Overview of Development of Residential-Use Air-to-Water Heat Pump Using Natural Refrigerant to Achieve Carbon Neutral Society

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Heating and hot water supply using heat pump technology has attracted attention as a key technology to achieve carbon neutrality due to its lower greenhouse gas emissions compared to equipment using fossil fuels. In Europe, existing refrigerants which have high global warming potential (hereinafter referred to as GWP) fluorine compounds are being converted to propane (shown as refrigerant number R290, hereinafter referred to as R290), a natural refrigerant with an extremely low GWP. However, the refrigerant R290 is highly flammable and requires strict safety management. Against this background, Mitsubishi Heavy Industries Thermal Systems, Ltd., has developed Hydrolution EZY, a newly designed heat pump outdoor unit that uses refrigerant R290, achieving both high safety and marketability, such as low noise and high-temperature 75°C hot water supply.

1. Introduction

Since heat pumps transfer heat by changing the state of the refrigerant, they can produce more heat from the same amount of energy compared to combustion equipment. In addition, they use electricity, so their compatibility with renewable energy is high. On the other hand, from the standpoint of global warming prevention, the F-gas Regulation came into effect in Europe in 2024, stipulating that the GWP of refrigerants used in air-to-water heat pump units (devices that heat/cool water using thermal energy of the atmosphere, hereafter referred to as "ATW units") must be less than 150 by 2027, and that the use of hydrofluorocarbon (hereinafter referred to as HFC) refrigerants for ATW Monobloc shall be prohibited by 2032. Conventional ATW units use the HFC refrigerant R32, with a GWP as high as 675, and thus an alternative refrigerant is urgently needed.

With such a background, the refrigerant used in ATW units in Europe is being switched to propane (R290), with a GWP of 3. Characteristics of major refrigerants are shown in **Table 1**. R290 is characterized by higher hot water supply temperatures and excellent efficiency, due to its high condensation temperature operation. However, since R290 is also highly flammable, designing a system to minimize the risk of fire in case of a leak is necessary. At this time, Mitsubishi Heavy Industries Thermal Systems, Ltd. (hereinafter referred to as MTH) has developed a heat pump water cooling and heating unit for residential use that ensures high safety through risk assessment and solves issues related to conventional ATW units, such as low hot water supply temperature and noise, by utilizing the characteristics of the refrigerant and various measures for the source of noise, namely the fan and compressor.

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Table 1 Comparison of major refrigerants

	R410A	R32	R290
GWP (Global Warming Potential)	2088	675	3
Safety classification	A1 (no flame propagation)	A2L (Lower flammability)	A3 (higher flammability)
Critical temperature (°C)	71.3	78.1	96.7
Pressure at 45°C (MPa)	2.73	2.79	1.53
Refrigeration capacity (R32 = 100) *	91	100	54
COP (R32 = 100) *	98	100	104
Refrigerant density (kg/m^3)	34.6	25	11.7

* When evaporation temperature is 5°C, suction superheat is 5K condensation temperature is 45°C, and compression efficiency is 0.7

2. Adoption of Monobloc system

In Europe, heating systems for residential use generally circulate hot water generated by a heat source unit such as a boiler to indoor units. Indoor units are commonly floor heating systems in addition to radiator-based air-conditioning. When replacing the heat source supplying hot water to these systems with a heat pump, the Monobloc system which has a comparatively smaller workload in construction is used.

A system diagram of Monobloc is shown in **Figure 1**. Conventional ATW systems have a water heat exchanger, which exchanges heat between the refrigerant and water, located outside the outdoor unit. In contrast, this is installed inside the outdoor unit for Monobloc. Although the disadvantage of Monobloc is a larger outdoor unit compared to conventional types for this reason, it has the advantages of overall space-saving due to the built-in refrigerant piping and easy on-site work, which only requires installation of water piping. In addition, its greatest advantage to using R290 is that there is no risk of refrigerant leakage due to improper work during on-site installation, ensuring safety.

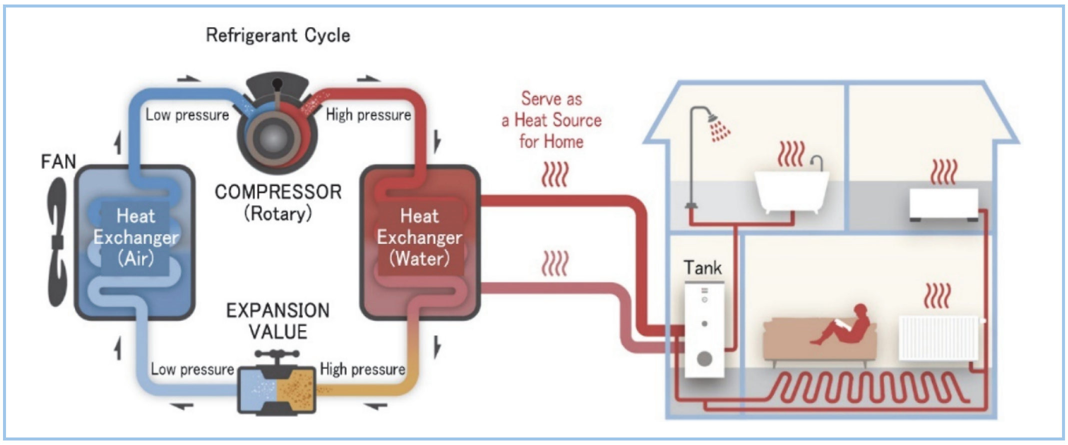


Figure 1 Overview of Monoblock system

3. Risk assessment of R290

As described above, R290 is highly flammable, so ensuring safety throughout the product lifecycle is a major issue. Therefore, in addition to complying with safety laws and standards, in-house safety standards have been established and incorporated into the unit specifications. To determine these standards, a risk assessment was conducted to identify hazardous events.

3.1 Procedure of risk assessment

Working group consisting of in-house experts and European sales office staff members was organized to classify product life cycle into five stages - transportation/storage, installation/commissioning, use, repair, and disposal. In addition, risk assessments were carried out at each stage. The greatest risk when using highly flammable refrigerants is fire caused by refrigerant leakage. Ignition of refrigerant occurs under the following three conditions are met: (i) occurrence of a refrigerant leak, (ii) formation of a flammable zone where the refrigerant concentration is equal to or greater than the ignition concentration, 2.1 vol%, and (iii) presence of an ignition source. Each working group created an exhaustive list of events that could cause these risks and developed countermeasures by product hardware, software, training, etc. (**Figure 2**). Identification of hazardous events based on risk assessments during installation/storage, use, and repair, as well as their countermeasures and training infrastructures are introduced in this report.

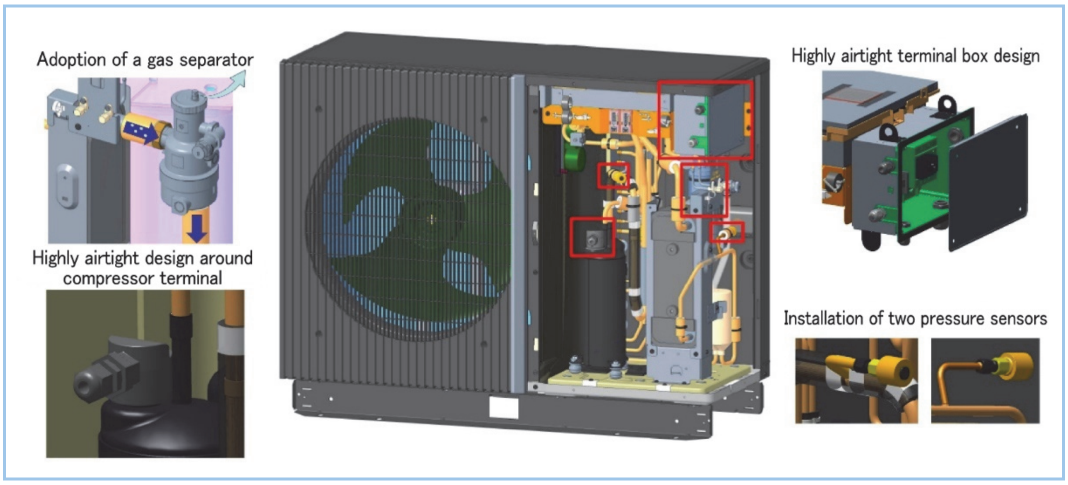


Figure 2 Reflecting safety measures for the unit

3.2 Hazardous events during installation/commissioning and their countermeasures

After a unit is delivered to the installation site (residence), an installer installs and commissions the unit.

(1) Improper selection of the installation site increases the risk of the refrigerant concentration reaching the ignition concentration due to refrigerant retention, and ignition from a surrounding ignition source in the event of refrigerant leakage. For this reason, strict installation restrictions, such as prohibiting installation in areas with inadequate ventilation, including semi-basements and machine rooms, were established. In addition, based on the results of the following described refrigerant leak simulations, areas around the unit where the refrigerant concentration could reach the ignition concentration in the event of refrigerant leakage are identified, and guidance and training to prevent items that could be ignition sources from being installed in such areas is provided.

(2) Risk reduction during installation and repair work is dependent on the skill level of the worker, which is difficult for the manufacturer to control. Therefore, guidance and training are provided so workers will carry a refrigerant detector during work in order to quickly recognize a refrigerant leak.

(3) During installation, if the wiring between the power supply and the outdoor unit is incorrect, there is risk of short circuit, which can be a source of ignition. Even in the event of such a short circuit, the refrigerant will not ignite if the ambient refrigerant concentration is below the ignition concentration. Therefore, a terminal block for wire connection is installed in a newly designed, highly airtight terminal block box. This airtight condition greatly reduces the risk that the refrigeration concentration in the area around the terminal block will reach the ignition concentration due to a leak and retention of the refrigerant.

3.3 Hazardous events due to long-term use and their countermeasures

Long-term use is a concern because there is a risk of short circuit due to frayed wires caused by vibration during operation or age-related deterioration.

(1) In the case of improper wiring of the functional components, a short circuit may occur due to the accumulation of dust and other substances at the terminals. Therefore, for functional components installed in the machine room, such as pressure sensors and expansion valves, products with a structure that integrates the wiring are used to reduce the risk of a short circuit.

(2) Of components mounted around the refrigerant circuit, the compressor terminals have the highest current flow and are considered to have a higher risk of failure compared to other components. Therefore, the compressor terminals are covered with a highly airtight cover to

prevent the refrigerant concentration in this section from reaching the ignition concentration.

(3) If the water heat exchanger, which exchanges heat between the refrigerant and water, is damaged, the refrigerant may leak into the room through the water circuit. Therefore, a gas separator is installed inside the unit in order to discharge any refrigerant in the water circuit out of the water circuit. The gas separator is fitted with a cover so that the refrigerant can flow to the lower part of the machine room.

(4) Some electronic components such as relays may generate minute sparks. While this is not a problem during normal use, it can pose a risk in an environment filled with refrigerant at the ignition concentration. Therefore, for functional components (relays, pressure switches, thermostats, etc.) which may cause sparks, explosion-proof certified components that do not have a risk of ignition during normal use are used.

(5) By mounting two pressure sensors in the refrigerant circuit, the fluctuation of refrigerant pressure during operation can be closely monitored and abnormality can be detected quickly.

3.4 Hazardous events during repair and their countermeasures

In the event an abnormality occurs in the unit, a service technician visits to the site to repair it.

(1) To replace a functional component in the refrigerant circuit, removing the refrigerant from the circuit must be performed first. If this removal work is not performed properly, there is an increased risk of the refrigerant leaking. For this reason, videos and documents on work procedures using an explosion-proof refrigerant recovery machine have been prepared, and guidance and training are provided.

(2) To replace functional components such as the compressor in equipment that uses a conventional refrigerant, soldered joints between pipes must be unsoldered in order to disconnect them after the refrigerant has been recovered. However, there is the risk that the refrigerant from the refrigerant circuit may not be completely removed when unsoldering. Therefore, the procedure to replace the functional components is set so that the refrigerant pipes are first cut to disconnect them and then the soldered joints are unsoldered. This procedure opens the refrigerant circuit before unsoldering, which significantly reduces the risk of residual refrigerant.

3.5 Consideration of training infrastructure

Before introducing products using highly flammable R290 onto the market, the risk assessment team, regulatory investigation team, contract team, and training team organize the sales structure and contractual matters, and create a training program for workers. Training is conducted with printed materials and videos.

4. Simulation and actual equipment verification of refrigerant leakage

Simulation of a refrigerant leak was conducted by risk assessment. According to simulation results, because the machine room was airtight, the refrigerant concentration did not fall below 2.1 vol%, the ignition concentration, for more than one hour after leakage occurred, and pressure inside the machine room increased by about 180 Pa due to the leaking refrigerant. If pressure inside the machine increases, the risk of refrigerant entering into the terminal box or compressor terminals, which also carry the risk of becoming a source of ignition, increases.

As a countermeasure, a φ60 discharge hole was installed in the base (bottom plate). The refrigerant, which has a higher density than air, can escape through the discharge hole, thereby controlling pressure increase in the machine room. It was also found that by agitating and discharging the leaked refrigerant in the machine room using a fan, the refrigerant concentration in the machine room can be reduced to less than 1.05 vol%, half of the ignition concentration, in approximately 10 minutes (**Figure 3** and **Figure 4**). This keeps the refrigerant concentration below the ignition concentration until a service technician can arrive on site, thus ensuring safety. In addition, drilling a φ60 hole in the base makes it easy to check for a refrigerant leak in the machine room during installation and maintenance work by placing a refrigerant detector under the unit.

Furthermore, agitating the leaked refrigerant using the fan was found to be maximally effective in preventing the formation of a flammable area around the outdoor unit (**Figure 5**).

Simulation results confirmed the effectiveness of the countermeasures, so verification using actual equipment equipped with the countermeasures was carried out. As a result, the refrigerant concentration decreased to 1.05 vol% in approximately 8 minutes due to fan agitation after the refrigerant leakage stopped, thus validating the analysis. The refrigerant concentration in the power terminal box and the compressor terminal cover was also confirmed to remain less than the ignition concentration of 2.1 vol%, thus ensuring the safety.

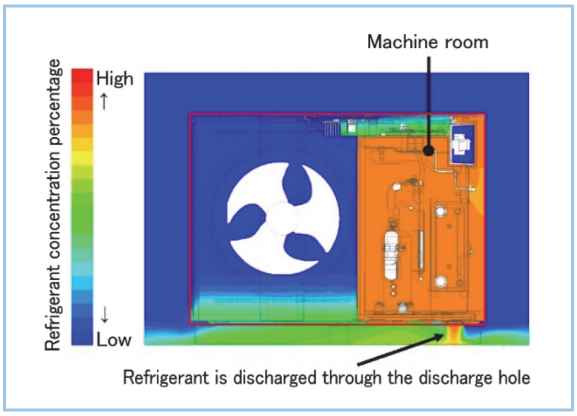


Figure 3 Distribution of refrigerant concentration inside the unit

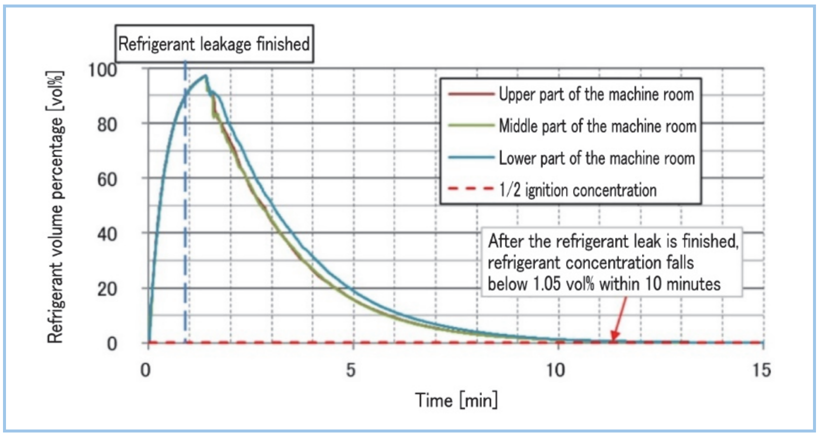


Figure 4 Change in refrigerant concentration in case of fan operation

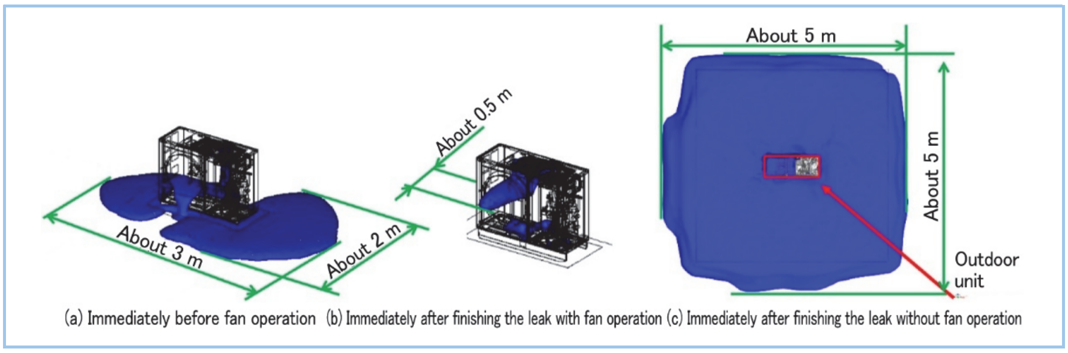


Figure 5 Area with a refrigerant concentration of 1.05 vol% around outdoor unit (viewed from above)

5. Technology to improve marketability

Efforts were made to provide the following additional functions in order to improve the market competitiveness as well as performance and safety required for a heat pump water cooling and heating unit.

5.1 Lower noise

Since heat pump water cooling and heating units are often installed in environments close to the user, such as on residential walls, and tend to be noisier than boilers, efforts were made to reduce the noise level. Noise from the unit is mainly generated by two sources: the fan and the compressor. First, in order to reduce noise but provide the same air flow rate, fan speed was reduced and fan size was increased compared to the current unit. Next, to reduce the compressor noise, anti-vibration rubber was inserted between the compressor and the sub-base, which had been connected to the base only by dedicated rubber dampers. This double vibration isolation structure suppresses compressor vibration and its propagation, thereby reducing noise. Furthermore, unlike conventional units, a high performance sound absorbing insulation material is attached on the box - shaped compressor cover panel. As a result of these measures, noise level when operated at maximum capacity decreased by 7 dB compared to the current unit (**Figure 6**).

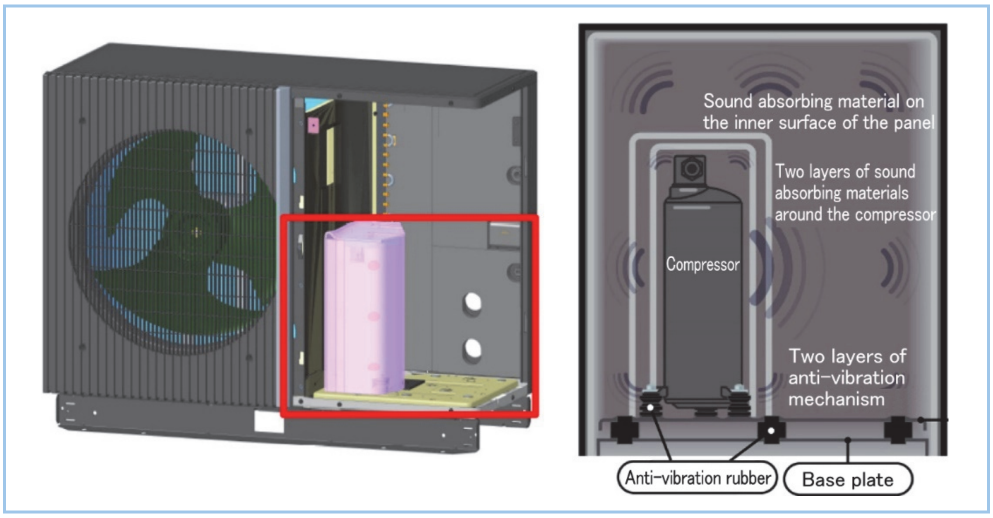


Figure 6 Lower-noise structure

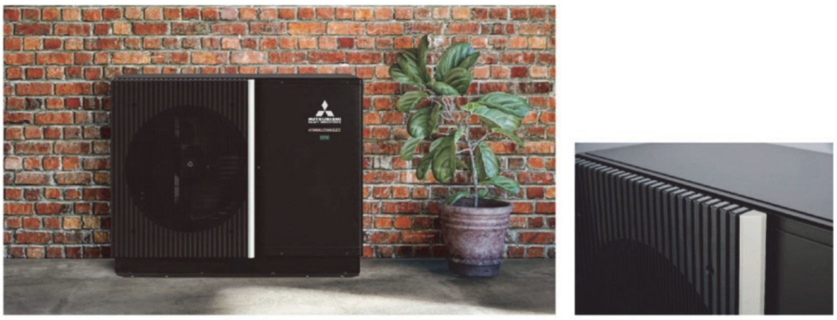
5.2 High-temperature 75°C hot water supply

Since heat pump water cooling and heating units are often used to replace boilers, high-temperature hot water supply similar to that of boilers is required. High-temperature hot water supply is also advantageous in terms of reducing the size of the tank as increased energy is stored in the tank, and in terms of sanitary measures against legionella and other contaminants. Regarding characteristics of R290, a higher condensation temperature at a pressure lower than conventional R32 can be achieved. Accordingly, this new model using R290 can provide high-temperature up-to-75°C hot water supply in a wide range of atmospheric temperatures from -25°C to 43°C, using a refrigerant control and a compressor optimized for R290, in contrast to conventional units using R32 which can provide a maximum hot water supply temperature of 60°C.

5.3 Design for Europe

In Europe, where the developed unit is to be sold, not only performance and price, but also design, are strongly demanded. In order to attract new customer segments, the developed unit has an exterior design that has been updated from previous models and is black in color to harmonize with European housing.

The fan guard on the front of the unit, which significantly affects the appearance of the unit, is made of resin and is accented with silver vertical lines. The structure of the fan guard makes it difficult to see the fan from an oblique angle and has a concave-convex shape parallel to the vertical lines of the front panel, creating an exterior design with a strong impression while harmonizing with various installation environments (**Figure 7**).



(a) Product image (b) Enlarged view of fan guard

Figure 7 Product exterior view

5.4 Other features

(1) The highest seasonal coefficient of performance rank A+++ (floor heating condition) in Europe was achieved.

(2) When R290 is used and the refrigerant amount is reduced, the amount of enclosed greenhouse gas decreases by 99.8% in CO_2 equivalency compared to conventional model.

(3) Specifications of the developed unit and a conventional model are compared in **Table 2**.

Table 2 Comparison of specifications of the developed unit and the conventional model

	Conventional model	Developed unit
Type	FDCW71VNX-W	FDCM71VNX-P
Refrigerant (contained amount)	R32 (1.84 kg)	R290 (0.85 kg)
Maximum noise level	69 dB(A)	62 dB(A)
Seasonal coefficient of performance (heating)	4.50 (A++)	4.61 (A+++)
Maximum hot water supply temperature	60°C	75°C
Operating temperature range	-20°C to 43°C	-25 to 45°C

6. Conclusion

A residential-use heat pump water cooling and heating unit that uses R290, a natural refrigerant with a low global warming potential, was developed. R290 is highly flammable, so safety must be ensured. The developed unit complies with laws and safety regulations. A risk assessment for its entire product lifecycle was conducted and the results were reflected in the product design and development of sales/training materials. For safety measures, analysis and actual equipment tests were carried out to quantitatively evaluate effectiveness. In addition, in order to improve marketability, the developed unit achieved high-temperature hot water supply, lower noise, and an updated exterior design.

Through this development, a foundation for the development of various outdoor heat pump units using R290 has been established. As a result of this development, 6.0 kW and 7.1 kW models are first to be introduced to the market. In the future, the MTH product lineup will expand by the development of large-capacity models and products with different specifications. MTH will continue to develop units using propane, a natural refrigerant, and contribute to carbon neutrality.