DEVELOPMENT OF LARGE-CAPACITY HEAT PUMP PERFORMANCE-EVALUATING APPARATUS

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Abstract: Heat pumps are expected to be increasingly used in efforts to boost primary energy-saving and mitigate the greenhouse effect due to their high efficiency. In the industrial field, heat pumps will require higher efficiency and temperature performance. Recently, several manufacturers commercialized high-temperature and large-capacity heat pumps for industrial use. Customers require a means of determining efficiency and capacity not stated on the specification sheet, but no such equipment exists. CRIEPI, as a third party, thus decided to establish an evaluation apparatus and its specifications were examined. Consequently, we established an evaluation apparatus including an environmental chamber (temperature: -20 - +50 °C, relative humidity: 30 - 90 %), heat-source and heat sink water-supplying facility (temperature: 10 - 90 °C) and steam-cooling facility. Using this apparatus, we can evaluate steam-generation heat pumps of less than 600 kW, high-temperature air-heating heat pumps of less than 200 kW, water-source chillers of less than 2100 kW and air-source heat pumps of less than 350 kW. In addition, we can also use the apparatus for joint development with manufacturers and for national project research.

Key Words: Heat pump, Environmental chamber, Evaluation method, Air source, Water source

1 INTRODUCTION

Heat pumps are expected to become more popular and common and contribute to primary energy-saving (energy conservation), abating greenhouse gases (preventing global warming) and increasing renewable energy consumption (expansion of renewable energy). In the Japanese residential and commercial sectors, heat pumps have already penetrated in the form of air-conditioners. In addition, a heat pump water heater (Eco Cute), using CO_2 as a refrigerant, was developed and commercialized in 2001 (Saikawa et al. 2000). By 2013, total accumulated shipments exceeded four million.

Conversely, in the industrial sector, because heat pumps will have to achieve higher output temperatures, higher efficiency (lower running costs), and lower initial costs, heat pumps for the heating process are uncommon. Hence, the CO_2 heat pump water heater, which is a comparatively low-priced household appliance and capable of generating hot water at a temperature of 65-90 °C, is one of the prime candidates for industrial heat pumps. In addition, recent years have seen manufacturers overcome the difficulty of commercializing heat pumps for industrial use, and installation examples have been reported. These include, for example, a hot-wind generation heat pump (KANDO 2012), a high-temperature water-generation heat pump (KOBAYASHI et al. 2012, YONEDA et al. 2012), a steam-generation heat pump (Kobe Steel 2014a), a circulation-type high-temperature heat pump (OUE and OKADA 2013, IBA et al. 2012, TAKAYAMA et al. 2012, SHIBA et al. 2012).

Before installing such a heat pump, it is important to provide an objective and highly reliable evaluation result adapted to the actual state of use and promote effective energy conservation and prevention of global warming. In addition, customers often request the submission of equipment performance details (in terms of efficiency and capacity), which are not described in catalogs and technical notes. Moreover, performance evaluations are also important for continuous improvement. However, the lack of third party apparatus capable of evaluating large-capacity and high-temperature-output heat pumps for industrial use means such evaluation has previously been performed on-site. Naturally, the accuracy and reproducibility of such on-site evaluation are lower than that of evaluation apparatus; hence the strong push to establish an evaluation apparatus capable of evaluating various heat pumps.

Within CRIEPI, the authors have been involved in numerous heat-pump development projects (SAIKAWA et al. 2000, HASHIMOTO et al. 2012 and OSAGAWA et al. 2012), have performed numerous subsequent evaluations (FUJINAWA et al. 2012), helped establish evaluation methods, and acquired appropriate experience. Accordingly, we decided to build a large-scale heat pump evaluation apparatus with which we could evaluate various heat pumps, including those for widespread industrial use in future. In this report, firstly, the specification of the evaluation apparatus is discussed based on the investigation into the developed heat pumps. Secondly, verification of the reliability of the established apparatus is discussed.

2 HEAT PUMPS FOR INDUSTRIAL AND COMMERCIAL USE

Heat pumps for industrial use, which have been commercialized by Japanese manufacturers in recent years, are summarized in **Table 1**. Water-to-water (water source) heat pumps are shown in **Table 1(a)**, while air-to-water (air-source) heat pumps are shown in **Table 1(b)**. In each table, the manufacturer’s name, product name, applicable heat-source temperature, applicable output temperature, compressor type, refrigerant, supply system (heating method), rating output temperature, rating heating capacity and rating COP are described. Here, “Circulation” in the supply system column means circulation heating, while “One-Through” in the same column means one-through heating. “One-through heating” means heating a quantity of water or air at a time from low to high temperature.

The heat-source inlet temperature of water-to-water heat pumps is distributed within the range 10-90 ^{o}C, while the heat-source temperature of air-to-water heat pumps ranges from -25 - 40 ^{o}C. The maximum output temperatures for water, air and steam are 90 ^{o}C, 120 ^{o}C, and 175 ^{o}C respectively. When the evaluation apparatus specification is discussed, a specification superior to the current level is necessary; referring to world technological review (WATANABE 2012) in addition to this table.

3 DESIGN OF THE TESTING APPARATUS

3.1 Specification Development

To evaluate air-to-water heat pumps (air-source heat pumps and air-cooled chillers), an environmental chamber in which constant temperature and humidity are maintained for a certain period is required. Hereinafter, the heat pump and the chiller to be evaluated are referred to as the "Machine to be tested". As shown in Table 1, it is preferable to ensure as

Table 1: Summary of heat pumps for industrial and commercial use in Japan

(a) Water-to-water heat pumps

Manufacture / Product Name	Applicable Temperature Range[℃] Source Temp. / Output Temp. (0 20 40 60 80 100 120 140 160)	Compressor Type	Refrigerant	Supply System	Heat source temperature (Cooling Capacity)	Output temperature (Heating Capacity)	Heating (Total) COP
MHI (Hot Water) Water to Water Centrifugal Heat Pump, ETW-L	Source 10℃–50℃; Hot Water 50℃–90℃	Two-stage turbo	R134a	Circula-tion	50℃ (403kW)	90℃ (547kW)	3.7 (6.5)
KOBELCO (Hot Water) HEMII-HR90	Source 10℃–40℃; Hot Water 70℃–90℃	Two-stage twin-screw	R134a +R245fa	Circula-tion	17℃ (173kW)	90℃ (272kW)	2.7 (4.5)
MAYEKAWA (Hot Water) Water source Eco Cute unimo W/W	Source -5℃–37℃; Hot Water 65℃–90℃	Recipro-cating	R744 (CO_2)	One Through	37℃ (95kW)	65℃ (117kW)	5.1 (9.3)
Science Inc. (Hot Water) Eco Multi Heat Pump WSR	Source -10℃–45℃; Hot Water 40℃–80℃	Scroll	R134a	Circula-tion	40℃ (40kW)	80℃ (67kW)	2.4 (3.7)
ZENERAL HEATPUMP (Hot Water) Heat Pump for washing process	Source 10℃–30℃; Hot Water 40℃–85℃	Scroll	R134a	Circula-tion	20℃ (29kW)	65℃ (43kW)	3.0 (5.1)
MAYEKAWA (Hot Air) CO_2 Hot Air Heat Pump Eco Sirocco	Source -5℃–40℃; Hot Air 80℃–120℃	Recipro-cating	R744 (CO_2)	One Through	30℃	100℃ (110kW)	3.7
KOBELCO (Steam) Steam Grow Heat Pump SGH120	Source 25℃–65℃; Steam 100℃–120℃	Two-stage twin-screw	R245fa	Circula-tion	65℃	120℃ (0.1MPaG) (0.5ton/h)	3.5
KOBELCO (Steam) Steam Grow Heat Pump SGH165	Source 35℃–70℃; Steam 135℃–175℃	Single-stage twin-screw	R245fa +R134a	Circula-tion	70℃	165℃ (0.6MPaG) (0.9ton/h)	2.5

Remarks : MHI=MITSUBISHI HEAVY INDUSTRIES, KOBELCO=KOBE STEEL, MAYEKAWA=MAYEKAWA MFG,

(b) Air-to-water heat pumps

Manufacture / Products Name	Applicable Temperature Range[℃] Ambient Temp. / Output Temp. (-20 0 20 40 60 80 100 120 140)	Compressor Type	Refrigerant	Supply System	Ambient tempera-ture	Heating output temperature (Heating Capacity)	Heating COP
KOBELCO (Hot Water) HEM-90A	Ambient -10℃–40℃; Hot Water 65℃–90℃	Two-stage twin-screw	R134a +R245fa	Circula-tion	25℃ (Summer)	90℃ (176kW)	2.80
Toshiba Carrier (Hot Water) Circulative heating heat pump CAONS700	Ambient -20℃–40℃; Hot Water 50℃–90℃	Twin-rotary	R410A +R134a	Circula-tion	16℃ (Spring / Autum)	65℃ (70kW)	3.11
Toshiba Carrier (Hot Water) Circulative heating heat pump CAONS140	Ambient -20℃–40℃; Hot Water 50℃–90℃	Twin-rotary	R410A +R134a	Circula-tion	16℃ (Spring / Autum)	65℃ (14kW)	3.10
MITSUBISHI ELECTRIC (Hot Water) Hot Water Heat Pump	Ambient -10℃–40℃; Hot Water 35℃–70℃	Scroll	R407C	Circula-tion	16℃ (Spring / Autum)	65℃ (45kW)	3.07
MHI (Hot Water) Commercial Eco Cute Q-ton	Ambient -25℃–43℃; Hot Water 60℃–90℃	Scrotary (Scroll+ Rotary)	R744 (CO_2)	One Through	16℃ (Spring / Autum)	65℃ (30kW)	4.30
MAYEKAWA (Hot Water) Commercial Eco Cute unimo A/W	Ambient -10℃–43℃; Hot Water 65℃–90℃	Recipro-cating	R744 (CO_2)	One Through	16℃ (Spring / Autum)	65℃ (74kW)	4.18

Remarks : MHI=MITSUBISHI HEAVY INDUSTRIES, KOBELCO=KOBE STEEL, MAYEKAWA=MAYEKAWA MFG,

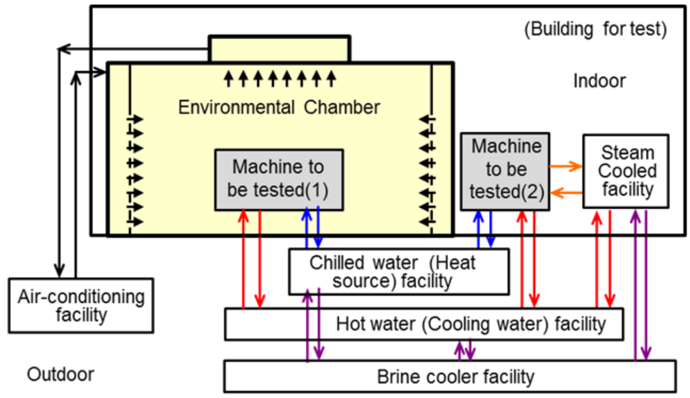
List of reference: Kobe Steel 2014a, Kobe Steel 2014b, Kobe Steel 2014c, MAYEKAWA MFG. 2014a, MAYEKAWA MFG. 2014b, Mitsubishi Heavy Industry 2014a, Mitsubishi Heavy Industry 2014b, MITSUBISHI ELECTRIC 2014, Science Inc. 2014, Toshiba Carrier 2014, ZENERAL HEAT PUMP 2014 wide a configurable temperature and humidity range as possible. Moreover it is also necessary to supply water of which the temperature has been adjusted to the chamber, given that water is a major output medium. The configurable temperature range and flow rate of water are also as wide as possible. There is little need to endow the chamber with the function of a calorie meter because the measurement accuracy of water temperature, water flow rate and power consumption are relatively superior to that of airflow rate. The heating and cooling capacity for the chamber are thought to be around 350 kW due to advances in the modulation of chillers (and heat pumps) in recent years.

Conversely, to evaluate water-to-water heat pumps (water-source heat pumps and water-cooled chillers), systems supply water at two different temperatures are necessary. One is a facility that supplies hot water as heat sink water to a machine to be tested, and the other is a facility that supplies chilled water as a heat source. The hot water supply facility must also heat the return water from the machine to be tested, while the chilled water supply facility must cool the return water from the machine to be tested. As a minimum, we would like to evaluate the 2100 kW turbo chiller, which is in the capacity volume zone of turbo chillers.

We would also like to evaluate a water heat source high-temperature air-generating heat pump and a steam-generation heat pump which was commercialized as a heat pump for high-temperature operation. The heatproof temperature of air-cooling equipment should be set at around 200 ^{o}C, considering technical advancements in hot-air generating heat pumps, although the present output temperature is 120 ^{o}C. The maximum steam temperature to be evaluated should be set at around 200 ^{o}C, considering the technical progress of steam-generating heat pumps, despite the present output steam temperature is 175 ^{o}C.

Figure 1 is a schematic diagram of an evaluation apparatus and a list of machines to be tested assumed to be open to evaluation. According to the previous discussion, there is a need for the evaluation apparatus to comprise an environmental chamber, an air-handling unit, a hot-water supplying facility, a chilled water-supplying facility, and a steam-cooling facility. The environmental chamber should be sufficient to accommodate the machine to be tested and not cause any air short-circuit. The configurable temperature and humidity ranges must also be sufficiently wide to evaluate any kind of heat pumps. To evaluate heat-recovery heat pumps, a hot water supply facility that can supply hot water at 50 ^{o}C or more is necessary.

Most existing evaluation apparatus were constructed with the aim of executing evaluation tests perfectly and in accordance with standards. Conversely, our evaluation apparatus is constructed, to facilitate fundamental study, the development of a unique heat pump and flexible evaluation according to the actual state of use. The lack of precedent means there is a need to discuss the specifications. If we constructed such apparatus, we could evaluate a steam-generation heat pump with a rated power output of less than 600kW, a high-



Machines to be tested

1. Industrial hot water or steam supply heat pumps
   - heat output ≤ 600 kW (= 1 ton/h of steam)
   - supply temperature ≤ 200℃ (= 0.8 MPaG)
2. Industrial hot air supply heat pumps
   - heat output ≤ 200 kW
   - supply temperature ≤ 200℃
3. Industrial or commercial chillers (or icemakers)
   - heat output ≤ 2,100 kW
     (= 600 USRT of centrifugal chiller)
4. Commercial air-conditioning cold or hot water supply heat pumps
   - cooling capacity ≤ 350 kW (= 100 USRT)
   - heating capacity ≤ 350 kW

Figure 1: Outline of heat pump performance-evaluating apparatus

temperature (up to 200 °C) air-heating heat pump with a rated power output of less than 200 kW, a water-source chiller with a rated power output of less than 2100 kW and an air-source heat pumps with a rated power output of less than 350 kW.

3.2 Environmental Chamber

We decided to build an environmental chamber to maintain constant temperature and humidity under given conditions for air-cooled chillers or air-source heat pumps, rather than air-conditioners.

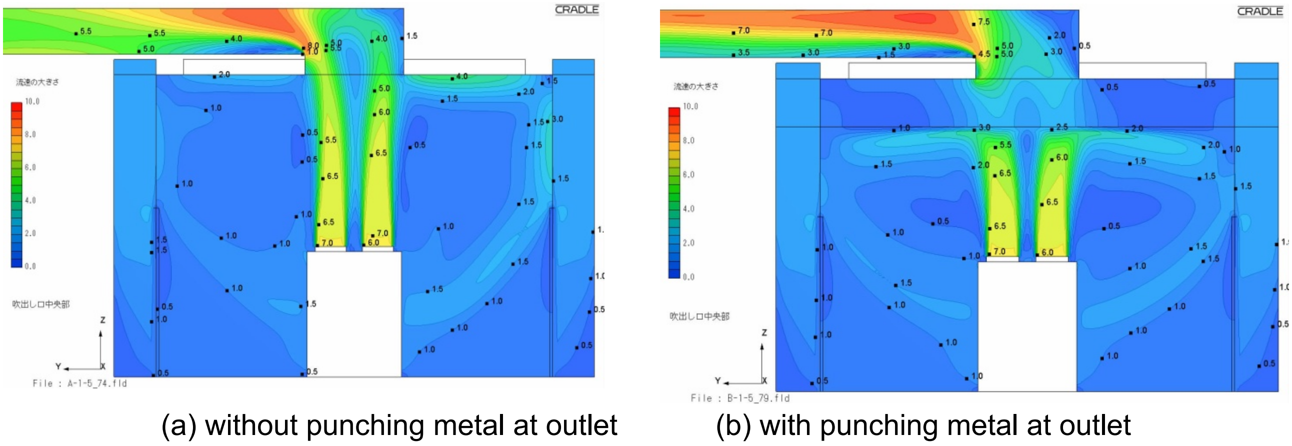
The psychrometric condition inside the chamber is controlled by an air-handling unit set up outside and psychrometric-controlled air is supplied to the chamber through a supply duct. The air heated or cooled by traversing the machine to be tested returns through the return duct into the air-handling unit and air thus circulates. In the inside of the air-handling unit, air is initially dehumidified with a dry desiccant rotor, cooled with an air-cooled condensing unit, heated by an electric heater, and finally humidified with an electric steam boiler.

Air is supplied from three sidewalls which set up a punching metal plate to make air flow uniform, and returned to the ceiling space. At the ceiling, however, there is no punching metal plate due to the negative effect predicted by numerical airflow analysis as follows:

- In the absence of a machine to be tested, a punching metal plate uniforms the airflow to the ceiling.
- For tall machines to be tested with large airflow discharge, the existence of a punching metal plate results in recirculation airflow (as shown in Figure 2(b)) which may prompt a change in suction temperature.

Numerical analysis also shows that a larger width of the ceiling space results in a lower recirculation airflow rate. Based on this result, the width of the ceiling space was extended as far as possible.

Referring to the previous discussion, we decided that the configurable range for temperature was from -20 - 50 °C, that for relative humidity was from 30-90 %RH, the air speed at the center of the chamber was less than 0.5 m/s, and the airflow rate was 2200m^3/min, as specifications of an environmental chamber (Table 2(a)). The heating and cooling capacities requested for the air-handling unit were set to 350 kW due to the maximum module capacity of the air-cooled chillers and air-source heat pumps. In case of hot-air heat pump evaluation, a machine to be tested (hot-air heat pump) will be set up inside the environmental chamber, hot air flow into the return duct of the chamber, and cooled together in the air-handling unit.

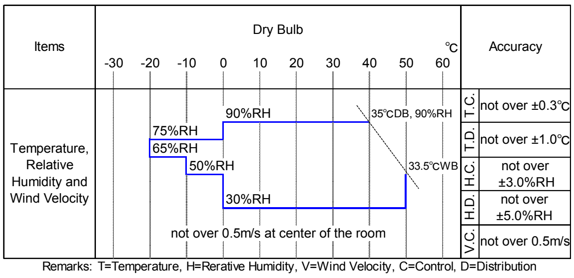


(a) without punching metal at outlet (b) with punching metal at outlet

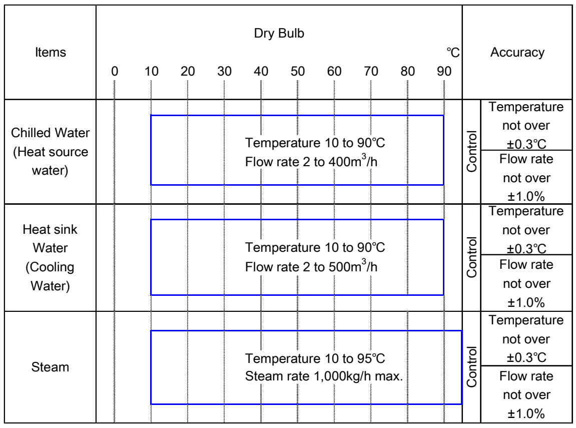
Figure 2: Air speed counter map in psychrometric control room by numerical analysis (provided by TOYO ENGINEERING WORKS)

Table 2: Requested testing apparatus specifications

(a) Environmental Chamber



(b) Hot and Chilled water facility



3.3 Brine Cooling Facility

A brine-cooling facility is established to supply coolant to the "chilled (heat-source) water facility", "hot (cooling) water facility" and "steam-cooling facility". The facility comprises three air-cooled brine chillers, one brine tank, and primary and secondary brine pumps. The primary brine is cooled with the brine chillers and stored in the brine tank, while the secondary brine is supplied from the tank to each facility. The warmed secondary brine is then returned to the tank, and recooled with the chillers. Plate-type heat exchangers are used to cool the hot water, chilled water, and condensed water. The cooling capacity of each facility is controlled by adjusting the auto three-way valve in front of the heat exchanger.

3.4 Chilled (Heat Source) Water Facility

The chilled water facility comprises a chilled (heat source) water tank, electric heaters, water pumps, flow-control valves, and plate-type heat exchangers. Three water pumps and flowmeters with different flow-rate ranges are equipped; one of which is selected according to the target water flow rate. In addition, the water flow rate supplied to the machine to be tested can be adjusted with a flow-control valve.

To save energy, a plate-type (heat-recovery) heat exchanger is installed between the chilled water and hot water; both of which returning from the machine to be tested.

The return chilled water is subsequently further cooled with the brine and stored in the chilled (heat-source) water tank. The chilled water is heated with electric heaters in the tank to control the temperature accurately. The temperature and flow rate of the chilled water are extensively configurable from 10-90 ^{o}C and 2 to 400m^3/h, respectively (Table 2(b)).

3.5 Hot (Cooling) Water Facility

A hot (cooling) water facility is constructed with a hot (cooling) water tank, electric heaters, water pumps, flow-control valves, plate-type heat exchangers, and a cooling tower. Because the temperature and flow-rate control method are the same as for the chilled (heat source) water facility, an explanation is omitted. Moreover, hot (cooling) water adjusted with this facility is supplied to the "steam-cooling facility" and used as a coolant for steam condensation. The temperature and flow rate of the hot water are extensively configurable from 10-90 ^{o}C and 2 to 500m^3/h, respectively (Table 2(b)).

3.6 Steam-Cooling Facility

The steam-cooling facility comprises a condensed water tank, an electric heater, a water pump, a pressure-control valve, and plate-type heat exchangers. The supply (condensed) water temperature is adjusted using an electric heater and a plate-type heat exchanger cooled with the brine. Steam is condensed using two plate-type heat exchangers cooled by the coolant supplied by “hot (cooling) water facility” and condensed water sent to the condensed water tank. The temperature of the discharge steam can be controlled by adjusting the pressure-control valve because the discharge steam can be considered saturated. The temperatures of the supply water and the pressure and flow rate of the discharge steam are extensively configurable; from 10-95 ^{o}C, 0-0.8 MPaG and 2 to 1000 kg/h, respectively (Table 2(b)).

3.7 Measurement Instruments

The evaluation apparatus is provided with measurement instruments as shown in Table 3.

Four-line type high-precision resistance thermometers connected to a high-precision temperature logger (NETSUSHIN NX3100) were prepared to measure the temperature. High-precision power meters (YOKOGAWA WT3000) were also prepared to determine the electricity consumption of machines to be tested. Using these, single-phase AC electricity measurements for twelve devices or triple-phase AC electricity measurements for six devices are possible.

The temperature (dry bulb) and humidity (wet bulb) were measured using a high-precision resistance thermometer in an air sampler. In addition, a relative humidity meter (VISALA HMT 330) and high-precision mirror-type dew point meter were used in parallel.

Table 3: List of sensors included in the measurement apparatus

Temperature (logger)	Four-wire resistance temperature sensor PT 100 Ω (Class A) x 24 Netsushin NX3100 (Accuracy = ± 5 mK)
Dew Point	SHINYEI DewStar S-1 (Mirror Type) (Accuracy = ±0.2 C DP)
Humidity	Visala HMT330 (Accuracy = ±(1.0+reading x 0.008) %RH)
Chilled water volumetric flow rate	TOKYO KEISO electromagnetic flowmeter EGM2100C (0-300L/min ±0.5% of reading), EGM4100C (0-5000 L/min, 0-10000 L/min, ±0.5 % of reading)
Hot water volumetric flow rate	TOKYO KEISO electromagnetic flowmeter EGM2100C (0-300L/min ±0.5% of reading), EGM4100C (0-6000 L/min, 0-10000 L/min, ±0.5 % of reading)
Steam volumetric flow rate	TOKYO KEISO SWIRLMAX (vortex flowmeter) VFM4070C (11 - 100kg/h, 24 - 500 kg/h, 61 - 1000 kg/h, ±1% of reading)
Steam mass flow rate	TOKYO KEISO Coriolis mass flowmeter MMM7300C-T15 (0 - 1500 kg/h, ±0.1% of reading)
Flocculated water volumetric flow rate	TOKYO KEISO electromagnetic flowmeter EGM4100C (0-30L/min ±0.5% of reading)
Spray water mass flow rate	EMERSON MicroMotion (Coriolis mass flowmeter) F025 (72 to 174 kg/h, ±0.24% of reading)
Hot air volumetric flow rate	TOKYO KEISO SWIRLMAX (vortex flowmeter) VFM4070C (42 – 940 Nm^3/h, 272 - 5000 Nm^3/h, 615 - 10000 Nm^3/h, ±1% of reading)
Electric power consumption	YOKOGAWA WT3000 (power accuracy = ±0.06%) with CT60, CT100, CT200 and Current clamp 751552
Data acquisition system	YOKOGAWA MW100 x 3 (Software : Hablis Wave Researcher V4)

Coriolis-type mass flowmeters and electromagnetic flowmeters were prepared for liquid flow-rate measurements, while the hot- and chilled water facilities had three flowmeters which respectively varied in measurement range; one of which was selected according to the flow-rate. The steam-cooling facility has three vortex flow meters and a Coriolis-type mass flowmeter and one of the three vortex flowmeters was selected to suit the steam flow rate. The Coriolis-type mass flowmeter was set up after the condensing heat exchanger to allow measurement of the condensed water mass flow rate. Comparing the mass flow rate achieved by the Coriolis mass flowmeter and the steam flow rate by the vortex flowmeter facilitates high-precision steam flow rate measurements. For hot airflow measurement, three flowmeters were prepared; one of which was used properly according to the flow rate.

All the data, including on dew point, electricity, temperature, flow rate and etc. were saved on a PC.

4 VERIFICATION OF FACILITIES

We performed no-loaded verification (operating a facility without a machine to be tested) and verified the control and distribution accuracies of air temperature, relative humidity and velocity in the environmental chamber as well as the control accuracy of water temperature and flow rate. We also performed loaded verification using an air-cooled brine chiller, which is part of the brine-cooling facility and verified the control accuracy of air temperature and relative humidity in the environmental chamber and the water temperature and flow rate.

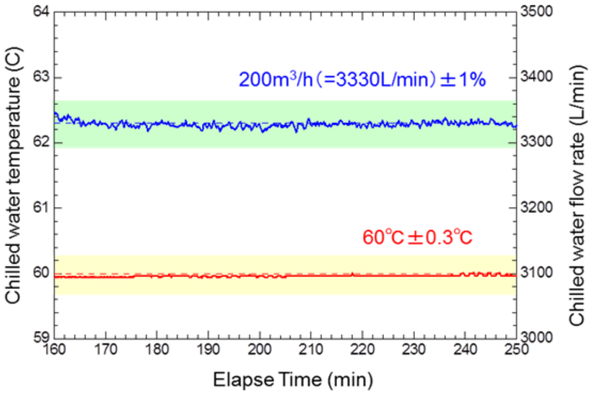
4.1 No-Loaded Verification of the Environmental Chamber

Verifications of temperature and humidity control accuracy in the environmental chamber were performed under seven conditions to contain specifications (dry-bulb temperature range from -20 - +50 ^{o}C and relative humidity range from 30-90 %RH as shown in Table 2(a)). The outlet temperature and humidity from the air-handling unit were selected as controlled objects, though the dry-bulb and wet-bulb temperatures in the movable air sampler in the environmental chamber may also be selected as controlled objects. The verification results confirmed that the control accuracy of the temperature and humidity went under 0.3 ^{o}C and less than 3.0%RH respectively.

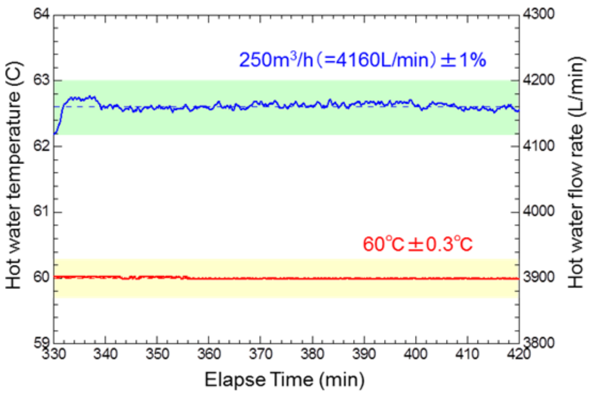
The uniformity of the dry bulb temperature, relative humidity, and air velocity were discussed. We installed 42 corresponding sensors every 1m and 1 and 2m in height above the floor on a plane of the chamber center, 2m wide and 6m deep. It was understood as meeting the specifications according to the results of verifications under frosting temperature condition (dry bulb temperature of 2 ^{o}C and wet bulb temperature of 1 ^{o}C).

4.2 No-Loaded Verification of Chilled (Heat Source) Water Facility

The control accuracy of chilled (heat source) water temperature and flow rate was discussed. For each temperature of 10, 30, 60, and 90 ^{o}C, we performed verifications under four flow-rate conditions of 2, 50, 200 and 400m^3/h, respectively. In other words, we performed sixteen verifications. Based on these results, under all conditions, it was confirmed that the control accuracies of temperature and flow rate respectively declined to under 0.3 ^{o}C and under 1.0 %. One example for water temperature of 60 ^{o}C and flow rate of 200m^3/h is shown in Figure 3(a).



(a) Chilled water temperature and flow rate



(b) Hot water temperature and flow rate

Figure 3: No-loaded verification results

4.3 No-Loaded Verification of Hot (Cooling) Water Facility

The control accuracy of the temperature and flow rate was also discussed for the hot (cooling) water facility as well as the chilled (heat source) water facility. For each of the temperature conditions of 10, 30, 60 and 90 °C, we performed verifications under the four flow-rate conditions of 2, 50, 250, and 500m^3/h. In other words, we performed sixteen verifications. Consequently, under all conditions, it was confirmed that the control accuracy of the temperature and flow rate went under 0.3 °C and 1.0% respectively. One example for water temperature of 60 °C and flow rate of 250m^3/h is shown in Figure 3(b).

4.4 No-Loaded Verification of Steam-Cooling Facility

It was revealed that the steam-cooling facility performed according to specifications.

4.5 Verification of the Environmental Chamber with Air-Cooled Brine Chiller

One of three brine chillers of the brine-cooling facility was transported to the environmental chamber as shown in Figure 4 and verification was performed, to confirm the control accuracy of air temperature, relative air humidity, chilled water inlet temperature, and chilled water flow rate.

After the evaluation apparatus operated under the condition where the air-inlet temperature, relative air humidity, chilled-water inlet temperature and flow rate set at 10 °C, 40%RH, 10 °C, and 1100 L/min respectively, it was confirmed that the individual control accuracies went under 0.3 °C, 3.0%, 0.3 °C, and 1.0%, respectively as shown in Figure 5. Here, operator changed the set-point of the air-inlet temperature from 35 °C to 32 °C at 12 minutes and changed it to 35 °C again at 32 minutes manually. By this operation, it was possible to suppress excess rises in temperature due to abrupt change in operation condition.

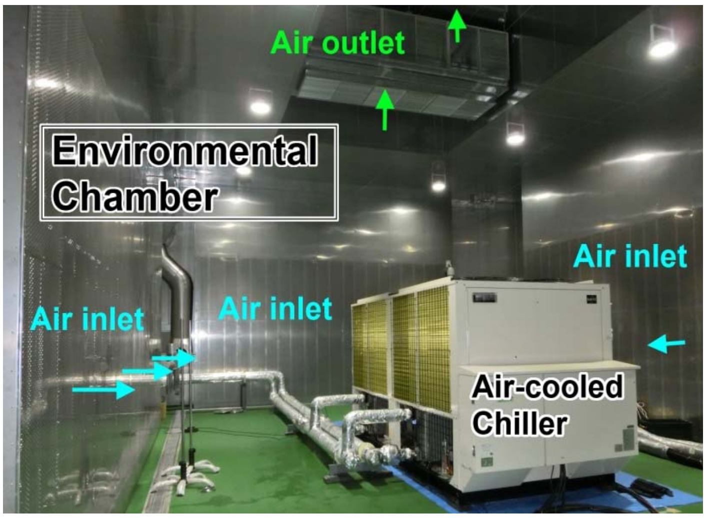


Figure 4: Installation photographs of an air-cooled chiller

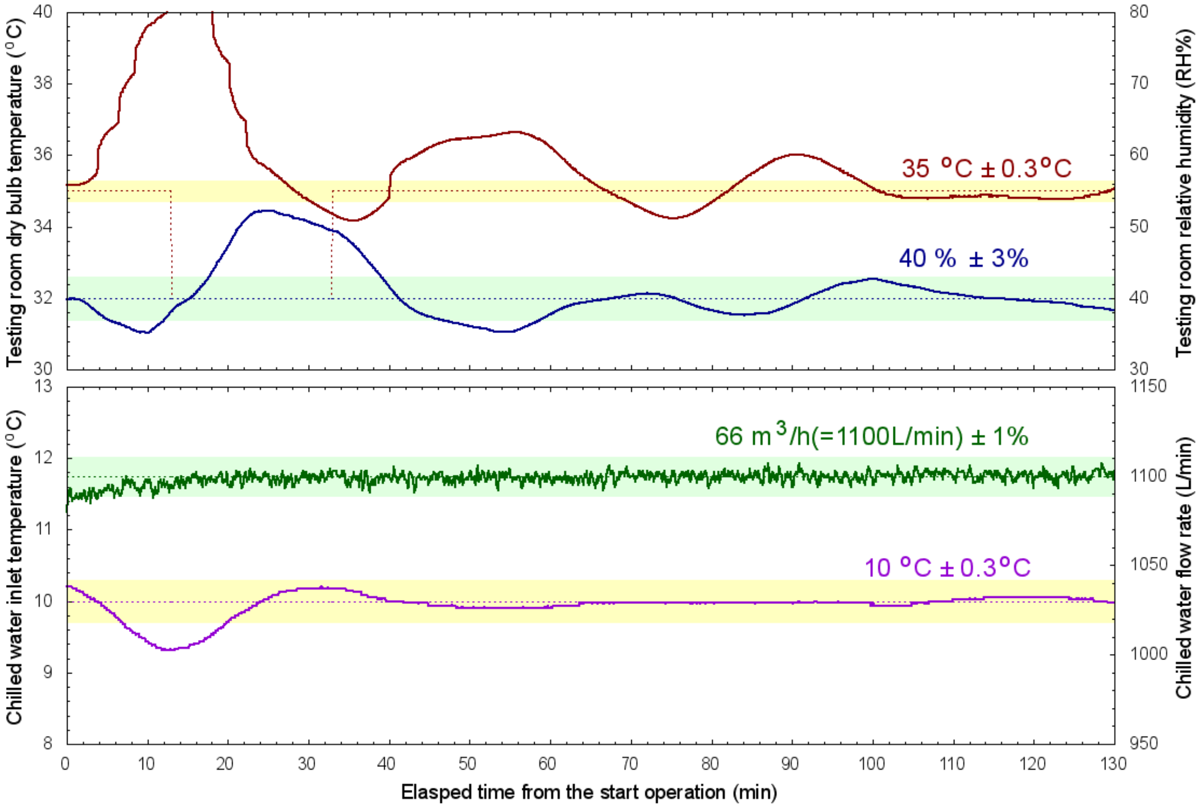


Figure 5: Loaded verification results of air temperature, air humidity, water flow rate and water temperature with an air-cooled brine chiller of 350kW

5 FEATURES OF EVALUATING APPARATUS

The main characteristic of the apparatus is high flexibility in evaluation. There are unique features as follows:

- Air-source heat pumps and air-cooled chillers of less than 350kW can be evaluated. The configurable dry bulb temperature and relative humidity are sufficiently wide (-20-50 °C, 0-90 %RH) and water inlet temperature does not depend on the dry bulb and relative humidity and is configurable from 10-90 °C.
- High-temperature (up to 200 °C) air-heating heat pumps of less than 200 kW can be evaluated.
- Water to water heat pumps and chillers of less than 2100 kW can be evaluated. Chilled water temperature and hot water temperature are configurable from 10-90 °C independently.
- Steam-generation heat pumps (maximum outlet saturated temperature up to 200 °C) of less than 600 kW (about 1 ton/h steam) can be evaluated. For this evaluation, we established steam cooling facility. We are preparing an evaluation of a steam-generation heat pump (Figure 6).

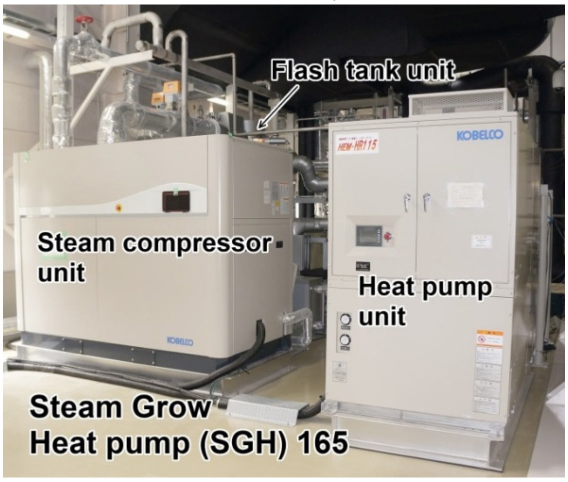


Figure 6: Installation photographs of a steam-generation heat pump

6 CONCLUSION

An apparatus capable of evaluating various medium- and large-capacity heat pumps, including high-temperature output heat pumps introduced into an industrial heating process in a factory, was designed and established. In future, we must accumulate experience of controlling this apparatus, for example, extended nonstop evaluation and a cyclic frosting-defrosting evaluation.

In addition, to facilitate energy conservation and global warming prevention, based on spreading the heat pump into industrial processes, we must develop and evaluate industrial heat pumps.

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REFERENCES

FUJINAWA, T., MAE, M. and HASHIMOTO, K. 2012, “Performance evaluation of multifunction CO_2 refrigerant heat pump water heater. - Evaluation method including hot water supply and floor heating-”, *Proc. of the 2012 JSRAE Annual Conference*, C324 (in Japanese)

HASHIMOTO, K., SAIKAWA, M., MISUMI, S., TAIRA, T. and KUME, Y. 2012, “Development of a compact CO_2 heat pump for industrial drying.”, *Proc. 10th IIR Gustav-Lorentzen Conference on Natural Refrigerant*, GL-173

IBA, I., KIKKAWA, K., KATAYAMA, K., HONGO, I., MIYAOKA, Y. and HAYASHI, D. 2012, “Energy conservation activities by using air-to-water heat pump water heater”, *Proc. of the 2012 JSRAE Annual Conference*, F121 (in Japanese)

KANDO, M. 2012, “Case studies of high temperature heat pump to the industrial field from system study to operation.”, *Proc. of the 2012 JSRAE Annual Conference*, F112 (in Japanese)

KOBAYASHI, H., KOBAYASHI, T., YOSHIDA, S., KIMATA, Y. and SATO, H. 2012, “Commercial use CO_2 heat pump water heater with scrotary compressor.”, *Proc. of the 2012 JSRAE Annual Conference*, F234 (in Japanese)

Kobe Steel 2014a, Catalog of Steam Grow Heat Pump, http://www.kobelco.co.jp/machinery/products/rotation/heatpump/sgh/index.html (in Japanese)

Kobe Steel 2014b, Catalog of HEM II-HR90, http://www.kobelco.co.jp/machinery/products/rotation/heatpump/hr90/index.html (in Japanese)

Kobe Steel 2014c, Catalog of HEM-90A, http://www.kobelco.co.jp/machinery/products/rotation/heatpump/90a/index.html (in Japanese)

MAYEKAWA MFG. 2014a, “Eco Cute. Transcritical CO_2 heat pumps. The future is now, and it's beautiful.”, http://www.mayekawa.com/products/features/eco_cute/

MAYEKAWA MFG. 2014b, Catalog of ECO SIROCCO, http://www.mayekawa.co.jp/ja/products/heat_pumps/03/ (in Japanese)

Mitsubishi Heavy Industry 2014a,"Water to Water Heat Pump (industrial use)", http://www.mhi.co.jp/en/products/detail/water_to_water_heat_pump.html

Mitsubishi Heavy Industry 2014b, "Air to Water Heat Pump (commercial use)", http://www.mhi.co.jp/en/products/detail/air_to_water_commercial.html

MITSUBISHI ELECTRIC 2014, “Hot water heat pump”, http://www.mitsubishielectric.co.jp/hvac_r/conditioning/products/chillingunit/409.html (in Japanese)

OSAGAWA, Y., HASEGAWA, H, HASHIMOTO, K., FUJINAWA, T., KAIDA, T., ISHIKAWA, M., HONMA, T., KAMIOKA, H., ISHIDA, H., TAKAYAMA, Y. 2012, “Development of CO_2 heat pump hot-water space heating system using cascade heat pump cycle.”, *Proc. of the 2012 JSRAE Annual Conference*, C222 (in Japanese)

OUE, T. and OKADA, K. 2013, “Air-sourced 90 C hot water supplying heat pump “HEM-90A”.”, *KOBELCO Technology Review*, No.32, pp.70

SAIKAWA, M., HASHIMOTO, K., KOBAYAKAWA, T., KUSAKARI, K., ITO, M. and SAKAKIBARA, H. 2000, “Development of Prototype of CO_2 Heat Pump Water Heater for Residential Use”, *Proc. 4th IIR Gustav-Lorentzen Conference on Natural Working Fluids*

Science Inc. 2014, Catalog of WSR eco multi heat pump, http://www.science-inc.jp/heat-pump/ (in Japanese)

SHIBA, Y., TANIFUJI, K., NAKAYAMA, H. and SAKURABA, I. 2012, “Development and introduction of a heat pump for washing process.”, *Proc. of the 2012 JSRAE Annual Conference*, F114 (in Japanese)

TAKAYAMA, T., SUZUKI, H., IBA, I., HONGOU, I., SAKURABA, I., MIYAOKA, Y. and NAKAYAMA, H. 2012, “Development of high temperature water circulation type heat pump for industries. - Air-to-water heat pump with a maximum leaving water temperature of 90 ^{o}C-.”, *Proc. of the 2012 JSRAE Annual Conference*, F122 (in Japanese)

Toshiba Carrier 2014, Catalog of CAONS, http://www.toshiba-carrier.co.jp/products/industry/caons/index_j.htm (in Japanese)

YONEDA, H., ONO, M. and TAMURA, T. 2012, “100kW CO_2 water heat source heat pump development and study for the global food processing industries.”, *Proc. 9th IIR Gustav-Lorentzen Conference on Natural Refrigerant*, 136

WATANABE, C. 2012, "International trends in industrial heat pump technology.", *Proc. of the 2012 JSRAE Annual Conference*, F114 (in Japanese)

ZENERAL HEAT PUMP 2014, Catalog of “heat pump for washing process”, http://www.zeneral.co.jp/senjokoutei/senjokouteiyou.html (in Japanese)