Development of Two-Stage Compressor for CO_2 Heat-Pump Water Heaters

HAJIME SATO*1 YOSHIYUKI KIMATA*2
YOHEI HOTTA*2 TOSHIYUKI GOTO*1
HISAO MIZUNO*3 HIROYUKI KOBAYASHI*4

The use of CO_2 heat-pump water heaters is becoming more widespread in response to energy conservation requirements. This paper describes the development of a high-efficiency compressor for commercial CO_2 heat-pump water heaters. The new compressor is the world's first to employ a two-stage compression structure, a combination of rotary and scroll mechanisms that can resolve specific issues of CO_2 refrigerant such as large pressure difference and high operating pressure, and it provides the most suitable compression mechanism for the operating conditions of a heat-pump water heater. Consequently, efficiency improvement and higher reliability can be realized under a wide range of operating conditions. MHI's newly developed "Q-ton" CO_2 heat-pump water heater is equipped with the developed compressor, and thus heating capacity and efficiency can be significantly improved in comparison with conventional water heaters. These improvements have made it possible to introduce heat-pump water heaters in cold regions.

1. Introduction

Nowadays, traditional fossil-fuel water heaters are being replaced by heat-pump systems in response to energy conservation requirements and concerns about global warming. CO_2 as a refrigerant has low global warming potential (GWP), is non-flammable and is appropriate for high-temperature hot-water supply due to its refrigerant properties. Accordingly, CO_2 has been widely utilized as a refrigerant for household heat-pump water heaters, and its use is also increasing in commercial and industrial fields. On the other hand, CO_2 has a high operating pressure, leading to larger leakage and mechanical losses at the compressor. Therefore, the reduction of these losses is essential to improve the performance of CO_2 heat-pump water heaters.

To resolve the issues described above, the authors have developed a novel compressor for commercial CO_2 heat-pump water heaters. The new compressor is based on two-stage compression, using a combination of scroll and rotary mechanisms to enable the reduction of leakage and mechanical losses. In addition, by employing intermediate gas injection, the new compressor has attained high heating capacity and high efficiency under a wide range of conditions.

This paper describes our efforts to improve the efficiency and reliability of the new compressor and introduces a commercial CO_2 heat-pump water heater equipped with the new compressor.

2. Structure of the New Two-stage Compressor

Table 1 compares the characteristics of CO_2 (employed here as a refrigerant for heat-pump water heaters) and other common refrigerants. Alternatives to chlorofluorocarbon refrigerants (HFC refrigerants), which are typically used in current refrigeration and air conditioning systems, have high global-warming potential (GWP). Therefore, the shift to refrigerants with lower GWP is

*1 Nagoya Research & Development Center, Technology & Innovation Headquarters
*2 Air-Conditioner Designing & Engineering Department, Air-Conditioning & Refrigeration Systems
*3 Group Manager, Air-Conditioner Designing & Engineering Department, Air-Conditioning & Refrigeration Systems
*4 General Manager, Quality Assurance Department, Air-Conditioning & Refrigeration Systems

an important issue in the refrigeration and air conditioning fields. Although some equipment uses natural refrigerants such as ammonia or hydrocarbons, these refrigerants have not been widely used in refrigeration and air-conditioning systems because of their toxic or flammable properties. On the other hand, since CO_2 has no flammability, low toxicity and is suitable for high-temperature hot-water supply due to its refrigerant properties, it has been widely used as a refrigerant in household heat-pump water heaters. However, CO_2 has high operating pressure and a high pressure difference compared with conventional refrigerants. This results in an increase of leakage and mechanical losses. Therefore, it is especially important for the development of CO_2 compressors to make the proper selection of its basic structure.

Table 1 Comparison of refrigerant characteristics

		Global-warming potential	Toxicity	Flammability	Pressure (20°C) (MPa)
Alternative to chlorofluorocarbon refrigerant (HFC refrigerants)	R410A	2,090	Low	None	1.34
	R134a	1,430	Low	None	0.47
Natural refrigerants	NH_3 (ammonia)	1 or less	High	Low	0.76
	C_3H_8 (propane)	3	Low	High	0.74
	CO_2 (carbon dioxide)	1	Low	None	5.63

In order to establish the basic structure of the new compressor, the number of compression stages, the shell pressure and the type of compression mechanism are studied. **Table 2** compares compressor performances according to structure. Based on this study, the following structures are employed for the developed compressor.

(1) Two-stage compression

The pressure difference between discharge- and suction-pressure of CO_2 refrigerant is several times larger than that of conventional HFC refrigerants. This leads to an increase of gas leakage and mechanical losses. However, by introducing two-stage compression, which decreases the pressure difference in each stage, higher efficiency and higher reliability can be obtained.

In addition, the developed compressor is equipped with an intermediate gas-injection mechanism to increase COP (coefficient of performance) and heating capacity. By employing two-stage compression, gas injection can be introduced between the first and second stages, and thus mixture loss can be reduced in comparison with single-stage compression with direct injection to the compression chamber.

Table 2 Comparison of compressor performance according to structure

Number of compression stages	Shell pressure	Compression mechanism		Shell thickness	Gas injection	Reliability		Efficiency	
		First stage	Second stage			First stage	Second stage	First stage	Second stage
Single stage	Discharge pressure			–	–				
	Suction pressure			+	–				
Two stages	Discharge pressure			–	+*1				
	Intermediate pressure	Scroll	Scroll	+	++	+*2	+*2	+	++
		Scroll	Rotary	+	++	++	–	+	+
		Rotary	Scroll	+	++	++	++	++	++
		Rotary	Rotary	+	++	++	–	++	+
	Suction pressure	Scroll	Scroll	+	+*1	+*2	+*2	+	++
		Scroll	Rotary	+	+*1	++	–	+	+
		Rotary	Scroll	+	+*1	–	++	++	++
		Rotary	Rotary	+	+*1	–	–	++	+

*1 Connection piping between first and second stages is required.
*2 An oil pump must be placed in the middle of the shaft.

(2) Intermediate pressure shell

Since the operating pressure of CO_2 is much higher than that of conventional HFC, shell pressure has a great impact on the shell thickness and hence on the compressor weight. This impact grows as the size of the compressor becomes larger, such as in commercial and industrial applications. Because of this, it is effective to keep the design shell pressure low to ensure a lightweight compressor. The developed compressor adopts an intermediate pressure shell so that the discharge pressure does not directly affect the shell, realizing downsizing and a reduction in weight.

(3) Combination of scroll and rotary mechanisms

The compression mechanism is one of the most important factors in determining the efficiency and reliability of a compressor. Particularly in a two-stage compressor, it is necessary to select appropriate compression mechanisms for the respective operating characteristics of the first and second stages. It is generally known that the mechanisms of a positive-displacement compressor include reciprocating, screw, scroll, and rotary mechanisms. The developed compressor employs rotary and scroll mechanisms for the first and second stages respectively as the most suitable compression mechanisms for a heat-pump water heater. This innovative combination of scroll and rotary mechanisms enables high reliability and high efficiency under a wide range of operating conditions.

Figure 1 shows the structure of the developed compressor.The compressor is driven by a brushless DC motor located in the middle of the compressor and has two compression chambers on either side of the motor. The rotary-type first-stage compression chamber is located on the lower side of the motor and is connected to a suction pipe via a suction accumulator. The scroll-type second-stage chamber is located on the upper side of the motor and is connected to a discharge pipe via a discharge chamber.

Refrigerant gas is introduced into the first-stage compression chamber through the accumulator and is compressed to intermediate pressure. The compressed gas is then discharged into the shell. Injection gas is introduced into the shell through the gas-injection port and is mixed with compressed gas from the first stage. The mixed gas is then introduced into the second-stage compression chamber and compressed to discharge pressure. The compressed gas is discharged to the outside of the compressor through a discharge pipe on top of the shell.

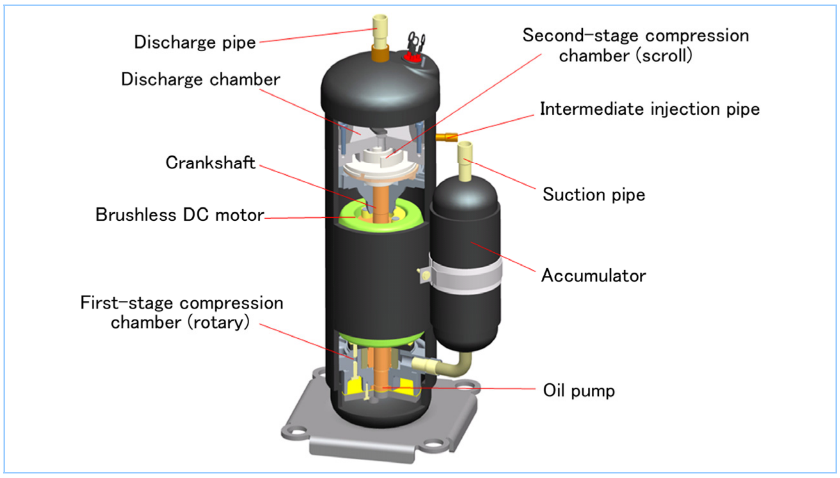


Figure 1 Structure of the developed two-stage compressor

3. Efficiency of the Developed Two-stage Compressor

To verify improved efficiency, performance tests of the developed two-stage compressor and a conventional single-stage scroll compressor were carried out. **Figure 2** shows a comparison of the efficiency with respect to operating pressure ratio between the new compressor and the conventional compressor. The vertical scale represents the values obtained by dividing the efficiency of a compressor by the efficiency of the conventional compressor at a compression ratio of 3. For the conventional compressor, the efficiency dropped significantly with an increasing operating-pressure ratio due to increased leakage and mechanical losses. On the other hand, the developed compressor showed little loss of efficiency, even with an increased operating-pressure ratio, through the use of the two-stage compression mechanism. The developed compressor resulted in a 15% improvement in efficiency at a compression ratio of 3 and more than 30% improvement at a compression ratio of 4 or higher compared with the conventional compressor. Hence, the developed two-stage compressor achieved significant efficiency improvement under a wide range of operating conditions.

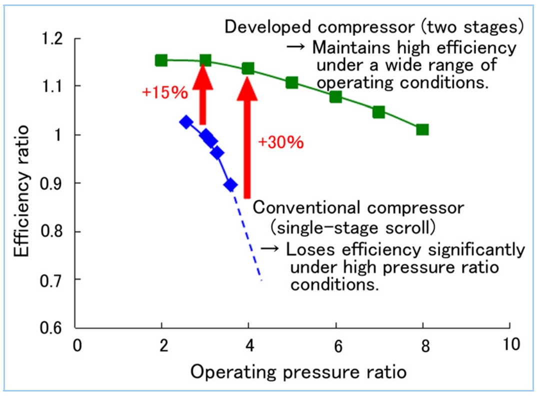
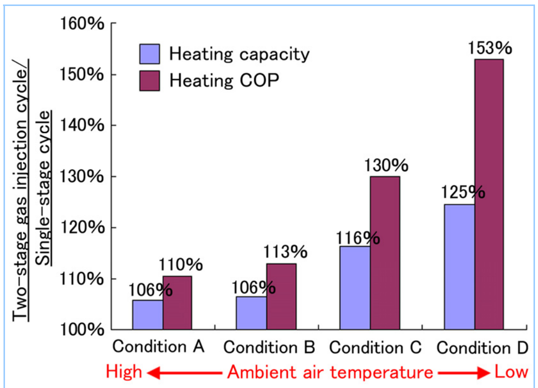


Figure 2 Differences in efficiency with respect to operating-pressure ratio



	Ambient air temperature (°C)	Inlet/outlet water temperature (°C)
Condition A	16	27/65
Condition B	7	9/65
Condition C	−7	6/65
Condition D	−20	5/65

Figure 3 Improvement of capability according to operating condition

In order to evaluate the performance improvement of a heat pump system equipped with the developed two-stage compressor, a performance comparison between a two-stage cycle with intermediate gas injection and single-stage cycle was conducted under four different ambient air temperature and inlet water temperature conditions. **Figure 3** shows the improvement in heating capacity and COP (Coefficient of Performance) of a two-stage intermediate gas injection cycle equipped with the developed two-stage compressor compared with a single-stage cycle equipped with a conventional compressor. For each of the conditions, improvement over the conventional cycle was observed. The improvement ratio increased as the ambient air temperature decreased because the refrigerant flow rate of the gas cooler was increased by the gas injection, and the efficiency of the compressor was improved by employing the developed two-stage compressor. The new compressor showed a 25% improvement of heating capacity and a more than 50% improvement of COP under deep-freeze conditions (cond. D).

These results indicate that the developed two-stage compressor offers special advantages for applications operating under large temperature differences, such as refrigeration or chilling units as well as heat pump water heaters in cold region.

4. Reliability Assurance of the Developed Compressor

Since the pressure difference of CO_2 refrigerant is several times higher than that of conventional HFC refrigerants, the load on sliding parts such as bearings increases significantly in comparison with that of conventional refrigerants. For most existing CO_2 compressors, special efforts have been required to assure their reliability such as applying a hard coating to the sliding surfaces and reducing the contact pressure on the bearings. However, by adopting a two-stage compression mechanism, the developed compressor decreases the pressure difference in each stage to a level equivalent to that of conventional HFC refrigerants. Thus, the load on sliding parts can be reduced to a similar level to that of conventional HFC compressors.

Providing a proper oil supply to all sliding mechanical parts in both the first and second stages is one of the issues unique to the two-stage compression structure. **Figure 4** shows the supply pathways for lubricating oil and refrigerant in the developed two-stage compressor.

The developed compressor is equipped with a positive-displacement oil pump at the lower end of the crankshaft. The lubricating oil is pumped from the oil storage at the bottom of the compressor and introduced into the oil channel in the crankshaft. The oil is then supplied to the journal bearings of the first and second stages. Afterward, lubricating oil is supplied to the other sliding parts and the compression chambers. To assure the reliability of a compressor, it is necessary to supply a proper amount of oil to all sliding parts. In the developed compressor, the capacity of the oil pump and the dimensions of the oil channel are optimized in terms of the amount of oil required by each bearing and the pressure drop in the oil channel. As a result, proper lubrication can be provided to all sliding parts.

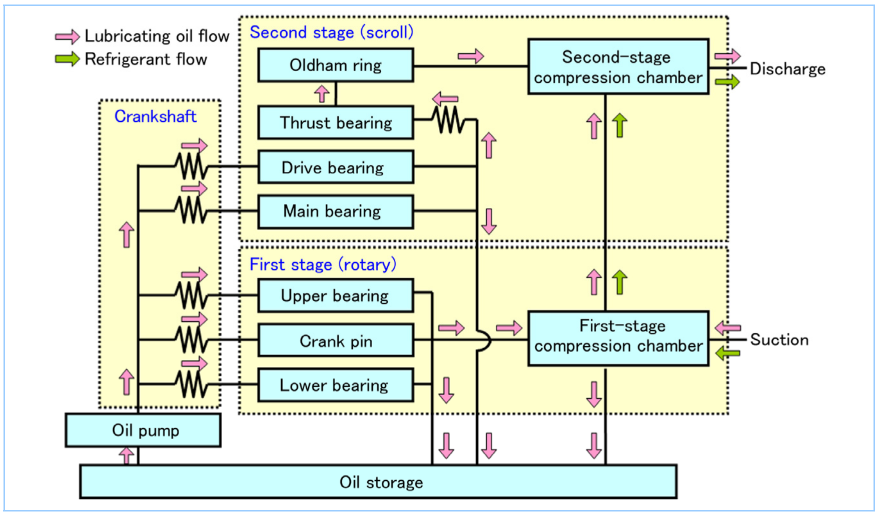


Figure 4 Flow pathways for refrigerant and lubricating oil in the developed compressor

5. Application of the Developed Two-Stage Compressor to a Commercial Heat-pump Water Heater

The developed two-stage compressor is installed on our recently developed "Q-ton" commercial CO_2 heat-pump water heater.[1] "Q-ton" now has the following features:

- Two-stage compression and an intermediate gas-injection cycle are adopted.
- The rated heating capacity is 30 kW and is sustainable at ambient air temperatures as low as -7°C.
- The COP on rated conditions reaches 4.3, which is the highest level in the industry.
- A 90°C hot water supply is available even at ambient air temperatures as extreme as -25°C.

Figure 5 shows the variation in heating capacity and COP with respect to ambient air temperature. Because conventional heat-pump water heaters are hampered by decreased heating capacity at low ambient temperatures, their applicability in cold regions has been limited. However, the developed system achieves both high heating capacity and high COP under the conditions at low ambient temperatures by adopting two-stage compression and an intermediate gas-injection cycle using the new two-stage compressor. Consequently, Q-ton makes it possible to introduce heat-pump water heaters in cold regions, which has always been a difficult problem.

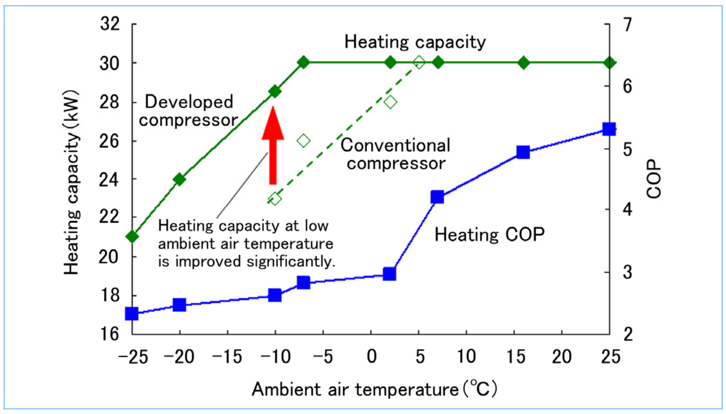


Figure 5 Variation in heating capacity and COP with respect to ambient air temperature

6. Conclusion

MHI developed a two-stage compressor for commercial CO_2 heat-pump water heaters. Employing the world's first combination of rotary and scroll mechanisms and intermediate gas injection, the developed compressor realized high reliability and high efficiency operation under a wide range of conditions. Q-ton, a commercial CO_2 heat-pump water heater equipped with the developed compressor, achieved significantly improved heating capacity and COP in comparison with previous water heaters and makes it possible to introduce heat-pump water heaters in cold regions, which has always posed difficulties. We would like to continue our pursuit of enhancing compressor performance to offer energy savings and earth-friendly products to our customers.

Reference

1. Development of the “Q-Ton” CO_2 Refrigerant Heat Pump for Industrial Water-Heater Systems for Use at Outside Air Temperatures Down to -25^{o}C, Mitsubishi Heavy Industries Technical Review Vol. 48 No. 4 (2011) pp. 86-88