Railway Air Conditioning Systems for European Market Using Natural Refrigerant R290 (Propane)

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Abstract

With the tightening of refrigerant regulations toward achieving a sustainable society, the railway air conditioning industry is seeking natural refrigerants with Low Global Warming Potential (GWP) and low environmental impact. R290 (C3H8 (propane)) has drawn attention as a refrigerant offering excellent cooling performance and low environmental impact, but given that it is highly flammable, risk assessment and fire prevention measures are essential for its adoption. Accordingly, Mitsubishi Electric Corporation developed a safe and highly reliable railway air conditioning system compliant with European regulations, and designed and verified a refrigeration cycle using R290. We achieved both environmental performance and safety and established practical applicability as a railway air conditioning system by using a reduced-refrigerant design, running multiple small independent refrigeration cycles, placing brazed joints in optimal locations, and adopting a rapid discharge mechanism for leaked refrigerant. This achievement has been adopted for a commuter train air conditioning system in Munich, Germany, and will contribute to expanding the application of R290 throughout the railway air conditioning industry.

1. Introduction

Mitsubishi Electric Klimat Transportation Systems S.p.A., an Italian subsidiary, received an order for a railway air conditioning system using R290 natural refrigerant for commuter trains in Munich, Germany. This is the first time a Japanese company received an order for an air conditioning system using R290 for railway rolling stock[*1]. With refrigerants being reviewed from the perspective of reducing greenhouse gases in recent years, the introduction of environmentally considerate refrigerants is being sought. This development explores adopting R290 refrigerant, which has low environmental impact, in the railway air conditioning industry—yet, given that R290 has a high level of flammability, measures are required to reduce refrigerant leakage and fire risks. This paper outlines the design of the refrigeration cycle used to develop a safe and highly reliable R290-based air conditioning system compliant with European regulations, as well as its safety measures.

2. Shifting from Conventional Refrigerants to Natural Refrigerants, and Regulatory Changes

The Sustainable Development Goals (SDGs) are guidelines adopted by UN member states in 2015, with the aim of to solving issues such as poverty, inequality, and environmental degradation by 2030. With 17 goals and 169 targets, they seek to achieve a society that leaves no one behind while maintaining a balance between the economy, society, and the environment. Companies play an important role in achieving these SDGs, and they must review their business strategies to help prevent global warming and address environmental pollution. The promotion of decarbonization and fluorocarbon refrigerant regulations in particular are driving the need to reduce CO_2 emissions and lower environmental impact.

European fluorinated gas regulations (commonly known as the “F-gas Regulation”)[(1)] were promulgated in 2006 and came into effect in 2015, with the aim of reducing emissions of HFCs (hydrofluorocarbons), PFCs (perfluorocarbons), and SF_6 (sulfur hexafluoride). In addition to regulations on products and equipment, sales volumes are being reduced in stages through an HFC quota system.

*1 As of September 19, 2024, based on Mitsubishi Electric Corporation research

The Kigali Amendment (MOP28) to the Montreal Protocol is a framework for the phased reduction of the production and use of fluorocarbon refrigerants as part of measures to ensure protection of the ozone layer and combat global warming. As a result, refrigerant and air-conditioning equipment manufacturers are being forced to shift to Low GWP refrigerants. Per- and Polyfluoroalkyl Substances (PFAS), which are organofluorine compounds, also remain in the environment for long periods of time and are of concern for their impacts on living organisms—in Europe, their use is restricted by regulations governing PFAS. With the new regulatory proposal in 2023, some fluorocarbon refrigerants are also included, and after the transition period ends they will be prohibited, so future developments will need to be closely monitored.

R22 refrigerant had been mainstream in the past in Japan's air-conditioning industry, however, following amendments to the Montreal Protocol, production was phased down by 2020, and the shift to R407C and R410A progressed. R410A is used for residential and commercial air conditioning, while R407C is used domestically and R134a is used overseas for railway air conditioning systems.

With recent regulatory tightening, residential and commercial air conditioning is shifting to R32, which has a relatively low GWP, and conversion to even lower-GWP refrigerants is also being considered. In the European railway industry, demand is also increasing for HVAC (Heating, Ventilation, and Air Conditioning) systems using the natural refrigerant R290, from the perspective of reducing environmental impact. A comparison of refrigerants is shown in Table 1.

Table 1 Refrigerant comparison

	R22	R134a	R407C	R410A	R32	R290
Application	Old air conditioners	Car air conditioners	Air conditioners (R22 replacement)	Air conditioners	Air conditioners	Air conditioners (Low-GWP compliance for the European market)
Ozone Depletion Potential (ODP)	0.055	0	0	0	0	0
GWP	1810 *2	1430 *2	1774 *2	2088 *2	675 *2	0.02 *3
PFAS regulations	Not applicable	Applicable	Applicable	Not applicable	Not applicable	Not applicable

*2 Evaluation criteria based on the IPCC Fourth Assessment Report(2)
*3 Evaluation criteria based on the IPCC Sixth Assessment Report(3)

3. Characteristics of R290 as a Refrigerant

While R290 is extremely highly flammable given that it is generally known as propane gas, as a refrigerant it has excellent thermodynamic properties compared with other refrigerants such as R407C and R32.

(1) High-efficiency, energy-saving refrigerant

R290 has the characteristics of high evaporating pressure (low pressure) and low condensing pressure (high pressure). Therefore, when operating the refrigeration cycle under the same conditions, using R290 results in a lower compression ratio and can reduce the work done by the compressor (power consumption). For this reason, it can be said to be a very advantageous refrigerant for achieving energy savings.

(2) Suitable for operation in high outdoor-temperature environments

R290 not only has relatively low condensing pressure (high pressure) but also has the characteristic of low discharge gas temperature. The lower the discharge gas temperature, the more thermal stress on internal compressor components is reduced, thereby reducing compressor load during operation in high outdoor-temperature environments.

As an example showing these characteristics, Table 2 summarizes differences in the states of each refrigerant when cooling operation is performed at an evaporating temperature of 10°C and a condensing temperature of 45°C, assuming constant compression efficiency and volumetric efficiency of the compressor. This table shows that R290 is an excellent refrigerant with the characteristics of a small compression ratio and low discharge temperature.

Table 2 Comparison of refrigerant states during cooling operation

	R290	R32	R407C
Evaporating pressure (low pressure)	0.64MPa	1.11MPa	0.65MPa
Condensing pressure (high pressure)	1.53MPa	2.80MPa	1.75MPa
Compression ratio (condensing pressure ÷ evaporating pressure)	2.39	2.52	2.69
Discharge temperature	53°C	77°C	62°C

Evaporating temperature 10°C, condensing temperature 45°C

4. Risk Management for Flammable Refrigerants

As outlined in Chapter 2, the air conditioning industry is required to respond to various refrigerant regulations aimed at reducing environmental impact, however, R32 and R290 are flammable refrigerants, and R290 in particular is classified as a highly flammable refrigerant. Ensuring safety against ignition is required to use these flammable refrigerants safely.

Refrigerant ignites when all these three conditions are met: (1) Rapid leakage, (2) Presence of an ignition source, and (3) Formation of a flammable range. Therefore, risk assessment for flammable refrigerants determines ignition probability by multiplying the probabilities of these three conditions, and determination is made in accordance with each device's safety criteria. This risk assessment should be evaluated across the entire product lifecycle from delivery to disposal (logistics, installation, use, maintenance, and disposal).

Ignition probability of refrigerant = (1) Rapid leakage × (2) Presence of an ignition source × (3) Formation of a flammable range

When using the highly flammable refrigerant R290, sufficient safety measures are required based on this risk assessment. Specifically, measures must be taken to reduce the probability of rapid refrigerant leakage occurring, reduce the probability of encountering ignition sources, and also prevent the formation of a flammable range by reducing refrigerant charge and discharging leaked refrigerant.

5. Features of the Railway Air Conditioning System for the European Market

Measures against the ignition risk of leaked refrigerant are essential when introducing R290 into railway air conditioning systems that have a high level of public importance. In particular in Europe, as part of safety measures, the upper limit of refrigerant charge in refrigeration systems is specified by the European standard EN (European Norm) 378-1[4]. This upper limit is determined based on the flammability of the refrigerant used (lower flammability limit (LFL)) and the installation environment of the HVAC system; if this limit is exceeded, additional safety measures based on a risk assessment according to the usage environment, as outlined in Chapter 4, are required.

A standard railway air conditioning system is a unit type in which the indoor unit and outdoor unit are integrated, as shown in Fig. 1, and is mounted on the roof of the vehicle. The refrigeration cycle has a fully hermetic structure in which all related components are joined with brazing.

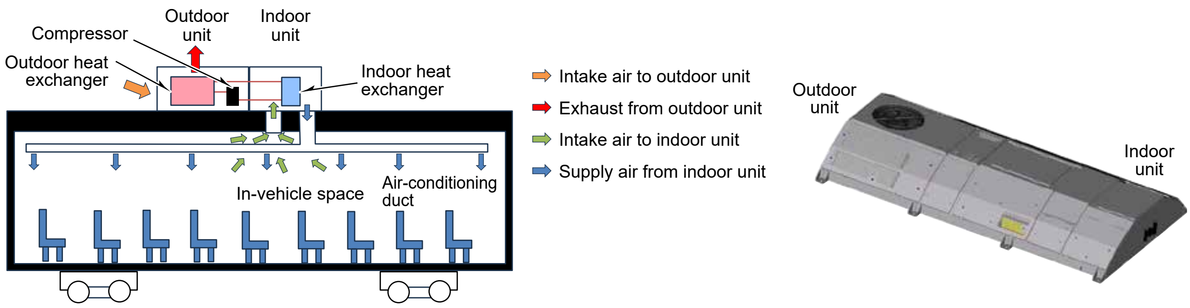

Fig. 1 Roof-mounted unit-type railway air conditioning system

The developed HVAC unit with R290 outlined in this paper is characterized by implementing the following three safety measures in this roof-mounted unit.

5.1 Multiple small refrigeration circuit design

Compliance with EN 378-1(4) is required to adopt R290 in railway air conditioning systems for the European market. The HVAC system outlined in this paper is mounted on the roof of a railway vehicle for the German market with an overall length of about 17m and a floor area of about 40m^2; based on its installation environment, the maximum charge limit m_{max} of R290 is calculated using the formula shown in EN 378-1 as follows.

$$m_{max} = 2.5 \times LFL^{5/4} \times h_o \times A^{1/2}$$

- LFL (R290 lower flammability limit): 0.038kg/m^3
- H_o (HVAC system installation height): 2.2m
- A (floor area of the installation space): 40m^2

According to this calculation, the maximum charge limit for R290 is 583g.

The cooling capacity required per vehicle for this class of railway vehicles in Europe also is generally about 32kW; however, if a design similar to a refrigeration cycle using conventional R407C is applied, the amount of R290 required for one HVAC unit would be 5,000g, which is about nine times the maximum charge limit. Therefore, we improved the heat exchanger design and achieved a reduced-refrigerant design. Specifically, as shown in Table 3, by reducing the tube diameter of the heat exchanger and increasing its row pitch, the internal volume of the heat exchanger was reduced to about 1/4 of the conventional design. This design reduced the refrigerant amount and, while maintaining performance equivalent to the conventional unit, suppressed the required refrigerant amount per vehicle to 2,000g.

Table 3 Comparison of heat exchanger specifications

		R407C (conventional unit)	R290 (developed unit)
Reduced tube diameter (mm)		Outer diameter 6 (thickness 0.21)	Outer diameter 5 (thickness 0.36)
Increased tube row pitch (mm)		13.00	17.32
Increased tube stage pitch (mm)		15.00	20.00
Reduced fin pitch (mm)		3.50	2.00
Indoor heat exchanger volume (L)		80.5	62.1
	Inner tube internal volume (L)	10.1	2.6
Outdoor heat exchanger volume (L)		98.3	62.0
	Inner tube internal volume (L)	12.3	2.6

Furthermore, by dividing this refrigerant and charging 500g each into four independent small refrigeration circuits, it was kept within the EN 378-1 requirements and below the lower flammability limit. This eliminated the need for special safety measures and risk assessment against fire risk, ensuring a high level of safety for the HVAC system.

The design with four refrigeration cycles is also suitable for railway air conditioning systems not only for ensuring safety, but also in the following respects.

(1) Comfortable control of cabin temperature

ON/OFF control of each refrigeration cycle means cooling capacity can be adjusted in five steps—0%, 25%, 50%, 75%, and 100%—making it possible to maintain the cabin temperature to an appropriate level.

(2) High redundancy and reliability

Four independent refrigeration cycles ensure high redundancy and also contribute to stable train operation. As global warming progresses, outdoor temperatures are rising, and the importance of HVAC systems is increasing further to improve in-vehicle comfort. For railway vehicles with a high level of public importance, high redundancy of HVAC systems is a key factor directly linked to sound train operation.

The developed unit is designed to meet these requirements and is an HVAC system that balances safety, comfort, and reliability.

5.2 Eliminating brazed refrigerant piping in the in-vehicle area

If refrigerant leaks within the in-vehicle area of the HVAC system, because that area and the passenger compartment are connected via the return opening and supply opening, there is a possibility that leaked refrigerant may flow into the passenger compartment. The refrigerant charge will be kept below the limit specified by safety standards; however, the risk of refrigerant leakage into the passenger compartment should be reduced as much as possible.

Therefore, to further improve safety, the internal layout design of the HVAC system was improved as shown in Fig. 2. Conventionally, the connection area between the hairpin tubes of the in-vehicle heat exchanger and piping, which was included in the in-vehicle area, was newly established as a “second outdoor area,” and seamless piping with no brazed joints was adopted for piping that penetrates the in-vehicle area sandwiched between the first outdoor area and the second outdoor area.

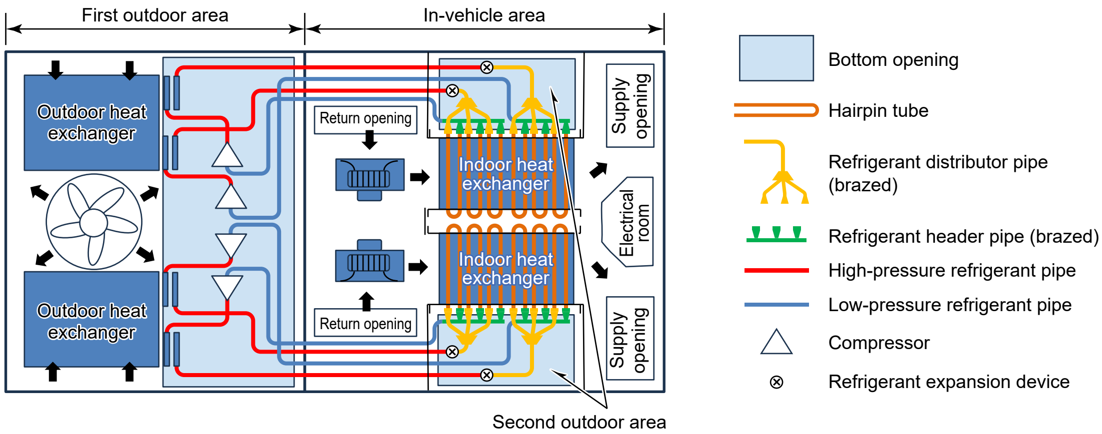

Fig. 2 Layout diagram of refrigeration cycle components

This design change completely eliminated brazed joints, which carry a high risk of refrigerant leakage, from the in-vehicle area, making it possible to keep the risk of refrigerant leakage into the passenger compartment extremely low.

5.3 Measures to discharge leaked refrigerant from the brazed section

Although the brazed section was positioned placed outside the in-vehicle area, measures are necessary so that refrigerant will not remain within the area even if it leaks there. Therefore, in the developed unit, an opening was provided in the bottom surface of the area where brazed components are located. The light-blue area shown in Fig. 2 (bottom opening) corresponds to this opening.

Because R290 has a higher specific gravity than air, even if it leaks in the brazed section, it moves to the bottom of the unit and is released to the outside through the opening. railway air conditioning systems are installed on the roof and the surroundings are an open space; leaked refrigerant disperses and its concentration will not rise into the flammable range, thereby ensuring safety.

6. Conclusion

From the perspective of preventing global warming, we examined fire countermeasures for applying R290 to railway air conditioning systems and proposed a design method for a safe and highly reliable refrigeration system. In particular, designs that combined practicality and safety—such as limiting the refrigerant charge based on EN 378-1[4], multiple small refrigeration circuit design, eliminating brazed joints in the in-vehicle area, and a rapid discharge mechanism in the event of refrigerant leakage—were effective. This enabled us to take an important step toward expanding the application of R290 in the railway air conditioning industry. Going forward, we will continue research aimed at further improving safety and efficiency based on broader field testing and operational data.

References

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