Development of High Temperature Water Circulation Type Heat Pump for Industries (Air-to-Water Heat Pump with a Maximum Output Water Temperature of 90°C)

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Abstract: There are various heating processes in industrial manufacturing and many heating equipment, such as boilers and electric heaters, are used. Although boilers have issues on heat loss since they are often centralized and transport vapor to destinations by long pipe arrangements. In addition, electric heaters have issues on high energy consumption. Therefore, in industrial heat source fields, highly energy-efficient and high-output-water-temperature heat pumps are expected to replace existing centralized boilers or electric heaters, as a means of energy saving and cost reduction. Although, in the case of circulation heating use with low difference in input-output water temperature, former heat pump had a problem that energy saving effect becomes deficient as output water temperature rises. As a solution, we have developed an air-source circulation type heat pump for high-temperature water, which is highly energy efficient and enables decentralization of heat source. By taking advantage of the cascade refrigerating system, we have achieved a maximum output water temperature of 90°C, an energy efficient operation, and peak power reduction of 70% in contrast with electric heaters.

Key Words: air-source heat pumps, industrial application, high temperature water, water circulation, cascade refrigeration cycle

1 INTRODUCTION

In recent years, demands are increasing for greater efforts to prevent global warming and create low-carbon societies. It is possible to contribute to protection of the global environment by using high-efficiency heat pumps for not only air conditioning but also various purposes such as hot-water supply. However, at present, heat pumps are not widely used at factories as industrial heat sources for production processes.

Production processes at factories involve a variety of heating treatment and extensively use heat sources such as steam boilers and electric heaters. Usually, boilers are concentrated and installed in a power house as shown in Figure 1. In this configuration, the generated steam is transported over long pipes to the locations where heat is required. Consequently, a large amount of heat is lost along the pipes. In addition, boilers have combustion loss, exhaust, and drain loss. Thus, the energy that is actually used is limited to 30% to 50% of the input energy. Some processes require direct steam while others use hot water. Our survey indicates that, to keep the internal tank temperature constant, the energy consumed by circulation heating systems that use water at a temperature of 90ºC or lower amounts to approximately 67 million GJ only in Japan (Takayama et al. 2012).

Recently, industrial heat pumps have been developed and put to use in many factories. Nevertheless, there are growing market demands for a rise in temperature of circulating heating water, higher heat pump efficiency, and a compact design suitable for installation in narrow spaces near production lines. To satisfy these demands, we have developed an air-source heat pump which enables a highly efficient production of high- temperature water. This paper provides the configuration, features, and benefits of the new heat pump system.

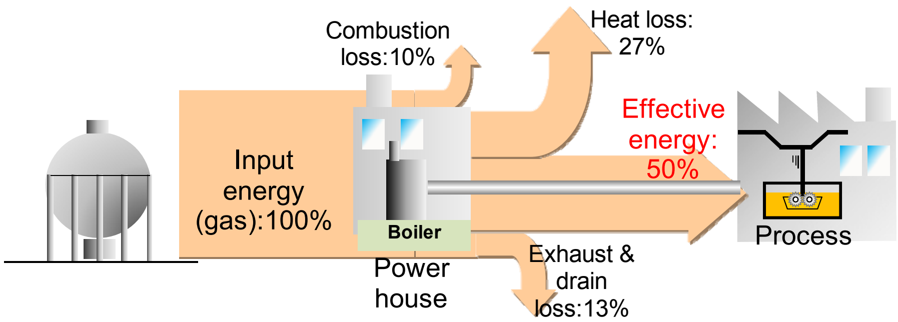


Figure 1: Image of energy loss in heating process using boiler as heat source

2 CONFIGURATION OF DEVELOPED SYSTEM

2.1 Target temperature of hot water

Figure 2 shows the temperature ranges and types of heat used for industrial processes. It shows that processes such as washing, degreasing, and sterilization use hot water at a temperature in the range from about 50 to 120ºC. According to our survey, 80% of all the industrial processes use hot water in the temperature range of up to 85ºC. To support these processes that require high-temperature water, the new system sets the maximum output water temperature to 90ºC.

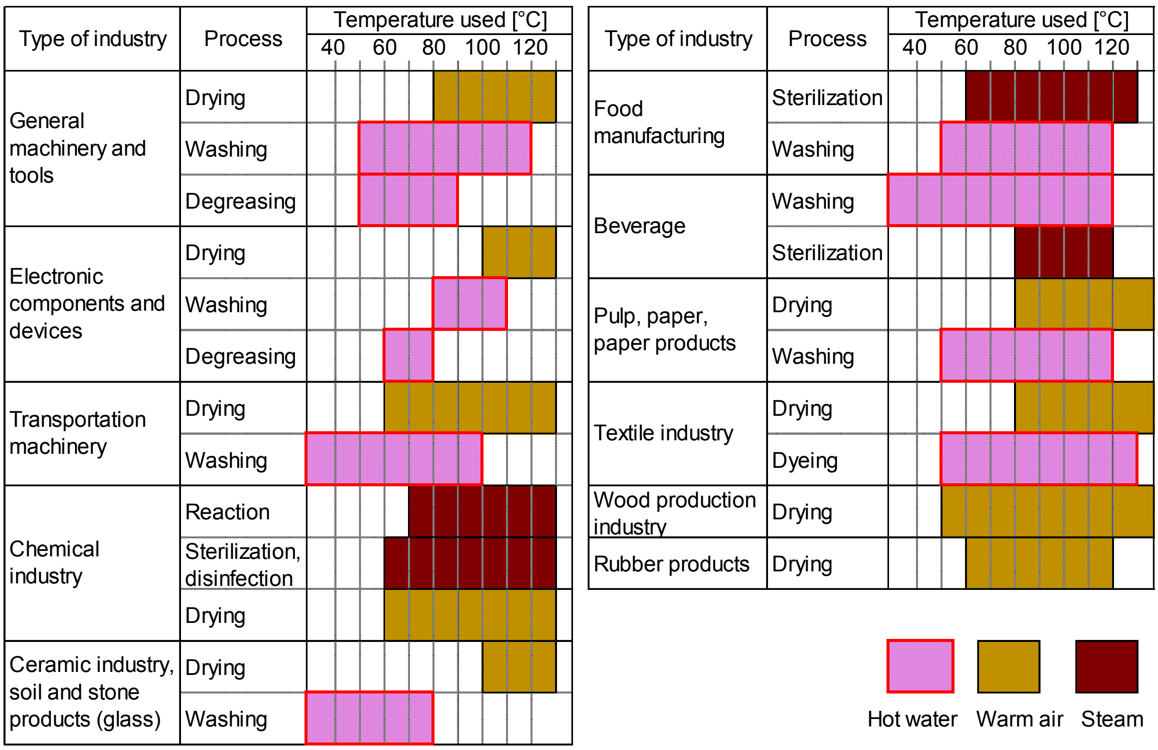


Figure 2: Temperature ranges and types of heat used for industrial purposes

2.2 One-through type heat pump and circulation type heat pump

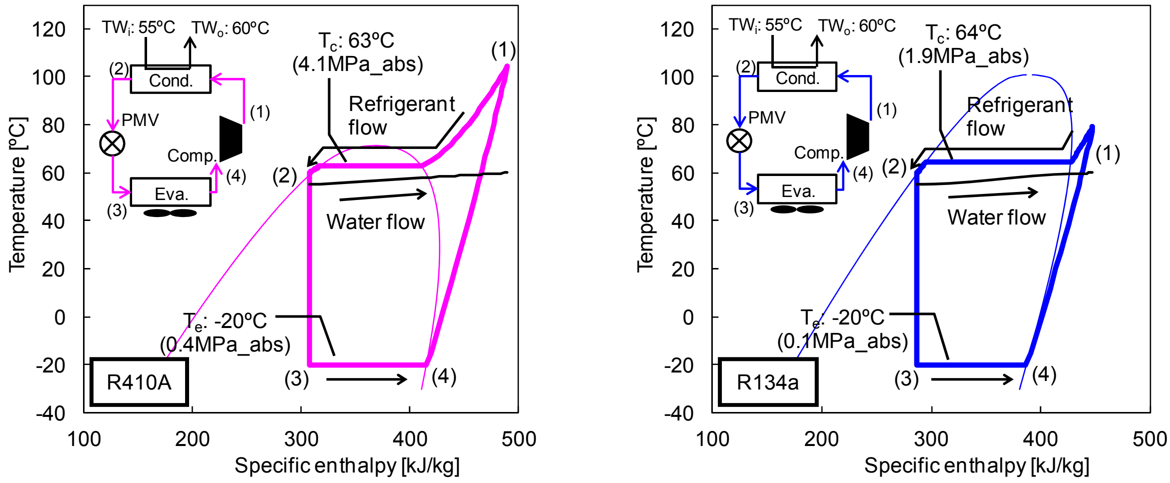
Characteristics of one-through type heat pump and circulation type heat pump are shown in Table1. A one-through type heat pump is hot water heating system which heats the water with high difference in input-output water temperature by a low water flow rate. The heat pump water heater for residential use diffused in Japan corresponds to this. One-through type heat pump water heater heats water and fills it in a tank when hot water is not used. The collected hot water is used whenever it is needed. A circulation type heat pump is used for the keeping-warm use which heats the water of with low difference in input-output water temperature by a high flow rate. The heat pump for floor heating for residential use and heating operation of a chilling unit correspond to this. Circulation type heat pump water heater always heats water according to load. As mentioned above, it has become clear from our survey that a circulation type is commonly used for processes such as maintaining the chemical temperature in a tank for industrial heating processes. Assuming a one-through type to be used for industrial use, a large capacity tank is necessary and time to heat hot water is limited at long operating factories, resulting inconvenience and increase in size of the system. Therefore, a circulation type is chosen for the developed system.

Table 1: Characteristics of one-through type heat pump and circulation type heat pump

Heating type	One-through type heat pump	Circulation type heat pump
Characteristics	•Water is heated with high difference in input-output water temperature by a low water flow rate. (e.g. TW_i=17ºC, TW_o=65ºC, F=4.3 L/min: Heating capacity = 14 kW) •Water is heated and collected in a tank, and collected hot water is used.	•Hot water is heated with low difference in input-output water temperature by a high water flow rate. (e.g. Tw_i=60ºC, TW_o=65ºC, F=40.9 L/min: Heating capacity = 14kW) •Hot water is always heated according to load.
Merits	•Water can be efficiently heated by heat pump.	•Tank capacity may be small. •No worry of hot water run out.
Demerits	•A large capacity tank is necessary. •Hot water may run out if too much is used.	•Heating with a large difference in water temperature requires time. •Less efficient than a one-through type when heated by heat pump.
Popular usage	•Water heater for residential, light commercial use.	•Floor heating for residential use. •Warmth-keeping for industrial use

2.3 Refrigeration cycle

When a single stage refrigeration cycle is used for circulation heating of water, one compressor is used for a high pressure ratio operation. As a result, the efficiency of the system is lowered by an increase in the power consumption of the compressor and a decrease in heating capacity. Unlike one-through heating especially such as by a hot-water supply system using a heat pump, circulation heating that uses a high input water temperature increases the condensing pressure of the refrigerant. In addition, it has been known that the efficiency of the system substantially drops as the temperature of water rises. Figure 3 is a diagram showing the relation between temperature and specific enthalpy in a single stage refrigeration cycle when an air-source circulation type heat pump is placed in a low-temperature environment. With refrigerant R410A shown in Figure 3 (A), it can be predicted that the output water temperature is 60ºC at best if it is assumed that the heat pump operates within the ranges of pressure and temperature used for ordinary air conditioning. By contrast, if a low-pressure refrigerant, such as R134a shown in Figure 3 (B), is used, the output water temperature can be raised more easily than if R410A is used because the condensing pressure of the refrigerant falls. In a low-temperature environment, however, the evaporation pressure of the refrigerant drops, giving rise to a problem that the installation location of the system is limited to indoors where the ambient temperature is relatively high.



(A) R410A (B) R134a

Figure 3: Temperature vs. specific enthalpy diagram in a single stage refrigeration cycle (TW_i = 55°C, TW_o = 60°C, T_e = -20°C, S.H. = 5°C, ΔT = 5 K)

To realize a heat pump that can be installed outdoors and deliver circulation heating with a maximum output water temperature of 90ºC, the new system has adopted a cascade refrigeration cycle. Figure 4 shows the relation between temperature and specific enthalpy in a cascade refrigeration cycle. This refrigeration cycle generates heat energy with a higher temperature difference by using a low-temperature refrigeration cycle and a high-temperature refrigeration cycle, which are independent of each other and exchange heat with each other via an intermediate heat exchanger.

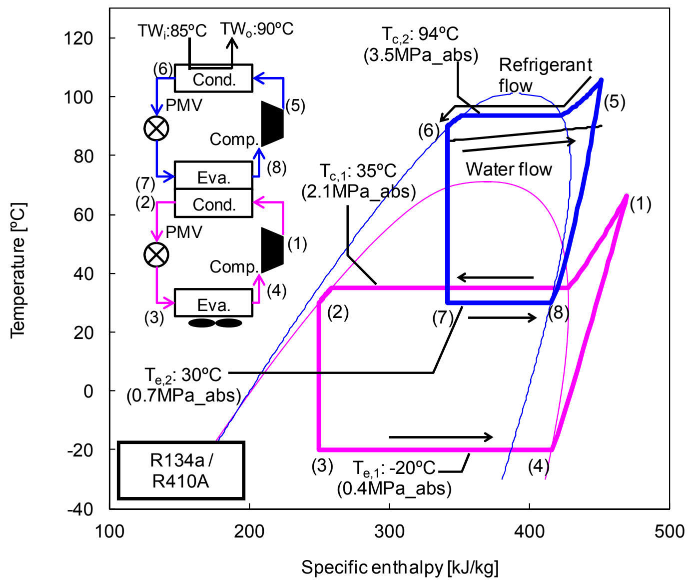


Figure 4: Temperature vs. specific enthalpy diagram in a cascade refrigeration cycle (low-temperature refrigerant: R410A, high-temperature refrigerant: R134a, TW_i = 85°C, TW_o = 90°C, $T_{e,1}$ = -20°C, $T_{c,1}$ = 35°C, $T_{e,2}$ = 30°C, $S.H._{1,2}$ = 5 K, $S.C._1$ = 5 K, ΔT = 5 K)

In the case of the cascade refrigeration cycle, two compressors compress the respective refrigerants, lowering the pressure ratio. Thus, the problems of the single stage refrigeration cycle, such as limits to the ambient temperature and output water temperature, and a drop in the efficiency of the system, can be solved. The new system uses R410A as the refrigerant of the low-temperature refrigeration cycle and R134a, which is suitable for high-temperature generation, for the high-temperature refrigeration cycle, so as to output high-temperature water even at low ambient temperatures.

2.4 Configuration of refrigeration cycle

Figure 5 shows the refrigerant pipe arrangement of the new system. The new system has a heat source unit for the low-temperature refrigeration cycle and a supply unit for the high-temperature refrigeration cycle placed in separate units, and each unit is connected with a refrigerant pipe to the other. By using a separate unit for each refrigeration cycle, the new system can flexibly meet various installation restrictions and conditions. The air heat exchanger and refrigeration cycle control of the heat source unit is optimized based on an outdoor installation type high-efficiency air conditioner for light commercial use.
The supply unit is newly designed as a compact indoor installation unit, based on the concept to place the system near the process and supply hot water with little heat loss.

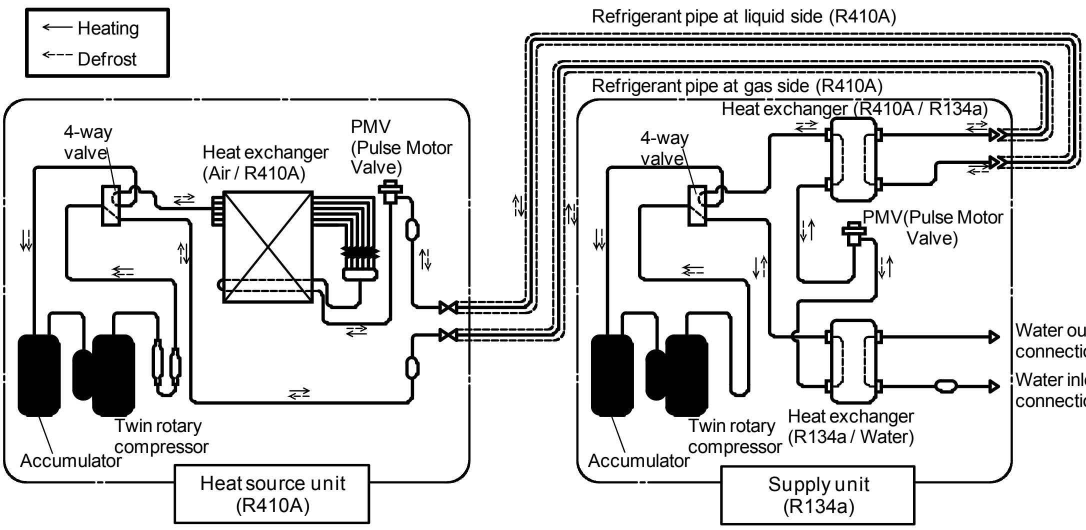


Figure 5: Refrigerant pipe arrangement

3 ENERGY SAVING PERFORMANCE

3.1 Refrigeration cycle control

In order to operate the two independent refrigeration cycles efficiently, controlling the refrigerant temperature in the intermediate heat exchanger is important. Figure 6 illustrates the influences of the intermediate temperature (condensing temperature of R410A), output water temperature, and the ambient temperature of the heat source unit on the coefficient of performance (COP) of the system. As can be seen from this figure, the intermediate temperature at which COP reaches the maximum level changes with the output water temperature and ambient temperature of the heat source unit. The new system controls the intermediate temperature by detecting the ambient temperature and operating status. High-efficient operation is realized by optimally controlling the intermediate temperature.
Figure 7 shows the influences of intermediate temperature control on the COP of the system. This figure indicates that COP improves up to 5% at low output water temperature conditions

when using optimum control of intermediate temperature. As a result of implementing optimum control of the intermediate temperature, the new system has achieved COP of 3.5 at an ambient temperature of 25ºC DB / 21ºC WB, output water temperature of 65ºC, and a heating capacity of 14 kW, when the heat source unit is installed indoors. Even when the heat source unit is placed outdoors, it has achieved COP of 3.1 at an ambient temperature of 16ºC DB / 12ºC WB and an output water temperature of 65ºC.

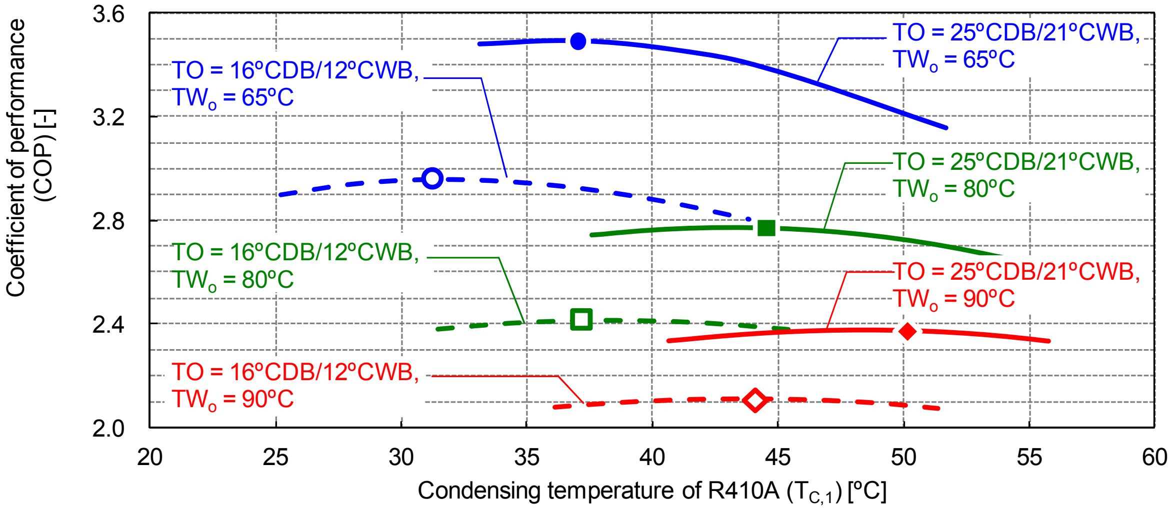


Figure 6: Intermediate temperature and COP (at TW_o - TW_i = 5 K)

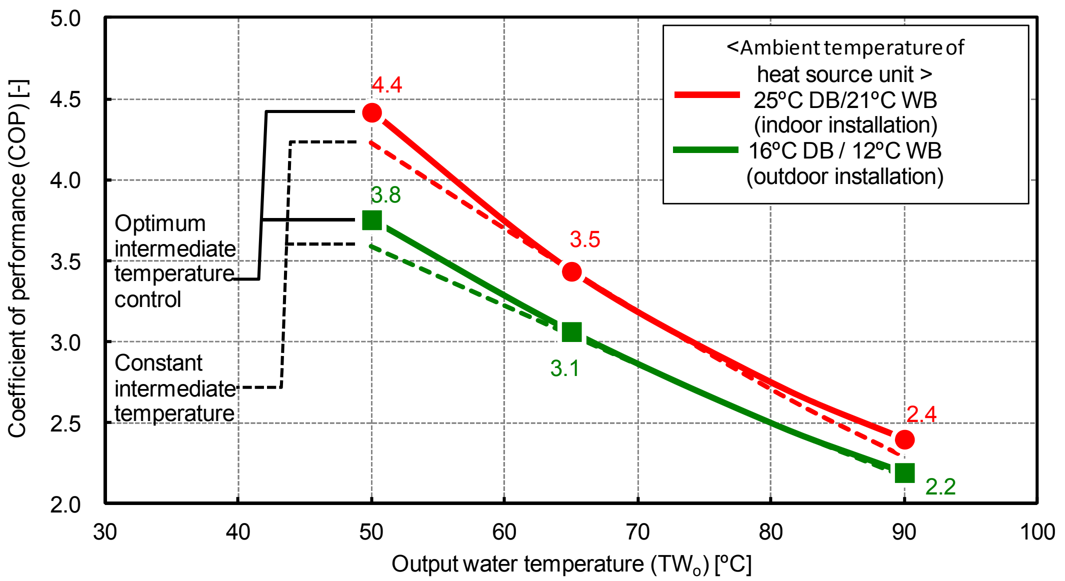
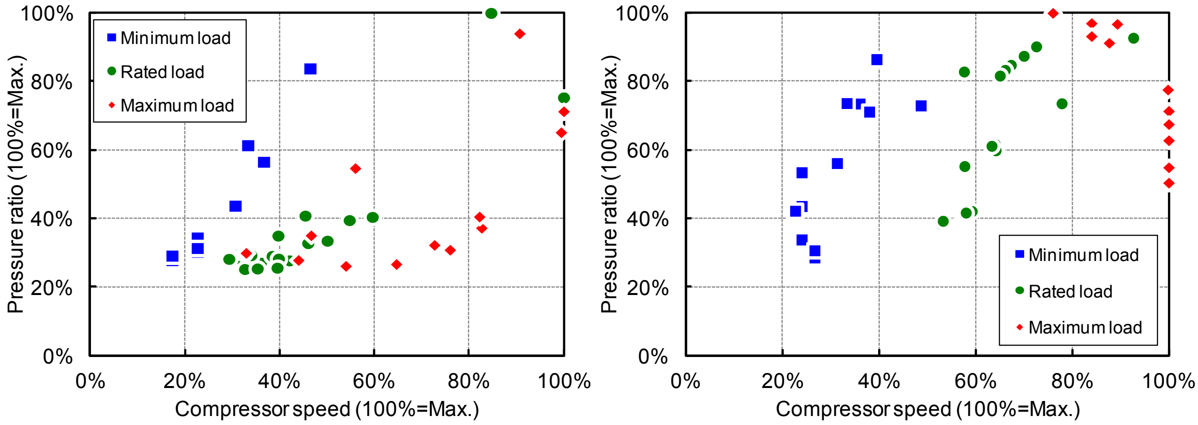


Figure 7: Influences of ambient temperature of the heat source unit and output water temperature on COP (at heating capacity 14 kW, TW_o - TW_i = 5 K)

3.2 Compressor

As one factor that contributes to enhancement of the operation efficiency, the partial load characteristics of the twin rotary compressors of the new system can be cited. Since the rotary compressor has a discharge valve, over-compression, which might occur with an ordinary compressor with the pressure ratio fixed, will not take place. Therefore, the partial load efficiency can be enhanced by operating this rotary compressor with an inverter. In the cascade refrigeration cycle scheme that uses two compressors, the effect of the high partial load efficiency of the rotary compressor will especially stand out because, as shown in Figure 8, the pressure ratio and compressor speed of each compressor substantially vary depending on the operating conditions such as the ambient temperature, output water temperature, and heating capacity. Figure 9 shows the relation between heating capacity at a given ambient temperature of the heat source unit and COP. It can be seen that, even if the ambient temperature and heating capacity change, the new system maintains a high COP due to the rotary compressor. A new compressor for R134a that has a high efficiency and can secure reliability in a high-temperature region has been developed for the supply unit.



(A) Heat source unit (R410A) (B) Supply unit (R134a)

Figure 8: Operation range of each compressor (TO -15 to 43ºC DB, TW_O 50 to 90ºC)

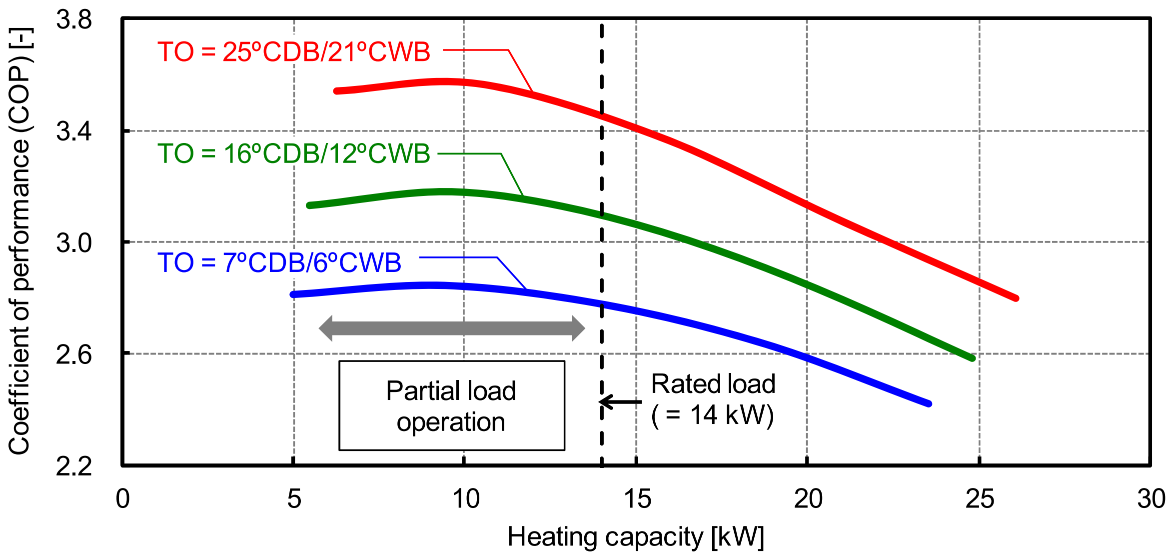
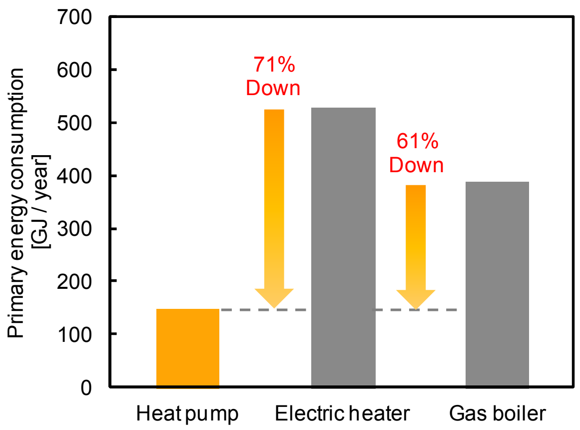


Figure 9: Low load performance (TW_o = 65ºC, F = 41 L/min)

3.3 Primary energy consumption

Figure 10 shows the result of estimating primary energy consumption of the conventional gas boiler and electric heater and that of the new system. As can be seen from this figure, a substantial reduction in energy consumption of 60% to 70% from that of the existing heat sources can be expected when the new system is introduced.



-Estimate conditon-

•Operating time:
16H/days(7:00-15:00, 16:00-24:00), 20days/month

•Heating load: 14kW

•Ambient temperature: 25°CDB

•Output water temperature: 65°C

•System efficiency:
Electric heater 100%, Gas boiler 50%

•Calorific value:
Electric 9.97MJ/kWh (8:00-22:00), 9.28MJ/kWH(22:00-8:00)
(Act on the Rational Use of Energy, revision in 2013)
Gas 46.0MJ/m^3

Figure 10: Estimated primary energy consumption

4 FEATURES OF SYSTEM

4.1 Control of water temperature

Water temperature may have a significant impact on the quality of the products produced in processes using hot water in industrial fields. Focusing on the capability of the temperature of hot water to follow up with fluctuations of the load, a new water temperature control method suitable for the cascade refrigeration cycles is developed. As shown in Figure 11, the new system was installed to a production process facility to check its ability to control water temperature when the load fluctuates. This facility heats chemicals used in a process to degrease the parts of a compressor used in an air conditioner. The chemicals are heated by the water heated by the new system via a heat exchanger installed in the tank of the chemicals.

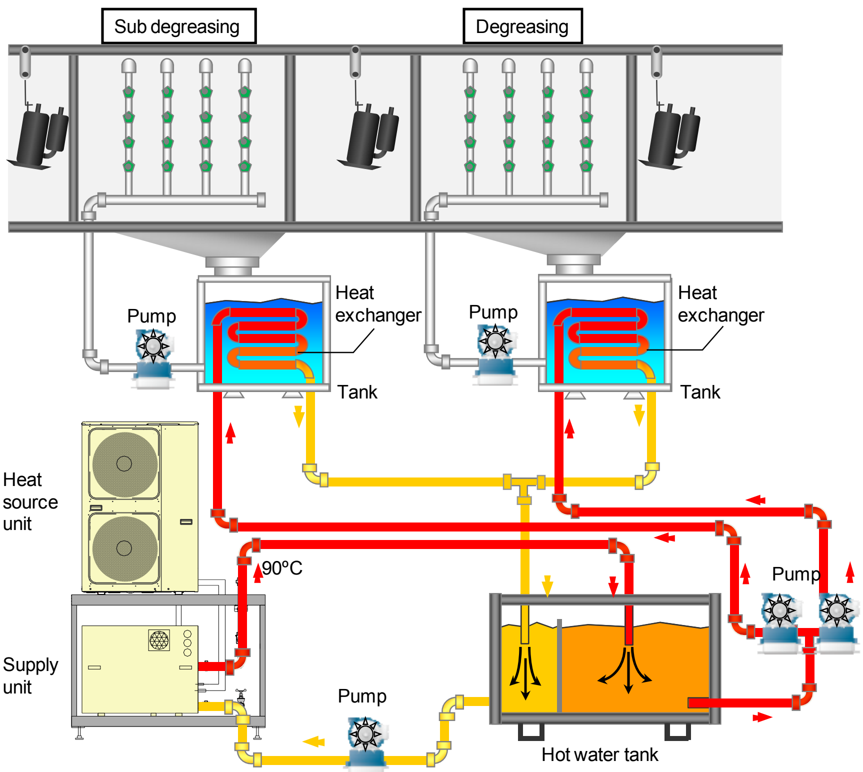


Figure 11: Outline of facility

Figure 12 shows water temperature changes of the new system installed to the facility. The output water temperature is set to 90ºC. The points where inlet water temperature is decreasing rapidly show that many parts of compressor are degreased in the facility and load is increasing. This figure indicates that the output water temperature changes are kept to within 0.6ºC unless the load heavily fluctuates. When the load suddenly increases, the output water temperature temporarily drops more than 1ºC. However, it rises smoothly and quickly to the set water temperature because the speed of the compressor follows up with the fluctuation of the load. In this experiment, it was confirmed that it takes less than 3 minutes for the output water temperature to go back to the set water temperature after a sudden fall due to the load fluctuation.

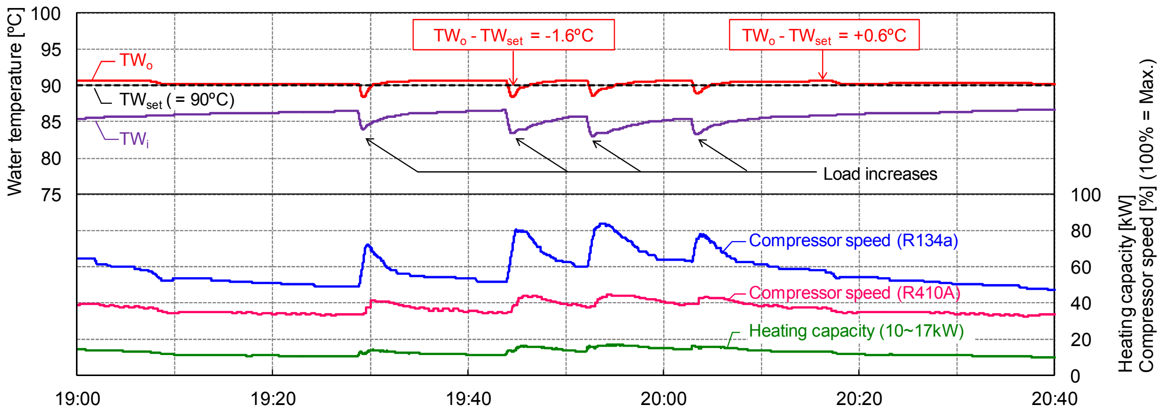


Figure 12: Time-series changes in hot water temperature (TO = 28ºC DB)

4.2 Specifications

The specifications of the new system are shown in Table 2. Both the heat source unit and supply unit are designed to be as compact as 0.29 m^2 so that they can be installed in narrow spaces in factories. The heat source unit can operate in an ambient temperature range of as low as -15ºC DB to as high as 43ºC DB, being able to produce hot water of 50ºC to 90ºC. In addition, the heat source unit and supply unit or several supply units can be piled in accordance with the layout of production process. They can also be installed separately. The refrigerant pipe can be extended up to 30 m and with a level difference of up to 10 m.

Table 2: Specifications of developed system

Unit	Heat source unit	Supply unit
Appearance		
Refrigerant	R410A	R134a
Ambient temperature	-15 to 43ºCDB	5 to 43ºCDB
Humidity	5 to 85%RH	
Dimensions (Width x Depth x Height)	900 mm x 320 mm x 1,340 mm	900 mm x 320 mm x 700 mm
Weight	90 kg	91 kg
Power supply	3 Φ 200 V (50 Hz / 60 Hz)	
Rated heating capacity	14.0 kW	
Rated COP(at TO = 25ºCDB/21ºCWB, TW_i = 60ºC, TW_o = 65ºC)	3.5	
Output water temperature	50 to 90 ºC	

These features improve the degree of freedom of installation layout. By installing the heat source unit at a location where exhaust heat is generated in the factory, the system can obtain the effect of gathering exhaust heat, enabling a much higher efficient operation.

4.3 Other features

The developed system is capable of connecting up to four systems in parallel for a link operation to support various heat load capacities. If a centralized management controller is connected, the operation of up to eight groups, with one group consisting of one to four units, can be controlled. The system also has several functions to input/output signals, in consideration of application to industrial processes. As for output functions, no-voltage contact output signals that can start and stop external pumps and auxiliary heat sources, such as, heaters, and boilers, as well as operation signals and failure signals, are provided. The developed system uses heated hot water as the heat source for defrosting operation. Moreover, when inlet water temperature is low, it takes time for the output water to reach the preset temperature (e.g. about 45 min. at TW_i = 16ºC, TW_{set} = 65ºC, tank size 200 L). As a solution for these matters, the system is equipped with a control function which operates an auxiliary heater at defrosting operation or when input water temperature is low. Decrease of water temperature is prevented at defrosting operation and heating time is shortened by auxiliary heater control. As input functions, contact input signals that are used to start or stop the system from an external circuit and input the interlock signals of an external pump and auxiliary heat sources, and analog circuits that can input temperature from an external temperature sensor and externally set water temperature are provided. In addition, other easy-to-use specifications for industrial use, such as large-size LED pilot lamps on the supply unit, are incorporated.

5 CONCLUSION

To reduce heat loss from concentrated groupings of steam boilers, we have developed a small, highly efficient heat pump system suitable for distributed installation. The results obtained during the research and development of this system are as follows:

- A maximum output water temperature of 90ºC was achieved due to the use of cascade refrigeration cycles. The system can operate in a wide range of ambient temperatures from as low as of -15ºC DB to as high as of 43ºC DB.
- Separate units connected with a refrigerant pipe are used for the low-temperature and high-temperature refrigeration cycles. Consequently, the new heat pump system can flexibly meet various installation restrictions and conditions. Each unit is designed to be compact so that it can be installed in narrow spaces in factories.
- By providing an optimum intermediate temperature control feature and inverter-driven, twin rotary compressors, the system can operate with a high efficiency over a wide range of ambient and water temperatures and can respond to changes in heating capacity.
- It can be expected that the energy consumed by conventional heat sources, such as electric heaters and boilers, can be reduced 60% to 70% by introducing the new system.
- A water temperature control method suitable for the cascade refrigeration cycles is developed. This control method allows the speed of the compressors immediately respond to sudden change in the load, and the water temperature to reach and stabilize the set water temperature quickly.

The new system was introduced into the market in April 2012. This system is expected to have a significant effect in energy saving at factories. In addition, we developed other models

that can meet the customers' needs, such as heat pump systems with heating capacity of 4.5 kW and 70 kW (Iba et al. 2012, Tateishi et al. 2013). A circulation heating heat pump that can directly heat washing solvents is also under development.
In the future, we would like to contribute to energy conservation and protection of the global environment by supplying products that can further expand the application range of heat pumps and replacing existing heat sources with heat pumps in accordance with various usage of heat.

6 NOMENCLATURE

F: Water flow rate, L/min
S.H.: super heat, K
S.C.: sub cool, K
T_c: Condensing temperature, ºC
T_e: Evaporation temperature, ºC
TW_i: Input water temperature, ºC
TW_o: Output water temperature, ºC
TW_{set}: Set water temperature, ºC
TO: Ambient temperature, ºCDB, ºCWB
ΔT: Minimum temperature difference between water and refrigerant, K
$_1$: Low-temperature refrigeration cycle
$_2$: High-temperature refrigeration cycle

7 REFERENCES

T. Takayama, H. Suzuki, I. Iba, I. Hongou, I. Sakuraba, Y. Miyaoka, and H. Nakayama 2012. "Development of High Temperature Water Circulation Type Heat Pump for Industries", Proceedings of the JSRAE Annual Conference, F122.

I. Iba, K. Kikkawa, K. Katayama, I. Hongou, Y. Miyaoka, and D. Hayashi 2012. "Energy conservation activities by using Air-to-Water Heat Pump Water Heater", Proceedings of the JSRAE Annual Conference, F121.

A. Tateishi, H. Tanno, and T. Morita 2013. "Development of 90ºC leaving hot water temperature circulation heating heat pump chiller "CAONS™700"", Proceedings of the 47th Japanese Joint Conference on Air-conditioning and Refrigeration, pp.163-166.