TIPS FOR COMPOSING HEAT PUMP SYSTEM FOR HOT WATER SUPPLY EQUIPMENT FOR COMMERCIAL USE

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Abstract: The performance of heat pumps has drastically improved in the field of air conditioning, and heat pumps now serve as effective measures for CO_2 reduction in the field. Meanwhile, in the field of commercial hot water supply systems where combustion-based systems are predominant, the adoption of heat pump hot water supply systems is expected to contribute significantly to CO_2 reduction. At present, the use of heat pump systems is being promoted in the field of commercial hot water supply systems. However, the optimal design method for heat pump hot water supply systems has not yet been established due to the fact that there are different types of hot water supply systems still being sold by manufacturers and that it requires approaches and techniques in the planning and designing phases that are different from the conventional techniques. Therefore, the Heat Pump & Thermal Storage Technology Center of Japan established a working team for the design of commercial heat pump hot water supply systems at the Center and explored the optimal method. This paper describes a design method for the construction of an optimal commercial heat pump hot water supply system and thereby strives to contribute to the widespread use of heat pump hot water supply systems in the future.

Key Words: heat pumps, heat pump hot water supply, composing heat pump system

1 INTRODUCTION

Japan's CO_2 reduction target for a 25% reduction compared to the 1990 level has become widely known and has triggered controversy. It is unquestionable, however, that we must reduce CO_2 emissions in society as a whole. Moreover, we must examine and understand the actual changes in CO_2 emissions in Japan before we discuss the target of 25%.
As the media are warning, Japan's greenhouse gas emissions have not decreased compared to the 1990 level.
The fourth assessment report issued by the IPCC (Intergovernmental Panel on Climate Change), an organization that publishes assessment reports on global warming, concluded that global warming is an indisputable fact and assumes that further global warming will be inevitable as mankind will continue to depend on fossil fuel for ongoing development. Although CO_2 reduction has become a hot public issue, the actual reduction of CO_2 achieved in the home or workplace has not been significant.
This paper first examines the structure of energy consumption in Japan and then discusses effective ways to reduce CO_2.

1.1 The Amount Of CO2 Emissions In The Consumer Sector Continues To Increase

Please refer to the following Table 1 to see which sector is the major cause of increasing CO2 emissions in Japan. The table shows an excerpt of data published by the Ministry of the Environment and lists top four sectors that produce most CO2 emissions.

Table 1 Which sector is the major cause of increasing CO_2 emissions in Japan

	1990	2006	Increase/Decrease (%)
Industrial Sector	482	460	-4.6%
Transport Sector	217	254	17.1%
Commercial and Other Sectors	164	229	39.6%
Residential Sector	127	166	30.7%

As the table shows, although the industrial sector is a major source of CO_2 emissions, the amount of CO_2 emissions has decreased compared to the 1990 level. On the other hand, CO_2 emissions in the residential and commercial (commerce, services, and other) sectors, which are closely related to our daily lives, have significantly increased (by 30% to 40% compared to 1990 levels), showing that these sectors are the major source of Japan's increased CO_2 emissions. Unless we take appropriate action to reduce CO_2 emissions in these sectors, we will not be able to achieve our CO_2 reduction goal.

1.2 Actual Conditions Of Energy Use In The Commercial Sector

Regarding the energy use in the commercial sector of Japan, the chart below (Figure 1 &Figure 2) shows the overview of the structure of recent energy consumption. Among the energy uses, thermal demand, such as hot water supply, cooling, and heating, accounts for approximately half of the total.

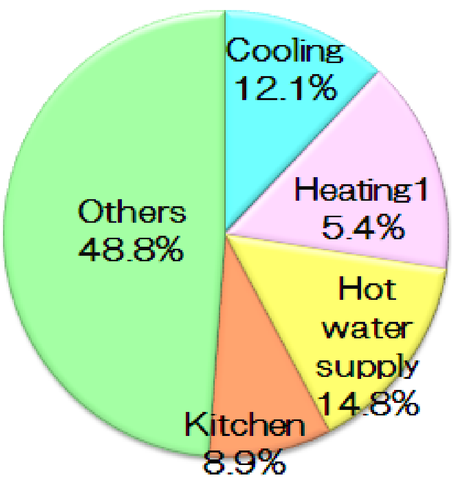


Figure 1 Actual conditions of energy use in the commercial sector

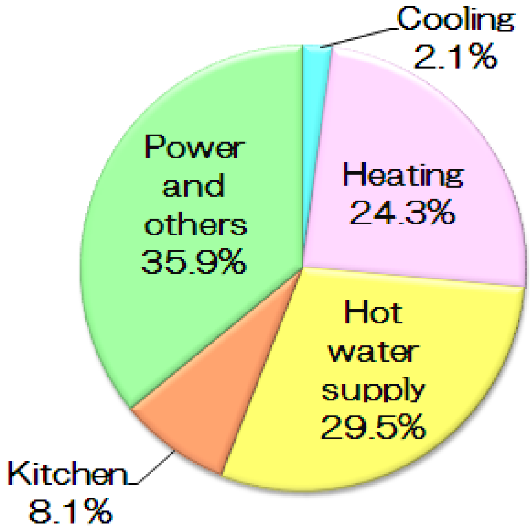


Figure 2 Actual conditions of energy use in the residential sector

(Reference :EDMC Handbook of Energy & Economic Statistics in Japan (2010))

Table 2 Most of the demand for hot water supply is fulfilled by systems based on the direct combustion of fossil fuels on the demand side

			← Combustion of fossil fuels		→
Hot water supply (Residential sector)	Electric	Solar Heat	City Gas	LPG	Kerosene
	12%	3%	38%	30%	17%

		←Combustion of fossil fuels→		
Hot water supply (Commercial sector)	Electric	Gas	Kerosene	others
	4%	43%	43%	10%

Since most of the demand for hot water supply is fulfilled by systems based on the direct combustion of fossil fuels on the demand side, it is hoped that these combustion-type systems will shift to heat pump hot water supply systems. (see Table 2)
If thermal demand in the consumer sector, such as commercial and residential sectors, continues to be fulfilled by fossil fuels, then CO2 emissions cannot be reduced, and global warming is inevitable. However, in recent years, more people strive to improve economic and environmental efficiency at home and more than 2.60 million households installed residential EcoCute across the nation in 2010. (see Figure 3)

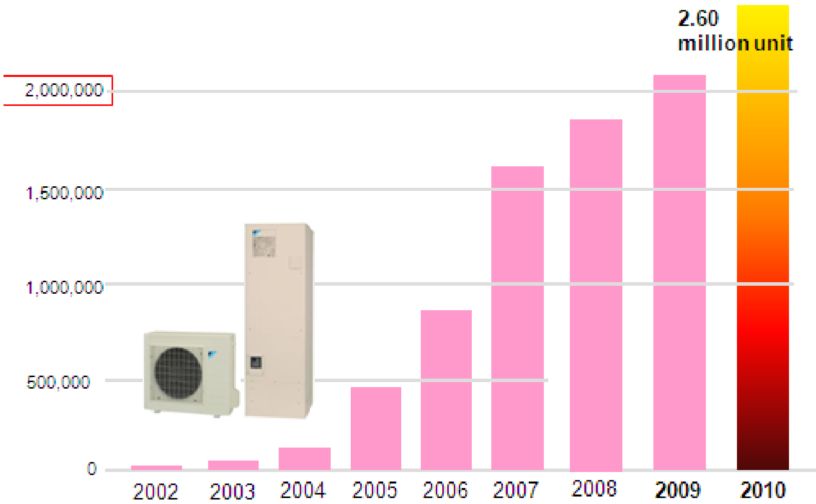


Figure 3 Changes in the number of residential EcoCute units sold 2.60 million units

1.3 Mechanism Of Heat Pump Hot Water Supply Systems

Let us review the heat pump technology here. “Heat pump” literally means to pump up heat. Although water flows only from high to low places due to gravity, its flow can be reversed, that is, from low to high places if a pump is used. It is the heat pump that achieves the same effect for “heat.” A heat pump moves heat from low temperature to high temperature. In particular, it is a technology for using atmospheric heat at room temperature (or river water or geothermal energy) as thermal energy by pumping up and “moving” it. In short, the heat pump technology enables the use of thermal energy for hot water supply without burning fossil fuels.
Another striking advantage of a heat pump is its excellent energy efficiency. A heat pump extracts many times more energy than the input energy. In the hot water supply system in the above chart, for example, a heat pump works as follows: Suppose the extracted atmospheric heat is “3” and “1” electricity is put in for a compressor to compress the refrigerant, then the heat exchanger for the hot water supply collects the amount of <1 + 3 = 4> heat. That is, four times more energy than the input energy can be obtained as heat. In such a case, we say the COP (coefficient of performance) is 4. (see Figure 4)Since heat pump technology obtains many times more energy output than energy input without burning fossil fuels, it has drawn the world’s attention as a measure against global warming.

1.4 Heat Pump System, A Technology To Use Renewable Energy

The source of atmospheric heat (geothermal heat or hydrothermal heat of river and seawater can also be used) that a heat pump hot water supply system mainly uses is solar energy. That is, the heat that heat pumps collect is renewable energy.
Figure 5 below is a conceptual diagram showing how air heated by the sun is used for heating or hot water supply via heat pump.

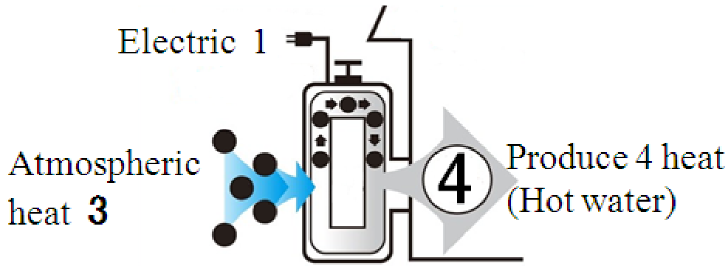


Figure 4 Mechanism of heat pump hot water supply systems

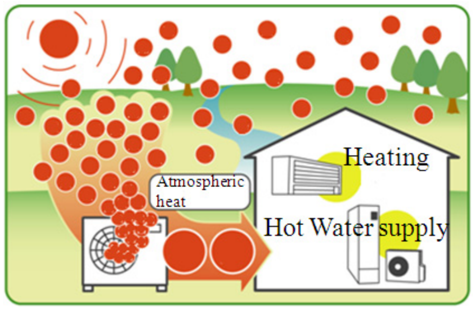


Figure 5 A conceptual diagram showing how a heat pump system uses air heat derived from the sun.

It seems that the amount of renewable energy can be
defined as follows: the amount of renewable energy that a heat pump system uses = the amount of energy available for use (energy the heat pump extracted) x (1- 1/COP). COP represents the efficiency of the heat pump (coefficient of performance). This formula indicates that the amount of renewable energy is obtained after subtracting the amount of energy required to operate the heat pump from the amount of heat obtained by the heat pump. If the example of COP = 4 is applied to the above formula, then the amount of renewable energy that a heat pump can use = the amount of energy available for use x 3/4. Since COP = 4 is the case where “1/4” of energy (for example, electricity) is required to extract “1” energy available for use, the amount of renewable energy that a heat pump can use is equal to “3/4,” which proves that the above formula matches our assumption.

2. TIPS FOR COMPOSING HEAT PUMP SYSYTEM FOR HOT WATER SUPPLY EQUIPMENT

2.1 Design Procedures

A commercial heat pump hot water supply system features high environmental and energy-saving performance and is expected to be widely used in the future. However, it requires a design approach and points to remember of its own, which are different from those of conventional hot water supply systems based on the combustion of fossil fuels. With an eye to future widespread use, the Heat Pump & Thermal Storage Technology Center of Japan has combined its expertise in commercial heat pump hot water supply systems and created a guidebook to facilitate prompt, accurate designs. When creating the guidebook, we formed a Commercial Heat Pump Hot Water Supply System Review Team, a special working team to review the design of a commercial heat pump hot water supply system, within the Heat Pump & Thermal Storage Technology Center of Japan. With a design expert invited from a major construction company as the chief, designers with considerable experience in designing commercial heat pump hot water supply systems from design offices and specialists from manufacturers of commercial heat pump water heaters and electric power companies combined their knowledge to review the design and create the guidebook. Moreover, a case catalog was added, which explains design approaches by intended use of hot water and provides support that ensures the construction of proper systems.

Since heat pump hot water supply systems will be widely used in the future, the guidebook is written in such a way that even those designers without much experience in designing commercial heat pump hot water supply systems can design with ease by following example cases. In particular, by describing how to create a hot water supply balance chart from hot water supply load and the amount of heat stored in a hot water cylinder, system adequacy can be evaluated so that events like running out of hot water will not occur.

From the practical perspective, a heat pump water heater excels as a conventional combustion-based hot water supply system in environmental and energy-saving performance due to the high operational efficiency. The price, however, is significantly more than the combustion-type system. It is necessary, therefore, to enhance economic efficiency by lowering the initial costs, which can be achieved by controlling heat source equipment capacity by pursuing the optimal balance with the hot water cylinder, while maintaining the same performance level as the combustion type. Based on this view, a method for the design of heat pump hot water supply systems is introduced below.

2.1.1 Design flow

Figure 6 shows the procedures for the design of a heat pump hot water supply system.

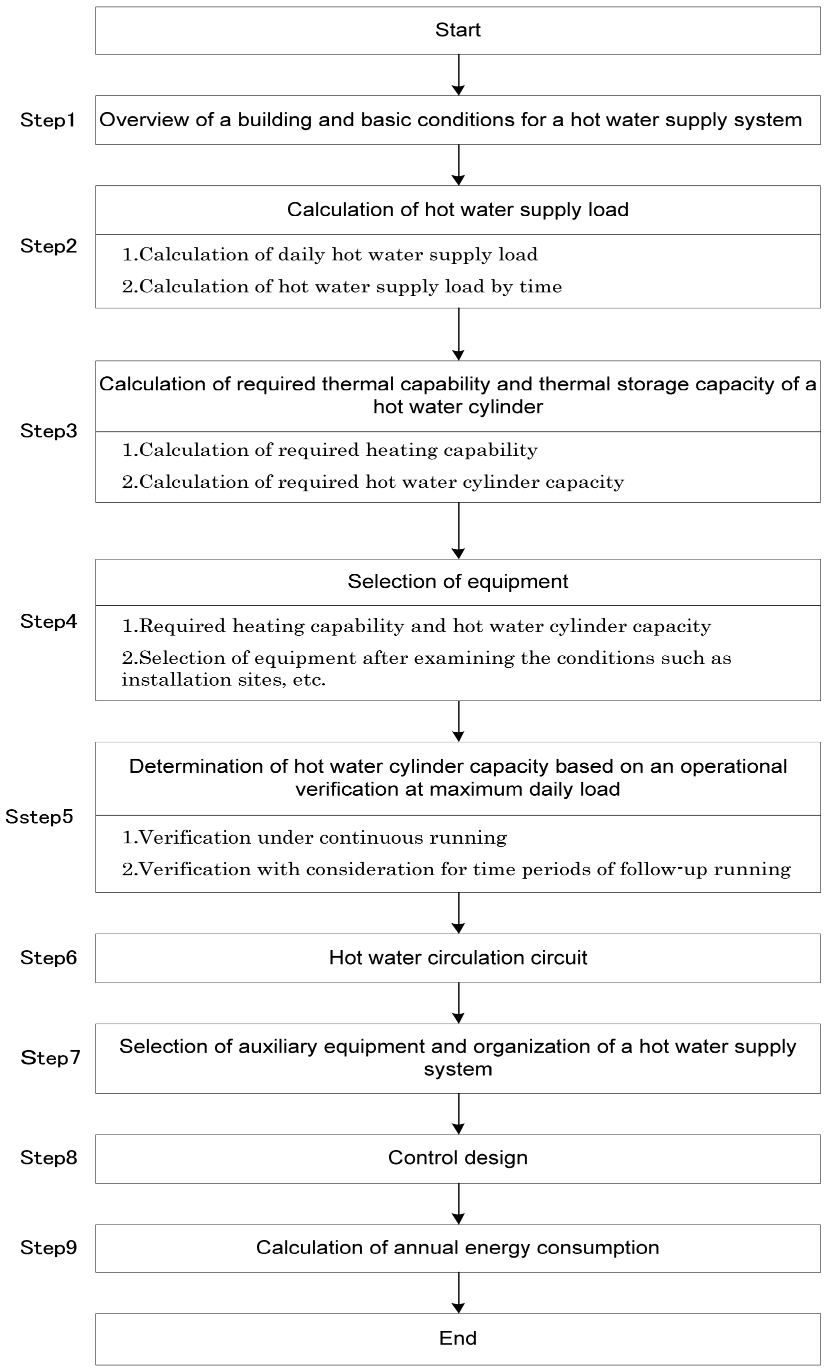


Figure 6 Heat Pump Hot Water Supply System Design Procedures

2.1.2 Calculation of hot water supply load by time

A heat pump hot water supply system comprises a heat pump water heater and a hot water cylinder. The difference from a combustion-type hot water supply system is that the hot water goes through a hot water cylinder in this system, and the operating time for the heat pump water heater does not necessarily match the hot water supply time. Therefore, it is essential to first determine when to operate the heat pump hot water system during the day. In order to make the determination, changes in the hot water supply load must first be obtained. For major business categories, patterns by time are listed in a report*1 and the handbook*2 of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan. See Figure 7 and Table 3.

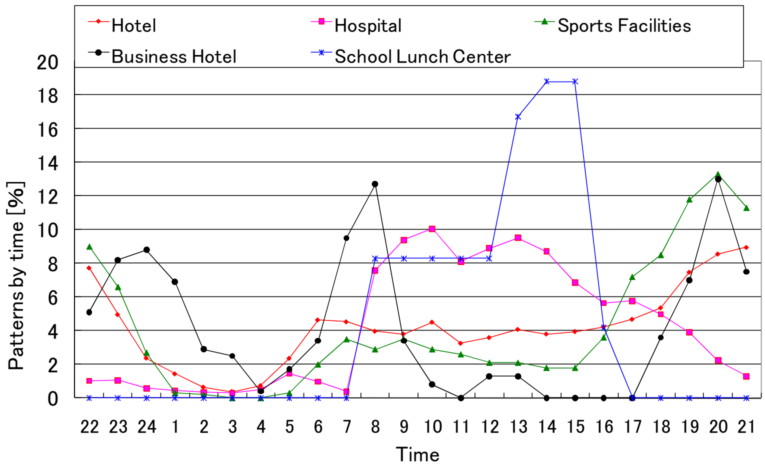


Figure 7 Developments of hot water thermal load

Table 3 Development patterns of hot water thermal load (load patterns by time) (%)

Time	By References *1			Measured Data	
	Hotel	Hospital	Sports Facilities	Business Hotel	School Lunch Center
22	7.74	1.03	9.00	5.10	0.00
23	4.96	1.06	6.60	8.20	0.00
24	2.37	0.58	2.70	8.80	0.00
1	1.43	0.45	0.30	6.90	0.00
2	0.64	0.35	0.20	2.90	0.00
3	0.38	0.29	0.00	2.50	0.00
4	0.73	0.48	0.00	0.40	0.00
5	2.35	1.45	0.30	1.70	0.00
6	4.64	0.97	2.00	3.40	0.00
7	4.53	0.39	3.50	9.50	0.00
8	3.97	7.58	2.90	12.70	8.30
9	3.80	9.39	3.50	3.40	8.30
10	4.51	10.06	2.90	0.80	8.30
11	3.25	8.10	2.60	0.00	8.30
12	3.59	8.90	2.10	1.30	8.30
13	4.08	9.52	2.10	1.30	16.70
14	3.80	8.71	1.80	0.00	18.80
15	3.95	6.87	1.80	0.00	18.80
16	4.23	5.65	3.60	0.00	4.20
17	4.68	5.77	7.20	0.00	0.00
18	5.36	4.97	8.50	3.60	0.00
19	7.48	3.90	11.80	7.00	0.00
20	8.57	2.23	13.30	13.00	0.00
21	8.96	1.30	11.30	7.50	0.00
計	100	100	100	100	100

2.2 Calculation Of Required Thermal Capability And Hot Water Cylinder Capacity Based On A Hot Water Supply Balance Chart (Step 3)

A heat pump hot water system comprises a heat pump water heater and a hot water cylinder. When selecting these devices, first calculate the required thermal capability and hot water cylinder capacity and then choose ones with specifications that meet the calculated capability and capacity.

2.2.1 Calculation of thermal capability required for a heat pump water heater

Calculate the thermal capability required for a heat pump water heater from the daily hot water load and the daily operating hours of a heat pump water heater using Formula (1) and create a hot water supply balance chart at the same time. In this phase, the operating hours are set at 20 hours from 22:00 to 18:00.

$$Qhp = \frac{Qhwd}{Thp} \tag{1}$$

Qhp: Thermal capability required for a heat pump water heater [kW]
Qhwd: Daily hot water load kWh/day]
Thp: Heat pump operating hours [h]＝20 hours/day

2.2.2 Calculation of required hot water cylinder capacity using a hot water supply balance chart

Create a hot water supply balance chart and a hot water supply balance calculation sheet from the hot water supply load patterns and the required thermal capability and operating hours of a heat pump water heater. Formula (2) is the formula for calculating the required hot water cylinder capacity from the required amount of heat stored in a hot water cylinder:

$$Vsts = \frac{Qsts \times 1{,}000}{(Thwst - Tw) \times Cw \times \rho} \tag{2}$$

Vsts: Required hot water cylinder capacity [L]
Qsts: Required amount of heat stored in a hot water cylinder [MJ]
Thwst: Temperature in a hot water cylinder [℃]
Tw: Temperature of water supplied [℃]
Cw : Specific heat of water 4.186[kJ/kg・℃] *ρ*: Water density [1.0 kg/L]

2.2.3 Procedures and points to remember for the creation of a hot water supply balance chart

An example of a hot water supply balance chart is shown in Figure 8 and Table 4 and its creation procedures and points to remember are given below:
The amount of hot water used is obtained from the amount of hot water used per day and the hot water supply load patterns by time (see 2.1.2).

i) ① Calculate the hot water load from the amount of hot water used each time, the hot water temperature (60℃), and the temperature of the water supplied.
ii) ② When selecting the required thermal capability and hot water cylinder capacity, set the operating hours to 20 hours (continuous running).
iii) ③ The thermal capability required for heat source equipment shall be the value obtained by multiplying the value calculated using Formula 1 and ② operating hours.
iv) For ⑤ the amount of input heat and ⑥ the amount of heat radiation, “+” indicates the

amount of input heat to a hot water cylinder while “–”indicates the amount of heat radiation from the cylinder. They can be obtained from the formula <Heating capability of a heat pump water heater – hot water load>.

v) ⑦ The amount of heat stored in a hot water cylinder is the accumulation of values obtained from ⑤ the amount of input heat and ⑥ that of heat radiation. The amount of heat stored in a hot water cylinder should not be 0 or less. If a lack of heat occurs in the heat budget when 22:00 is the time when the heat is first stored, the initial value at 22:00 should be after the shortage is offset in the hot water cylinder.

vi) The rate of storing heat in the hot water cylinder shall be the percentage of the maximum ⑦thermal storage capacity of the cylinder.

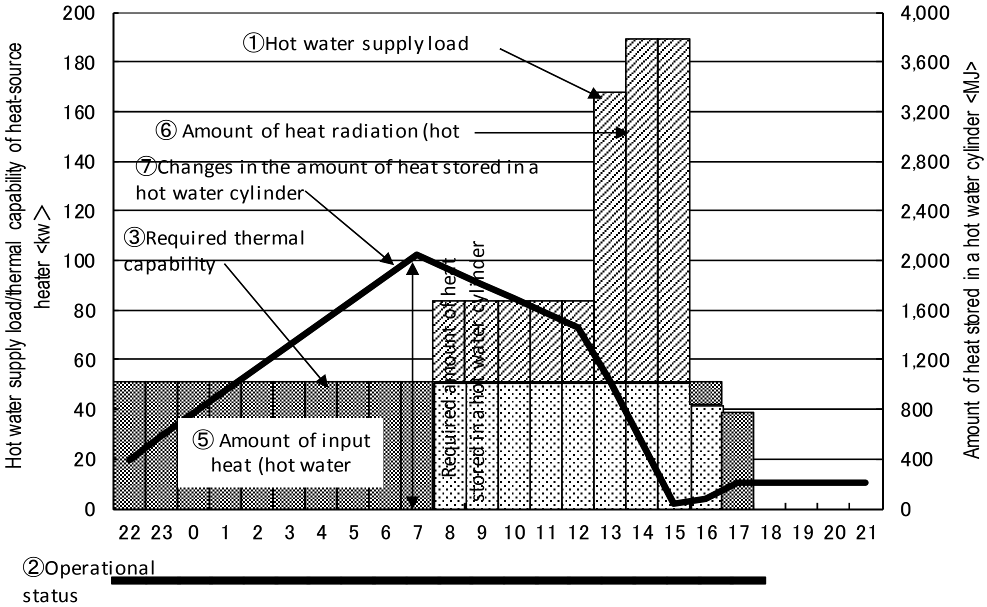


Figure 8 Hot Water Supply Balance Chart (The amounts of heat stored in the hot water cylinder have been corrected to positive values.)

Table 4 Hot Water Supply Balance Calculation Sheet (The amounts of heat stored in the hot water cylinder have been corrected to positive values.)

Time	Outside Air Temperature [℃]	Water supply Temperature [℃]	Amount of hot water used [L/h]	①Hot water supply load [kW]	② Operating hours [h]	③Required thermal capability of heat source equipment [kW]	④Power consumption [kW]	⑤Amount of input heat⑥ Amount of heat radiation ※1 (③-①) [kW]	⑦Amount of heat stored in a hot water cylinder (figures in parentheses are in <kW>) <MJ> [MJ]	Rate of heat storage in a hot water cylinder [%]
22		5	0	0	1	51		51	396(110)	19
23		5	0	0	1	51		51	580(161)	28
0		5	0	0	1	51		51	764(212)	37
1		5	0	0	1	51		51	947(263)	46
2		5	0	0	1	51		51	1131(314)	55
3		5	0	0	1	51		51	1314(365)	64
4		5	0	0	1	51		51	1498(416)	73
5		5	0	0	1	51		51	1682(467)	82
6		5	0	0	1	51		51	1865(518)	91
7		5	0	0	1	51		51	2049(569)	100
8		5	1,245	84	1	51		-33	1930(536)	94
9		5	1,245	84	1	51		-33	1811(503)	88
10		5	1,245	84	1	51		-33	1692(470)	83
11		5	1,245	84	1	51		-33	1574(437)	77
12		5	1,245	84	1	51		-33	1455(404)	71
13		5	2,505	168	1	51		-117	1034(287)	50
14		5	2,820	189	1	51		-138	537(149)	26
15		5	2,820	189	1	51		-138	40(11)	2
16		5	630	42	1	51		9	72(20)	4
17		5	0	0	0.76	39		39	213(59)	10
18		5	0	0		0		0	213(59)	10
19		5	0	0		0		0	213(59)	10
20		5	0	0		0		0	213(59)	10
21		5	0	0		0		0	213(59)	10
合計			15,000	1,008	19.76	1,008				

. Night shift rate = Σ (④ Night power consumption)/④Total power consumption

*1: "+" indicates input heat into the hot water cylinder whereas "-" indicates heat radiation from the cylinder

2.3 Conditions Of A Hot Water Supply System

Since the conditions for the installation of a hot water supply system vary with the type and installation site of a hot water cylinder as shown in Figure 9. The main points to remember as common to all cylinder types are listed below.

i) Securing of hot water pressure
ii) Measures against negative pressure
iii) Measures for hot water circulation load

Measures for hot water circulation load, which are explained in detail in section 4 "Hot Water Circulation Circuit (Step 6)," are basically divided into the following two approaches: one is based on a heat pump water heater and the other is by installing an electric heater or a heat pump unit. When a heat pump water heater is used, it should be noted that the measures differ depending on the equipment specifications (limits to entrance temperature) and the type of hot water cylinder.

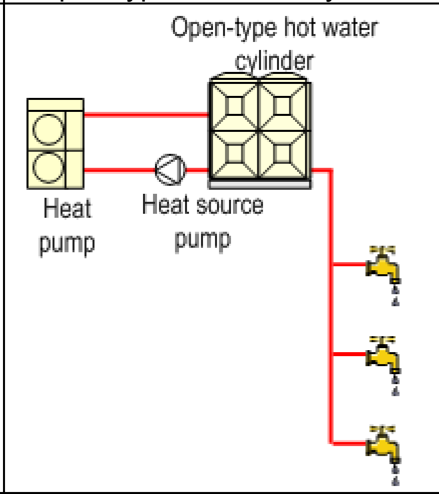
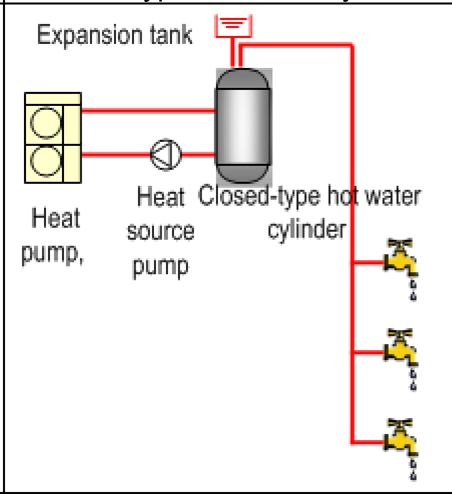
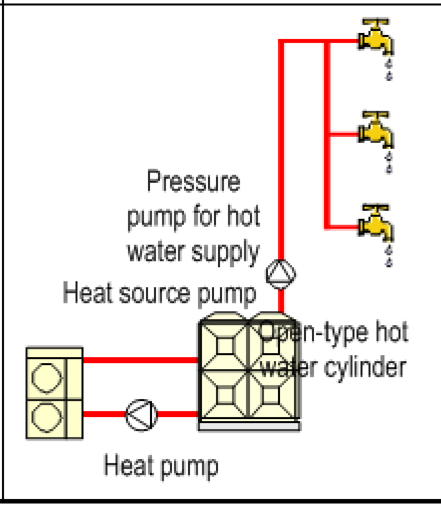
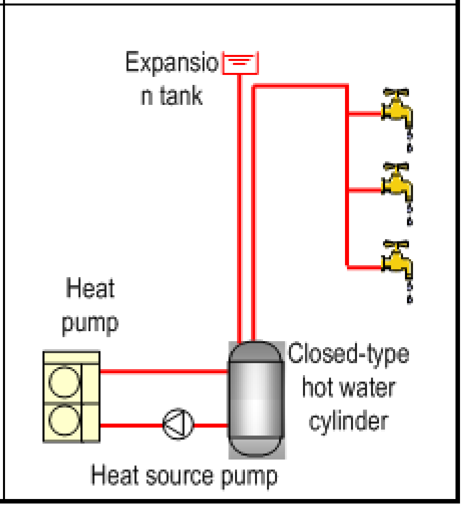
Installation site	Open-type hot water cylinder	Closed-type hot water cylinder
Installed on the top floor (supplies hot water to the lower levels)		
Installed on the ground floor (supplies hot water to the upper levels)		

Figure 9 Overview of hot water supply systems by type and installation site of a hot water cylinder

2.4 Hot Water Circulation Circuit (Step 6)

Hot water circulation enables immediate provision of hot water, such as for a shower, and requires re-heating to compensate for any heat loss in the pipes. In the heat pump hot water supply system, the basic concepts underlying the design of a hot water circulation circuit fall roughly into the following three groups.

2.4.1 Basic Concepts

Below are the basic concepts for the design of a circulation piping circuit for a heat pump hot water supply system: (see Figure 10)

i) Install a dedicated electric heater or heat pump unit in the circulation piping circuit as a measure to address heat radiation inside the circulation piping circuit.
ii) Use the heat-source equipment of a heat pump water heater as a measure to address heat radiation.
iii) Use a unit-type circulation system equipped with a function for immediate provision of hot water.

In i), the temperature of hot water stored can be set to 90℃ and the circulated hot water supply temperature can be set to 65→55℃. In ii), it is required that the ceiling of the entrance water temperature for the heat pump heat source equipment should be higher than 55℃ and that the temperature of hot water stored should be at the same level as the circulated hot water supply temperature (60℃). In this case, however, it should be noted that the operating efficiency of heat source equipment will be lowered. In iii), it is often the case that a hot water cylinder dedicated to circulation will have mixing valves installed (by a manufacturer and by a builder, respectively). Since the exit temperature of a heat pump (when circulated) varies with the equipment type, care should be taken when designing, constructing, and managing the system.

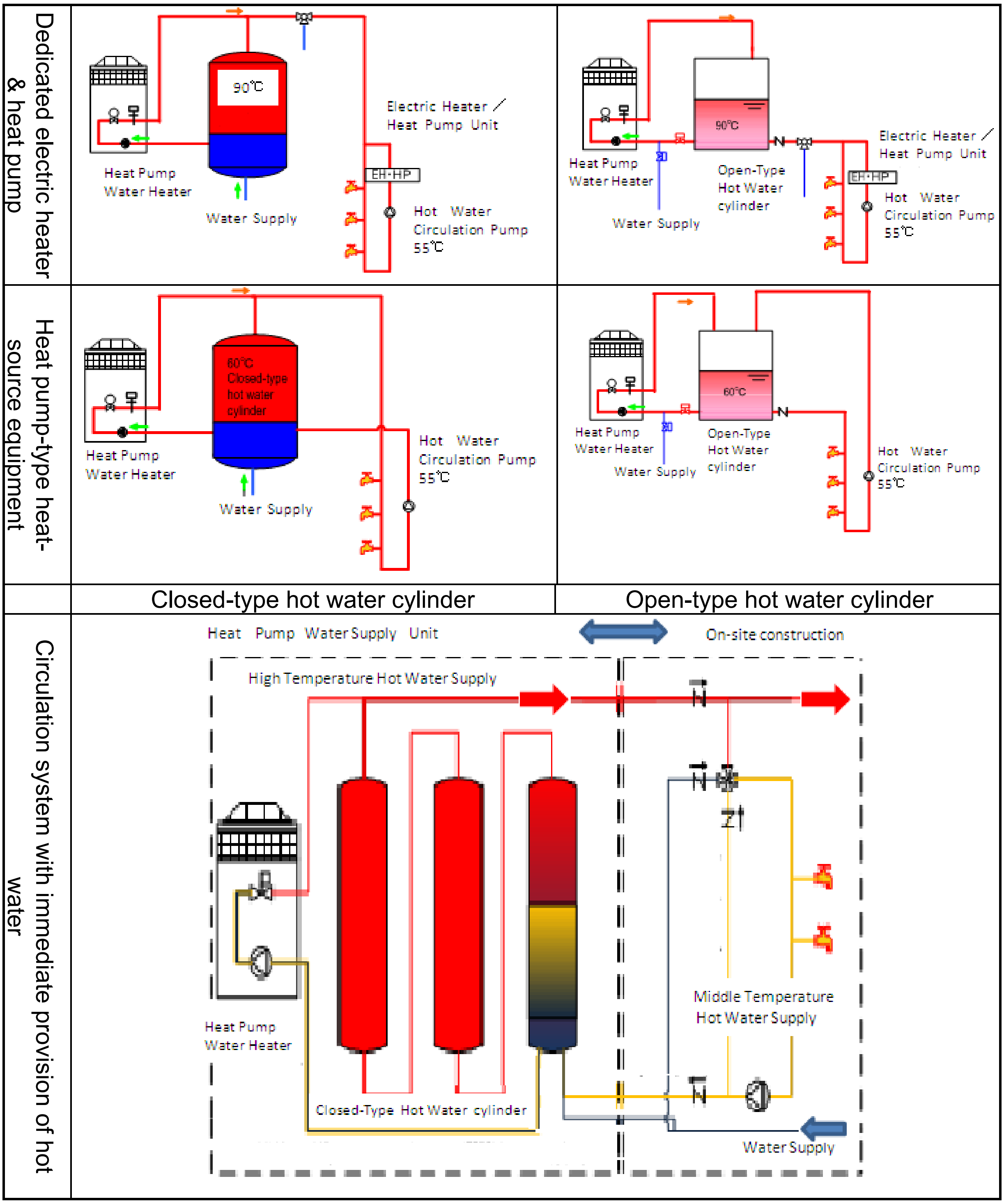


Figure 10 Circulation circuit-type hot water supply system

3. ACNOWLEDGEMENT

Since the completion of the guidebook on the design of commercial heat pump hot water supply systems, we have been holding seminars to promote understanding among designers and facility owners. In 2010, seminars were held in Tokyo, Osaka, and Nagoya, and the number of participants was approximately 1400 in 2010, demonstrating high expectations for commercial heat pump hot water supply systems. The high expectations are partly due to the fact that there has been no guidebook on commercial heat pump hot water supply systems like this one that combines knowledge of experts. Meanwhile, in the fall of 2009, architectural equipment design standards for the design of equipment in government facilities were revised and issued under the supervision of the Ministry of Land, Infrastructure, Transport and Tourism. A description of a heat pump hot water supply system was added to the revised standards, showing that the government has also embarked on the adoption of heat pump hot water supply systems.

The authors of this paper are concerned about the fact that due to the worst recession in a century, cheap hot water supply systems that produce lots of CO2 are still being sold. As mentioned in the previous chapter, about 80% to 90% of hot water supply systems are based on the combustion of fossil fuels, which puts a damper on CO2 reduction efforts. Once installed, water heaters with high CO2 emissions will continue emitting extra CO2 for their lifespan (8 to 10 years or more). “The amount of emissions for the coming ten years is determined NOW.” Easy equipment selection will lead to the acceleration of global warming for many years to come. When installing new equipment or upgrading existing ones, please adopt a heat pump hot water supply system, such as EcoCute. Moreover, when introducing such a system, please refer to the guidebook on the design of hot water supply systems or instructions provided by manufacturers to ensure that the design, operation, and management of the system will all contribute to the enhancement of CO2 reduction efficiency.

This paper owes significantly to the outcome of activities by the working team for the design of commercial heat pump hot water supply systems at the Heat Pump & Thermal Storage Technology Center of Japan, and we would liked to extend our sincere thanks to Team Leader Akira Yoshida, designers from design offices and specialists from manufacturers of commercial heat pump water heaters and electric power companies.