Development of Japan’s First Air-source Circulation Type Heat Pump Using R454C

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Mitsubishi Heavy Industries Thermal Systems, Ltd. worked on product development for an air-source circulation type heat pump using environmentally-friendly low-GWP refrigerant that contributes to energy saving in the industrial field, and successfully launched a product that realizes the hot water temperature at outlet of 75°C at an outside air temperature as low as -20°C, while featuring a high efficiency of the rated COP of 3.3. We also actually introduced this product as a heating source of hot water for washing production equipment and confirmed its economic efficiency and environmental effects. Through the introduction of a hybrid system of this product and an existing gas-fired steam heater, in which this product covers the base heat load, it is expected that the running cost and CO_2 emissions will be reduced by about 50%, leading to a substantial reduction in environmental load.

1. Introduction

In machine parts manufacturing factories, steam boilers and electric heaters using fossil fuels are widely used to produce hot water in the production processes of the degreasing and washing of parts after cutting. Recently, the use of heat pumps, which contribute to energy saving through their superior efficiency, has been increasing. Many conventional high-temperature heat pumps, however, are water-source heat pumps that recover heat from hot wastewater from plants. They require the installation of water pipes and pumps for the circulation of cold and hot water, resulting in high installation cost and difficulty in securing installation space.

For conventional heat pumps, refrigerants with GWP values in the range of 1430 to 2090 are used. Along with the enforcement of the Law Concerning the Discharge and Control of Fluorocarbons, the use of refrigerants with lower GWP values has been demanded from the viewpoint of reducing the effects of global warming.

To solve the problems of high installation cost and installation space, which have been obstacles to the introduction of conventional heat pumps, we developed the “Q-ton Circulation” circulation type heat pump, which uses air as a heat source and low-GWP refrigerant to reduce environmental load. The equipment achieves high energy efficiency and the hot water temperature of 75°C at outlet at an outside air temperature as low as -20°C.

2. Overview of the developed heat pump

Table 1 lists the specifications of this product, and **Figure 1** depicts its appearance. "Q-ton Circulation" is an air-source circulation heat pump that uses R454C low-GWP refrigerant and it can supply hot water of 75°C at an outside air temperature in the range of -20°C to 43°C. The heating capacity and COP of this product are given in **Figure 2**. The COP value is 3.3 at an outside air temperature of 25°C, which is the rated condition.

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Generally, the heating capacity of an air-source heat pump is reduced as the outside air temperature is lowered. In this product, a two-stage compression refrigeration cycle was adopted, which allowed the heating capacity of 30 kW to be secured at an outside air temperature of -20°C. Furthermore, the hot water temperature of 75°C at outlet can be realized at an outside air temperature of -20°C.

Figure 1 Appearance of the product

Table 1 Specifications

Model			EQA401
Output		kW	40 (Max. 50)
Rated COP		—	3.3
Adjustable range of hot water temperatures at outlet		°C	40 to 75
Operating range	Hot water temperature at outlet	°C	40 to 75
	Outside air temperature	°C	-20 to 43
Dimension		mm	2048 × 1350 × 720
Refrigerant		—	R454C (10.8kg)
Flow rate		m^3/h	1.72 to 9.00

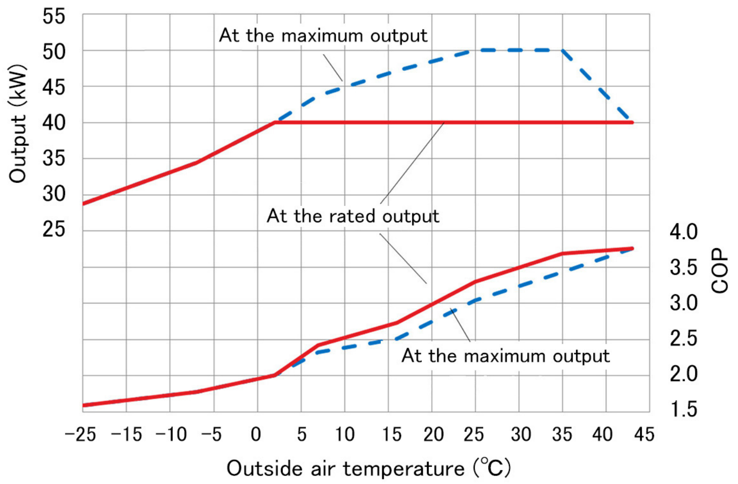

Figure 2 Relationship between COP and outside air temperature

3. Selection of low-GWP refrigerant

First, it was decided that a low-GWP refrigerant that could achieve the hot water temperature at outlet of 75°C at an outside air temperature in the range of -20°C to 43°C, which is a requirement of the product specifications, should be adopted as the refrigerant for this product. **Figure 3** presents critical temperatures, boiling points and GWPs of various refrigerants. To satisfy the aforementioned requirement of the product specifications, it was desirable to adopt a refrigerant with a performance equivalent to that of the current R407C refrigerant. Therefore, low-GWP refrigerants R454C and R455A were selected as candidates that meet the requirement, and **Table 2** lists their properties.

Next, the candidates for refrigerant were compared in terms of the temperature glide, which is important to an air-source heat pump. **Figure 4** shows the temperature glides of the R32/HFO mixed refrigerants. The temperature glide of R455A is 11.9 deg. Since it has a large temperature glide, an evaporation heat exchanger may frost at low outside air temperatures. On the other hand, the temperature glide of R454C is 7.7 deg, which is less different from the temperature glide of R407C of 6.2 deg. Therefore R454C can be handled in the same manner as R407C.

According to the above results, R454C was selected as the low-GWP refrigerant for this product.

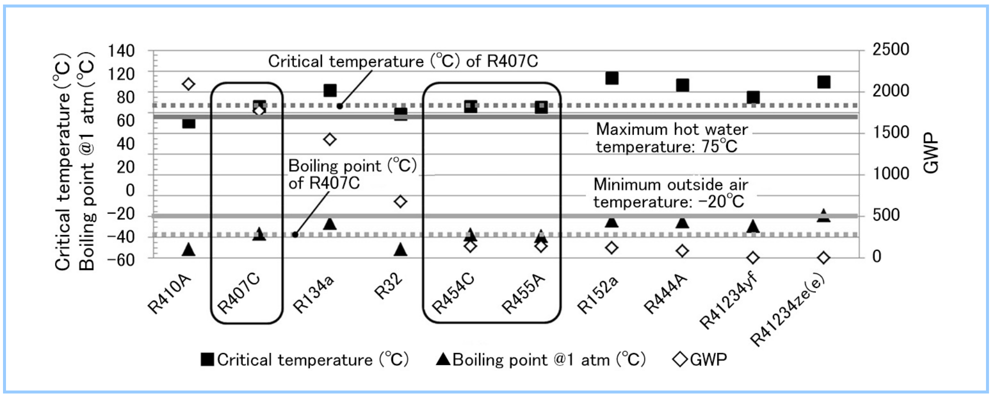

Figure 3 Properties of the candidates for refrigerant

Table 2 Properties of the candidates for refrigerant (calculated using the NIST REFPROP Ver.10)

Refrigerant	R407C	R454C	R455A
GWP	1620	146	145
Mixing ratio (wt%)	R32/R125/R134a 23/25/52	R32/R1234yf 21.5/78.5	R1234yf/R-32/R-744 75.5/21.5/3
ASHRAE classification	A1	A2L	A2L
Boiling point @1 Atm (°C)	-36.6	-37.8	-39.2
Critical temperature (°C)	86.1	85.7	85.2

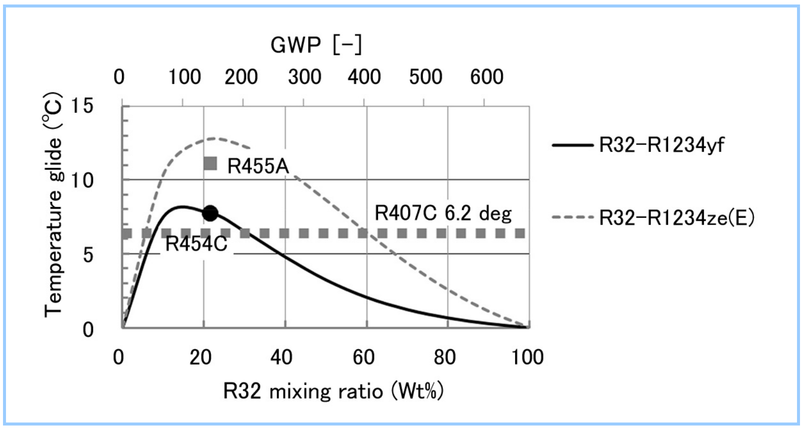

Figure 4 Temperature glides of the mixed refrigerants
(Calculated using the NIST REFPROP Ver.10. Use conditions: Vapor, Saturated gas temperature of 5°C)

4. Two-stage compression cycle

As previously described, high-efficiency heat pumps are widely used as alternative technologies to electric heaters and steam boilers in fields requiring the production of hot water. On the other hand, when an air-source heat pump like this product is used to realize a hot water temperature at a low outside air temperature, the refrigerant compression ratio becomes very high, resulting in reduced efficiency or limited hot water temperatures at outlet. To solve this problem, a two-stage compression cycle with two compressors being connected in series was adopted in this product.

Figure 5 shows the circuit diagram for the refrigerant in this product and the compressor efficiency characteristics in a single-stage compression cycle and a two-stage compression cycle. In a single-stage compression cycle, the pressure ratio in one compressor became high and the efficiency of the compressor was reduced. The adoption of a two-stage compression cycle allowed the compression ratio in one compressor to be reduced and the compressor to be operated at the most efficient point. As a result, the efficiency was increased by 13% compared with operation in a single-stage compression cycle.

This product is also equipped with two inverter compressors, thereby controlling the intermediate pressure of the refrigerant with the inverters so that the best operational efficiency is obtained. Furthermore, gas injection is performed to prevent the reduction of the heating capacity at low outside air temperatures.

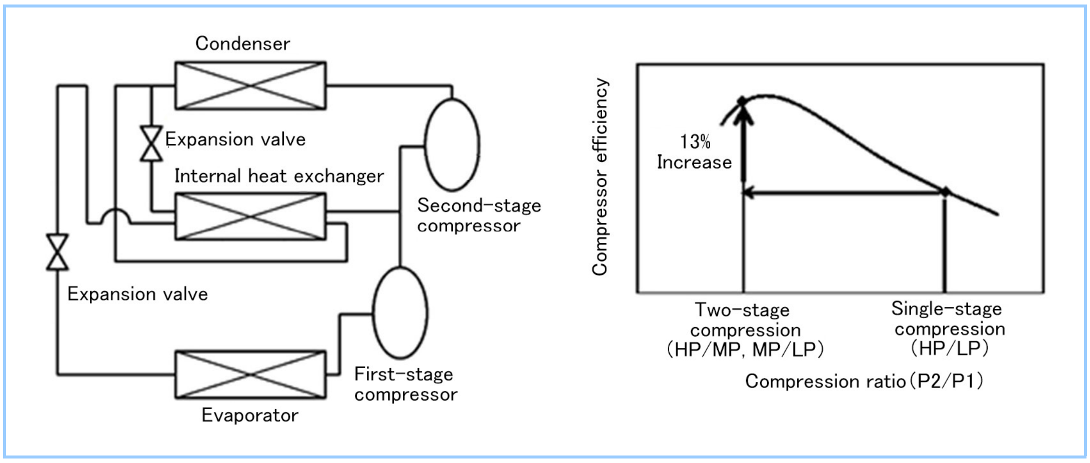

Figure 5 Refrigerant circuit diagram and comparison of compressor efficiency in single-stage compression and two-stage compression

5. Optimization of the compressor for two-stage compression cycle

Generally, lower-stage compressor in a two-stage compression cycle requires a larger displacement compared with the higher-stage compressor due to the characteristic of economizer cycle. On the other hand, the R454C refrigerant has a low density, and when a conventional compressor is used, the displacement is insufficient, causing the reduction of the heating capacity. If a larger-size and larger-volume compressor is used, the reduced capacity can be compensated, but it leads to increase in cost for such a compressor.

To solve this problem, the three-dimensional scroll compressor (1) was adopted in this product. The increased volume prevented the reduction of the heating capacity due to low density. To achieve this without changing the outside dimensions, the structure was designed as follows:

(1) Adoption of three-dimensional scroll compressor (3D scroll)
(2) Redesign of scroll involute
(3) Optimization of rotation axis balance
(4) Expansion of ejection port

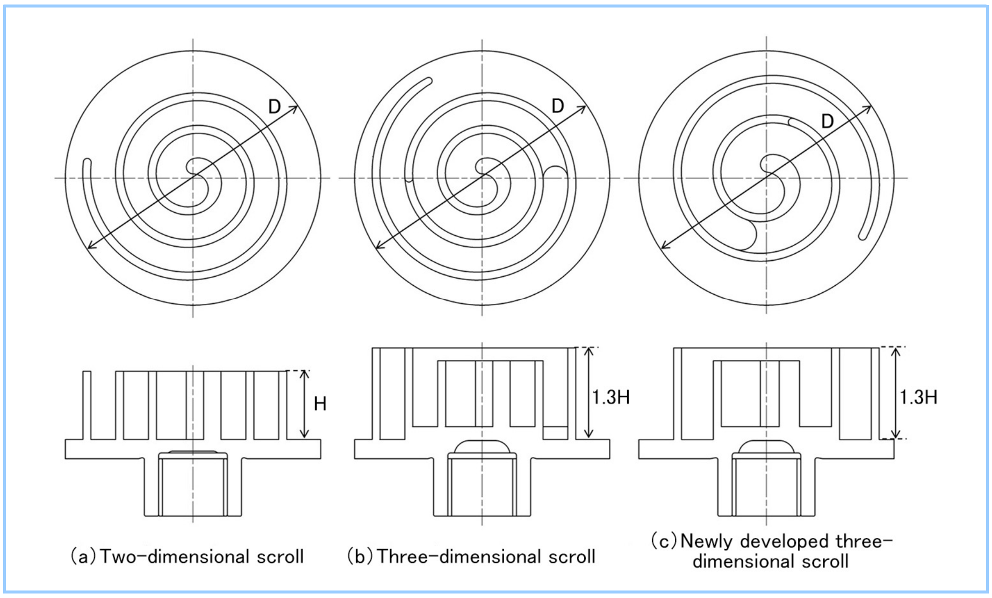

Figure 6 Outlines of the scrolls

Figure 6 illustrates the outlines of the scrolls. The displacement of (b) three-dimensional scroll was increased by 1.4 times compared with that of (a) two-dimensional scroll, but further increase of displacement was required for a large-volume system. To increase a displacement, generally, the lap height and the diameter are increased, but the durability may be reduced or the outside dimensions may be increased. Therefore, we reviewed the scroll involute and the number of windings, so that the displacement was further increased. Figure 6 (c) gives the new scroll involute.

The number of windings was reduced to optimize the internal volume ratio. If any change is made just for the purpose of increasing the displacement, over-compression is caused in the compression process on the first stage, and this results in the reduction of the efficiency. As a result of changing the scroll involute and the number of windings, the compression ratio could be reduced while the displacement was increased.

6. Reliability, safety, serviceability

The R454C refrigerant used in this product is a slightly flammable (A2L) refrigerant. R32 which is generally used in air conditioners for household and business falls under the same class. Unlike R32 and R1234yf, however, R454C is not designated as a specified inert gas. Therefore, concerning handling of the refrigerant, we established the risk assessment to secure safety. We have notified customers about the content of the notification required for execution of recovery or filling of the refrigerant and the necessity for the installation of a refrigerant leakage detector and a ventilator when this product is placed indoor.

The legal refrigerant ton is less than 3 tons (2.99 tons), and this product is not regulated by the High Pressure Gas Safety Act. Therefore, no prior notification is required in installation or service.

In the service aspect, a 24-hour remote monitoring system was adopted, and even if an unexpected trouble occurs, the recovery work at the field can be conducted immediately.

7. Energy saving

We have been conducting a field test of this product for the purpose of heating a washing tank of a food factory since September 2018. The prediction result for the annual running cost and the reduction of CO_2 emissions based on the operational data for the period of September 2018 to March 2019 is shown in **Table 3**. The electricity rate was calculated from the actually measured amount of electric power consumed by this product. In addition, the running cost before the introduction of this product was calculated by back calculating the fuel consumption of the existing boiler from the heating capacity of this product and the comparison of the energy saving effects was conducted. The system diagram in the field test is presented in **Figure 7**.

Table 3 Prediction result for running cost and CO_2 emissions

			Gas boiler	Heat pump	Reduction
Energy consumption	Gas	Nm^3	369		
	Electricity	kWh		828	
Running cost		×1000JPY	24	12	49.8%
Energy consumption in crude oil equivalent		GJ	15	8	46.1%
CO_2 emissions		ton-CO_2	0.8	0.4	53.0%

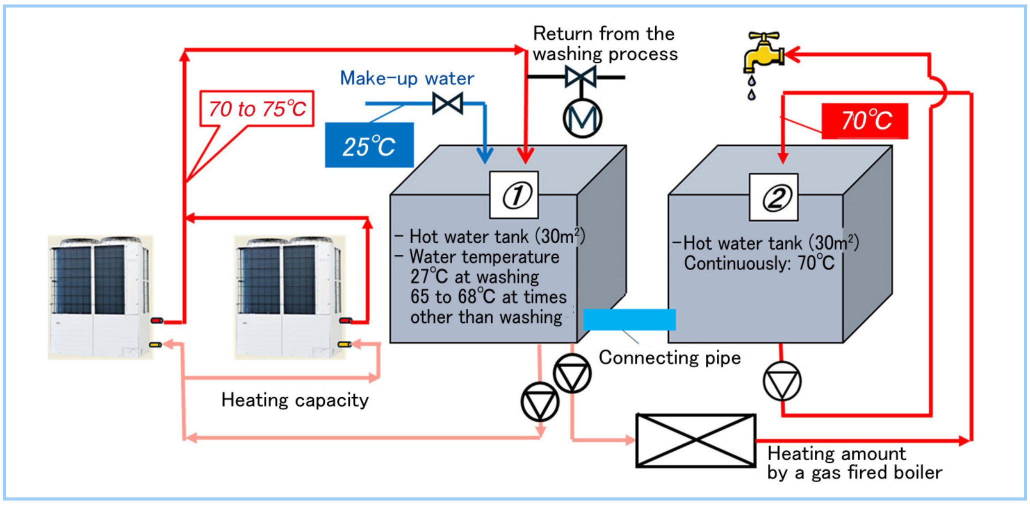

Figure 7 Comparison of the washing tank heating systems for food factory

The result showed that the running cost was reduced to 50% of that of the conventional system and the CO_2 emissions were reduced to 53% of that of the conventional system. It is expected that the COP can be improved by increase of the continuous operation time and both the annual running cost and CO_2 emissions can be reduced to about 54% in the future.

In addition, the energy consumption in crude oil equivalent can be reduced by over 40%. Introduction of this product brings to customers the merit of contributing to energy reduction required by the revised energy saving law.

8. Conclusion

(1) The refrigerant R454C with the GWP value of 146 was adopted for the first time in Japan, so that environmental load was substantially reduced.

(2) A two-stage compression refrigeration cycle was adopted, and the hot water temperature at outlet of 75°C was realized at a wide range of outside air temperatures from -20°C to 43°C. In addition, the substantial energy saving was realized at the high efficiency of the rated COP of 3.3. It is expected that opportunities to introduce heat pumps in the industrial and business fields will increase.

(3) The adoption of an air-source heating system allowed the easy installation without securing hot wastewater and conducting installation and piping works of pumps, and thus solved the problems of high installation cost and installation space, which were obstacles to introduction.

Reference

(1) M. TANIGUCHI, H. SATO, Y. TAKASU1 and Y. KIMATA, Development of Large Capacity 3D Scroll Compressor for First Stage of Two-stage Compression System, 24th International Compressor Engineering Conference at Purdue, July 9-12, 2018, Paper 1232.