Pioneering Industrial Heat Pump Technology in Japan

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Abstract:
Industrial heat pumps for hot water supply, hot air supply, heating of circulating hot water and steam generation have been developed with a pioneer spirit in Japan. This paper describes the industrial heat pump technology reported by the IEA HPP Annex 35 national expert meeting of Japan. Firstly, a trans-critical CO_2 cycle heat pump, single-stage compression reverse Rankine cycle heat pumps, two-stage compression reverse Rankine cycle heat pumps, a cascade reverse Rankine cycle heat pump and a hybrid vapor recompression system are presented as the high-temperature heat pumps for industrial processes. Secondly, the industrial applications of these heat pumps are described. Lastly, low GWP refrigerants for high-temperature heat pumps are discussed.

1 INTRODUCTION

Heat pump technology is important to boost the reduction of CO_2 emissions, reduce primary energy consumption, and increase the amount of renewable energy used due to the high energy efficiency of heat pumps. To further enhance these effects, the scope of industrial applications is also expected to expand. In particular, the development and spread of high-temperature heat pumps for hot water supply, hot air supply, heating of circulating hot water and steam generation must be supported. Industrial heat pumps for these uses have been developed with a pioneer spirit in Japan.

Under the International Energy Agency (IEA) Heat Pump Program (HPP), Annex 35 (Application of Industrial Heat Pumps) was carried out from May 2010 to April 2014. The objective of the Annex 35 is to reduce the use of energy and emissions of greenhouse gas emissions by the increased application of heat pumps in industry. IEA HPP Annex 35 national expert meeting of Japan consists of members from universities, research institutes, electric power, engineering and manufacturing companies. Japanese representative organizations for the IEA HPP are New Energy and Industrial Technology Development Organization (NEDO) and Heat Pump & Thermal Storage Technology Center of Japan (HPTCJ). This paper describes the pioneering industrial heat pump technology reported by the IEA Annex 35 national expert meeting of Japan.

2 DEFINITION AND GENERAL TYPES OF INDUSTRIAL HEAT PUMPS

The IEA Annex 35 national expert meeting of Japan defined industrial heat pumps as follows; heat pumps used for heat recovery and heat upgrading in industrial processes, and for heating, cooling and air-conditioning in industrial buildings.

Generally, heat pumps are classified as shown in Table 1. Closed-cycle mechanical heat pumps use mechanical compression of a refrigerant to achieve temperature lift. Most common mechanical drives are electric motors. In this paper, the closed-cycle mechanical heat pumps as the most common type are mainly presented, and open-cycle mechanical vapor recompression heat pumps and open-cycle thermal vapor recompression heat pumps are also described.

Table 1: General Types of Industrial Heat Pumps

Type
Closed-cycle mechanical heat pumps
Open-cycle mechanical vapor recompression heat pumps
Open-cycle thermal vapor recompression heat pumps
Closed-cycle absorption heat pumps

3 DISTRIBUTED HEAT PUMPS AND HEAT RECOVERY IN FACTORIES

At a company producing cars, auto parts, electrical equipment, food, etc., steam is produced in the energy center, supplied to all areas of the factory, and used in the manufacturing process. However, overall energy efficiency is generally low, due to boiler losses, heat losses from piping, steam leakage losses in traps, and drain recovery losses. Reports suggest that total energy efficiency has improved from 26.6 % to 38.7 % (ECCJ 2007). Moreover, another research has been reported indicating that the most commonly used steam temperature zone is in the range 55-80 °C (Iba 2011). In addition, many electric heaters are used for these processes for which temperature control is required.

Accordingly, significant energy savings are expected by replacing some steam supply system and electric heaters with low energy efficiency with distributed high-temperature heat pumps for hot water, hot air supply, heating of circulating hot water or steam generation. Heat recovery – i.e. the simultaneous utilization of cooling and heating or the utilization of waste heat - should be considered (Watanabe 2012).

4 HIGH-TEMPERATURE HEAT PUMPS FOR INDUSTRIAL APPLICTIONS

The configuration of the heat pump cycle is important to achieve a large temperature difference between the heat output and heat source temperatures efficiently. In addition, the technologies of compressors and refrigerants, which can withstand high temperatures, are also important to deliver high-temperature output. Heat exchange technologies against dust and dirt are also another key issue since the industrial process fluid or industrial waste water used as a heat source for heat pumps contains dust and dirt such as oil stains, metal chips, and so forth.

4.1 Trans-critical CO_2 Cycle

Figure 1 shows a trans-critical CO_2 cycle on a temperature-entropy diagram. Liquid coexists with gas in the area surrounded by a liquid line and a vapor line. The word "trans-critical" means that low pressure 3.5 MPa is lower than the critical pressure 7.4 MPa of CO_2 and high pressure 12 MPa is higher than the critical pressure. While supercritical CO_2 is cooled down from 120 °C to 20 °C, air flows in the opposite direction to supercritical CO_2, absorbs heat from CO_2 in the counter flow heat exchanger and is heated from 10 °C up to 100 °C. Thus, a trans-critical CO_2 cycle heat pump can generate hot air as required.

Figure 2 shows the energy flows and outward appearance of the trans-critical CO_2 cycle heat pump for hot air supply, which can generate hot air at a temperature of 100 °C, with a heating capacity of 110 kW and COP of 3.4. The compressor is of the reciprocating type. This heat pump uses water as a heat source and can produce not only hot air but also cool water. The cooling capacity is 81 kW and cooling COP is 2.5 when entering water temperature is 30 °C and leaving water temperature is 25 °C. We can achieve further efficiency with utilizing both the hot air and the cool water simultaneously, and then the total COP reaches 5.9.

A reduction of 46 % in primary energy consumption was achieved by using this heat pump to the drying and cooling in laminate printing process compared with the conventional chiller cooling and boiler steam heating, as shown in Table 8 in chapter 5 (Kando 2012).

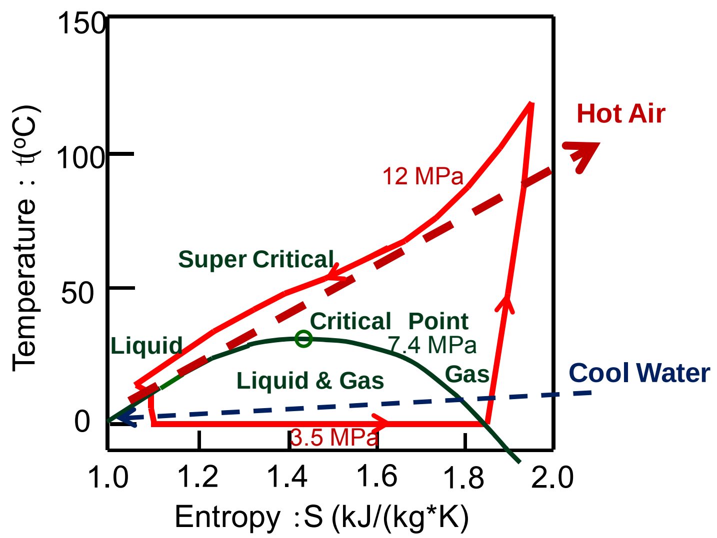

Figure 1: Trans-critical CO_2 Cycle

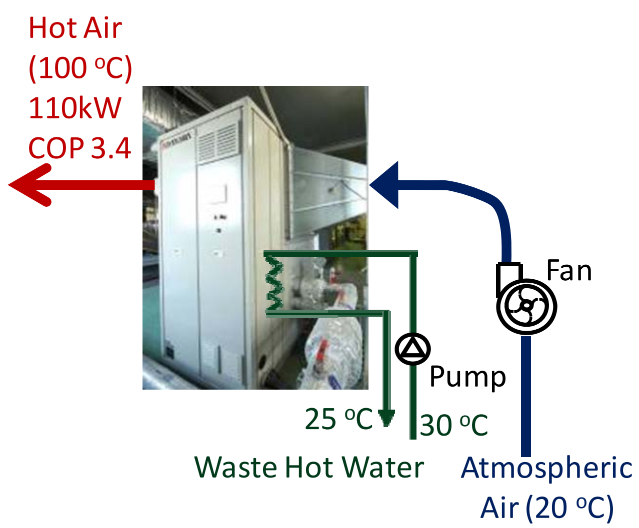

Figure 2: Energy Flows and outward Appearance of Trans-critical CO_2 Cycle Heat Pump for Hot Air Supply (Kando 2012)

4.2 Single-stage Compression Reverse Rankine Cycle using R134a

In many industrial processes, hot water cooled by 5-10 °C is re-heated and circulated. If a trans-critical CO_2 cycle heat pump is applied to such processes, the COP will often fall. The single-stage compression reverse Rankine cycle, using R134a as a refrigerant shown in Figure 3, is used for heating of circulating hot water at 60-80 °C, and delivers a high COP.

Figure 4 shows a schematic of a typical application of the single-stage compression reverse Rankine cycle water-source heat pump using R134a as a refrigerant. While cooling cutting liquid, this heat pump heats the liquid which washes the machined parts, thus providing simultaneous cooling and heating. Three operating modes - heating mode, cooling mode and heating and cooling mode - are available, using the heat exchanger between the air and refrigerant in either direction of heat flow, as required. The total COP in heating and cooling mode reaches 5.

A reduction of 73 % in primary energy consumption was achieved by using this heat pump to the cooling and heating compared with the conventional chiller cooling and boiler steam heating, as shown in Table 10 in chapter 5. At factories producing cars or auto parts, many heat pumps of this type has been adopted.

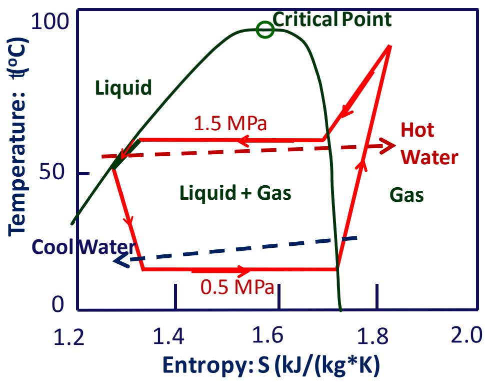

Figure 3: Single-stage Compression Reverse Rankine Cycle using R134a

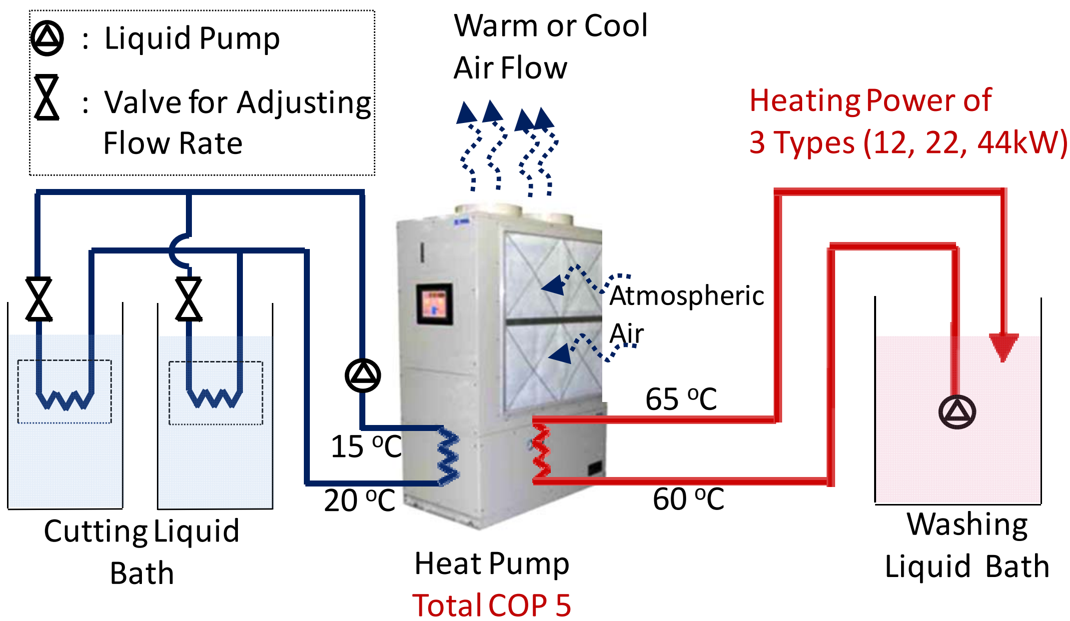

Figure 4: System Flow and Outward Appearance of Single-stage Compression Reverse Rankine Cycle Heat Pump using R134a for Heating and Cooling of Circulating Water (Shiba et al. 2012)

4.3 Two-stage Compression Reverse Rankine Cycle using R134a

Figure 5 shows two-stage compression reverse Rankine cycle using R134a as a refrigerant. If we wish to gain higher temperature than 80 °C efficiently with reverse Rankine cycle, large temperature difference between condensation and evaporation is necessary, so high pressure ratio of refrigerant is necessary. High pressure ratio is obtained by two-stage compression.

Figure 6 shows the system flow and outward appearance of the water-source heat pump for heating of circulating hot water with two-stage reverse Rankine Cycle using R134a. Table 2 shows the specifications of this heat pump. The heat pump can use waste heat at a temperature of about 10-50 °C and heat it up to 90 °C, which is supplied to processes where hot water is required. The heat pump mainly consists of an evaporator, a condenser, a compressor, an expansion valve, and an economizer. The heat pump uses a centrifugal compressor. To make the heat pump compact, the sizes of the motor, gear, and compressor are reduced. This makes it easier to introduce the heat pumps to factories and plants as it improves operability and controllability.

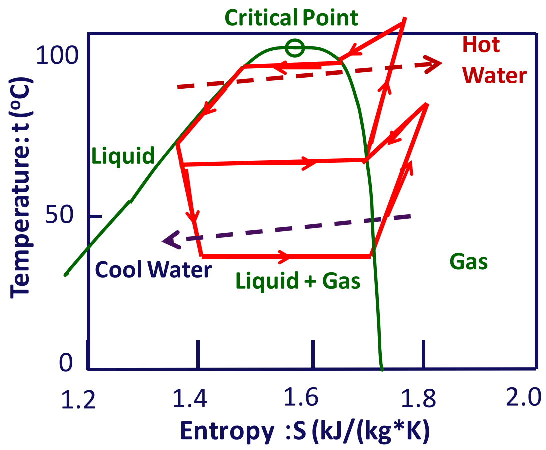

Figure 5: Two-stage Reverse Rankine Cycle using R134a

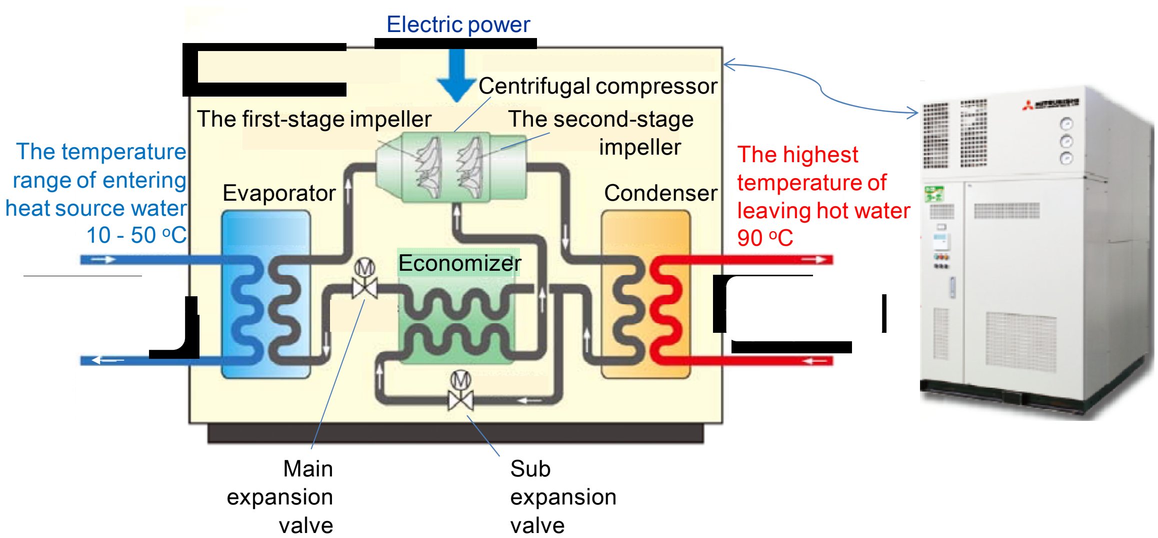

Figure 6: System Flow and Outward Appearance of Two-stage Compression Reverse Rankine Cycle Heat Pump for Heating of Circulating Hot Water using R134a (Okuda et al. 2011)

Table 2: Specifications of Two-stage Compression Reverse Rankine Cycle Heat Pump for Heating of Circulating Hot Water using R134a (Okuda et al. 2011)

Heating Power (kW)	547
Cooling Power (kW)	405
Electric Power Input (kW)	148
COP	3.7
Entering Hot Water Temperature (°C)	80
Leaving Hot Water Temperature (°C)	90
Entering Heat Source Water Temperature (°C)	50
Leaving Heat Source Water Temperature (°C)	45

4.4 Single-stage or Two-stage Compression Reverse Rankine Cycle using R245fa

Figure 7 shows a two-stage compression cycle using R245fa as a refrigerant. Since R-245fa has a critical temperature exceeding 150 °C, a single-stage compression or two-stage compression heat pump can be used for re-heating circulating hot water at a temperature exceeding 80 °C, or steam generation at a temperature exceeding 100 °C. Table 3 shows specifications of steam-generation heat pumps. The SGH 120 model generates steam at 120 °C with a flow rate of 0.51 t/h and a COP of 3.5 from a waste hot water input temperature of 65 °C. The SGH120 model has a two-stage compressor. R245fa is selected as the refrigerant of the SGH120 model. Figure 8 shows a schematic diagram of a steam-generation heat pump SGH165 model. The SGH165 model generates steam at 165 °C. The heat pump unit heats pressurized water, which is evaporated at a temperature of 100-110 °C in a flash tank after leaving the heat pump unit. After steam is generated in the flash tank, the steam compressor increases the steam pressure and temperature still further. The flow rate of the steam is 0.89 t/h and the COP reaches 2.5 from a waste hot water temperature of 70 °C. The SGH165 model has a single stage compressor. A mixture of R245fa and R134a is selected as the refrigerant of the SGH165 model, considering the capacity per unit refrigerant flow.

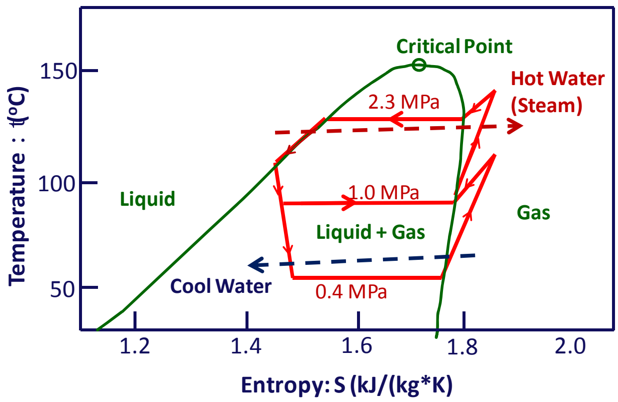

Figure 7: Two-stage Reverse Rankine Cycle using R245fa

Table 3: Specifications of Steam-generation Heat Pumps (Iizuka, K. et al. 2011)

model	SGH120	SGH165
Steam Pressure (MPa Gauge)	0.1	0.6
Waste Heat Temperature (°C)	65	70
Steam Flow Rate (t/h)	0.51	0.89
Heating Power (kW)	370	660
COP	3.5	2.5
Refrigerant	R245fa	a Mixture of R245fa and R134a
Refrigerant Compressor	Two-stage Twin-screw	Single-stage Twin-screw
Number of Steam Compressor	0	1

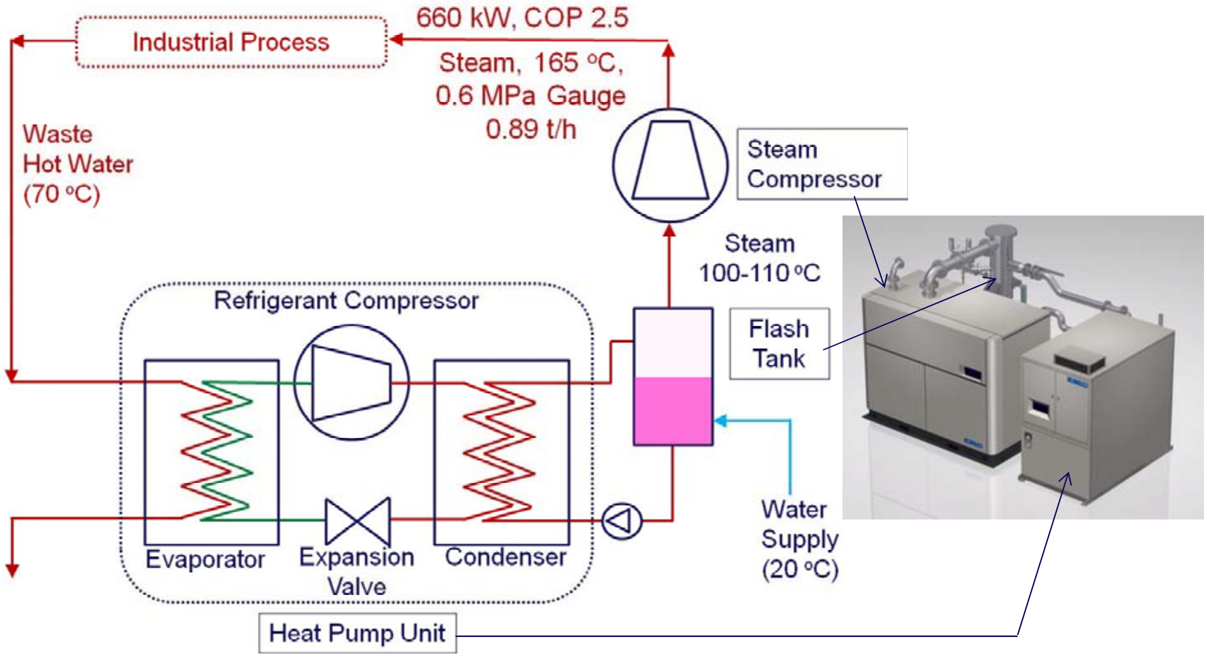

Figure 8: 165 °C Steam-generation Heat Pumps (Iizuka, K. et al. 2011)

4.5 Cascade reverse Rankine cycle using R410A and R134a

Figure 9 shows the cascade cycle on the temperature-enthalpy diagram, the energy flows and outward Appearance of the cascade cycle heat pump. The cascade cycle consists of an R134a cycle for the high-temperature side and an R410A cycle for the low-temperature side. Two independent cycles of the cascade cycle are connected with a heat exchanger. Since the heat absorbed in the lower temperature cycle is transferred to the higher temperature cycle, higher temperature heat can be produced even though the ambient air temperature for the lower temperature cycle is lower. Table 4 lists the specifications of the cascade heat pump. The cascade heat pump uses two units: a heat source unit that adopts the lower temperature cycle and a hot water supply unit that adopts the higher temperature cycle. Since both are connected by the refrigerant piping of R410A, the system has many application cases despite the variety of installation conditions. In the heat source unit, the heat exchanger and the control method of the refrigeration cycle are optimized based on the air-conditioning system. The hot water supply unit is installed indoor near the heat-use device. This concept allows heat loss to be reduced.

Table 4: General Types of Industrial Heat Pumps (Takayama 2012)

Rated Heating Power (kW)	14.0
Rated COP*	3.5
Leaving Temperature Range (°C)	50 - 90
Ambient air temperature range (°C)	-15 - 43

*: Atmospheric Air Temperature: 25°C Dry Bulb, 21°C Wet Bulb,
Entering Water Temperature: 60°C, Leaving Water Temperature: 65°C

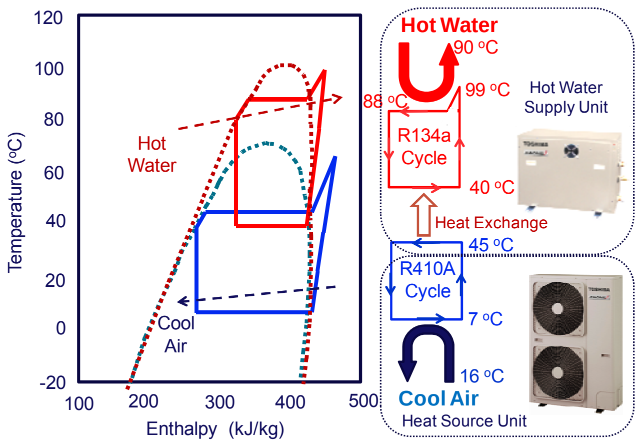

Figure 9: Cascade Reverse Rankine Cycle using R410A and R134a and the energy flows and Outward Appearance of the Cascade Heat Pump (Takayama 2012)

4.6 Hybrid Vapor Recompression System

Vapor recompression systems are increasingly adopted to raise pressure and temperature of low pressure vapor. However, when it comes to mechanical recompression systems, we have a problem of the large electric power demand. Therefore, an extensive use of the vapor recompression system has begun to be enabled by combining thermal vapor recompression with mechanical vapor recompression. The combined heat pump system of the mechanical vapor recompression and thermal vapor recompression, as shown in Figure 10, can reuse the low-pressure steam in the wort boiling process in the beer factory. The COP of the mechanical vapor recompressor in Figure 10 reaches 15-20, which is defined as the ratio of reused heat energy of exhaust steam to electric power consumed by the mechanical vapor recompressor.

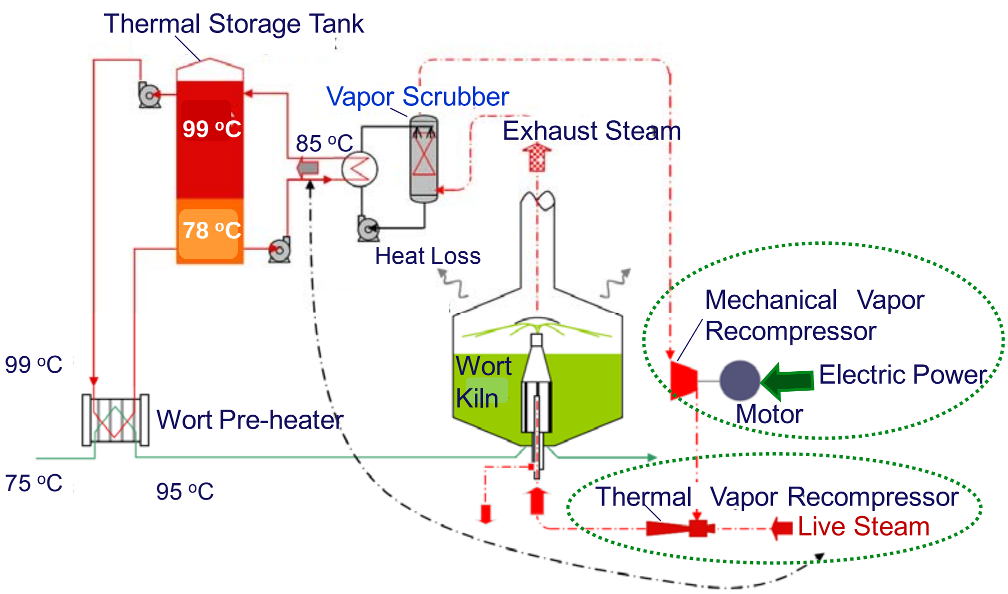

Figure 10: Hybrid Vapor Recompression System for Heating Wort Kiln (Mayekawa 2007)

5 INDUSRIAL APPLICATIONS OF HIGH-TEMPERATURE HEAT PUMPS

In general, industrial heat pumps can be characterized by a high coefficient of performance (COP) achievable through the use of various types of exhaust heat, simultaneous supply of cool and hot water or air, and long operating time through the year. Heat pumps can be used for HVAC (heating, ventilation and air-conditioning), hot water supply, heating, drying, dehumidification and other purposes as shown in Table 5.

Table 5: Examples of Application of Industrial Heat Pump (JEHC 2011)

Purpose of Use	Examples of application
HVAC	Factory HVAC, Clean Rooms, Protected Horticulture, Plant Factories
Hot Water Supply	Mechanical Part Washing, Process Liquid Heating
Heating	Hot Spring Water Heating, Snow Melting, Fish or Eel Farming, Aquariums
Heating, Cooling	Food Manufacturing, Electro-deposition Coating, Plating, Can Manufacturing
Drying, Dehumidification	Agricultural Produce, Marine Products, Printing, Coating, Drying
Concentration, Evaporation, Distillation	Wort Boiling, Milk, Sugar Solution, Amino Acid
Heat Recovery	Ethanol, Cooling Tower Exhaust Heat, Rectifying Tower Exhaust Heat

Many industrial heat pumps are in practical use throughout Japan. Among the many installed cases, here we focus on heat pump technologies of simultaneous supply of heating and cooling, vapor recompression, high-temperature heat supply and agricultural use because they are expected further growth in the future. 6 cases shown in Table 6-11 were picked out as typical examples of above mentioned prospective industrial heat pump technologies. All the 6 cases picked out in this section succeeded in the great amount of reduction of energy consumption. As a conversion factor of electric power to primary energy, 9.63 MJ/kWh is adopted, which is equivalent to 36.9% as the thermal power generation efficiency in the demand edge and based on the Japanese law on the rational use of energy. In most installed cases, the simple payout periods are 3-5 years.

A number of production processes require cool water and hot water at the same time. Good examples of the simultaneous supply of cool water and 90 °C hot water as well as the simultaneous supply of cool water supply and 80-120 °C hot air are shown in Table 6 and Table 8 respectively. The application of the heat pumps, which can heat circulating hot water up to 65 °C and chill circulating water down to 20 °C simultaneously, are shown in Table 10.

Effective use of lower temperature waste heat than 150 °C still has much room to be developed. The combined heat pump system of the mechanical vapor recompression and thermal vapor recompression can reuse the low pressure steam of 75 °C which is generated in distilling process in table 7. In addition, the adoption of heat pump systems with waste heat recovery is steadily growing in air-conditioning equipments. Table 9 shows an example of the system for recycled air conditioning in a painting booth at a temperature range 20-30 °C.

Heat pump application in agriculture is one of the noteworthy features in recent years. In conventional outdoor greenhouses, the installation of heat pump systems is increasing as a replacement of heavy oil combustion boilers in accordance with increasing energy efficiency of heat pumps. Table 11 shows the example for fruit cultivation which has high added values.

Table 6: Simultaneous Cooling and Heating Heat Pump for Noodle Production (Yoneda 2011)

Industry	Frozen Noodle Production
Process	Boiling, Cooling
Application	Simultaneous Hot Water (83 °C) and Cool Water (10 °C) Supply
Purpose	Reduction of Boiler Steam (Fuel Light Oil) with Pre-heating Boiler Feed Water and Waste Heat Recovery
System Overview	Water-to-Water Heat Pump with CO_2 Refrigerant (2 Unit) with Heating Capacity 36 kW (90 °C) and Cooling capacity 25 kW (5 °C) , Hot Water Tank Volume 24 m^3
Effect	Primary energy consumption was reduced by 19%.

Table 7: Combined Vapor Recompression System for Alcohol Distillation (Mayekawa 2007)

Industry	Whisky and Material Alcohol Production
Process	Distillation
Application	Vapor Recompression
Purpose	Reduction of Boiler Steam (Fuel Crude Oil) with Reuse of Vapor
System Overview	Combined Vapor Recompression System (1 Unit) with Vapor Flow Rate 4 t/h
Effect	Primary energy consumption was reduced by 43%.

Table 8: CO_2 Heat Pump Air Heater for Drying Process (Kando 2012)

Industry	Laminate Printing
Process	Drying, Cooling
Application	Hot Air Supply to Drying Zone and Cool Water Supply to Cooling Roller
Purpose	Reduction of Steam (Fuel Gas) and Waste Heat Recovery
System overview	Water-source Heat Pump Using CO_2 Refrigerant (1 Unit) for Hot Air Supply with Heating Capacity 110 kW, Operating Range of Hot Air Leaving Temperature 80-120 ^oC and That of Heat Source Water Entering Temperature 5 -32 ^oC
Effect	Primary energy consumption was reduced by 46%.

Table 9: Adoption of Heat Pump Technology in a Painting Process (Matsuo et al. 2012)

Industry	Production of Trucks, Buses, Cars and Other Automobiles
Process	Painting Booth for Finishing Coat and Recycled Air Conditioning
Application	Simultaneous Supply of Hot and Cool Water to Painting Booth Circulating HVAC
Purpose	Reduction of Boiler Steam (Fuel Gas), Waste Heat Recovery
System overview	Heat Recovery Heat Pump Using R407E (1 Unit) with Cooling Capacity 456 kW and Heating Capacity 566 kW
Effect	Primary energy consumption was reduced by 49%.

Table 10: Heat Pumps for Cutting and Washing Process (Shiba et al. 2012)

Industry	Automobile Parts Production
Process	Cutting, Washing
Application	Heating of Washing Liquid in the Washing Process (65^oC), Cooling of Cutting Liquid in the Cutting Process (15^oC)
Purpose	Reduction of Boiler Steam (Fuel Crude Oil) and Waste Heat Recovery
System overview	Air-source Heat Pumps Using R134a (8 Units) for Hot Water Supply with Heating Capacity 43.5 kW, Waste Heat Recovery Heat Pump Using R134a (6 Units) for Cooling and Heating of Circulating Water with Heating Capacity 22.3 kW
Effect	Primary energy consumption was reduced by 73%.

Table 11: Applying the Heat Pump Technology to Agricultural Production (JEHC 2011)

Industry	Fruit Cultivation
Process	Green House Air-conditioning
Application	Space Heating in Winter and Space Cooling in Summer
Purpose	Reduction of Fuel Heavy Oil in Winter and Air-conditioning in Summer
System overview	Air-to-Air Inverter-controlled Greenhouse Heat Pumps using R410A (7 Units) with Heating Capacity 18 kW (20 ^oC) and Cooling Capacity 16 kW (27 ^oC)
Effect	Primary energy consumption was reduced by 49%.

6 LOW GWP REFRIGERANTS FOR HIGH-TEMPERATURE HEAT PUMPS

Some development of the industrial heat pump, using R134a, R245fa, CO_2, etc. as a refrigerant, has been made recently. However, except for CO_2 which is a natural refrigerant with extremely low global warming potential (GWP), Hydrofluorocarbon (HFC) refrigerants such as R134a and R245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, R1234ze (Z) and R1234ze (E) are promising alternative materials for R245fa and R134a respectively because of their compatible thermodynamic properties. Practical application for high-temperature heat pumps are expected owing to the research such as the assessing the risks related to flammability.

Table 12: Properties of Refrigerants for High-temperature Heat Pumps

Refrigerant	Chemical formula	GWP	Toxicity and Flammability Classification*	Critical Temperature T_c (°C)	Critical Pressure P_c, (MPa)
R134a	CF_3CH_2F	1,430	A1	101.1	4.06
R1234ze(E)	$CFH=CHCF_3$	6	A2L	109.4	3.64
R245fa	$CF_3CH_2CHF_2$	1,030	A1	154.0	3.65
R1234ze(Z)	$CHF=CHCF_3$	<10	A2L	153.7	3.97
R1234yf	$CF_3CF=CH_2$	4	A2L	94.7	3.38

*: The toxicity and flammability classification for refrigerants is based on the ANSI/ASHRAE Standard 34-2010. "A" means a lower degree of toxicity, "1" means no flame propagation and "2L" means lower flammability with a maximum burning velocity of ≤10 cm/s.

7 CONCLUSION

The trend in industrial heat pump technology in Japan is towards the introduction of pioneering high-temperature heat pumps, such as trans-critical CO_2 cycle heat pumps for hot water and hot air supply, reverse Rankine cycle heat pumps for heating and cooling of circulating water and steam-generation heat pumps.

It is important, when intending to apply heat pumps for industrial applications, carefully to investigate the required final heat condition for each manufacturing process, in order to identify and quantify energy savings, economic efficiency, installation space etc. The dissemination of industrial heat pumps is more difficult than home-use air conditioners since the manufacturing process is basically a secret. It is important to provide demonstration installations that clearly show the benefits of heat pumps. It is believed that industrial heat pumps will penetrate further when the different requirements for industrial heat pumps are organized and generalized to some extent and many engineers engaged in energy management and production engineering understand the merits of the industrial heat pumps.

8 ACKNOWLEDGEMENTS

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