ANNUAL PERFORMANCE PREDICTION OF AIR OR WATER SOURCE CHANGEABLE HYBRID HEAT PUMP USING STANDING COLUMN WELL

Yoshiro Shiba, Assistant Manager, Development Dept., Zeneral Heatpump Industry Co., Ltd, Nagoya, Japan
Ryozo Ooka, Associate Professor, Institute of Industrial Science, University of Tokyo, Tokyo, Japan
Yujin Nam, Student, Institute of Industrial Science, University of Tokyo, Tokyo, Japan

Abstract: We simulated a system using a standing column well (SCW) as a water-heat source, with an air/water-to-water hybrid heat pump capable of switching between air and water cooling. Although single-tube wells can reduce costs because they do not require the construction of a new reducing well, water returning from the heat pump could create a short circuit, adversely affecting the system. It is also expected that the amount of power required by the pump could vary greatly depending on the level of the groundwater table and other factors. We performed a comparative assessment of annual performance factors (APF) for the differences between systems using R407C and R410A refrigerant, differences in temperature due to SCW short circuits, differences in well-pump power, and differences due to climatic zone. As a result, we calculated an APF of 5.24 for the base system. We also found that a 21% improvement to APF can be expected by changing from R407C to R410A. We additionally found that under each condition, air/water hybrid cooling improved APF by 2 to 7% compared to water cooling.

Key Words: ***heat pumps, SCW, efficiency***

1 INTRODUCTION

In general, well water is cooler than the ambient air temperature in summer, and warmer than the ambient air temperature in winter. This makes water-cooling heat pumps that use well water as a heat source more efficient than air-cooling heat pumps. When a standing column well (SCW) is used, however, the system is affected by short circuits caused by the returning water; for this reason, air cooling may temporarily be more efficient under certain weather conditions. A system that automatically compares the ambient air temperature and the temperature of the SCW intake water, and selects the most efficient method, should thus achieve a higher APF than either an air-cooling heat pump or a water-cooling heat pump using an SCW. We shall call such a system an “air or water source changeable air/water-to-water hybrid heat pump.” There is also a possibility that the strainer of the SCW could become clogged, so air cooling can be used as a backup when water cooling is not available. Figure 1 shows an air/water-to-water hybrid heat pump system using an SCW.

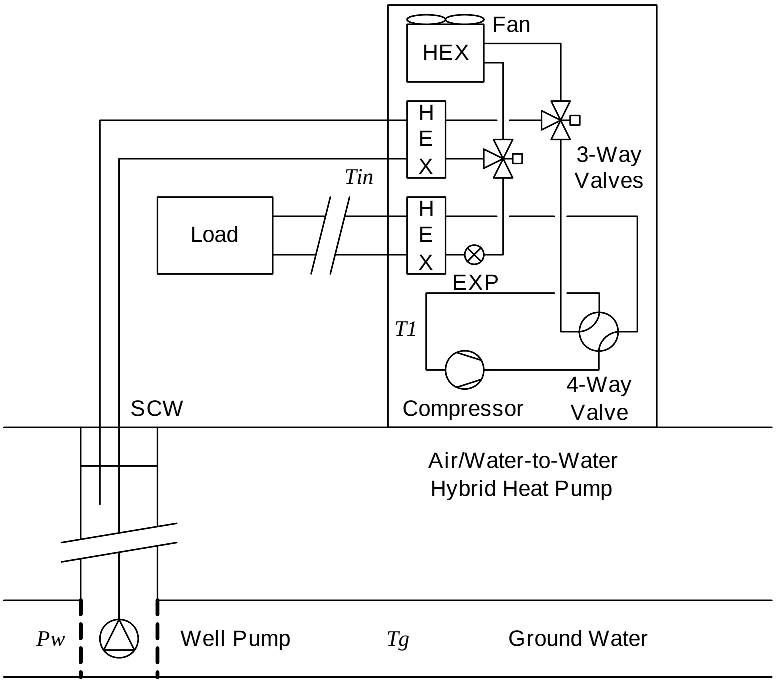

Figure 1: Air/Water-to-Water Hybrid Heat Pump and Standing Column Well (SCW)

2 PURPOSE

Here, we simulate the annual performance of a system combining an air/water-to-water heat pump with an SCW. In particular, we performed a comparative assessment of coefficient of performance (COP), seasonal performance factors (SPF), and annual performance factors (APF), varying the conditions of the heat-pump system, including well-pump power.

3 METHODS

3.1 Method for Calculating Heat Pump Performance

We calculated the performance of the air/water-to-water heat pump each hour, using a program for calculating heat-pump performance developed by Shiba et al. Although this program was originally meant for calculating the performance of a geothermal water-to-water heat pump, it can be adapted to an air-to-water heat pump. In other words, it is also able to calculate the performance of an air/water-to-water heat pump that automatically switches between an air and water heat source.

3.2 Air Conditioning Load Conditions

The air-conditioning load was calculated using the simple method described below, with reference to the load-calculation method used in the Ground Club Ver. 1.0 developed by Nagano et al.
We calculated the summer load [W/m^2] and winter load [W/m^2] per unit air-conditioned area in accordance with the following formula via the ambient air temperature [^{o}C], hours of sunlight [h], and total insolation [MJ/m^2], using coefficient of heat loss [W/(m^2・ ^{o}C)] and coefficient of sunlight acquisition, which are standard values for residential energy efficiency used in Japan. (Note that although the Japanese residential energy efficiency standard was used as a reference, the methods used were not in complete compliance with this standard.)

Per-unit summer load = {(*ambient air temp.* - 26) x *coefficient of heat loss* + *coefficient of sunlight acquisition* x *hours of sunlight* x *total insolation*/3.6 x 1,000}

Per-unit winter load = {(22 - *ambient air temp.*) x *coefficient of heat loss* - *coefficient of sunlight acquisition* x *hours of sunlight* x *total insolation*/3.6 x 1,000}

Here, only positive values for summer load and winter load are valid; all other values were assumed to be zero. Loads were calculated for one year, using hourly ambient air temperature, coefficient of sunlight acquisition, and hours of sunlight taken from climatic data. We also assumed air conditioning is operated from 8:00am to 6:00pm on weekdays (Monday through Friday). We additionally assumed that there are no fixed times of cooling and heating, and that the system would automatically switch between the two. The air-conditioned area was determined as follows.

air-conditioned area =MIN(Rated heat-pump cooling capacity/peak cooling load per unit area,
Rated heat-pump heated capacity/peak heating load per unit area)

Table 1 shows the calculated urban coefficient of heat loss and coefficient of sunlight acquisition. Table 2 shows the peak cooling/heating loads and seasonal load. Figure 2 shows a graph of the hourly load.

Table 1: Coefficient of Heat Loss and Coefficient of Sunlight Acquisition

City	Coefficient of Heat Loss [W/(m^2 ^{o}C)]	Coefficient of Sunlight Acquisition	Annual Average Outside (Ground Water) Temperature [^{o}C]	Climatic Zone
Sapporo/Hokkaido	1.6	0.08	9.7	Cold
Tokyo	2.7	0.07	17.4	Warm
Naha/Okinawa	3.7	0.06	23.4	Subtropical

Table 2: Load

City	Heat Peak Load [W/m^2]	Cool Peak Load [W/m^2]	Heat Seasonal Load [MJ/m^2]	Cool Seasonal Load [MJ/m^2]
Sapporo/Hokkaido	48	90	121	89
Tokyo	59	98	80	131
Naha/Okinawa	17	93	11	191

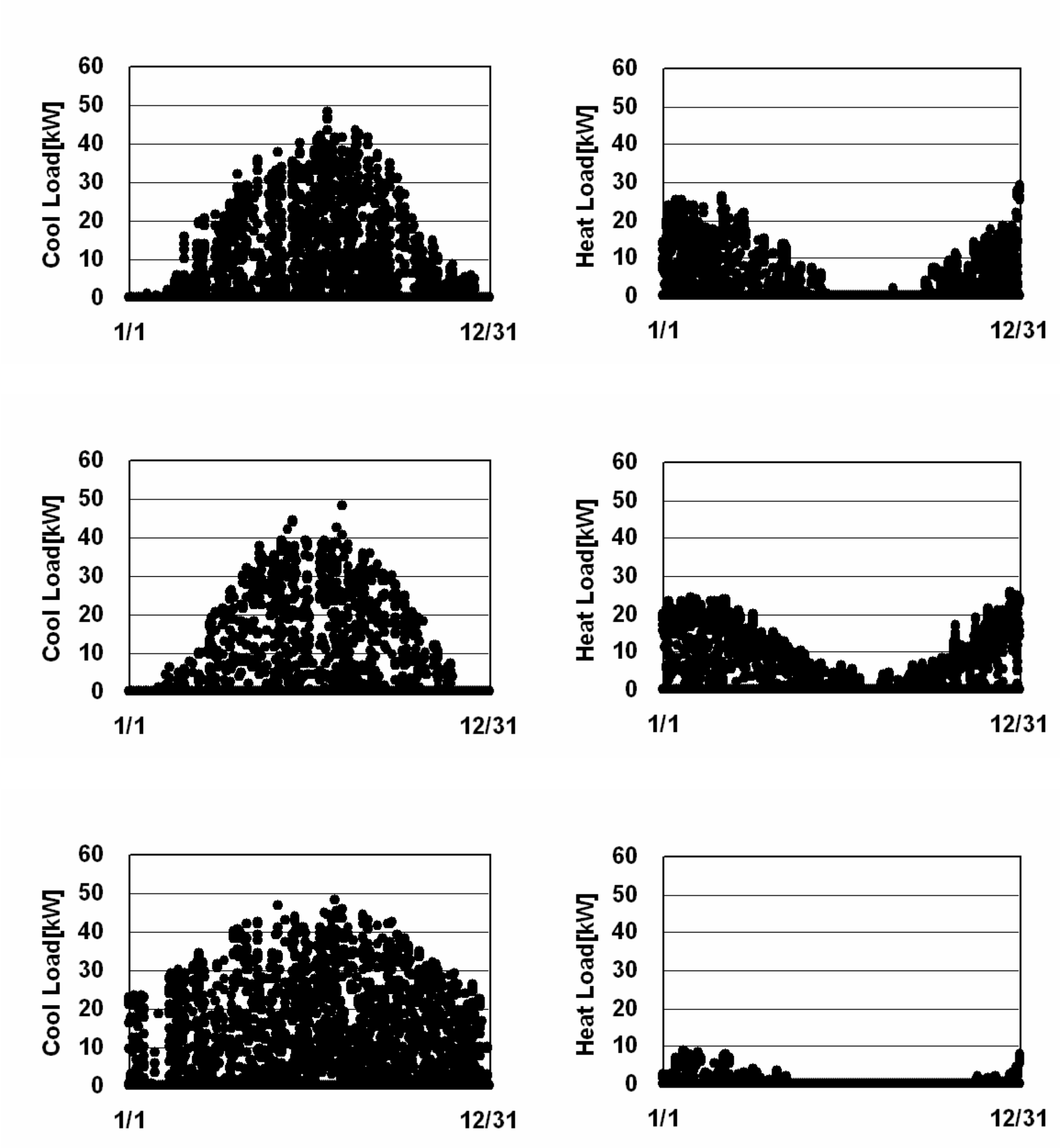

Figure 2: Annual Cool/Heat Load (Top: Tokyo, Middle: Sapporo, Bottom: Naha)

3.3 Air/Water-to-Water Hybrid Heat Pump

Table 3 shows the specifications of the air/water-to-water hybrid heat pump used in the calculations.

Table 3: Specifications of Air/Water-to-Water Hybrid Heat Pump

Standard Cooling Capacity	48kW (Cool Water 12 $^oC\rightarrow 7\ ^oC$)
Standard Heating Capacity	48kW (Hot Water 40→45 ^oC)
Compressor	Hermetic Scroll 11kW
Water Heat Exchanger	Brazing Plate
Air Heat Exchanger	Plate Fin
Fan	0.4kW×2

4 RESULTS

Combining an SCW with an air/water-to-water hybrid heat pump creates differences in performance characteristics due to the differences between each parameter. The parameters used in the calculations are as follows. Each condition is described below the table.

- Refrigerant: R410A (in development) or R407C (conventional systems)
- $DT = |Tg - T1|$: Difference in temperature [^oC] between groundwater and heat-pump intake; 5 or 10
- Pw : Well-pump power [kW]; 0.8 or 1.6 (each at constant speeds)
- City: Tokyo, Sapporo, or Naha

The formulas for calculating COP, SPF, and APF are as follows.

$$COP = Q/(Pc + Pf + Pw),$$
$$SPF = \int_{Season} Qdt \Big/ \int_{Season} (Pc + Pf + Pw)dt$$
$$APF = \int_{Year} Qdt \Big/ \int_{Year} (Pc + Pf + Pw)dt$$

Here, Q is capacity [kW], Pc is compressor power [kW], and Pf is fan power [kW]. The load is matched to the capacity using on-off control. It was assumed that both the fan and pump are stopped when the compressor is off. Although the calculation takes defrosting during air cooling into account, it does not take the impact of air short circuits, insolation, or other factors into account.

4.1 Results of Calculation of Parameters for Comparison

Table 4 shows the SPF and APF calculated for air-only, water-only, and air/water hybrid heat source by the performance-calculation program, with the conditions [Tokyo, R410A, DT: 5^{o}C,Pw: 0.8kW]. Figures 3, 4, and 5 show graphs of the hourly changes in COP.
SPF and APF are ordered Air < Water < Hybrid. The APF for air/water hybrid cooling was 18% greater than air cooling, and 2% greater than water cooling. The APF for air/water hybrid cooling was 5.24, which is a high figure.
Figure 5 shows a graph of the high COP for air cooling (Figure 3) and water cooling (Figure 4). This is the COP trend for the air/water-to-water hybrid heat pump.

Table 4: SPF and APF Prediction

Heat Sink/Source	Cool Load [kWh]	Energy Consumption [kWh]	Cooling SPF	Heat Load [kWh]	Energy Consumption [kWh]	Heating SPF	APF
Air		3,688	4.9		2,790	3.9	4.4
Water	17,896	3,050	5.9	10,869	2,528	4.3	5.16
Hybrid		2,995	6.0		2,490	4.4	5.24

* Conditions: Tokyo,R410A,DT:5^{o}C,PW:0.8kW

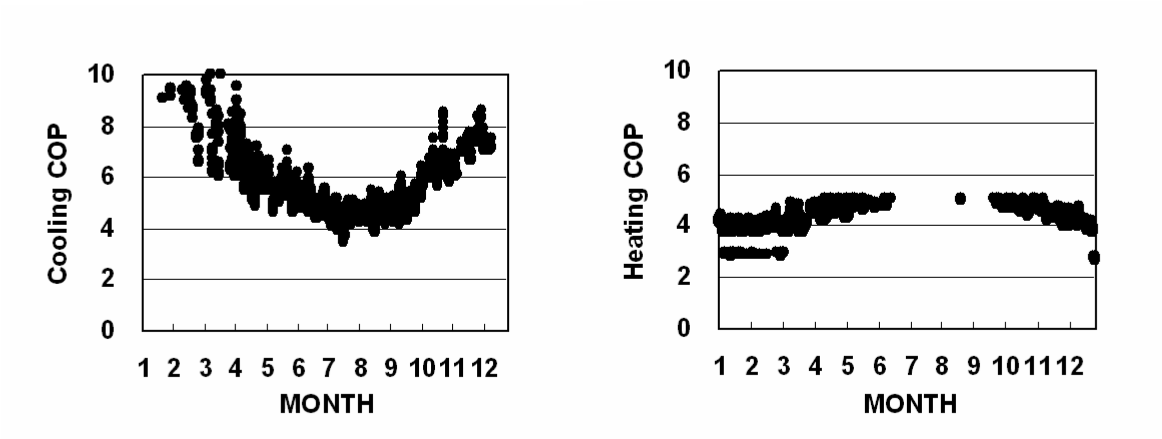

Figure 3: COPs of Air-to-Water Heat Pump (Tokyo,R410A)

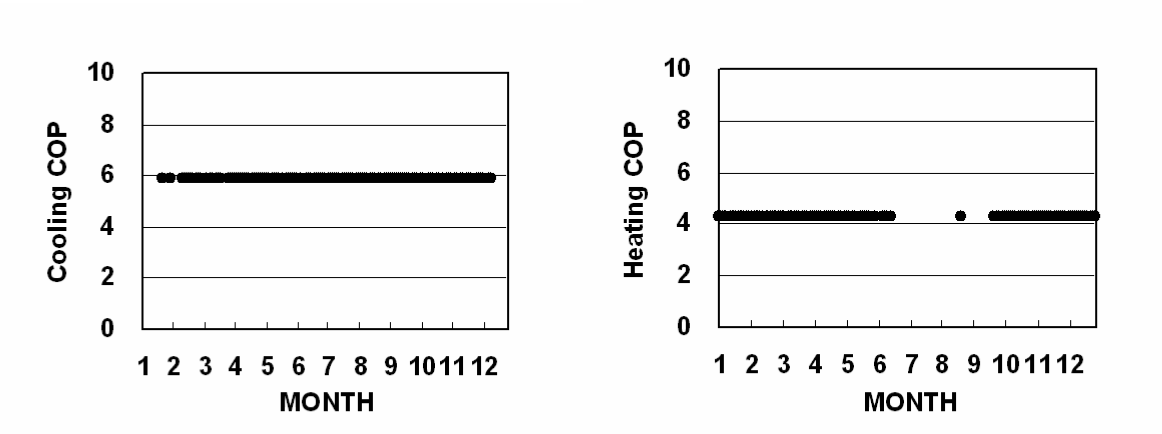

Figure 4: COPs of Water-to-Water Heat Pump (Tokyo, R410A, DT: 5^{O}C, PW: 0.8kW)

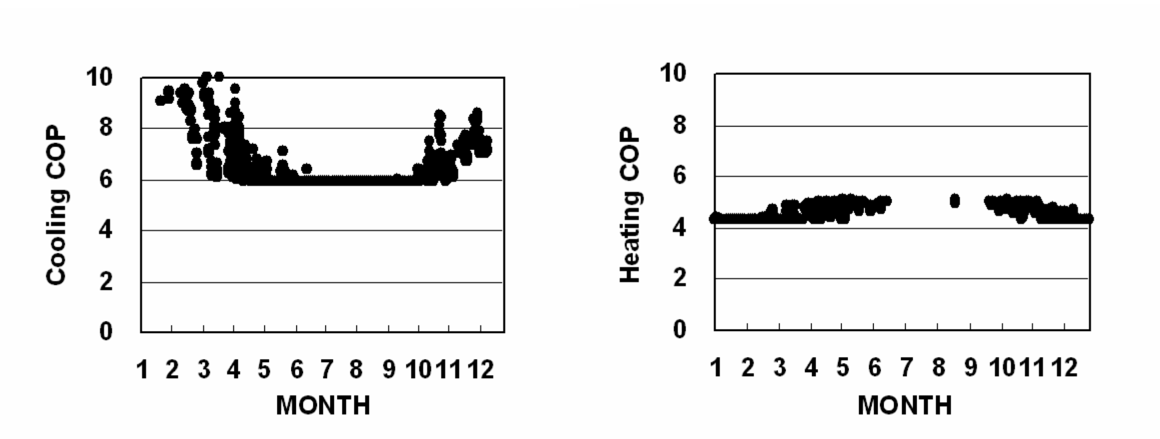

Figure 5: COPs of Air/Water-to-Water Hybrid Heat Pump (Tokyo,R410A,DT:5℃,PW:0.8kW)

4.2 Differences in Refrigerants

We performed calculations for the air/water-to-water heat pump using conventional R407C refrigerant. (The calculation was 4.1 for R410A.) Table 5 shows the displacement of each compressor. At the present time, there are actual air/water-to-water heat pumps using R407C refrigerant in existence, but there are not yet any using R410A refrigerant. These are thus the results of simulation using the performance-calculation program.
Table 6 shows the calculated SPF and APF with the parameters [Tokyo, R407C, DT: 5^{o}C, Pw: 0.8kW]. As with R410A, SPF and APF are ordered Air < Water < Hybrid. The APF for air/water hybrid cooling was 18% greater than air cooling, and 2% greater than water cooling. The air/water hybrid cooling APF for R407C was 4.35; the APF of the R410A air/water hybrid cooling was 21% higher.
Figure 6 shows a graph of hourly changes in COP for the air/water-to-water heat pump. The shape of the trend line is nearly the same as Figure 5, but shifted downward.

Table 5: Compressor Displacement

Refrigerant	Displacement [m^3/h]
R410A	28
R407C	42

Table 6: SPF and APF Prediction (R407C)

Heat Sink/Source	Cool Load [kWh]	Energy Consumption [kWh]	Cooling SPF	Heat Load [kWh]	Energy Consumption [kWh]	Heating SPF	APF
Air	17,896	4,595	3.9	10,869	3,226	3.4	3.7
Water		3,799	4.7		2,940	3.7	4.27
Hybrid		3,727	4.8		2,891	3.8	4.35

*Tokyo,R407C,DT:5 ^{o}C,PW:0.8kW

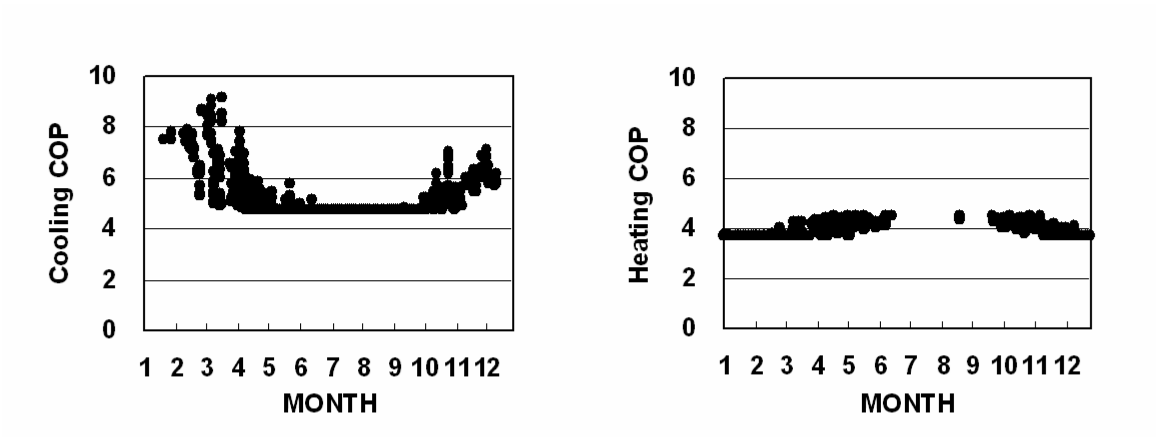

Figure 6: COPs of Air/Water-to-Water Hybrid Heat Pump (Tokyo,R407C,DT:5 ^{o}C,PW:0.8kW)

4.3 Impact of Differences in Groundwater Temperature

Short circuits from water returned from the SCW cause the temperature of the heat source water/cooling water of the heat pump to be inferior to the original groundwater temperature in terms of performance. Additionally, a water-water heat exchanger is sometimes used in order to reduce the impact of impurities in the groundwater on the heat pump's heat exchanger, but the average temperature difference of the heat exchanger is also unfavorable in terms of performance. The total of this temperature difference can be determined as DT. For simplicity, DT is assumed to be constant. For purposes of comparison, we calculated performance with a DT of 10^{o}C. (The calculation was 4.1 for DT of 5^{o}C.)
Table 7 shows the calculated SPF and APF with the parameters [Tokyo, R410A, DT: 10^{o}C, Pw: 0.8kW]. SPF and APF are ordered Air < Water < Hybrid. The APF for air/water hybrid cooling was 8% greater than air cooling, and 6% greater than water cooling. The air/water hybrid cooling APF for DT of 10^{o}C was 4.8; the APF for DT of 5^{o}C was 10% higher.
Figure 7 shows a graph of hourly changes in COP for the air/water-to-water heat pump. As with the other case, the shape of the trend line is nearly the same as Figure 5, but shifted downward.

Table 7: SPF and APF Prediction (DT: 10 ^{o}C)

Heat Sink/Source	Cool Load [kWh]	Energy Consumption [kWh]	Cooling SPF	Heat Load [kWh]	Energy Consumption [kWh]	Heating SPF	APF
Air	17,896	3,688	4.9	10,869	2,790	3.9	4.4
Water		3,583	5.0		2,788	3.9	4.5
Hybrid		3,385	5.3		2,628	4.1	4.8

*condition: Tokyo,R410A,DT:10 ^{o}C,PW:0.8kW

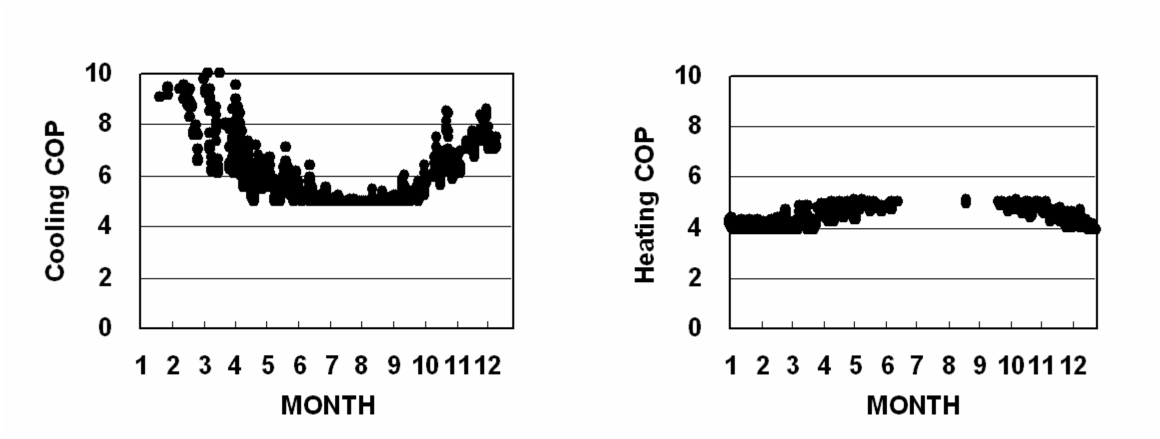

Figure 7: COPs of Air/Water-to-Water Hybrid Heat Pump (Tokyo,R410C,DT:10 ^{o}C,PW:0.8kW)

4.4 Impact of Well Pump Power

The well-pump power varies according to the level of the groundwater table and the length and diameter of the tube. Here, we calculated for power values of 1.6 kW, which is twice of 0.8 kW, in order to consider the impact of well-pump power. (The calculation was 4.1 for Pw: 0.8 kW.)
Table 8 shows the calculated SPF and APF with the parameters [Tokyo, R410A, DT: 5^{o}C, Pw: 1.6kW]. SPF and APF are ordered Air < Water < Hybrid. The APF for air/water hybrid cooling was 11% greater than air cooling, and 4% greater than water cooling. The air/water hybrid cooling APF for Pw: 1.6 kW was 5.0; the performance of air/water hybrid cooling for Pw: 0.8 kW was 6% higher.
Figure 8 shows a graph of hourly changes in COP for the air/water-to-water heat pump. As with the other cases, the shape of the trend line is nearly the same as Figure 5, but shifted downward.

Table 8: SPF and APF Prediction (PW: 1.6kW)

Heat Sink/Source	Cool Load [kWh]	Energy Consumption [kWh]	Cooling SPF	Heat Load [kWh]	Energy Consumption [kWh]	Heating SPF	APF
Air	17,896	3,688	4.9	10,869	2,790	3.9	4.4
Water		3,337	5.4		2,691	4.0	4.8
Hybrid		3,220	5.6		2,590	4.2	5.0

* Conditions:Tokyo,R410A,DT:5 ^{o}C,PW:1.6kW

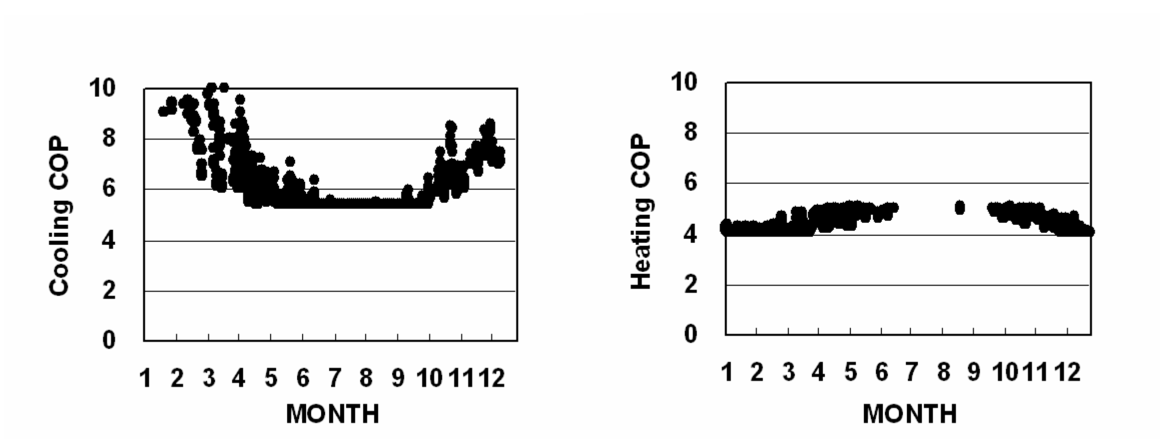

Figure 8: COPs of Air/Water-to-Water Hybrid Heat Pump (Tokyo,R410C,DT:5 ^{o}C,PW:1.6kW)

4.5 Impact of Variation in Climatic Factors

We performed the same calculations in a temperate region (Tokyo), a cold region (Sapporo), and a subtropical region (Okinawa). For each region, we assumed that the year-round groundwater temperature was equal to the yearly average ambient air temperature.
Table 9 shows the calculated SPF and APF with the parameters [Sapporo, R410A, DT: 5°C, Pw: 0.8kW]. SPF and APF are ordered Air < Water < Hybrid. The APF for air/water hybrid cooling was 20% greater than air cooling, and 7% greater than water cooling. The level of superiority over both air cooling and water cooling was greater than in Tokyo. The air/water hybrid cooling APF for Sapporo was 4.8; the APF of the air/water hybrid cooling in Tokyo was 10% higher.
Table 10 shows the calculated SPF and APF with the parameters [Naha, R410A, DT: 5°C, Pw: 0.8kW]. Unlike the other regions, the SPF and APF for cooling are ordered Water < Air < Hybrid. The APF for air/water hybrid cooling was 3% greater than air cooling, and 7% greater than water cooling. We found that although the level of superiority of the air/water hybrid cooling over water cooling was greater than in Tokyo, the level of superiority over air cooling was lower. The air/water hybrid cooling APF for Sapporo was 5.15; the APF of the air/water hybrid cooling in Tokyo was 2% higher.
Figures 9 and 10 show graphs of hourly changes in COP for the air/water-to-water heat pump in Sapporo and Naha, respectively. The shape of the trend lines can be seen to differ from the one in Figure 5.

Table 9: SPF and APF Prediction (Sapporo)

Heat Sink/Source	Cool Load [kWh]	Energy Consumption [kWh]	Cooling SPF	Heat Load [kWh]	Energy Consumption [kWh]	Heating SPF	APF
Air	13,321	2,206	6.0	10,869	3,841	2.8	4.0
Water		1,703	7.8		3,701	2.9	4.5
Hybrid		1,658	8.0		3,401	3.2	4.8

*Sapporo: Tokyo, R410A, DT: 5°C, PW: 0.8kW

Table 10: SPF and APF Prediction (Naha)

Heat Sink/Source	Cool Load [kWh]	Energy Consumption [kWh]	Cooling SPF	Heat Load [kWh]	Energy Consumption [kWh]	Heating SPF	APF
Air	27,698	5,519	5.0	1,564	343	4.6	5.0
Water		5,723	4.8		328	4.8	4.8
Hybrid		5,353	5.2		327	4.8	5.15

* Conditions: Naha,R410A,DT:5°C,PW:0.8kW

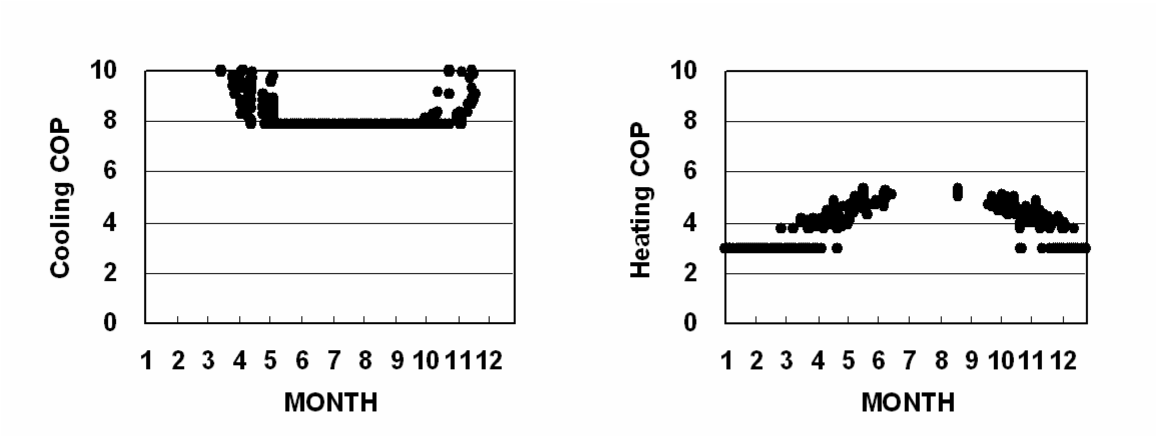

Figure 9: COPs of Air/Water-to-Water Hybrid Heat Pump (Sapporo,R410C,DT:5°C,PW:0.8kW)

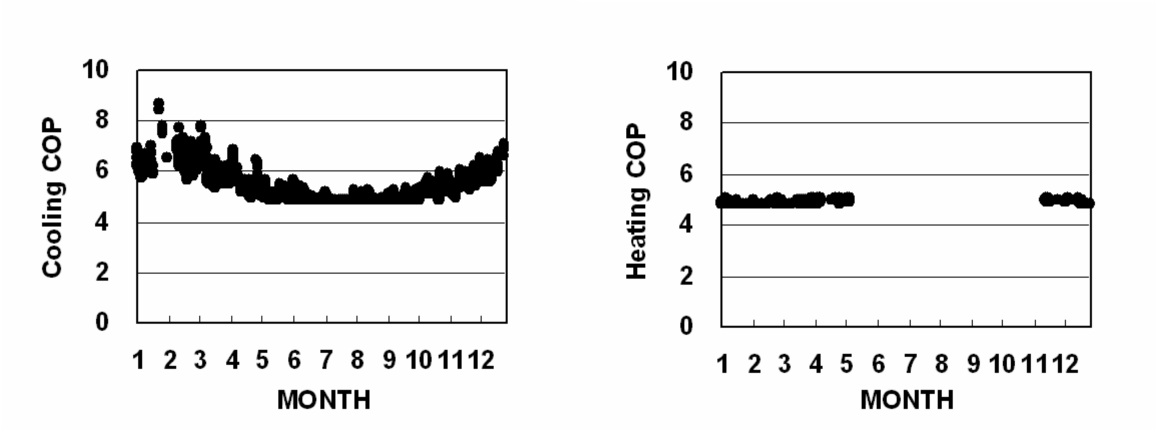

Figure 10: COPs of Air/Water-to-Water Hybrid Heat Pump (Naha,R410C,DT:5°C,PW:0.8kW)

5 CONCLUSIONS

We simulated the annual performance of an air/water-to-water hybrid heat pump using an SCW (capacity: 48 kW). As a result, we calculated an APF (including well pump) of 5.24 under base conditions. We also compared performance under the following conditions:

- System using R407C refrigerant versus system using R410A refrigerant
- Difference in temperature (DT) between groundwater and heat source water inlet: 5°C and 10°C
- Well-pump power (Pw): 0.8 kW and 1.6 kW
- Ambient air temperature data: Tokyo, Sapporo (Hokkaido), and Naha (Okinawa)

As a result, the following was found:

- A 21% improvement to APF can be expected by changing the refrigerant from R407C to R410A.
- A 10% improvement to APF can be expected by changing the DT from 10°C to 5°C.
- A 6% improvement to APF can be expected by changing the power (Pw) from 1.6 kW to 0.8 kW.
- The APF was 5.2 for Tokyo, 4.8 for Sapporo, and 5.2 for Naha.

We additionally found that under each condition, air/water hybrid cooling improved APF by 2 to 7% compared to water cooling, and by 2 to 20% compared to air cooling.
In the future, we will additionally consider the case where the compressor and pump are adapted to an inverter, as well as the use of a direct-expansion heat pump. Additionally, the present calculations were simplified by ignoring soil variation; Nam et al. plan to show a simulation taking the impact of soil into account.

6 REFERENCES

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