation of the heat pump units at an outside air-temperature of 10℃ and a tapped hot water temperature of 70℃ was 3.90. The system COP taking account of the heat loss from the primary piping, system tank unit, open tank, etc. of the system and the heat loss due to intermittent operation of the heat pump units, etc. was approximately 85% of the COP achieved during continuous operation of a single heat pump unit. This was achieved with the help of enhanced heat insulation, energy-saving operation control adopted to reduce intermittent operation, and other technologies. Hour-by-hour trends of the amount of hot water produced (= amount of heated water), the amount of hot water used (= amount of tapped hot water), and the amount of hot water remaining in the open tank (= amount of remaining hot water) are shown in Fig. 8.

Table 2; Hour-by-hour amount of tapped hot water assuming operation in a social welfare facility for the elderly (calculated for 60℃)

Time	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Amnt. of hot water	240	144	96	96	96	144	384	480	576	1920	2400	2592	2016
Time	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00		
Amnt. of hot water	2256	2448	2208	1680	1392	1440	1344	1056	576	336	240		

Amount of hot water for 1 day: 26160 L

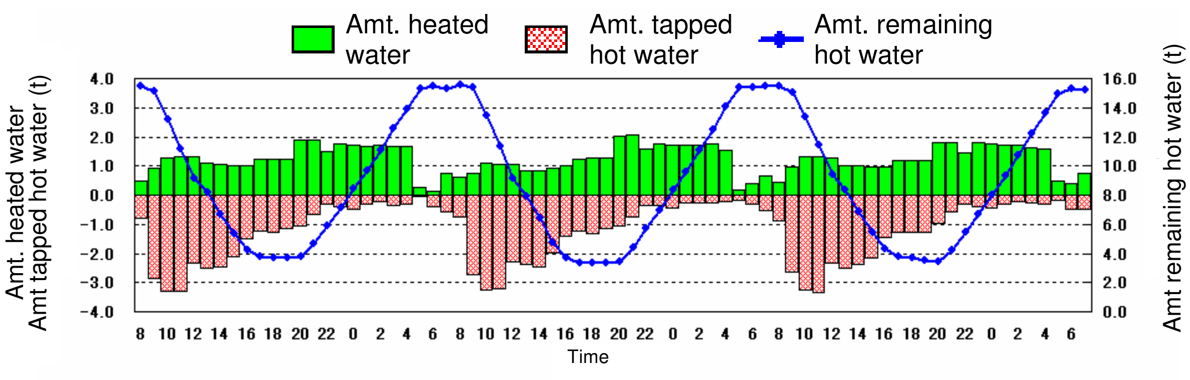


Fig. 8: Hour-by-hour trends of the amount of produced hot water, the amount of tapped hot water, the amount of hot water remaining in the open tank

Table 3; Results of continuous operation for three consecutive days.

	Outside air temp.	A	B	C	D =C/ B		E	F	G	H (F - A)×G/0.86	I = H/B System COP
	Average ℃	Water supply temperature ℃	HP power consumption, kWh	Amount of heat produced by HP, kWh	HP COP	Amount of heat of hot water tapped from the system tank, kWh	Open tank inlet temperature, ℃	Open tank outlet temperature, ℃	Amount of hot water tapped from the open tank, Ton	Amount of heat of hot water tapped from the open tank kWh	System cop at the open tank outlet
day 1	9.9	13.9	536.5	1958	3.65	1885	68.3	64.3	29.8	1746	**3.26**
day 2	11.9	14.0	470.0	1910	4.06	1831	68.3	63.9	29.0	1683	**3.58**
day 3	8.2	13.7	553.6	1958	3.54	1889	68.4	64.5	29.7	1751	**3.16**
Total			1560	5826	3.73	5598			88.5	5180	**3.32**
Ave.	10.0	13.9					68.3	64.2			

Table 4; Results of estimation of annual energy consumption and CO_2 emission

		Applied system	Gas boiler water-heating system
Scale of the system		Social welfare facility for the elderly with an accommodation of 130 persons. Daily amount of hot water used every hour is shown in Table 5.	
Outline of the system		14-kW heat pump unit 8 units System tank unit 1 unit 18-ton open hot-water storage tank 1 unit	No. 173 boiler fueled by municipal gas supply 2 units Single-unit heating efficiency 91% 2-ton closed hot-water storage tank 1 unit
System efficiency		Season / Efficiency of heat source equipment / System efficiency Spring/fall: 4.45 / 3.78 Summer: 5.04 / 4.28 Winter: 4.00 / 3.40 The system efficiency is calculated as [efficiency of heat source equipment×85%].	Season / Heating efficiency / System efficiency All seasons: 0.91 / 0.82 The system efficiency is calculated as [combustion efficiency×0.9] from the performance evaluation of the gas water heater.
Spring/Fall Outside air 16℃ Water temp. 17℃ April, May, June, Oct. Nov. 152 days	Amount of hot water used at 65℃	26,000 L/day	Same as on the left
	Water-heating load	(65-17)×26,000/860×152 days 220,577 kWh/season	Same as on the left
	Energy consumption	220,577/3.78 58,454 kWh/season	220,577/0.82 268,996 kWh/season
Summer Outside air 25℃ Water temp. 24℃ July, Aug., Sept. 92 days	Amount of hot water used at 65℃	26,000 L/day	Same as on the left
	Water-heating load	(65-24) x 26,000 / 860x92 days 114,037 kWh/season	Same as on the left
	Energy consumption	114,037/4.28 26,644 kWh/season	114,037/0.82 139,070 kWh/season
Winter Outside air 7℃ Water temp. 9℃ Dec., Jan., Feb., March 121 days	Amount of hot water used at 65℃	26,000 L/day	Same as on the left
	Water-heating load	(65-9)×26,000/860×121 days 204,856 kWh/season	Same as on the left
	Energy consumption	204,856/3.40 60,252 kWh/season	204,856/0.82 249,827 kWh/season
Annual water-heating load		539,470 kWh/year	Same as on the left
Annual energy consumption		145,250 kWh/year	657,890 kWh/year
Annual energy consumption Comparison on basis of primary energy		393,773 kWh/year ← **40% reduction**	657,890 kWh/year
Annual CO_2 emission level		145,250×0.339 49,240 kgCO_2/year ← **58% reduction**	657,890×860/10,750 = 52,631 m^3 52,631×2.21 116,315 kgCO_2/year

5.3.4 Estimation of annual energy consumption and CO_2 emission level based on the results of evaluation in Section 5.3.3

Taking the above-mentioned results into consideration, the annual energy consumption and the annual CO_2 emission level associated with our system, as operated in a social welfare facility for the elderly, where 26 tons of hot water is used per day, were estimated in comparison with a gas boiler water-heating system. For this estimation, it was assumed that the temperature of hot water tapped from the heat-pump water heater was 65℃. Results of the estimation are shown in Table 4. The main points are described below. For an application where 26 tons of hot water is used per day in the Tokyo area:

- The electrical energy consumption is 145,250 kWh/year, and 393,773 kWh/year if converted for primary energy.
- The annual energy efficiency for producing hot water is 3.71 (annual water-heating load/annual power consumption).
- Energy consumption can be reduced by approximately 40% (264,117 kWh/year) compared with a gas boiler water-heating system on the basis of primary energy.

- The annual CO_2 emission level is 49,240 $kgCO_2$/year, which is a reduction of approximately 58% compared with a gas system (67,075 $kgCO_2$/year).

Notes: - Electricity Primary energy units: 9,760 kJ/kWh
- CO_2 emission level: 0.339 $kgCO_2$/kWh (actual number in 2006 according to Tokyo Electric Power Company)
- Gas Calorific value of gas: 10,750 kcal/m^3
- CO_2 emission level: 2.21 $kgCO_2$/m^3 (Tokyo Gas Co., Ltd., CSR Report 2006 Data Sheet)

5.4 Controller

The control section for controlling the entire water-heating system is implemented with a touch panel controller that has the following features. With this touch panel controller, customers can benefit from easier operation and better energy-saving efficiency, as well as quick service. The external appearance of the system control unit is shown in Fig. 14. The main features are as follows.

(1) Rough and precise operation-mode settings are possible with an easy operation.
(2) The current amount of hot water remaining in the tank and the trend of the amounts of remaining hot water in the past can be checked on the monitor screen. By monitoring this trend, it is possible to make settings for energy-saving storage of hot water specific to each customer, where no excessive hot water is stored, while still avoiding running out of hot water.
(3) The operating status and malfunction information can be distributed in a timely manner to personal computers and mobile phones of persons concerned. This allows speedy service to be provided.
(4) Service personnel can check detailed operation data in the event of malfunction of a unit in the field. This allows the service personnel to quickly analyse the cause of the malfunction and take countermeasures.

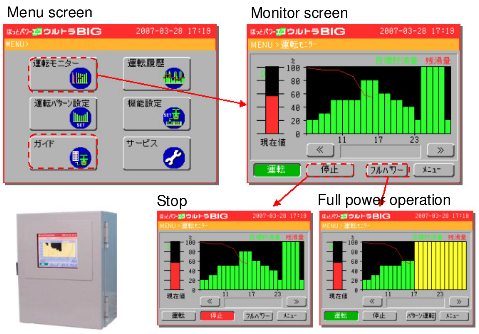


Fig. 9: Main features of the system Control unit

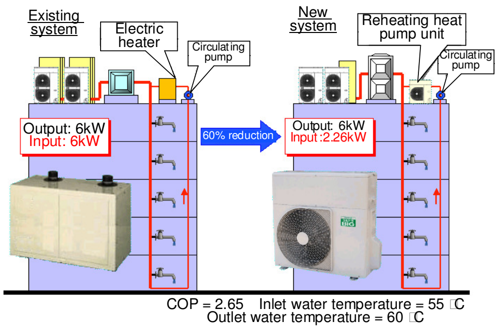


Fig. 10: System for heat retention

5.5 Reheating heat pump unit for heat retention of the circulation circuit

Conventional heat retention of circulating hot water has been performed using an electrical heater, as shown in Fig. 10. For this reheating heat pump unit, heat retention of circulating hot water is performed using a heat pump, which can reduce power consumption by a factor of approximately three. The heat retention temperature of the circulation circuit can be set from 45 to 60℃. The performance of the reheating heat pump unit when the temperature of hot water is increased from 55℃ to 60℃ is shown in Table 5.

Table 5; Basic performance of the reheating heat pump unit

	Spring/fall	**Summer**	**Winter**
Outside air-temperature	16 ℃	25 ℃	7 ℃
Heating capacity	6 kW		
Power consumption	2,260 W	1,950 W	2,670 W
COP	2.65	3.08	2.25
Circulating flow rate	16 L/min		

The thermal dose needed for heat retention of the circulation circuit varies depending on the configuration of the piping installation in the field. Since our system allows up to four reheating units to be arranged side by side, the maximum heating capacity is calculated as 24 kW. This reheating unit includes, at the top, a water heat exchanging unit with a triple piping system, where the water-side pressure loss is significantly decreased, and an outdoor unit of an energy-saving air conditioner designed for residential use serving as the base. The basic components are shown in Fig. 11.

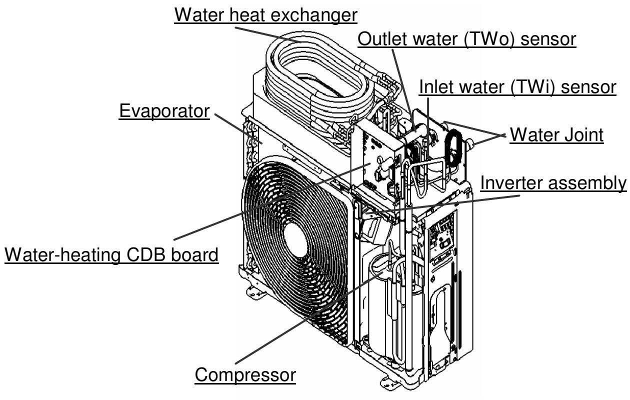


Fig. 11: Basic components of the reheating unit

5.6 Field test

5.6.1 Outline of the evaluation system

A field test started in October 2007 in the Toshiba dormitory for single employees, shown in Fig. 12:

- Accommodation capacity: 200 persons
- Communal bathtub: 11 ton
- No. of showers and faucets: 33
- Water-heating system
  - Heat pump unit: 6 units
  - Open tank: 18 ton
  - Reheating unit for heat retention of circulation circuit: 1 unit
- Conventional water heater: Heavy oil boiler
- Temperature of hot water tapped from the heat pump unit: 70 ℃

Fig. 12: External appearance of the field test system

5.6.2 Operating status in spring and fall

(1) Operating status from October 15, 2007 to October 21, 2007

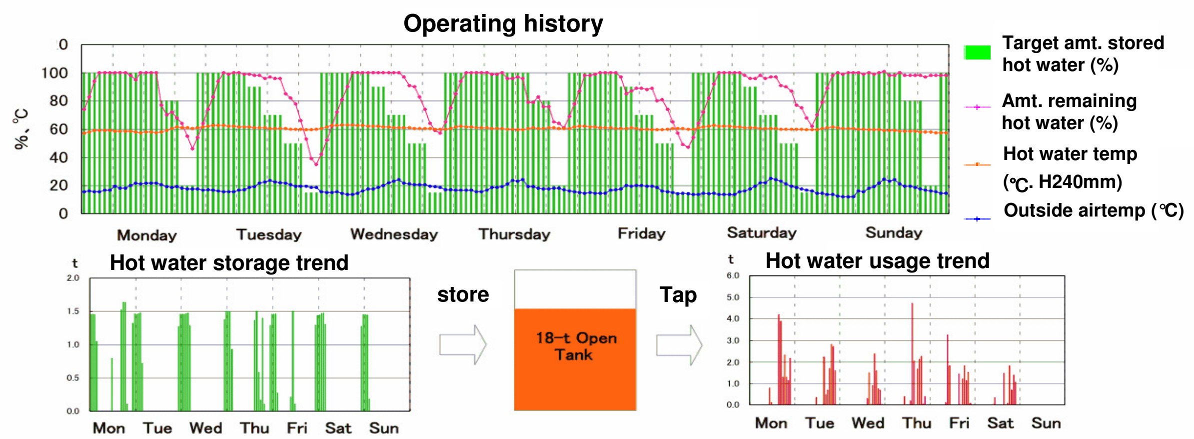
The operating status is shown in Fig. 13. The amount of hot water used varied from 7 to 17 tons/day, depending on day, at an average outside air temperature of 15.3 ℃. [Energy consumption at the open tank outlet/total power consumption] = system COP over one week was 3.61, which is the performance initially aimed at. As shown in the graph, since the amount of hot water remaining in the tank changed by a relatively large amount, better energy conservation can be achieved by decreasing the amount of hot water remaining in the tank to a level just before the hot water runs out.

The efficiency of the water-heating system = system COP was defined as follows for the calculation. The energy output by the heat-pump water-heating system in a day is expressed as follows:

Output energy = Tc-(Ta-Tb),

where Ta is the hot-water storage energy in the open tank at time 00:00, Tb is the hot-water storage energy at 23:59, and Tc is the hot-water tapping energy obtained from the amount of hot water tapped from the open tank.
In the water-heating system, the total electricity consumption has the following three components: Power consumption W1 of the heat pump units, power consumption W2 of the heater or reheating heat pump unit for heat retention of the hot-water storage tank, and power consumption W3 of a stirring pump for maintaining the bathwater at a uniform temperature. Hence, the daily system COP can be calculated as follows:

System COP = Output energy/Total power consumption = {Tc-(Ta-Tb)}/(W1+W2+W3)



	Outside air (°C)	Water supply (°C)	Amt. hot water used (t)	Power consumption (kWh)	Hot water tapping energy (kWh)	System COP
15th (Mon)	18.4	17.8	17.3	228.5	885.0	3.87
16th (Tue)	18.6	17.8	12.6	135.9	449.0	3.30
17th (Wed)	18.3	17.8	8.2	157.1	605.0	3.85
18th (Thu)	18.2	17.8	13.9	179.3	731.0	4.07
19th (Fri)	16.3	17.6	12.5	144.9	471.0	3.25
20th (Sat)	17.5	17.6	6.9	135.1	473.0	3.50
21st (Sun)	17.1	17.5	0.0	56.9	136.0	2.39
Average, Total	17.8	17.7	71.5	1037.6	3748.0	3.61

Fig. 13: Operating status of field test in spring and fall (07-10-15 through 10-21)

(2) Energy usage over four weeks (October 15 to November 11, 2007)

The energy usage for producing hot water with the heat-pump water heater was monitored for four weeks, and based on the values obtained in this manner, the amount of primary energy used, the operating costs, and the CO_2 emission level were estimated when hot water was produced with a heavy oil boiler, as conventional equipment, instead of the heat-pump water-heating system. These estimations were compared with measurements obtained when the heat-pump water-heating system was used. Results of the comparison are listed in Table 6. The heat-pump water heater uses 34% less primary energy. In Japan, there is an electricity rating system where the period from 22:00 on one day to 8:00 the following morning is regarded as night time, during which the electricity cost is significantly low for machines that store heat using night-time electrical power. Since our system has a night-time operating rate of 80%, the electricity cost can be reduced substantially. Due partly to the currently high cost of heavy oil, the difference in the four-week operating cost between our system and a heavy oil boiler was 90,802 yen, showing that our system reduced the cost by 81%. The four-week CO_2 emission level was reduced by 2,710 kgCO_2, or 67%.

6 CONCLUSION

We were able to produce a heat-pump water heater system for commercial use which has greater general market appeal over combustion-based water heaters. Compared with gas boiler systems, our system can attain energy conservation of approximately 40% on the basis of primary energy and reduce the CO_2 emission level by at least 50%. The number of

Table 6; Comparison of operating characteristics between the heat-pump water-heating system and a heavy-oil boiler system

	Actual measurement data with the heat-pump water-heating system	When water is heated with a heavy oil boiler (estimated values)
Amount of hot water tapped	274.6 ton/4 W	Same as in the left
Hot-water tapping energy	13,838 kWh/4W	Same as in the left
Energy consumption	Power consumption 3,987 kWh/4W	Amount of heavy oil used 1,499 L/4W
System efficiency	System COP 3.47	Combustion efficiency 85%
Amount of primary energy used	10,811 kWh/4W ←	16,282 kWh/4W
	Reduction by 5,471 kWh/4W (34%)	
Operating cost	22,327yen/4W ←	119,920 yen/4W
	Reduction by 97,593 yen/4W (81%)	
CO_2 emission level	1,352 $kgCO_2$/4W ←	4,062 $kgCO_2$/4W
	Reduction by 2,710 $kgCO_2$/4W (67%)	

Electricity	Primary energy units: 9,760 kJ/kWh = 2,332 kcal/kWh	Heavy oil	Heating energy: 9,341 kcal/L Boiler combustion efficiency: 85%
Electricity cost	Day time: 12.00yen/kWh Night time: 4.00 yen/kWh		Price: 80.00 yen/L
	CO_2 emission: 0.339 $kgCO_2$/kWh		CO_2 emission: 2.71kg CO_2/L

gas water heaters installed for commercial use in Japan is two million, when converted to 14-kW equivalent units. If 600,000 gas water heaters are replaced with heat-pump water heaters, the annual reduction in CO_2 emission level that can be achieved is 8×600,000 = 4.8 million tons of CO_2/year. This is equivalent to a 2% reduction in the current annual emission level in commercial use (238 million tons CO_2).

The following issues need to be solved to promote the wide-spread use of heat-pump water heaters:
(1) Smaller installation space;
(2) Reduction in initial cost;
(3) More flexible installation;
(4) Further energy conservation;
(5) Measures for cold regions, etc.

Fig. 14: Potential applications of the heat-pump reheating function

We hope to encourage widespread global use of heat-pump water heaters by addressing these challenges.
The reheating function is playing a role in the applications shown in Fig. 14, where combustion-based units and electrical heaters are currently used.
A significant advantage can be offered by replacing these combustion-based units and electrical heaters with heat pumps. As another important subject, we also wish to promote the adoption of heat pumps to realize this reheating function.