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Industrial Heat Pumps and Their Application Examples in Japan

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Abstract

This paper describes the industrial heat pump technologies presented at the Japanese national expert meeting for the IEA HPP Annex 48 "Industrial Heat Pumps, Second Phase". Firstly, flows of heat recovery and utilization in industrial processes are presented. And heat demands and exhaust heat sources in various industries are also presented. Secondly heat recovery heat pumps and their application examples are described. The heat recovery heat pumps include a heat pump steam generator using R245fa as a refrigerant with a single-stage reciprocating compressor, a heat pump water heater using R134a as a refrigerant with two inverter driven single-stage twin rotary compressors and a single-stage economizer-cycle heat pump water heater using R134a as a refrigerant with a two-stage centrifugal compressor. It has been reported that the reduction of primary energy, CO_2 emission and running cost have reached 40-60% in the application examples of these heat recovery heat pumps. Lastly, Low GWP refrigerants HCFOs and HFOs as candidates of the substitute refrigerant of R245fa and R134a were described.

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Keywords: Indstrial Heat Pump; Heat Recovery; Steam Generator; Water Heater

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 usage due to the high energy-efficiency of heat pumps. To further enhance these effects, the scope of industrial applications is also expected to expand. Particularly the development and spread of heat recovery high temperature heat pumps for steam supply and heating of circulating hot water must be supported.

Under the International Energy Agency (IEA) Heat Pump Program (HPP) Annex 48 "Industrial Heat Pumps, Second Phase" is being carried out from April 2016 to April 2019. The participating countries is France, Germany (Operating agent), Japan, and the UK. This Annex is a follow-up-annex from the previous completed Annex 35 "Application of Industrial Heat Pumps" [1-3]. Industrial heat pumps within this Annex are defined as heat pumps in the medium and high power range and temperatures up to 150 °C, which can be used for heat recovery and heat upgrading in industrial processes, but also for heating, cooling and air-conditioning in commercial and industrial buildings.

The Japanese national expert meeting for the IEA HPP Annex 48 consists of members from universities, research institutes, electric power companies, engineering companies 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 industrial heat pump technologies presented at the Japanese national expert meeting for the IEA HPP Annex 48 "Industrial Heat Pumps, Second Phase". Firstly, flows of heat recovery and utilization in industrial processes are presented. And heat demands and exhaust heat sources in various industries are also presented. Secondly heat recovery heat pumps and their application examples are described. The heat recovery heat pumps include a heat pump steam generator using R245fa as a refrigerant with a single-stage reciprocating compressor, a heat pump water heater using R134a as a refrigerant with two inverter driven single-stage twin rotary compressors and a single-stage economizer-cycle heat pump water heater using R134a as a refrigerant with a two-stage centrifugal compressor. Lastly, Low GWP refrigerants HCFOs and HFOs as candidates of the substitute refrigerant of R245fa and R134a are described.

2. Heat recovery and utilization in industrial processes

Fig. 1 shows flows of heat recovery and utilization in industrial processes. Exhaust heat in industrial processes is recovered and upgraded to electricity, compressed air, medium or low pressure steam, hot water and cold water with heat recovery boilers, steam driven generators, steam driven air compressors, heat exchangers, binary generators, heat recovery heat pump steam generators, heat recovery heat pump water heaters and absorption heat pumps. Particularly heat recovery steam generators and heat recovery heat pump water heaters are important for heat recovery at a temperature below 100 °C and heat upgrade to a temperature below 150 °C efficiently.

Table 1 shows heat demands in various industries. There are many facilities and processes with heat demands in foods & beverages industry, pharmaceutical products industry, automobile & machinery industry and semiconductor & electronics industry. Table 2 shows exhaust heat sources in various industries. There are many facilities and processes with exhaust heat sources in foods & beverages, pharmaceutical products industry, automobile & machinery industry, chemical products industry and rubber industry. Heat recovery steam generators and heat recovery heat pump water heaters are expected to supply heat to the facilities and processes with circular marks in Table 1 using heat sources of the facilities and processes with circular marks in Table 2.

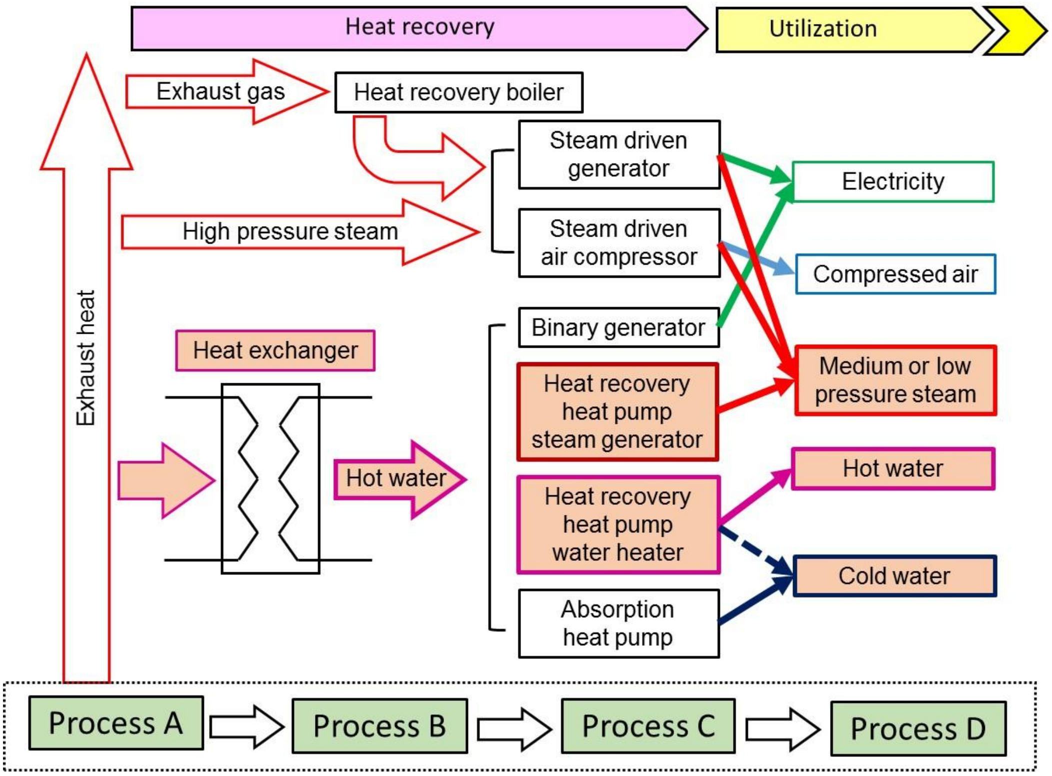

Fig. 1. Flows of heat recovery and utilization in industrial processes [4]

Table 1. Heat demands in various industries [4]

		Industry							
	Heat demands	Foods & Bever-ages	Pharma-ceutical products	Auto-mobile & Machi-nery	Semi-conductor & electronics	Chemical products	Rubber	Oil and pulp	Iron & steel
Heat demands in utility facilities	Preheating of supply water	●	●	●	●	●	●	●	●
	Washing equipment	●	●	●	●	-	-	-	-
	Water purifying apparatus	-	●	-	●	●	-	-	-
	Air-conditioning	●	●	●	●	-	●	-	●
	Dew condensation prevention	●	-	-	-	-	-	-	-
	Hot water supply	●	●	●	●	●	-	-	-
Heat demands in manufacturing processes	Powdery drying	●	●	-	-	-	-	-	-
	Coating	-	-	●	-	-	-	●	-
	Humidification	●	●	●	●	-	-	-	-
	Vulcanization	-	-	-	-	-	-	-	-
	Extraction	●	-	-	-	-	●	-	-
	Sterilization	●	●	-	-	-	-	-	-
	Brewery	●	-	-	-	-	-	-	-
	Thawing	●	-	-	-	-	-	-	-
	Solution	●	●	-	-	-	-	-	-

Table 2. Exhaust heat sources in various industries [4]

		Industry							
	Exhaust heat sources	Foods & Bever-ages	Pharma-ceutical products	Auto-mobile & Machi-nery	Semi-conductor & electronics	Chemical products	Rubber	Oil and pulp	Iron & steel
Exhaust heat from utility facilities	Cooling Water of refrigerators	●	●	●	●	●	●	●	●
	Cooling water of air compressors	●	-	●	-	-	-	-	-
	Cooling towers	●	-	●	-	●	●	●	●
	Exhaust heat from desulphurization equipment	-	-	-	-	-	-	●	●
	Drainage from hot water baths	●	●	●	-	-	-	-	-
	Reaction chambers	●	-	-	-	●	-	-	-
	Cooling water of co-generation systems	●	●	●	●	●	●	●	●
	Exhaust gas from drying furnaces	-	-	●	●	●	-	-	-
	Exhaust gas from baking furnaces	●	-	-	-	●	-	-	-
Exhaust heat from manufacturing processes	Extraction	●	-	-	-	-	-	-	-
	Washing	●	-	-	-	-	-	-	-
	Sterilization	●	●	-	-	-	-	-	-
	Drying	●	●	●	-	●	●	-	-
	Distillation	●	-	-	-	-	-	-	-
	Concentration	●	●	-	-	-	-	-	-
	Brewery	●	-	-	-	-	-	-	-
	Vulcanization		-	-	-	-	●	-	-
	Pre-heating cooling water	●	-	●	-	●	●	-	-

3. A heat recovery heat pump steam generator

Table 3 shows specifications of a heat recovery heat pump steam generator using R245fa as a refrigerant with a single-stage reciprocating compressor. Discharge steam temperature range is 100-120 °C, and discharge steam pressure is 0.1MPa Gauge. Maximum heating capacity is 35 kW, and maximum heating COP is 3.5. Temperature range of heat source water is 60-80 °C. The height is 1.83 m; the width is 1.00 m; the depth is 1.00 m. Maximum number of units able to be connected is 10. Fig. 2 shows utilization of the heat recovery heat pump steam generator integrated to an existing steam supply system under the pressure of 0.1 MPa gauge. And, Fig. 3 shows utilization of the heat recovery heat pump steam generator integrated to an existing steam supply system under the pressure of 0.4 MPa gauge.

Fig. 4 shows an application example of the heat recovery heat pump steam generator integrated to an existing steam supply system in a painting process in a factory of vending machines. The annual operating time of the process reaches 8,000 hours. It has been reported that 46% of primary energy consumption and 52% of energy cost are reduced by replacing an existing boiler with the heat pump steam generator. Fig. 5 shows an application example of the heat recovery heat pump steam generator integrated to an existing steam supply system in an air-conditioning system for a clean room in a factory of semiconductors. It has been reported that 40% of CO_2 emission and 55% of energy cost are reduced by replacing an existing boiler with the heat pump steam generator utilizing exhaust heat of jacket cooling water from an existing co-generation system. It is assumed in the calculation of running cost and CO_2 emission that Kerosene cost is 98 Japanese yen per litter; electricity cost is 15 yen per kWh; the CO_2 emission coefficient of electricity is 0.509 kg- CO_2/kWh.

Table 3. Specifications of a heat recovery heat pump steam generator [4]

Compressor	Reciprocating type
Number of compression stage	1
Refrigerant	R245fa
Discharge steam temperature range（pressure)	100-120 °C (0.1MPa Gauge)
Maximum heating capacity	30 kW
Maximum flow rate of steam	45kg/h
Maximum heating COP	3.5
Temperature range of heat source water	60-80 °C
Flow rate range of heat source water	500-2,000 kg/h
Size	Height 1.83 m, Width 1.00 m, Depth 1.00 m
Maximum number of units able to be connected	10

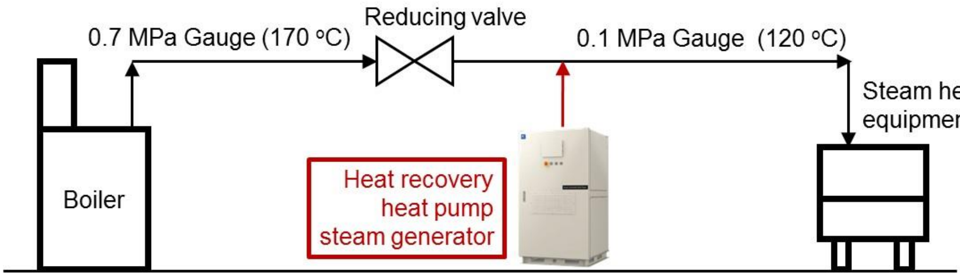

Fig. 2. Utilization of the heat recovery heat pump steam generator integrated to an existing steam supply system under the pressure of 0.1 MPa gauge [4]

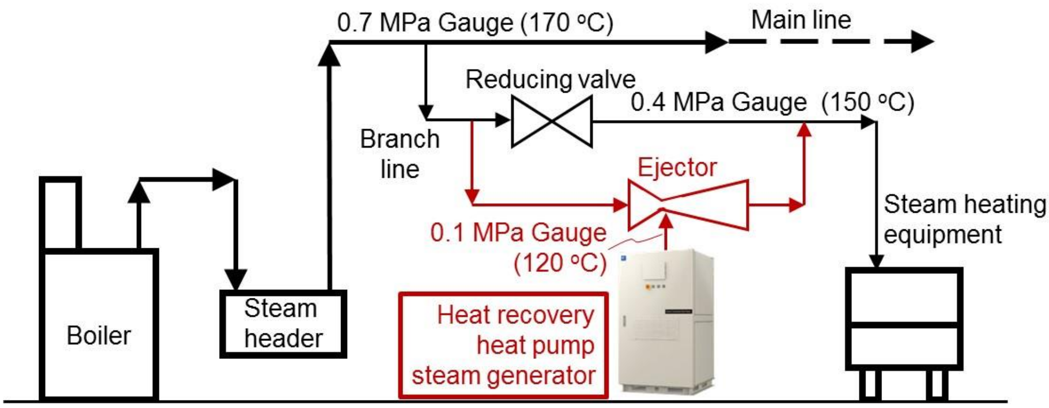

Fig. 3. Utilization of the heat recovery heat pump steam generator integrated to an existing steam supply system under the pressure of 0.4 MPa gauge [4]

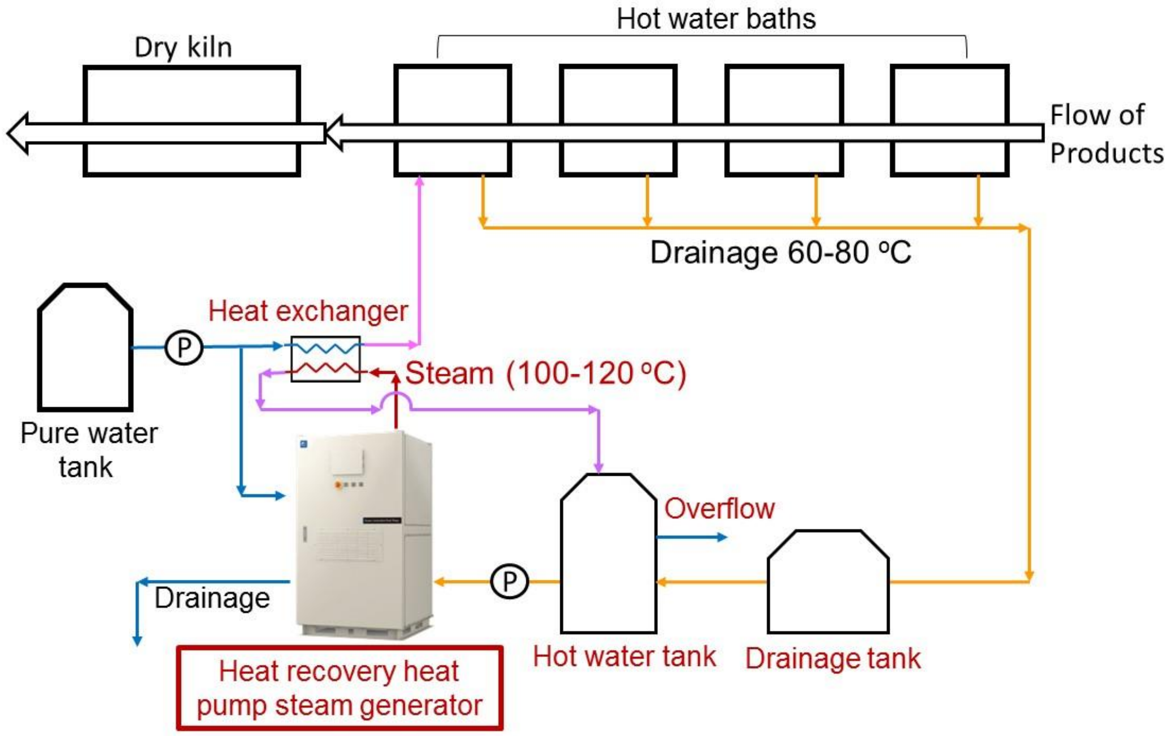

Fig. 4. An application example of the heat recovery heat pump steam generator integrated to an existing steam supply system in a painting process in a factory of vending machines [4]

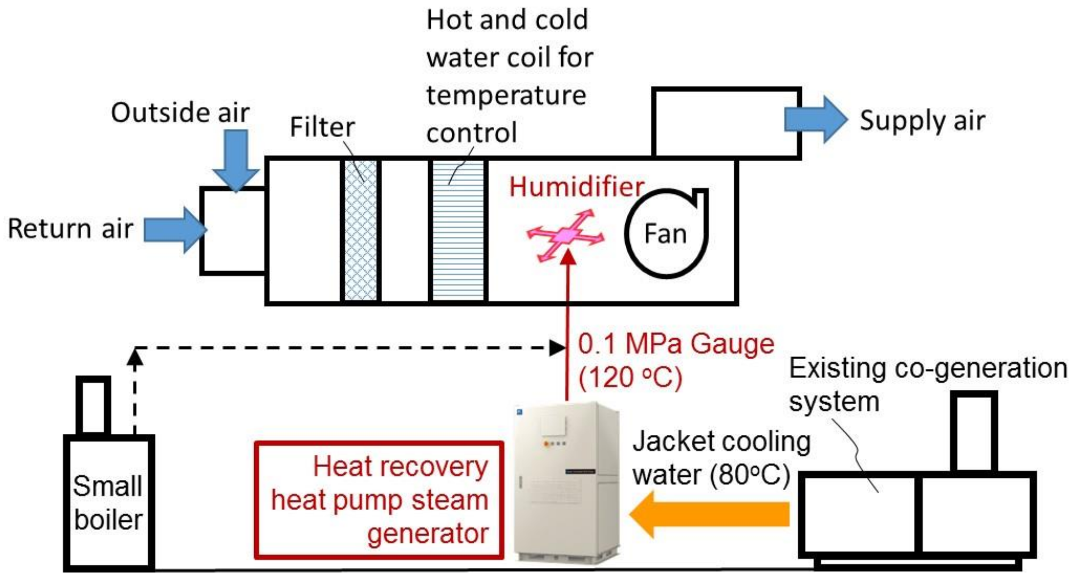

Fig. 5. An application example of the heat recovery heat pump steam generator integrated to an existing steam supply system in an air-conditioning system of a clean room in a factory of semiconductors [4]

4. A heat recovery heat pump water heater with two single-stage twin rotary compressors

Table 4 shows specifications of a heat recovery heat pump water heater using R134a as a refrigerant with two inverter driven single-stage twin rotary compressors. Temperature range of entering heat source water is 9-35 °C, and that of leaving heat source water is 13-40 °C. Temperature range of leaving hot water is 50-85 °C. Rated heating capacity is 60 kW, and rated heating COP is 3.4. Rated heat source water temperature is 37 °C (entering) and 30 °C (leaving). Rated hot water temperature is 73 °C (entering) and 80 °C (leaving). The height is 1.70 m; the width is 0.744 m; the depth is 1.05 m. Maximum number of units able to be connected is 128.

Fig. 6. Refrigerant circuits of the heat recovery heat pump water heater. As shown in Fig.6, the heat pump water heater has two independent refrigerant circuits to secure high reliability of compressors, but the condenser and the evaporator are three-fluid heat exchangers and common to two independent refrigerant circuits.

Fig. 7 shows an application example of the heat recovery heat pump water heater to a washing process. It has been reported that 48% of CO_2 emission and 52% of energy cost are reduced by pre-heating hot water with the heat pump water heater utilizing cooling water of the turbo refrigerator as a heat source.

Table 4. Specifications of the heat pump water heater with two inverter driven single-stage twin rotary compressors [5]

Compressor	Inverter driven twin rotary type (2 compressors for two independent refrigerant cycles)	Rated heating capacity	60 kW
Number of compression stage	1	Rated cooling capacity	42 kW
Refrigerant	R134a	Rated heat source water temperature	37 °C (entering) 30 °C (leaving)
Temperature range of heat source water (entering)	9-35 °C	Rated hot water temperature	73 °C (entering) 80 °C (leaving)
Temperature range of heat source water (leaving)	13-40 °C	Rated heating COP	3.4
Temperature range of hot water (leaving)	50-85 °C	Rated cooling COP	2.3
Size	Height 1.700 m, Width 0.744 m, Depth 1.050 m	Rated total COP	5.7
Maximum number of units able to be connected	128		

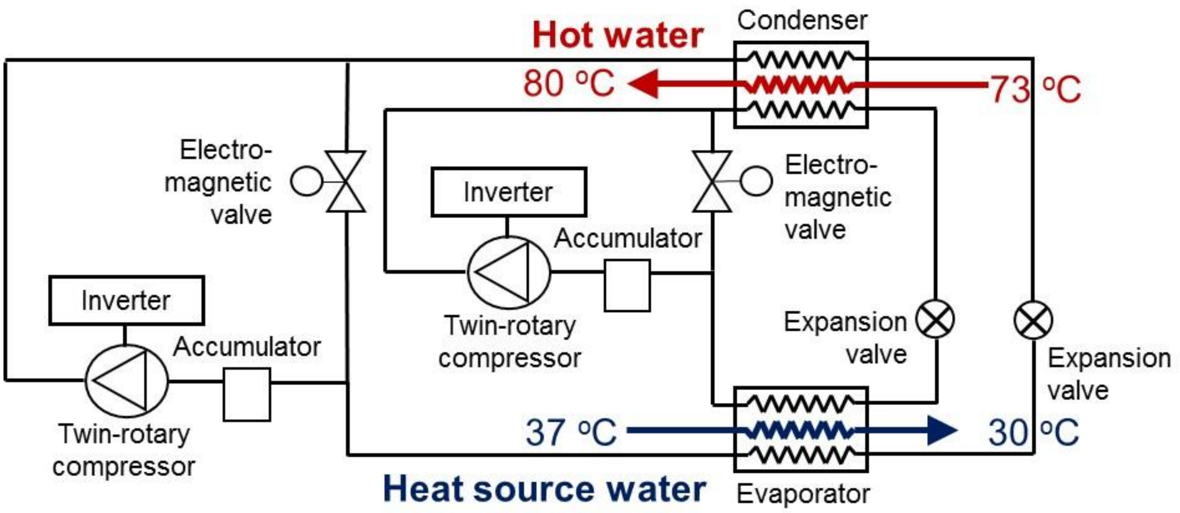

Fig. 6. Refrigerant circuits of the heat recovery heat pump water heater with two inverter driven single-stage twin rotary compressors [5]

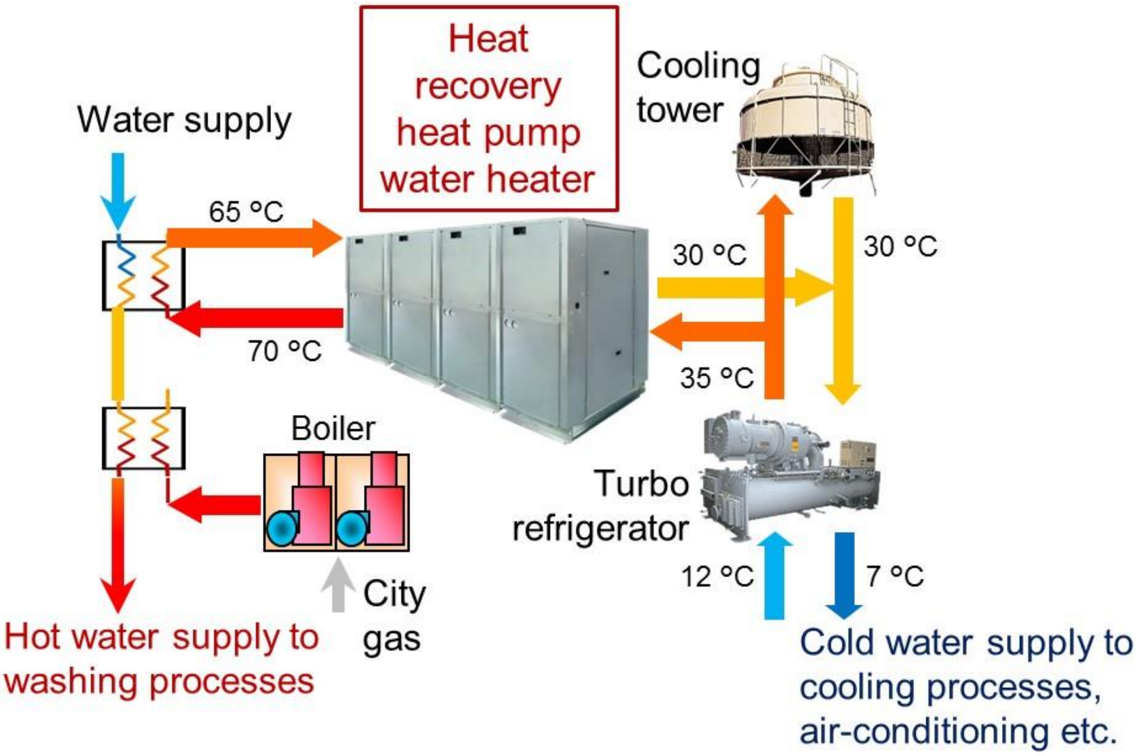

Fig. 7. An application example of the heat recovery heat pump water heater with two inverter driven single-stage twin rotary compressors to a washing process [5]

5. A heat recovery heat pump water heater with a two-stage centrifugal compressor

Table 5 shows specifications of a single-stage economizer-cycle heat pump water heater using R134a as a refrigerant with a two-stage centrifugal compressor. Fig. 8 shows the outside view (left) and flows (right) of the heat pump water heater. Fig. 9 shows contour maps of heating capacity (left) and heating COP (right). Fig. 10 shows an application example of the heat pump water heater to a process in a chemical plant. Table 6 shows the specifications of the heat pump water heater under the operation condition in the application example. It has been reported that 59.6% of CO_2 emission and 45.3% of energy cost are reduced in summer season, and 51.4% of CO_2 emission and 43.7% of energy cost are reduced in winter season by replacing an existing boiler with the heat pump water heater utilizing industrial hot waste water as a heat source. It is assumed in the calculation of running cost and CO_2 emission that electricity cost is 11 yen per kWh; A-type heave oil cost is 77 Japanese yen per litter; the CO_2 emission coefficient of electricity is 0.423 kg- CO_2/kWh; the CO_2 emission coefficient of A-type heave oil is 2.71 t- CO_2/kWh.

Table 5. Specifications of the single-stage economizer-cycle heat pump water heater with a two-stage centrifugal compressor [6]

Compressor	Centrifugal type (2 units)	Rated heating capacity	547 kW
Number of compression stage	2	Rated heat source water temperature	50 °C (entering) 45 °C (leaving)
Refrigerant	R134a	Rated hot water temperature	80 °C (entering) 90 °C (leaving)
Temperature range of heat source water (entering)	10-50 °C	Rated electrical power input	148 kW
Temperature range of hot water	50-90 °C	Rated heating COP	3.7
Size	Height 2.0 m, Width 1.55 m, Depth 1.20 m		

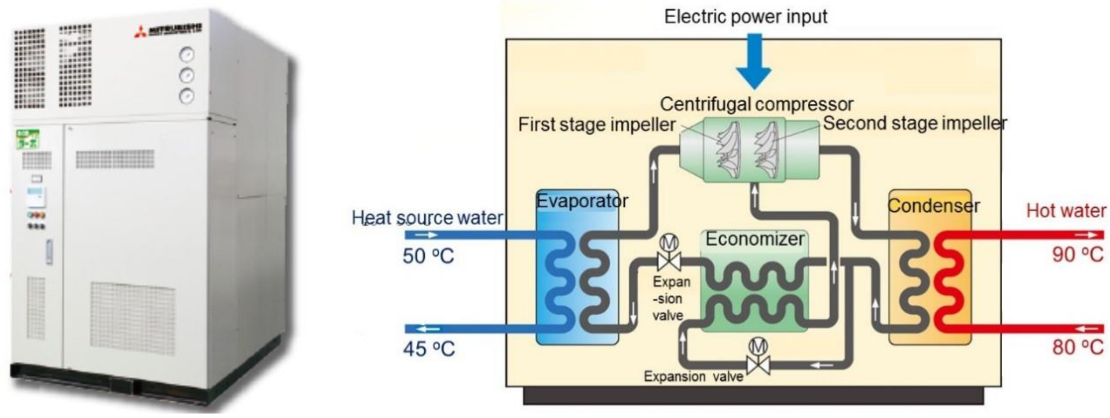

Fig. 8. Outside view (left) and flows (right) of the single-stage economizer-cycle heat pump water heater using R134a as a refrigerant with a two-stage centrifugal compressor [6]

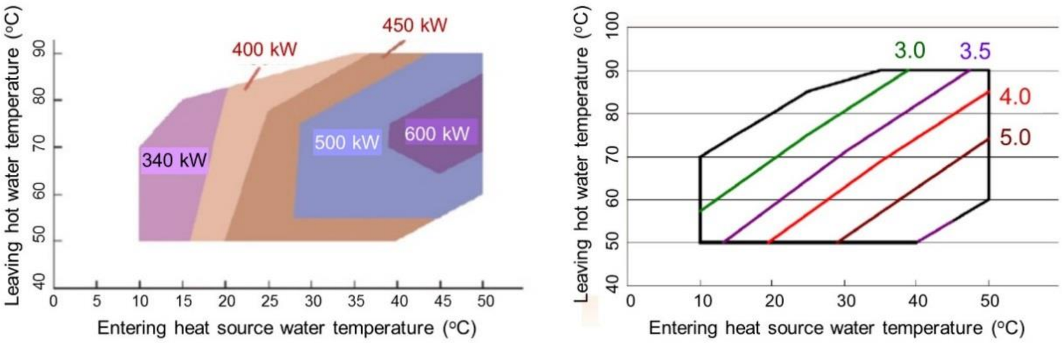

Fig. 9. Contour maps of heating capacity (left) and heating COP (right) [6]

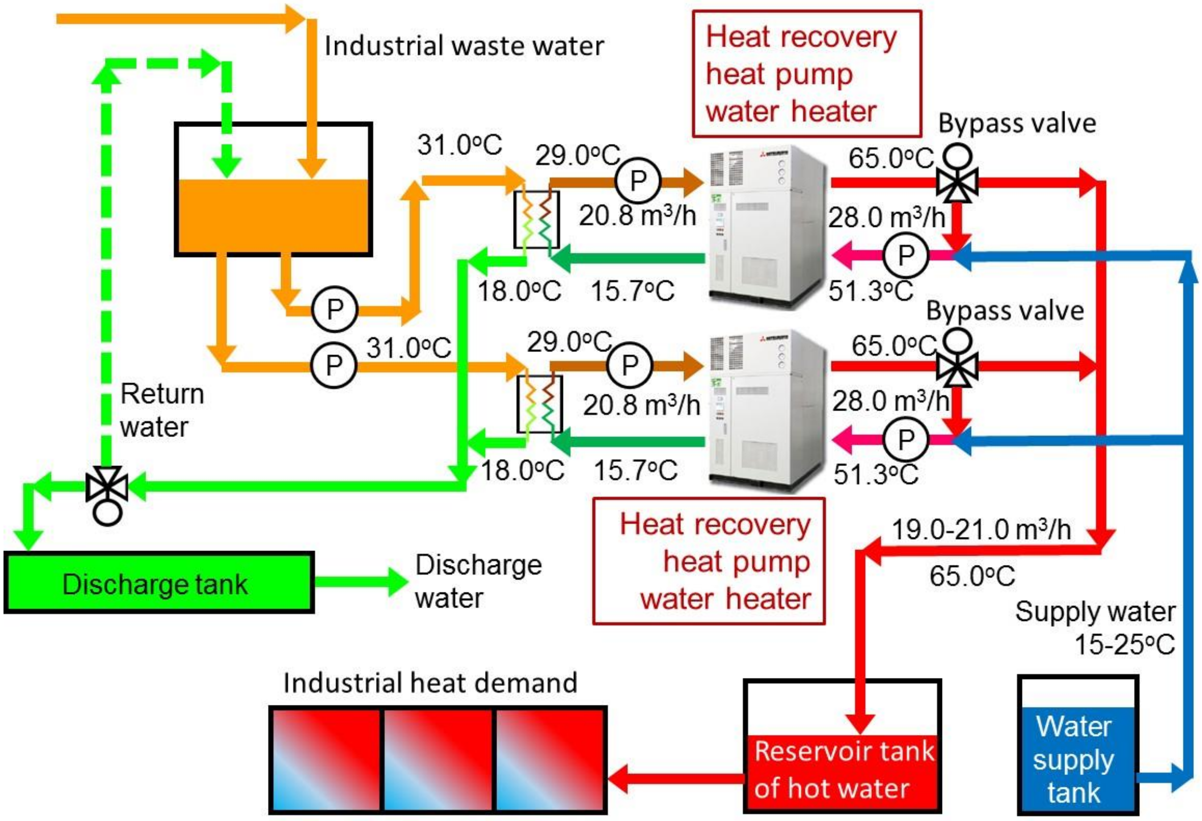

Fig. 10. An application example of the heat pump water heater with a two-stage centrifugal compressor to a process in a chemical plant [6]

Table 6. Specifications of the heat pump water heater [6]

Heating capacity	439 kW
Heat source water temperature	29.0 °C (entering)-15.7 °C (leaving)
Heat source water flow rate	20.8 m^3/h
Hot water temperature	51.3 °C (entering)- 65.0 °C (leaving)
Hot water flow rate	28.0 m^3/h
Electric power input	127 kW
Heating COP	3.5

6. Low GWP refrigerants for heat recovery heat pumps

Table 1 shows properties of refrigerants. Hydrofluorocarbon (HFC) R245fa is used for the heat recovery heat pump steam generator and R134a is used for the heat recovery heat pump water heaters. Hydrochlorofluoroolefins (HCFO) R1224yd(Z) [7] and R1233zd(E) are shown in the table as candidates of the substitute refrigerant of R245fa because the values of their critical temperature and boiling point are close to those of R245fa. The refrigerant R1224yd(Z) is developed in Japan and under application for registration to ASHRAE. Hydrofluoroolefins (HFOs) R1234yf and R1234ze(E) are shown in the table as candidates of the substitute refrigerant of R134a because the values of their critical temperature and boiling point are close to those of R134a. R1234yf and R1234ze(E) are mildly flammable refrigerants. Risk assessment of mildly flammable refrigerants was promoted for the application to mini-split air conditioners, variable refrigerant flow systems, and chillers by JSRAE [8]. These HCFOs and HFOs are expected to be used as refrigerants of heat recovery heat pumps in future. Experimental results on high temperature (65-80 °C) heat pumps using R1234yf are reported in Japan [9].

Table 7. Properties of refrigerants

Classification	Refrigerant number	Chemical formula	GWP_{100}	Safety *3	Critical pressure (M Pa)	Critical temperature (°C)	Boiling point*5 (°C)
HFC	R245fa	$CF_3CH_2CHF_2$	1,030*1	B1	3.65	153.9	15
HCFO	R1224yd(Z) *6	CF_3CF=CHCl	<1*2	(A1)*4	3.33	155.5	14
HCFO	R1233zd(E)	CF_3CH=CHCl	1*1	A1	3.62	166.6	18
HFC	R134a	CF3CH2F	1,300*1	A1	4.06	101.1	-26.1
HFO	R1234yf	CF3CF=CH2	<1*1	A2L	3.38	94.7	-29.4
HFO	R1234ze(E)	CHF=CHCF3	<1*1	A2L	3.64	109.4	-19.0

*1) GWP_{100} values: IPCC Fifth Assessment Report, Table 8.A.1.
*2) Measured by the National Institute of advanced Industrial Science and Technology (AIST) [7]
*3) A: lower toxicity, B: higher toxicity, 1: no flame propagation, 2L: lower flammability with a maximum burning velocity of ≤10 cm/s, 2: lower flammability with a maximum burning velocity of >10 cm/s, 3: higher flammability, ISO 817:2014.
*4) Provisional value by AGC Chemicals [7]
*5) Boiling temperature under standard atmosphere, 0.1013 MPa.
*6) R1224yd(Z) is under application for registration to ASHRAE.

7. Conclusion

In this paper, flows of heat recovery and utilization in industrial processes were presented, and heat demands and exhaust heat sources in various industries were also presented. Heat recovery heat pumps and their application examples were described. It has been reported that the reduction of primary energy, CO_2 emission and running cost have reached 40-60% in the application examples of these heat recovery heat pumps. Low GWP refrigerants HCFOs and HFOs as candidates of the substitute refrigerant of R245fa and R134a were described.

Acknowledgements

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