Development of Instantaneous Hot Water Dispenser Based On Water Source Heat Pump

Satoshi Yoshida, Researcher, LIXIL Corporation Products Company Noda Research Institute, Nakasato 3000, Noda-shi, Chiba, Japan
Ryozo Ooka, Professor, Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
Toshiyuki Hino, Research Advisor, The University of Tokyo, Tokyo, Japan
Kazuo Kodama, Graduate student, The University of Tokyo, Tokyo, Japan

Abstract: Natural energy use is important to reduce the energy consumption of buildings. However, there are advantages and disadvantages to the use of natural energy of traditional systems. It is difficult to reduce further energy consumption with traditional systems. Therefore, to achieve higher efficiency than traditional systems, a Multi-Source and Multi-Use Heat Pump (MMHP) system is proposed.
The MMHP system connects multiple heat sources such as solar heat, ground source and air source and multiple heat uses such as cooling, heating, and a hot water dispenser with the water loop. Each type of heat use side can utilize heat efficiently. However, there is a distinct lack of highly efficient hot water dispensers available to the MMHP system throughout the world. Therefore, we developed the Instantaneous Hot Water Dispenser based on Water Source (IHWD WS) heat pump.
In this paper, the IHWD WS heat pump was prototyped. The results show that the COP of the IHWD WS heat pump was 5.2 in winter and 8.5 in summer.

Key Words: heat pumps, hot water, efficiency, COP, ground source

1 INTRODUCTION

One of the causes of global warming is the increase in the world’s energy consumption (METI 2013). Building-related energy consumption accounts for about 40% of the total. (Abdeen-Mustafa O, 2008) Reduction of the energy consumption of these areas is required. Natural energy use is important to reduce the energy consumption of buildings. In recent years, natural energy has been used, for example, air-conditioning and domestic hot water supply. However, there are advantages and disadvantages to the use of natural energy of traditional systems. For example, when using solar heat, although the amount of heat is large, it is intermittent. There is disparity in the time of the supply and demand. For example, when using ground heat, the heat source temperature is stable, but there is a limit to the amount of heat available. The efficiency of heat pump systems gradually decreases with time and the ground source will be inaccessible unless balance is achieved between the heat extraction and injection from the ground as suggested by Li X et al. (2006). The use of air heat has spread because this system is simple. But the outside temperature affects the performance and the efficiency decreases when the demand is large.
On the one hand, there is simultaneous heating and cooling demand in a building, but flexibility of the heat has not existed until now, because it uses a single heat source. Therefore, to reduce the energy consumption of buildings further than traditional systems, the Multi-Source and Multi-Use Heat Pump (MMHP) system is proposed. The MMHP system connects multiple heat sources such as solar heat, ground source and air source and

multiple heat uses such as cooling, heating, hot water dispenser, and freezing are used as the heat source temperature. They are connected to each other by the water loop, so that each use type can utilize heat efficiently. The effectiveness of the MMHP system has been evaluated by the Ooka et al. (2011)
However, there is a distinct lack of highly efficient hot water dispensers based on the water source available to the MMHP system, because there is no system with a sufficiently stable large heat source like MMHP in the world. Therefore, we developed a hot water dispenser based on the water source. The water source is characterized by its ability to carry a large amount of heat instantly. Taking advantage of this, the hot water dispenser is the instantaneous type. Instantaneous Hot Water Dispenser based on Water Source (IHWD WS) heat pumps are almost non-existent in the world. And their operability has not been verified. This paper confirmed by experiment that the IHWD WS heat pump operates correctly and its COP is high.

2 MMHP SYSTEM SUMMARY

The MMHP system developed by OOKA et al. is shown in Figure 1. This system includes various equipment as the heat source such as horizontal ground heat exchangers using ground heat, outside equipment using air and solar power, and water circulation loops connected to each other.
The circulation water temperature is stably maintained by all the heat source equipment that can maintain the heat balance between the ground and surrounding ground temperatures, so this system requires no antifreeze. For example, in houses, cooling, heating, hot water supply, and freezing are used as the heat source, and heat is used efficiently because each type has a distributed heat pump using circulation water and heat is recollected with the water loops if exhaust heat exists. Additionally for the hot water dispenser, it is possible to use an instantaneous water heater without a storage tank. Please refer to the study (e.g. Ooka R et al. (2011)) for details of the system.

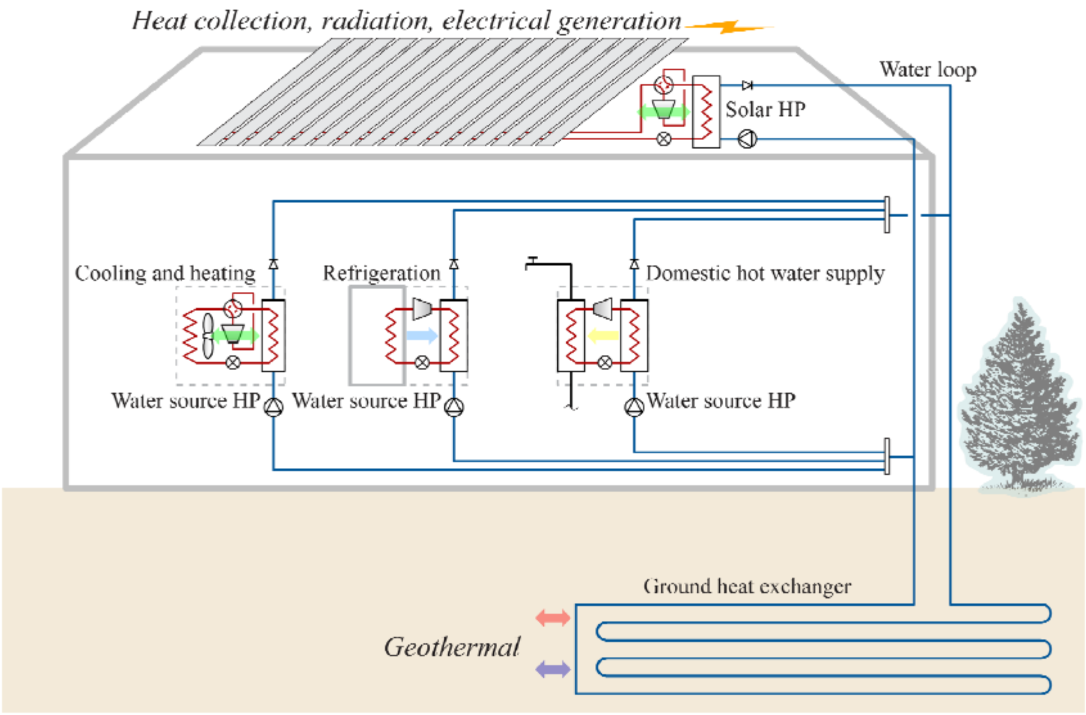

Figure 1. Concept of MMHP system

3 IHWD WS HEAT PUMP SUMMARY

3.1 Background of development of IHWD WS heat pump

In order to reduce the energy consumption of hot water dispensers, storage-type hot water dispensers based on an air-source heat pump are widespread in Japan. However, the colder it is, the greater the demand for hot water and the lower the efficiency of the air source heat pump. In addition, to protect against legionella bacteria, the hot-water-storage type requires a high temperature (60°C and over), which diminishes the efficiency of the heat pump. Therefore, we developed the Instantaneous Hot Water Dispenser Based on Water Source (here after IHWD WS) heat pump. The IHWD WS heat pump has the following advantages.

1) The high temperature heat source can be used for one year by connecting the IHWD WS heat pump to the MMHP system. Therefore, the IHWD WS heat pump can be operated with high efficiency also on a cold day.
2) Since it is an instantaneous hot water dispenser, it is not necessary to overly raise the temperature. The temperature used for washstands and the showers is about 40°C. Operation with a lower supply temperature allows the IHWD WS heat pump to operate with high efficiency.
3) Since there is no storage tank, cost reduction and space-saving are possible.

However, we did not verify the performance of the IHWD WS heat pump because no system with a sufficiently stable large heat source like MMHP exists in the world. Therefore, we built a IHWD WS heat pump and evaluated its performance.

3.2 Constitution of IHWD WS heat pump

Table 1 shows the prototype of specifications. The prototype was designed for a washstand. Heating capability is a maximum 14.4kW. It has a rotary-type compressor with an inverter fed motor drive. The refrigerant is HFC-410A.

Table 1. Prototype specification

Description		Specification
Performance	Temperature setting range	35～45 (°C)
	Heating capability	Max. 14.4 (kW)
Compressor	Type	Rotary (Inverter fed motor drive)
	Power dissipation	1.8 (kW)
Expander	Type	Drainer (Vapor trap)
Heat exchanger of heat source side	Type	Plate
	Surface area	1.2 (m^2)
	Volume	2.45 (L)
Heat exchanger of hot water side	Type	Plate
	Surface area	1.2 (m^2)
	Volume	2.45 (L)
Refrigerant	Type	HFC-410A
	Enclosed capacity	2.2 (kg)

Figure 2. Photograph of prototype

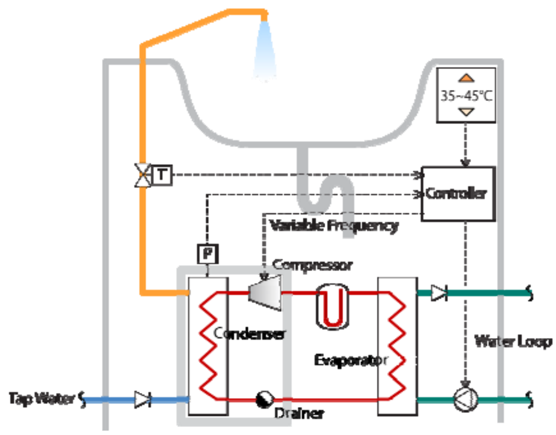

Figure 3. Details of prototype

Figure 2 shows a photograph of the prototype. The heat pump is under the washbowl. Figure 3 shows details of the prototype. The compressor is controlled by feedback of the hot water outlet temperature or the condensing pressure.

3.3 Estimation of the COP value of prototype.

The calculation conditions for the heat source temperature and hot water outlet temperature are shown in Table 2. The heat source temperature was set following the concept of the MMHP system. The hot water outlet temperature was set to 40°C for hand-washing and showering.

Table 2. Calculation conditions

Season of assumption	Heat source temperature (°C)	Hot water outlet temperature (°C)
In winter	12	40
In Spring and Autumn	17	40
In summer	22	40

The estimated COP was calculated based on Carnot's cycle. When it is assumed that a Carnot's cycle is realized, theoretical COP can be calculated by

$$COP_{th} = T_2 / (T_2 - T_1) \quad (1)$$

Where COP_{th} is theoretical COP. T_1 and T_2 are the condensing or evaporating temperature. The evaporating temperature is assumed to be 3K less than the heat source temperature in consideration of the heat exchange. The condensing temperature is assumed to be the hot water outlet temperature in consideration of the high temperature of the compressor discharge. However, actual COP decreases sharply compared to theoretical COP. So, the estimated COP is calculated by

$$COP_{est} = a \times COP_{th} \quad (2)$$

Where COP_{es} is estimated COP. a is the rate of Carnot's cycle and 0.6 in this paper. 0.6 is the efficiency of the equipment that is commonly used.
The calculation results for the condensing temperature and evaporating temperature and theoretical COP and estimated COP are shown in Table 3.
The estimated COP in winter was 6.1, in spring and autumn was 7.2, and in summer was 8.9. With the IHWD WS heat pump, a higher efficiency than the popular storage-type hot water dispenser based on the air-source heat pump can be expected throughout the year.

Table 3. Calculation result and the value used for calculation

Season of assumption	Evaporating temperature (°C)	Condensing temperature (°C)	Theoretical COP (-)	Estimated COP (-)
In winter	9	40	10.1	6.1
In spring and autumn	14	40	12.0	7.2
In summer	19	40	14.9	8.9

4 IHWD WS HEAT PUMP ACTUAL OPERATION

4.1 Set of operating conditions

In order to clarify the annual performance, three conditions were prepared. Table 4 shows the experimental conditions. The heat source temperature was set following the concept of the MMHP system. The heat source flow rate was set according to the capacity of the pump. The hot water inlet temperature adhered to the conditions on restriction of the equipment. The hot water outlet temperature was set to 40°C for hand-washing and the hot water flow rate was set to 5L/min for the same.

Table 4. Experimental conditions

Season of assumption	Heat source		Hot water		
	Temperature (°C)	Flow rate (L/min)	Inlet temperature (°C)	Outlet temperature (°C)	Flow rate (L/min)
in winter	12.0	22.5	Allow to chance	40	5
in Spring and Autumn	17.0	22.5		40	5
in summer	22.0	22.5		40	5

4.2 Actual operating conditions

Figure 4 shows the operating conditions of 17 minutes based on the assumption in spring and autumn. The hot water outlet temperature exceeds 40°C of the preset temperature from one minute after the start of the operation. After that, it is confirmed that the prototype produced 40°C water instantaneously. However, the hot water outlet exceeded the preset temperature for 1 to 8 minutes. It stabilized at 40°C after that. The power consumptions stabilized within about 1kW, when the hot water outlet temperature stabilized at 40°C. In this paper, the power consumptions are only those of the compressor. The heat source temperature fell gradually and became the condition temperature of the assumption in spring around 14 minutes later. The heat source flow rate was stable in about 22.5L/min. The hot water flow rate was stable in about 5L/min. The hot water inlet temperature was 18 ~ 21°C, but it rose by 2 - 5°C every 100-110 seconds. This is a malfunction.

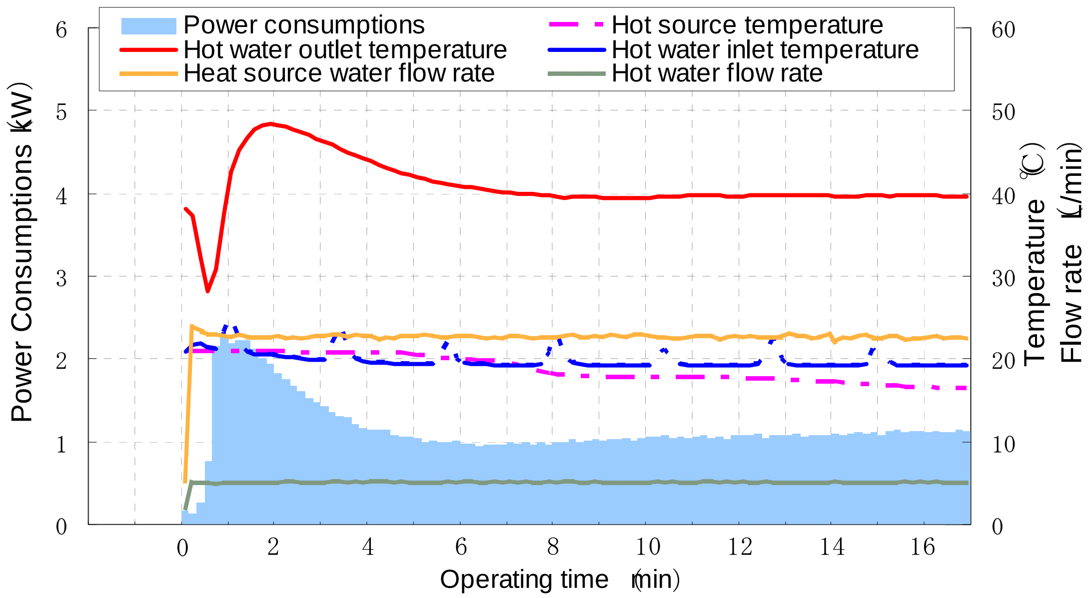

Figure 4. Actual operating conditions (In spring and autumn)

Figure 5 shows the operating conditions of 15 minutes of the assumption in winter. Figure 6 shows the operating conditions of 10 minutes of the assumption in summer. The power consumptions were different in Figure 4, Figure 5 and Figure 6. However, the other operating conditions were almost the same.

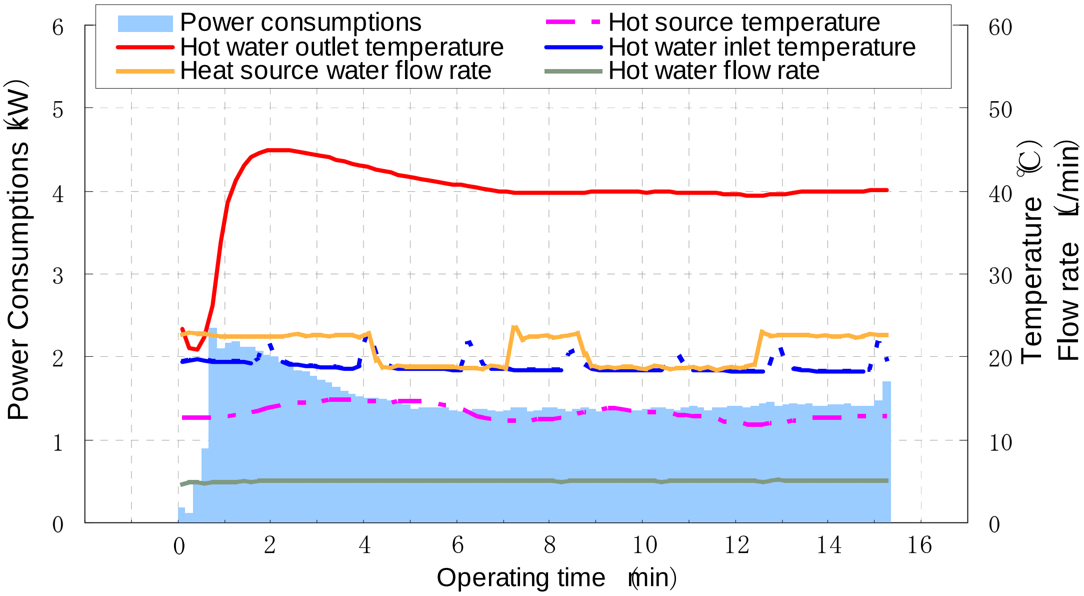

Figure 5. Actual operating conditions (In winter)

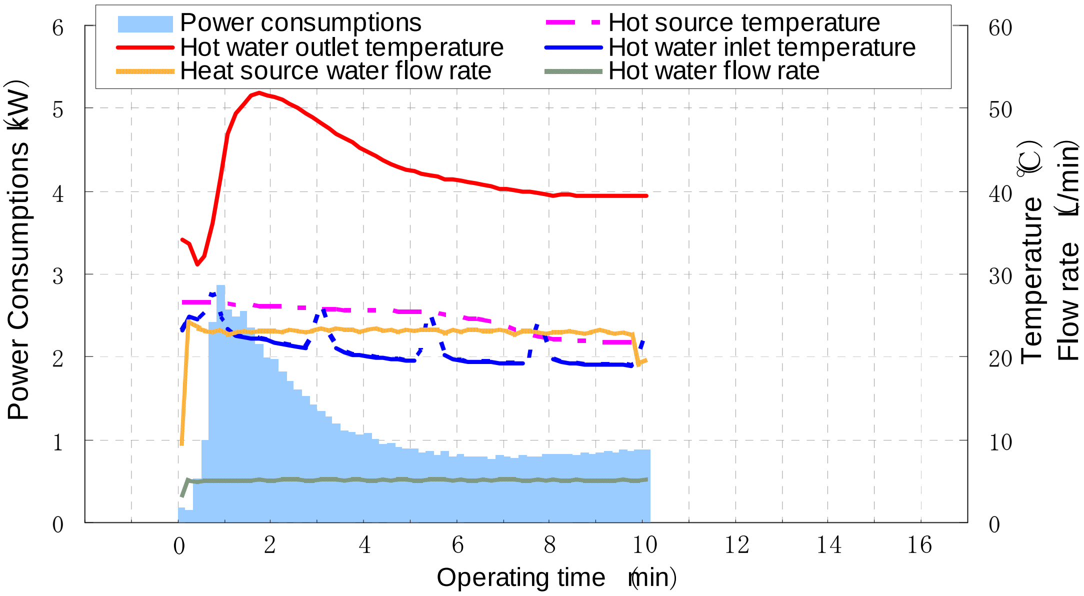

Figure 6. Actual operating conditions (In summer)

The operating conditions and problems with the in IHWD WS heat pump are summarized as follows.

1) 1-2 minutes is necessary to reach the preset temperature from the start of operation. The length of the start-up time is problematic. This problem is currently being addressed.
2) The temperature of the hot water outlet exceeded the preset temperature for 1 to 8 minutes. This excess is a problem. However, this problem was solved by changing the control method of the inverter. Detecting points for the control were changed to condensing pressure from the hot water outlet temperature. Figure 7 shows the results of the case after the problem has been resolved. The excess was stopped.
3) After that, it was confirmed that the prototype produced 40°C water instantaneously.

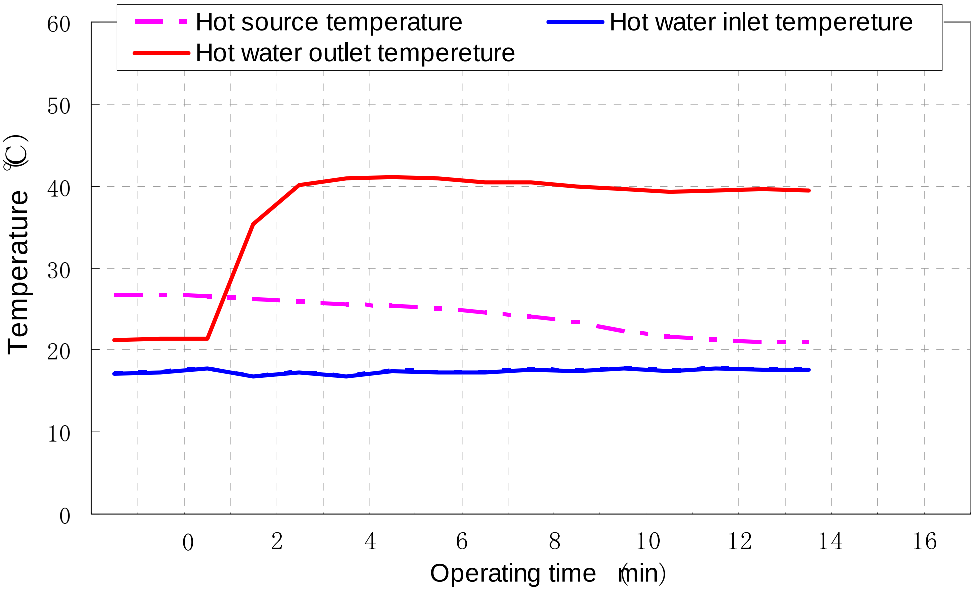

Figure 7. Actual operating conditions (changed control method)

4.3 Setting coefficient of performance

The actual COP is calculated using the following equations:

$$Q = (T_3 - T_4) * m_w * C_w \quad (3)$$

$$COP = Q / E \quad (4)$$

where:

Q: Heat quantity applied (kW), T_3: Hot water outlet temperature measured (°C), T_4: Hot water inlet temperature measured (°C), m_W: Hot water flow rate measured (L/min), C_w: Specific heat of water (kJ/kgK),*COP*: Actual coefficient of performance (-), E: Power consumptions measured (kW)

The average values when the operating condition was stable in the experimental condition were used. C_W is 4.18 kJ/kgK in this paper. E is the power consumption only for that of the compressor.

4.4 Result

Table 5 shows the operating conditions data. The actual COP values are calculated with the operating conditions data. Table 5 shows that the measured data and experimental conditions are almost the same. The power consumptions decreased when the heat source temperature increased.

Table 5. Condition data and data used for COP calculated

Season of assumption	Heat source		Hot water			Power Consumptions (compressor)
	Temperature (°C)	Flow Rate (L/min)	Inlet temperature (°C)	Outlet temperature (°C)	Flow Rate (L/min)	
in winter	12.2	22.5	18.4	39.7	5.0	1.44
in Spring and Autumn	17.0	22.5	19.2	39.7	5.0	1.10
in summer	21.8	22.5	19.1	39.5	5.0	0.84

Table 6 shows the heat quantity applied and actual COP calculated.

Table 6. Heat quantity applied and actual COP

Season of assumption	Heat quantity applied (kW)	Actual COP (-)
In winter	7.42	5.2
In spring and autumn	7.14	6.6
In summer	7.11	8.5

The actual COP in winter was 5.2. Actual COP became 0.85 times as compared with estimated COP 6.1.
Actual COP in spring and autumn was 6.6. Actual COP became 0.91 times as compared with estimated COP 7.2.
Actual COP in summer was 8.5. Actual COP became 0.96 times as compared with estimated COP 8.9.

Actual COP became slightly lower than estimated COP. This is because a-value used in equation (2) is different. a-value is decided depending on the equipment. The performance of the compressor in this prototype was worse in general types. Therefore, actual COP became slightly lower than estimated COP. However, actual COP was approximately the same as the estimated COP.

5 IHWD WS HEAT PUMP POSSIBILITY

5.1 Possibility of COP

The prototype refrigerant is HFC-410A. Its condensing temperature is constantly high in order to increase the temperature of hot water. Therefore, the irreversible loss of energy will increase. Lorentz's cycle is effective when the temperature change is large as with the hot water dispenser. The refrigeration cycle will approach Lorentz's cycle when CO_2 refrigerant is used. If CO_2 refrigerant is used for the IHWD WS heat pump, a further improvement in efficiency is expected. This chapter shows the possibility of increasing efficiency by estimating the COP when the IHWD WS refrigerant is changed to CO_2.
The estimated COP was calculated based on the theoretical COP of Lorentz's cycle.
Theoretical COP is calculated using the following equations (5). COP is calculated using the following equations (6).

$$COP_{L-th} = (T_5 + T_6)/(T_5 + T_6 - 2T_7) \quad (5)$$

$$COP_{L-est} = a \times COP_{L-th} \quad (6)$$

where:
COP_{L-th}: Theoretical COP of Lorentz's cycle (-), T_5: Temperature of refrigerant at inlet of condenser (°C), T_6: Temperature of refrigerant at outlet of condenser (°C), T_7: Evaporating temperature (°C), COP_{L-est}: Estimated COP of Lorentz's cycle (-), a: The rate of Lorentz's cycle (-)

Table 7 shows the calculation conditions. The heat source temperature was set following the concept of the MMHP system. The hot water outlet temperature was set to 40°C for hand-washing and showering. The hot water inlet temperature was set by reference to data of the Japan Tokyo Metropolitan Government Bureau of Waterworks in 2012.

Table 7. Calculation conditions

Season of assumption	Heat source temperature (°C)	Hot water inlet temperature (°C)	Hot water outlet temperature (°C)
In winter	12	7	40
In Spring and Autumn	17	15	40
In summer	22	27	40

Table 8 shows the calculation result and value used for calculation. The temperature of refrigerant at the inlet of the condenser is assumed to be 5K more than the hot water outlet temperature in consideration of the heat exchange. The temperature of refrigerant at the outlet of the condenser is assumed to be 5K more than the hot water inlet temperature in consideration of the heat exchange. The evaporating temperature is assumed to be 3K less than the heat source temperature in consideration of the heat exchange. These conditions were set by referring to the study by Hino et al. (2013)

Table 8. Calculation result and the value used for calculation

Season of assumption	Evaporating temperature (°C)	Temperature of refrigerant at outlet of condenser (°C)	Temperature of refrigerant at inlet of condenser (°C)	Theoretical COP of Lorentz's cycle (-)	Estimated COP of Lorentz's cycle (-)
In winter	9	12	45	15.5	9.3
In spring and autumn	14	20	45	16.5	9.9
In summer	19	32	45	16.0	9.6

Estimated COP of refrigerant CO_2 in winter was 9.3. This COP became 1.53 times as compared with estimated COP6.1 of refrigerant HFC-410A.
Estimated COP of refrigerant CO_2 in spring and autumn assumption was 9.9. This COP became 1.38 times as compared with estimated COP7.2 of refrigerant HFC-410A.
Estimated COP of refrigerant CO_2 in summer assumption was 9.6. This COP became 1.08 times as compared with estimated COP8.9 of refrigerant HFC-410A.
The COP of IHWD WS heat pumps can expect to reach a high value of 9.3-9.9.

5.2 Possibility of actual use

The IHWF WS heat pump has the following disadvantages.
1) The IHWF WS heat pump needs a heat source system of water. Therefore, the system become complex.
2) The IHWF WS heat pump cannot contribute to demand response. Considering the residence, the use of additional power may become necessary when the demand is large.
3) The required power is large.
4) In comparison with storage-type hot water dispensers, the required capacity of the compressor is increased.

Although the IHWF WS heat pump also has disadvantages, it dose have great potential for reducing energy consumption. Widespread use of such a water heat source system is for the effective use of natural energy is highly anticipated in the future. Therefore, we shall continue to promote technological development.

6 CONCLUSION

In this paper, we developed the Instantaneous Hot Water Dispenser based on Water Source (IHWD WS) heat pump to reduce the power consumptions of hot water dispensers. A prototype was actually manufactured and its operating performance was confirmed. Actual COP is 5.2-8.5 throughout a year. When it is improved, COP is expected to be 9.3-9.9. It showed great potential for reduction of energy consumption. However, there are problems in actual use of IHWD WS heat pump. For example, it cannot contribute to demand response, and its required power is large. The problems can be solved with storage batteries. Widespread of the IHWD WS heat pump can be expected.

ACKNOWLEDGMENT

The authors would like to thank Japan's environment ministry for providing funding for this research.

7 REFERENCES

Ministry of Economy, Trade and Industry, Agency for Natural Resources and Energy, "FY 2013 Annual energy report", Part two energy trend, pp.145

Abdeen Mustafa Omer, 2008, "Energy environment and sustainable development" Renewable and Sustainable Energy Reviews, 12, pp.2265–2300

Li X, Chen Z and Zhao J, 2006, "Simulation and experiment on the thermal performance of U-vertical ground coupled heat exchanger", Applied Thermal Engineering 26, pp. 1564–1571

Ooka R, Hino T, et al. 2011, "Development of multi-source and multi-use heat pump system", 10th IEA Heat Pump Conference

Hino T, Ooka R, Ono K, Yoshida S, Kodama K, 2013, "Energy Conservation Possibilities of Domestic Hot Water Supply by Water-Source Heat Pumps" SHASE scientific lecture miscellany, pp. 69-72