DEVELOPMENT OF AN AUTONOMOUS PERFORMANCE-TESTING SYSTEM OF WATER-SOURCE HEAT PUMPS AND ACTUAL PERFORMANCES OF JAPANESE SMALL WATER-SOURCE HEAT PUMP UNITS

K. Nagano, Assoc. Professor, Hokkaido University, Sapporo, Japan
T. Nogawa, M.C. Student, Hokkaido University, Sapporo, Japan
T. Katsura, Ph.D. Student, Hokkaido University, Sapporo, Japan
K. Shimakura, Technical Officer, Hokkaido University, Sapporo, Japan
A. Okamoto, SUNPOT Co., Ltd, Hanamaki, Japan

ABSTRACT

Big chillers and large capacity heating units are generally required for performance tests of a water source heat pump. However, such investments are hard for small factories and an on-site performance test is needed in some cases. On the other side, there are some requests that an actual operation as the demonstration of a water source heat pump in exhibitions and trade shows.

The authors developed an autonomous performance testing system of water source heat pumps which can also be applied to the ground heat source. Basically this testing system requires electric power only for compressor of heat pump and for circulating pumps. Heat sources and heat sinks are not needed. A plate-type heat exchanger between the primary side and the secondary side of a heat pump unit and a fan coil unit for heat release of waste heat enable this concept. Also, this testing system is very compact and transportable. This paper describes an outline of a developed autonomous performance testing system for water source heat pumps.

Recently in Japan, a few manufacturing companies have developed high performance small GSHP units for residential use with a variable speed compressor. In addition to mentioned above, actual performances of these novel small water source heat pump units made in Japan are also presented in this paper under various temperature conditions measured by this testing system.

Key Words: ***heat pump, water heat source, COP, GSHP, experiments***

1 INTRODUCTION

The ground source heat pump system (GSHP) for heating and cooling has attracted a great deal of interest not only in the commercial building market but also in the residential market in Japan. In fact, installed number has been doubled in the last year though total number of installed system was approximately 50 at the end of 2002. As the actual market size has been still very small for big manufacturing companies, small chiller type heat pump units appropriate for the ground heat source has been developed and distributed from small and medium-sized enterprises. Investment of the large scale heat pump testing installation which provides big chillers and large capacity heating units could be risky before the ground source heat pump system will take root in the market.

The authors developed a compact autonomous performance testing unit for a chiller type heat pump unit which can be applied to the ground heat source. The main feature of this testing unit is that autonomous operation without big chillers and heaters for cooling the condensing side and for adding heat from outside to the evaporator, when needed electric power to a compressor of a heat pump and circulating pumps is just supplied. Additionally, inlet temperature of the primary side of the heat pump, outlet temperature from the secondary side of the heat pump and flow rates of both sides are automatically controlled by three-way valves and digital controllers. Therewithal, this unit is a small size and can be transportable. This allows the following unique utilizations. For example, this unit plays outstandingly in the demonstration of the heat pump unit in the exhibitions and trade shows. Audiences can have experiences of actual noises and vibrations in operation. Also, they can enjoy surplus heat released from convectors or a floor heating mat.

This paper introduces the details of this compact autonomous performance testing unit for a chiller type heat pump unit first. Second, actual performances of two water source heat pump units made in Japan are also shown under various temperature conditions measured by this testing unit.

2 AN AUTONOMOUS PERFORMANCE TESTING SYSTEM OF WATER SOURCE HEAT PUMPS

2.1 Introduction of a Testing System

Figure 1 shows the developed autonomous performance testing system of the water source heat pump. This testing system consists from a hot and a cold buffer tank, brine circulation pumps, plate type heat exchangers, electronic three way valves and a connection to heat convectors for releasing waste heat. The large feature of this testing system is no need of big chillers for cooling the condensing side (secondary side) and electric heaters for heating up the evaporating side (primary side) for the operation. Instead of these outside devices cold brine from the outlet of evaporator and warm brine form the outlet of condenser accommodate heat each other through a proper heat exchanger and surplus heat is discharged to the atmosphere by heat convectors.

The outline of the testing system is explained here. First, cold brine kept at the constant temperature in a cold buffer tank comes through an evaporator of a heat pump unit by a circulating pump. Ethylene glycol solution is used as thermal medium for antifreeze liquid in this case. Then it goes to a heat exchanger to recover heat and returns to the original cold tank. On the other side, the secondary side is the same as the primary side except a part of the brine after a main heat exchanger (HEX1) goes to another small heat exchanger (HEX2) cooled by heat convectors.

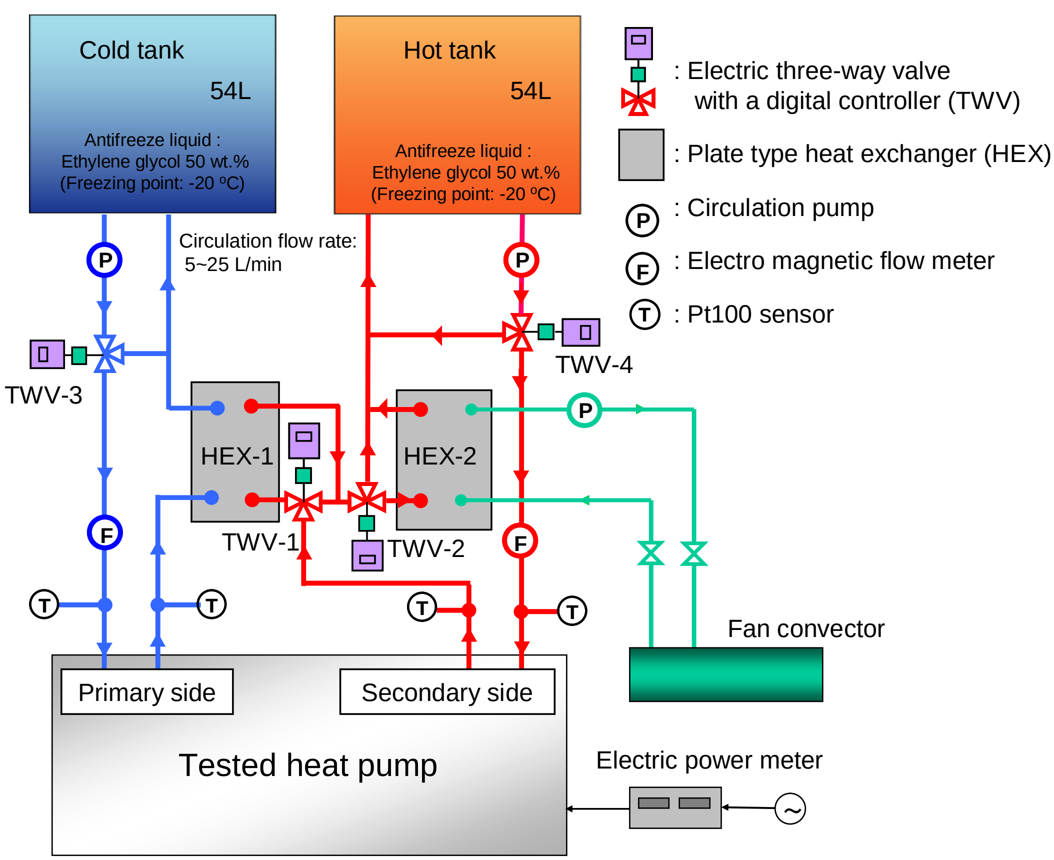


Fig. 1. Schematic diagram of the developed autonomous performance testing system

2.2 Operation of a Testing System

This system is operated automatically to be the constant inlet temperature for the primary side and the constant outlet temperature for the secondary side of the heat pump by using a combination of two electric three-way valves TWV-1 and TWV-2 with digital controllers when setting temperatures for the primary side and the secondary side are given in the controllers. In addition to the temperature control water flow rates of both sides are also kept at the set values by the other electric three-way valves TWV-3 and TWV-4 with digital controllers connected to the signals from magnetic flow meters.

Next, actions of the three way valves for the control of the temperature are described. TWV-1 remains to open on the bypass side against HEX-1 until the inlet temperature of the primary side reaches at the set temperature at the beginning of the operation. When the inlet temperature of the primary side gets to the set temperature, TWV-1 moves to the opposite side gradually and hot brine flows into HEX-1 in order to maintain the inlet temperature at the set value. On the other side, the outlet temperature of the secondary side is controlled by TWV-2 which adjusts the flow rate passing through HEX-2 for releasing waste heat to the outside convectors.

2.3 Measuring Sensors and Devices

Applied measuring devices are listed on Table 1. The inlet and the outlet brine temperatures of both sides are measured by sheathed Pt 100 temperature sensors. Here, used Pt100 sensors are calibrated in order that mutual errors of these are less than 0.01 K. Magnetic flow meters are applied to measure the volumetric flow rates of brine to an accuracy of 0.5 %. The concentration of ethylene glycol is determined by an optical densitometer to an accuracy of 1.0 % and its density and its specific heat are estimated by a property's charts. A digital integrating watt meters are used to measure the electric power consumption of a compressor of a heat pump unit.

Table 1. Measuring devices for a testing system

Measurement item	Measurement element	Equipments	Specification	Precision
Heat extraction and heating output	Inlet & outlet temperature	Platinum resistance thermometers	Pt100	0.01 C
	Flow rate	Electromagnetic flow meter	MGM1010K (Tokyo Keiso)	0.5 %
	Antifreeze liquid concentration	Antifreeze liquid concentration meter	Optical densitometer (Atago)	1%
	Antifreeze liquid density	Diagram of density according to temperature		
	Antifreeze liquid specific heat	Diagram of specific heat according to temperature		
Electric power consumption		Watt-hour meter	Digital Power Tester (Hioki E.E)	0.3 %

2.4 Data Acquisition System and Calculations

After confirming the steady state of the operation satisfactorily, the inlet and the outlet brine temperatures and flow rates of both sides are recorded at 5 seconds intervals and average values for fifteen minutes were adopted. A high accurate data acquisition system with high tolerance for noise from the power supply and background was used.

Heat extraction rate q_1 and heating output q_2 are calculated by the following equations.

$$q_1 = c_{pb1} \times \rho_{b1} \times V_{b1} \times (T_{in1} - T_{out1}) \qquad (1)$$

$$q_2 = c_{pb2} \times \rho_{b2} \times V_{b2} \times (T_{in2} - T_{out2}) \qquad (2)$$

Also, coefficient of performance (*COP*) of the heat pump unit is evaluated by

$$COP = q_2 / E \qquad (3)$$

Here, q_1: Heat extraction rate [kW], q_2: Heating output [kW], E: Electric power consumption rate [kW], c_{pb}: Specific heat of brine as a function of temperature [kJ/kg/K], ρ_b: Density of brine as a function of temperature [kg/m^3], V_b: Volumetric flow rate of brine [m^3/s], T_{in}: Inlet temperature [K], T_{out} : Outlet temperature [K], Subscript: 1: primary side, 2: secondary side

3 RESULTS OF MEASUREMENTS AND DISCUSSIONS

3.1 Measurements of a Conventional Small Water Heat Source Heat Pump Unit with a Two Horse-Power Compressor

3.1.1 Specification of a heat pump

Performance of a conventional small water heat source heat pump unit under various temperature conditions for ground heat source was evaluated. Table 2 shows specification of the tested heat pump unit. This heat pump unit has a two horse-power rotary-type compressor with a constant-speed motor which is driven by single-phase 200V-220V AC. Also, purpose-designed brazing-plate-type heat exchangers for refrigerant and water are applied for an evaporator and a condenser. A bellows type expansion valve was used. Used refrigerant is R407C.

Table 2. Specification of the tested conventional small heat pump unit

Parts	Type
Compressor	2 HP rotary type for R407C
Evaporator and Condenser	Brazing plate type
Expansion Valve	Bellows type

Table 3. Measured data under the condition of 35 ^oC for T_{2out}

T_{1in}	T_{2out}	E	q_1	q_2	COP	ΔT_1	ΔT_2	Degree of superheat	Low pressure	High pressure
[^{o}C]	[^{o}C]	[kW]	[kW]	[kW]	[N.D]	[^{o}C]	[^{o}C]	[^{o}C]	[MPa]	[MPa]
-15.6	35.2	1.29	1.22	3.05	2.37	1.42	2.73	13.9	0.15	1.50
-10.6	34.8	1.34	1.85	3.61	2.69	1.96	3.21	9.2	0.20	1.49
-5.3	34.6	1.38	2.57	4.26	3.09	2.60	3.75	8.4	0.25	1.50
-0.5	34.8	1.41	3.17	4.90	3.47	3.17	4.30	6.4	0.32	1.50
5.6	35.2	1.45	4.15	5.69	3.92	4.00	4.95	6.3	0.40	1.52
9.9	35.1	1.46	4.81	6.34	4.34	4.57	6.03	7.5	0.45	1.50
15.0	35.2	1.47	5.69	7.07	4.80	5.37	6.37	6.0	0.55	1.50
19.6	35.3	1.47	6.52	8.07	5.49	6.11	8.42	6.0	0.60	1.50

3.1.2 Measuring condition

The inlet brine temperature to the primary side and the outlet brine temperature from the secondary side were changed from -15 °C to 20 °C at 5 degrees intervals and from 20 °C to 55 °C at 5 degrees intervals, respectively. In these tests, the flow rates of the primary side and the secondary side were kept at about 17 L/min and about 18 L/min.

3.1.3 Results of measurements and discussions

Measured data under the condition of 35 °C for the outlet temperature of the secondary side is summarized in Table 3. Also, heating output, electricity consumption and *COP* with respect to the inlet brine temperature of the primary side are shown in Fig.2, Fig.3 and Fig.4. The outlet brine temperature of the secondary side is chosen as the parameter. From these figures, we can realize that heating output, electricity consumption and *COP* rises linearly according to the inlet brine temperature of the primary side. Heating output and *COP* under the condition of 0 °C for the inlet temperature of the primary side and at 35 °C for the outlet temperature of the secondary side are 5.0 kW and 3.5, respectively.

Fig. 5 indicates the degree of superheat at the outlet of an evaporator. This bellows type expansion valve was designed to keep 5 °C of superheat. However, it is found that degrees of superheat were between 6 °C to 9 °C when primary side temperature was above10 °C except one data point. Moreover, high degrees of superheat are observed at low temperature condition of primary side below 0 °C. This fact suggests that this type expansion valve is unfit for the ground coupled system.

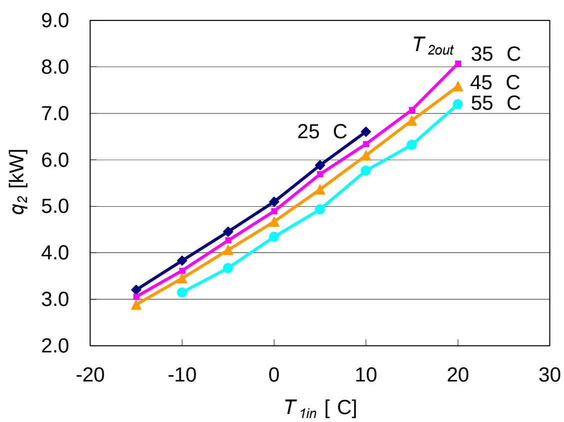


Fig. 2. Heating output according to T_{1in}

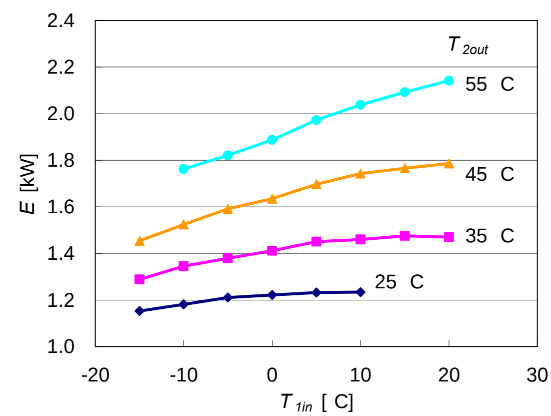


Fig. 3. Electric power consumption according to T_{1in}

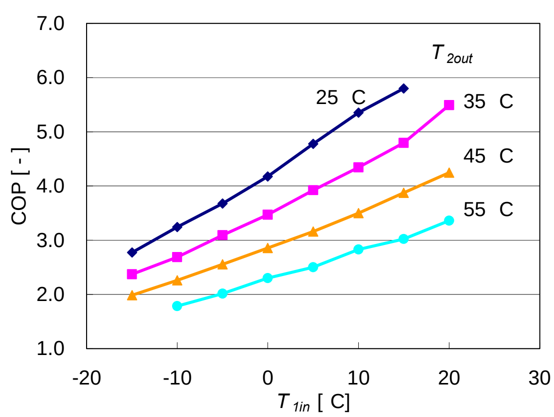


Fig. 4. *COP* according to T_{1in}

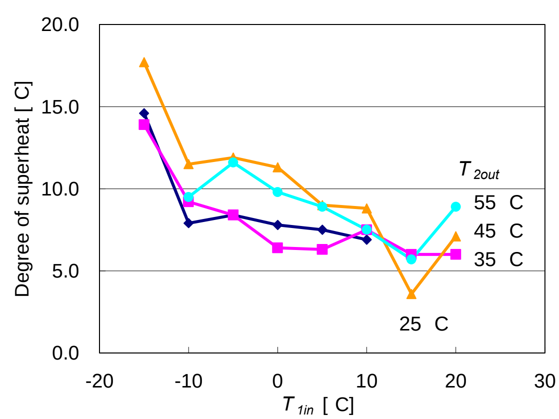


Fig. 5. Degree of superheat according to T_{1in}

3.2 Measurements of a Novel Small Water Heat Source Heat Pump Unit with a Variable Speed Two-Horse-Power Compressor

3.2.1 Specification of a novel heat pump

As shown in Table 4 the feature of this novel small water heat source heat pump unit is that it has a scroll type two horse power compressor for R410A driven by a variable speed motor with a DC inverter. This variable speed compressor enables the smooth change of heating output according to heating demand without the on-off action and the minimum allowable limit speed is 25 % of the maximum rotation. Higher performance under the actual use can be expected due to the depletion of numbers of start and stop. In addition to above, an electric expansion valve is adopted to obtain the maximum performance under any evaporating pressure conditions. The digital control values of this expansion valve were determined by the prior tests. Also, well purpose-designed brazing-plate-type heat exchangers for refrigerant and water were applied.

Table 4. Specification of the tested novel small heat pump unit with a variable speed compressor

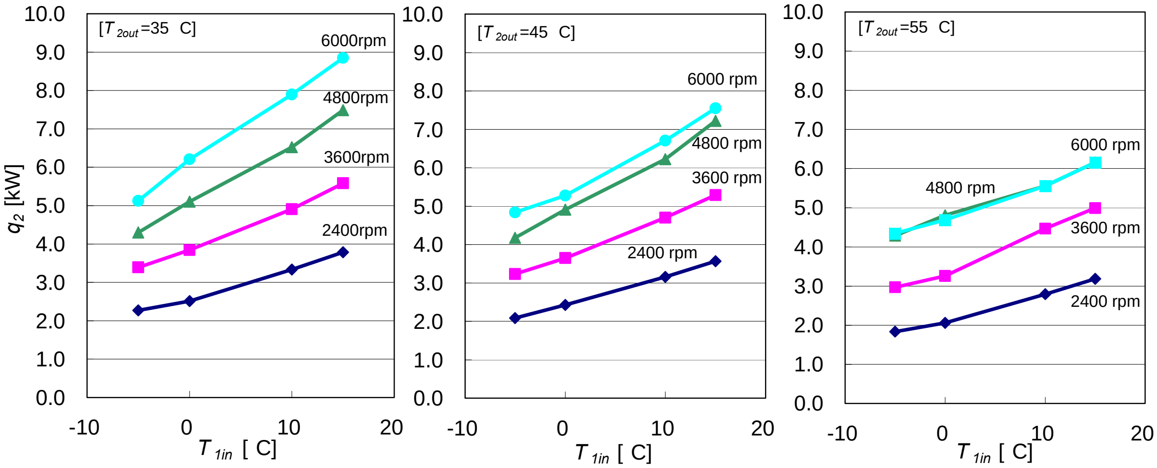
Parts	Type
Compressor	2 HP rotary type for R410A with inverter control
Evaporator and Condenser	Brazing plate type
Expansion valve	Electric control
Built-in circulating pump	110W 2

3.2.2 Measuring condition

In these tests, flow rates of the primary side and the secondary side were kept at around 20 L/min and at around 24 L/min, respectively. The inlet brine temperature to the primary side of a heat pump unit and the outlet brine temperature of the secondary side were changed from -5 ^{o}C to 15 ^{o}C at 5 degrees intervals and from 35 ^{o}C to 55 ^{o}C at 10 degrees intervals, respectively. When frequencies of an inverter are set at 40, 60, 80, and 99 Hz, rotating speeds of a compressor are 2400, 3600, 4800, and 6000 rpm.

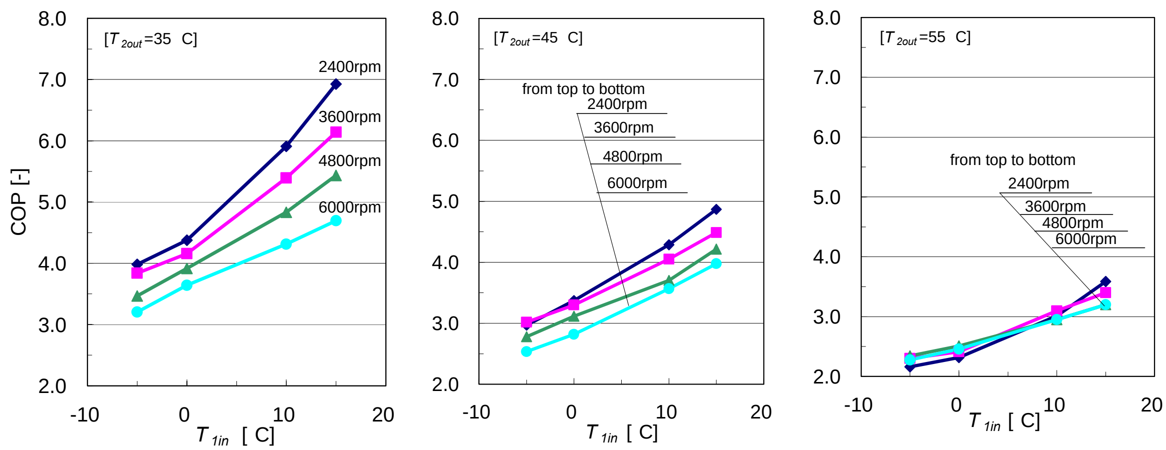
3.2.3 Results of measurements and discussions

Fig. 6 (a), (b) and (c) show q_2 according to T_{1in} for each rotating speed of a compressor at T_{2out} of 35, 45 and 55 ^{o}C, respectively. It is clear that q_2 is proportional to the T_{1in} in any case of T_{2out} for each rotating speed. q_2 takes maximum at the highest compressor speed and they are 6.2, 5.2, and 4.8 for T_{2out} of 35, 45, and 55^{o}C under the condition of 0 ^{o}C of T_{1in}, respectively. On the other hand, the relationship between *COP* and T_{1in} is indicated on Fig. 7 (a), (b) and(c) at T_{2out} of 35, 45 and 55 ^{o}C, respectively. When T_{2out} is 35 ^{o}C *COPs* increase almost linearly according T_{1in} and the gradient for lower rotating speed is much larger than that for higher speed. This means that performance under the partial heat load condition is quite high especially at the lower T_{2out} and such characteristic is very effective for floor heating system. On the other hand, *COP*s are similar at T_{2out} of 55 ^{o}C in any rotating speeds. However, when we confirm in detail of Fig. 7 (c) it is recognized that the middle rotating speed gives the highest *COP* at lower T_{1in} below 0 ^{o}C. The maximum *COP*s at 0 ^{o}C of T_{1in} are 4.5, 3.5 and 2.5 for T_{2out} of 35, 45 and 55 ^{o}C, respectively. In this time, q_{2out} are 2.5, 2.5~3.6 and 4.7 kW, respectively. Here, the magnitude frequency curve of hourly heating demands for the typical residential house in Sapporo is shown in Fig. 9. We find that 88 % of hourly heating demands appear under 4.0 kW. This fact suggests us that this heat pump unit with a variable speed compressor can bring higher seasonal performance in the actual use due to higher part load characteristic as well as the reduction of number of start and stop. Finally, *COP* and q_2 for each T_{1in} according to T_{2out} of 35, 45 and 55 ^{o}C, are denoted in Fig. 8 (a), (b) and (c). This diagram is effective to evaluate *SPF* when the heating demand is given such as shown in Fig.9 and the seasonal change of T_{1in} and needed T_{2out} for heating depended on the capacity of radiators are assumed. Then we can simply calculate annual power consumption and annual energy cost as well as amount of CO_2 emission per year.



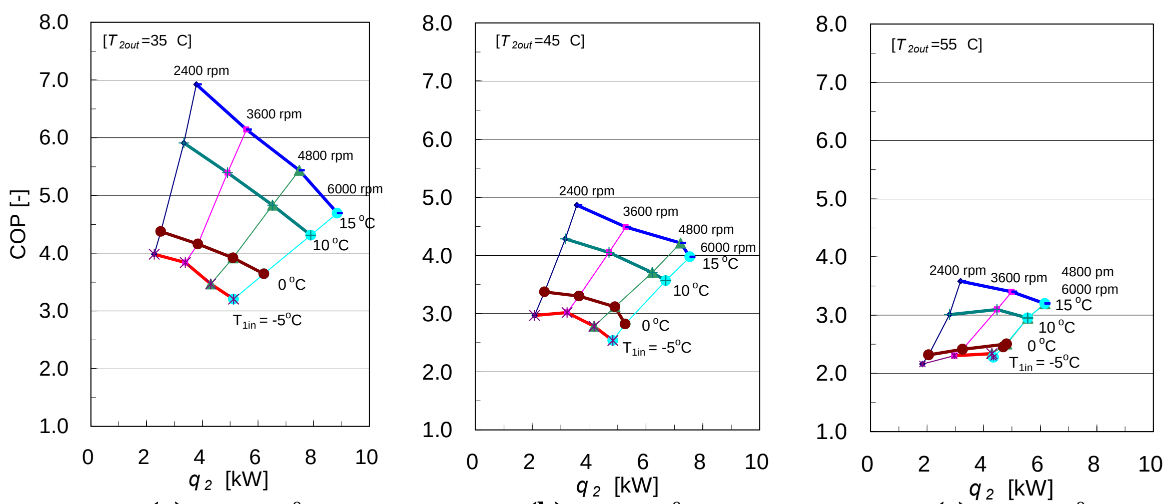
(a) T_{2out} =35 °C **(b)** T_{2out} =45 °C **(c)** T_{2out} =55 °C

Fig. 6. q_2 according to T_{1in} for each rotating speed of a compressor



(a) T_{2out} =35 °C **(b)** T_{2out} =45 °C **(c)** T_{2out} =55 °C

Fig. 7. *COP* according to T_{1in} for each rotating speed of a compressor



(a) T_{2out} =35 °C **(b)** T_{2out} =45 °C **(c)** T_{2out} =55 °C

Fig. 8. *COP* according to q_2 for each T_{1in}

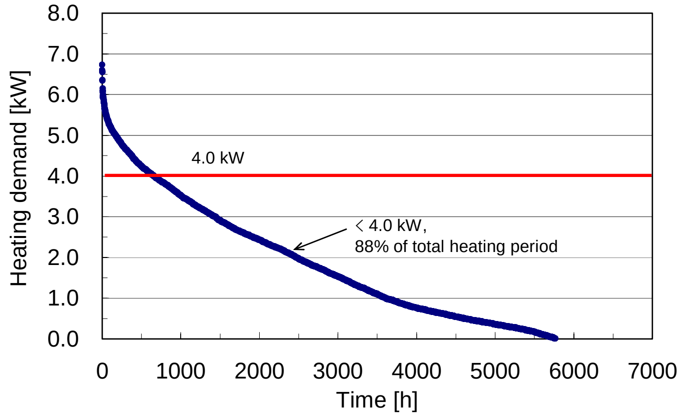


Fig. 9. Magnitude frequency curve of hourly heating demands for the residential house in Sapporo

4 CONCLUSIONS

1. An autonomous performance testing system of water source heat pumps was developed. This system needs no big chiller and no big heater for testing. All needed is only small cooler for heat release and a small convector is adequate for cooling in practical uses. All of the operation is automatically controlled. In addition, this is transportable. Therefore, this testing system is also appropriate for product demonstration of a real heat pump unit at the exhibition or the trade show.
2. Performances of a conventional small water heat source heat pump unit with a two horse-power compressor were measured. Obtained data shows that q_2 and *COP* under the condition of 0 ^{o}C for T_{1in} and 35 ^{o}C for T_{2out} are 5.0 kW and 3.5, respectively.
3. Measurement of performances of a novel small water heat source heat pump unit with a variable speed two horse-power compressor was carried out. The maximum heating capacities under the various temperature conditions and their *COP* are determined. In addition, part load performance was examined and higher *COP*s are clarified. This suggests that this heat pump unit which has a variable speed compressor can bring higher seasonal performance in the actual use for heating in addition to the possible increase of the performance due to the reduction of number of start and stop. Finally, relations of *COP* to q_2 for the each T_{2out} were obtained. This is effective to evaluate the amount of electricity consumed for heating and *SPF* during heating.

ACKNOWLEDGMENTS

We are grateful to Emeritus Prof. T. Mochida, Prof. S. Yokoyama and Dr. S. Takeda of Hokkaido University, Japan. A part of this study is a component of the 21st century COE program of the Ministry of Education, Culture, Sports, Science and Technology "Sustainable Metabolic Systems of Water and Waste for Area-Based Society" (Project representative: Prof. Y. Watanabe). Also, we would like to thank to Nippon Steel Company Corporation and Hokkaido Electric Power Co., Inc..

REFERENCES

ARI 1998. "ARI STANDARD 320-1998 for WATERSOURCE HEAT PUMPS", ARI, pp.1-10

ASHRARE 2000. "2000 ASHRAE Systems and Equipment Handbook" ASHRAE, pp. 45.10-45.14

EU 1997. "EN 255 - 2, Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors - Heating mode - Part 2: Testing and requirements for marking for space heating units"

TNO Environment, Energy and Process Innovation 2004. "Heat pump test"