# Rotary Compressor for a $CO_2$ Heat Pump Water Heater

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## 1. Introduction

"ECO-CUTE" is a natural refrigerant heat pump water heater that uses $CO_2$. The $CO_2$ refrigerant is highly efficient in water heating applications. However, because the operating pressure is very high and $CO_2$ has peculiar characteristics that are different from conventional refrigerants, we had to overcome some difficult technological challenges regarding the compressor used for this refrigerant. This report discusses these major technological challenges and the actual measures taken in the development of the Mitsubishi rotary compressor for $CO_2$ refrigerant.

## 2. Rotary Compressor

The rotary compressor mechanism consists of a rolling piston that rotates eccentrically in its cylinder and a vane installed in a vane slot in the cylinder that reciprocates along the slot causing the vane to move along the periphery of the rolling piston. As a result of the vane's movement, suction and compression chambers are formed inside the cylinder and the volume of each chamber changes in accordance with the rotation of the crankshaft to provide compression. Figure 1 shows a cross-sectional view of the Mitsubishi $CO_2$ compressor and Table 1 shows the major specifications thereof.

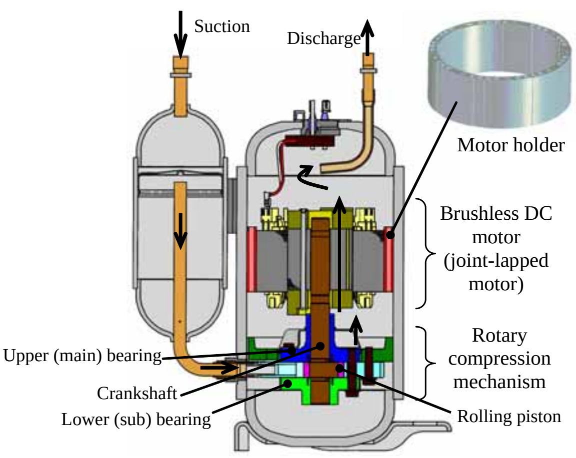


Fig. 1 $CO_2$ rotary compressor

Table 1 Specification of the $CO_2$ compressor

| | |
|---|---|
| Compression system | Single rotary |
| Displacement | 4.5 $cm^3$ |
| Refrigerant type | R744($CO_2$) |
| Motor | Brushless DC motor (joint-lapped motor) |
| Application | HP water heater |

## 3. Characteristics of $CO_2$ Refrigerant

### 3.1 Environmental and safety characteristics (2)

(1) $CO_2$ does not destroy the ozone layer. (Ozone depletion potential: ODP = 0.)*1
(2) $CO_2$ refrigerant has a low global warming potential. (Global warming potential: GWP = 1)*2
(3) $CO_2$ refrigerant is nonflammable.
(4) $CO_2$ refrigerant has low toxicity.

### 3.2 Operating characteristics of $CO_2$ as a refrigerant

(1) The operating pressure of $CO_2$ is high.
(2) The speed of sound in $CO_2$ gas is very high.
(3) The pressure of $CO_2$ rises to a high level in response to volumetric changes.
(4) The density of the $CO_2$ refrigerant gas is high.

$CO_2$ refrigerant has excellent environmental and safety characteristics, as listed above. However, the use of $CO_2$ as a refrigerant involves some peculiar characteristics compared with conventional refrigerants.

## 4. Influence of $CO_2$ Refrigerant on a Compressor and Countermeasures

The influence of the characteristics of $CO_2$ mentioned above on a $CO_2$ compressor is taken into consideration as described below.

### 4.1 Pressure-resistant structure

The most remarkable characteristic of $CO_2$ refrigerant is that it has a high operating pressure. To cope with this, the compressor enclosure's pressure resistance requirements must be studied.

Figure 2 shows the operating pressure levels of the R410A Freon refrigerant used for room air-conditioners and similar equipment and that of natural $CO_2$ refrigerant used in the ECO-CUTE, together with the specifications of the enclosures for the respective refrigerants. As shown in Fig. 2, the operating pressure of $CO_2$

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refrigerant is approximately three times that of R410A, which requires the board thickness of the enclosure to be increased by more than double, proportionately.

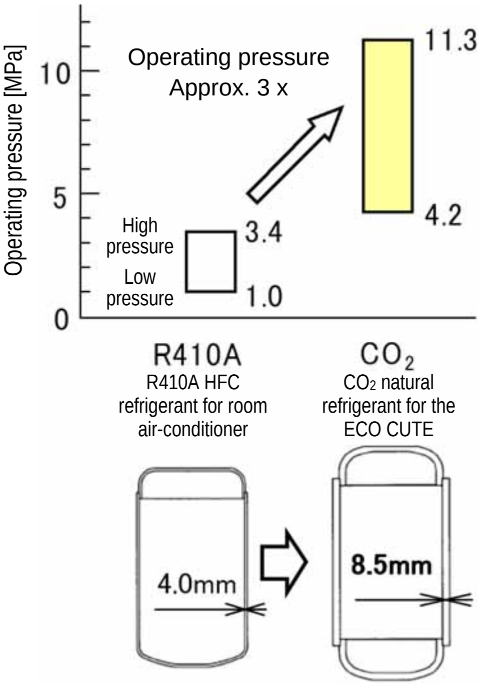


Fig. 2 Operating pressure of $CO_2$ and specification of the enclosure

### 4.2 Securing efficiency

With a $CO_2$ refrigerant, which is characterized by high operating pressure, the speed of sound is very high and pressure rises quickly in response to volumetric changes. The amount of gas that passes through gaps between components in the rotary compression mechanism and leaks into the suction chamber from the compression chamber increases, making it difficult to attain appropriate efficiency in the same way as that applied to conventional refrigerant compressors. As a solution, we reduced the gap between the cylinder bore and the outer diameter of the rolling piston to narrow the gas leakage path. Moreover, we increased to the compression chamber in comparison to that in a R410A refrigerant compressor, to increase the sealing effect between components.(3) This countermeasure has increased the efficiency of the compressor. In addition, the COP (coefficient of performance) of the water heater system equipped with this compressor increased to one of the highest levels in the industry.

### 4.3 Reduction in the oil circulation rate

One of the characteristics of the $CO_2$ refrigerant is that the gas has a high density. This particular characteristic affects the separability property of the refrigerant and the oil in the compressor's enclosure.

The gas, after being compressed by the rotary compression mechanism at the bottom of the compressor, is discharged into the space below the motor. Thereafter, the gas passes through the motor into the upper space in the enclosure. Finally, the gas is discharged through the discharge pipe at the top of the compressor. The gas in the space below the motor contains a lot of oil, which is separated out as it passes through the motor. Because the density of the $CO_2$ refrigerant gas is about twice that of an R410A refrigerant, a large amount of oil is transferred into the space above the motor together with the refrigerant gas as it rises up through the motor. As a countermeasure against this phenomenon, we installed an additional motor-holder, as shown in Fig. 1. Because the motor-holder has a number of vertical holes, the gas passage area in the motor section is expanded to reduce the flow rate of the gas passing through the motor, thus reducing the amount of oil flowing into the space above the motor. As a result, an oil circulation rate of 0.1% was attained (at 60 rps).

### 4.4 Achieving reliability of sliding portion

The high operating pressure of $CO_2$ refrigerant also seriously affects the reliability of the compressor's sliding portions. There are two types of sliding portions in the rotary compressor: one of them is the sliding portion around the crankshaft, which involves sliding of the main bearing, sub-bearing and rolling piston bore. Sliding is effected by the sliding bearing mechanism under thick-film lubrication conditions. Consequently, sliding durability can be secured under high operating pressure, if there are appropriate gaps in the bearing and oil of a suitable viscosity is used. The other sliding occurs around the vane, which is a part peculiar to rotary compressors. It is difficult to maintain thick-film lubrication conditions in this section: the section is easily subject to boundary or extreme-pressure lubrication conditions. It proved difficult to attain sliding durability in this section using the same method as that used in the R410A refrigerant compressor.

## 5. Achieving Reliability of the Sliding Portion around the Vane

This chapter focuses on achieving sliding durability of the sliding portion around the vane, which is one of the most important factors in realizing $CO_2$ rotary compressors.

### 5.1 Configuration of the sliding portion around the vane

Figure 3 shows the configuration of the sliding portion around the vane in a rotary compressor and forces acting on the vane. There are two points around the vane where sliding conditions are harsh. One of these is between the side surface of the vane and the vane slot in the cylinder. Achieving sliding durability at this point is discussed in the following section. The other is the sliding between the top of the vane and the periphery of the rolling piston. We coated the sliding part on the vane with a DLC-Si coating, which resulted in attaining sliding durability. This is one of the most difficult technologies applied in the development of the $CO_2$ compressor. A detailed explanation of this technology is provided in one of the other reports introduced in this issue; therefore, it will not be discussed in detail here.

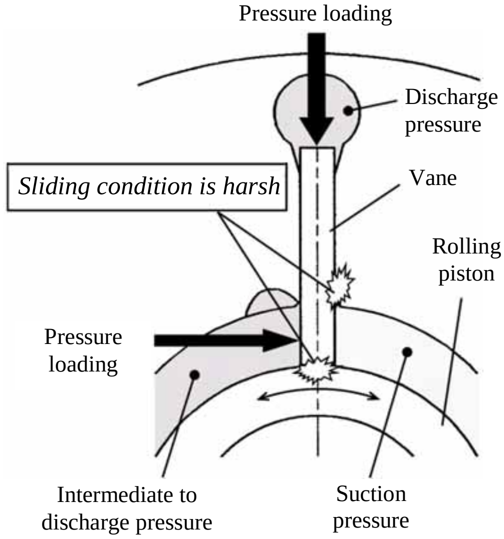


Fig. 3 Sliding portions around the vane

### 5.2 Achievement of sliding durability on the side surface of the vane

Figure 4(a) shows the detailed sliding conditions on the vane's side surface. The vane is inclined slightly due to pressure loading caused by the difference in pressures between the two sides of the vane: thereafter the side surface of the vane touches the corner of the vane slot bore in the cylinder. With the conventional R410A, the existing configuration gave sufficient sliding durability. However, the life test on this configuration, when using a $CO_2$ refrigerant, indicated faulty sliding within a short time.

To solve the problem, we installed a flexible structure in the vane slot in the cylinder, as shown in Fig. 4(b). This flexible structure is slightly bent when the side of the vane is loaded with pressure, thus expanding the contact area between the vane and the slot, which reduces contact pressure and eases the sliding condition.

There are two points that must be taken into consideration for the effective maintenance of this flexible structure. Firstly, the effect of reducing contact stress by expansion of the contact area as the flexible structure bends must be maintained. Secondly, the bend stress caused by the repetitive loading generated during the compressor's operation must be kept below the fatigue limit.

We then conducted a life test on the flexible structure, depending on several types of specifications. Figure 5 shows the bend stress of the flexible structure, the calculated value of the contact stress during contact with the vane, and the result of the life test with this particular specification.

The area where both the bend stress ratio and contact stress ratio of the flexible structure are below one, is the range in which the flexible structure is effective. We determined the specifications of the flexible structure based on the point indicated in the figure.

## 5. Conclusion

As described above, we improved the conventional R410A refrigerant compressor for the characteristics of the $CO_2$ refrigerant and successfully developed a new compressor with sufficiently high performance, oil circulation rate and reliability. The reliability of the vane sliding portions, in particular, was achieved by employ-

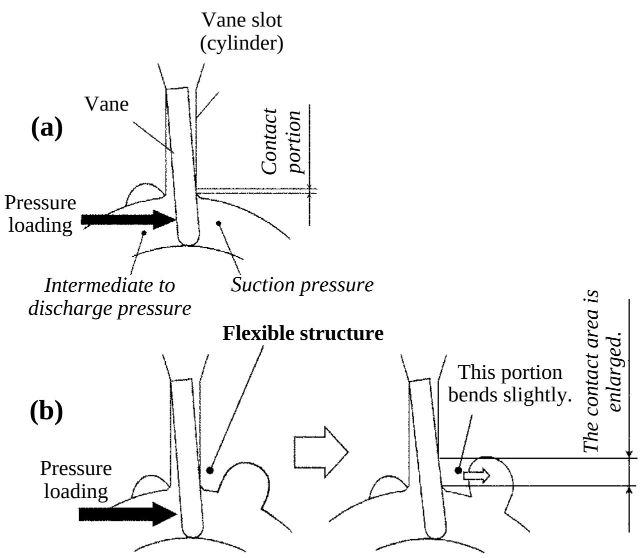


Fig. 4 Improvement in sliding condition of the vane's side

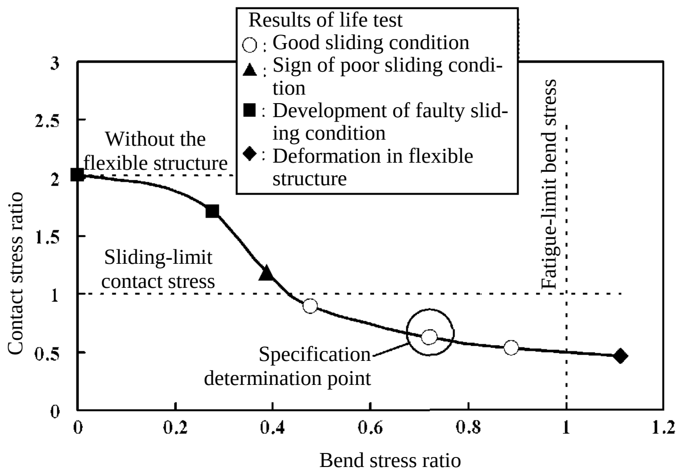


Fig. 5 Bend and contact stress at flexible structure

ing Mitsubishi's original technologies, such as the flexible structure for the cylinder vane slot and vane coating method (DLC-Si). As a result, we have successfully realized a compressor for a $CO_2$ refrigerant with a high operating pressure, namely the Single Rotary Compressor.

This compressor has been commercially supplied in Mitsubishi's ECO-CUTE range since autumn 2005 and has proved its top-of-the-industry performance and reliability in the market.

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