



Development of Refrigeration and Air-Conditioning Technologies for
Practical Use of Next-Generation Low-GWP Refrigerants

Overview

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Volume 1 Project Overview

Accelerated transition to next-generation refrigerants with low global warming potential (GWP) is required for the Kigali Amendment to the Montreal Protocol and Japan's Act on Rational Use and Proper Management of Fluorocarbons. However, several low-GWP refrigerants are flammable, and ensuring their safe use remains expensive. To address these challenges, Japan aims to develop refrigerants that simultaneously achieve sufficiently low GWP and flammability classified as A2L, and high energy efficiency.

The national research and development program titled "Development of High-Efficiency Refrigeration and Air-Conditioning Technologies toward the Practical Application of Next-Generation Low-GWP Refrigerants" (JPNP23001) was launched in 2023 with the support of the New Energy and Industrial Technology Development Organization (NEDO). In addition, this five-year project is currently being implemented through collaborations among universities, national research institutes, and industrial partners. The program integrates four parallel research themes: (1) screening and characterization of low-GWP refrigerant mixtures; (2) evaluation and mitigation of chemical instability and self-decomposition risks; (3) development of key components and materials for maintaining high system performance; and (4) establishment of performance evaluation methods and safety standards.

Through these themes, the program aims to accelerate the safe commercialization and international standardization of low-GWP refrigerants for air-conditioning and refrigeration systems, thereby contributing to the global decarbonization and sustainable growth of the HVAC industry.

Volume 2 Evaluation of the Properties of Low-GWP Mixed Refrigerants

1. R&D Overview and Outcomes (Kyushu Sangyo University)

The R&D subtheme “Evaluation of thermophysical properties, safety, and environmental impacts of low-GWP refrigerant mixtures; development of component technologies for compatible equipment; and performance evaluation of systems” aims to realize heat-pump air-conditioning systems compatible with low-GWP refrigerants in an integrated manner, as shown in Figure 2.1-1. Its scope extends from “screening of candidate refrigerant mixtures” (refrigerants A-1 and A-2), through “performance evaluation of refrigerant mixtures” (refrigerants B-1 and C-1), “evaluation of component equipment” (Equipment A-1, A-2, A-3, B-1, C-1, C-2, and C-3), and “system performance evaluation” (refrigerants D-1 and D-2), to “environmental impact assessment” (Refrigerant E-1). Within this framework, the present R&D topic, “Characterization of low-GWP refrigerant mixtures,” covers the portions corresponding to “screening of candidate refrigerant mixtures” (refrigerants A-1 and A-2), “performance evaluation of refrigerant mixtures” (refrigerants B-1 and C-1), “system performance evaluation” (refrigerants D-1 and D-2), and “environmental impact assessment” (Refrigerant E-1) in Figure 2.1-1.

First, candidate low-GWP refrigerant mixtures are screened, and the thermophysical properties of selected binary and ternary refrigerant mixtures are measured with high accuracy in “screening of candidate refrigerant mixtures” (refrigerants A-1 and A-2) and “performance evaluation of refrigerant mixtures” (refrigerants B-1 and C-1). Equations of state and mixture models are subsequently developed and incorporated into REFPROP, a thermophysical property calculation software released by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce. This enables the candidate next-generation green refrigerants to be efficiently narrowed down. In previous NEDO projects, refrigerant property evaluations focused mainly on GWP values, thermophysical properties, heat-transfer characteristics, and cycle performance. In contrast, additional important factors such as flammability, timing for commercialization of new refrigerant mixtures, refrigerant availability, and the results of refrigerant certification evaluation under ASHRAE Standard 34 are now considered in current projects. Through this screening, reliable foundational information is provided at an early stage for subsequent R&D leading to “evaluation of component equipment” (Equipment A-1, A-2, A-3, B-1, C-1, C-2, and C-3) and beyond.

In “system performance evaluation” (refrigerants D-1 and D-2), the refrigerant mixtures narrowed down in “screening of candidate refrigerant mixtures” (refrigerants A-1 and A-2) and “performance evaluation of refrigerant mixtures” (refrigerants B-1 and C-1) are evaluated as refrigeration cycles by incorporating them into systems using advanced heat exchangers, compressors, and refrigeration oils developed in equipment A-1, A-2, A-3, B-1, C-1, C-2, and C-3. Therefore, it is necessary to construct a refrigeration-cycle model test apparatus that enables a flexible system performance evaluation. At the same time, individual components, such as heat exchangers and compressors, are replaced as the development progresses. Cycle performance is evaluated and verified, and the results are sequentially fed back to refrigerants A-1, A-2, B-1, and C-1 to utilize them for more advanced system performance evaluation, simulation tests, and fabrication of actual equipment. At this stage, REFPROP incorporating the equations of state and mixture models developed in “performance evaluation of refrigerant mixtures” (refrigerants B-1 and C-1) is expected to serve as a common thermophysical property calculation tool. Even if discrepancies arise between actual equipment tests conducted in other commissioned or subsidized projects and simulation tests, development time can be shortened by establishing an environment for rapid cause identification through mutual collaboration.

In “environmental impact assessment” (Refrigerant E-1), life cycle climate performance (LCCP) evaluation is

conducted with commercialization in mind, and the market potential of products using new refrigerants is investigated from the perspectives of commercial viability and productivity. Specifically, an LCCP evaluation method is developed for air-conditioning equipment compatible with low-GWP refrigerant mixtures. Moreover, a life cycle assessment (LCA) is conducted, and the environmental impact per unit of such equipment is evaluated. The future demand for air-conditioning equipment compatible with low-GWP refrigerant mixtures is also estimated. By integrating the LCA results with future demand projections, the future environmental impact on Japan associated with the diffusion of such equipment is evaluated. The results are fed back to each research institution and company to support the formulation of research strategies. In addition, AI-based analysis tools have been developed and utilized for R&D items, such as refrigerants A-1, A-2, B-1, C-1, D-1, D-2, A-1, A-2, A-3, B-1, C-1, C-2, and C-3, thereby supporting greater efficiency in research and development.

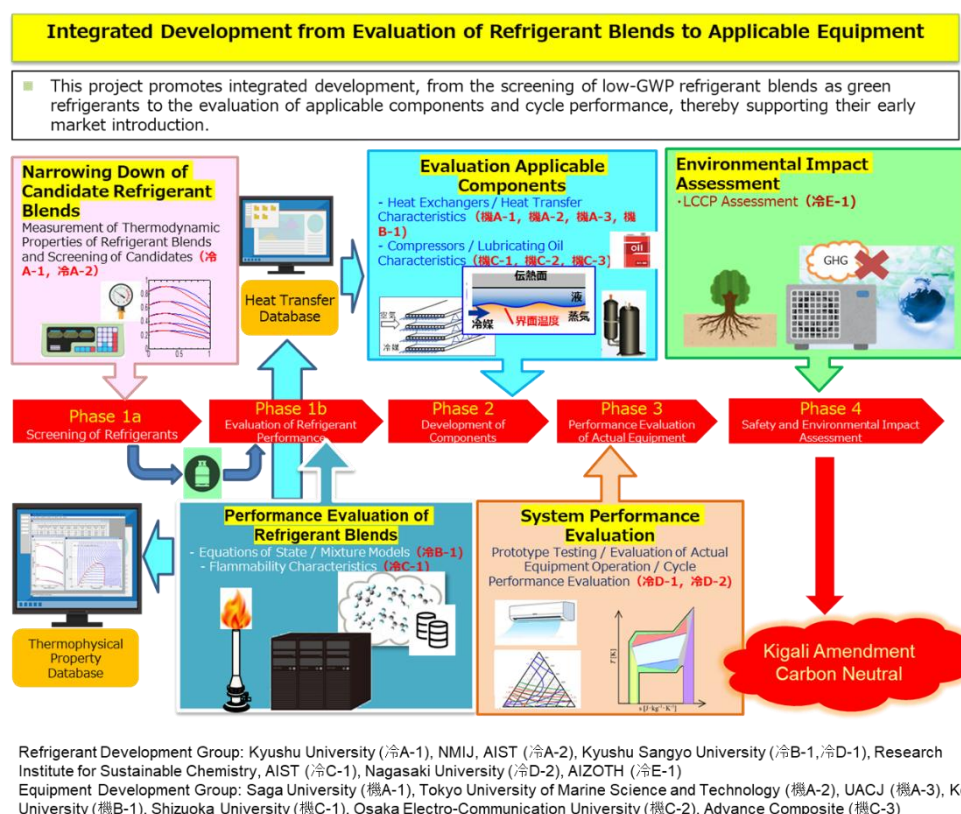


Figure 2.1-1 Workflow of the development of next-generation refrigeration systems

2. Acquisition of Thermophysical Property Data for Low-GWP Refrigerant Mixtures and Screening of Candidate Refrigerants (Kyushu University)

Under the Kigali Amendment to the Montreal Protocol, Japan is obligated to reduce its HFC production and consumption by 85% by the year 2036. The development of low-GWP refrigerants is required to achieve carbon neutrality by 2050. Accordingly, this study addresses the selection and screening of candidate refrigerants, acquisition of thermophysical property data, and characterization of refrigerant mixtures, which are indispensable in the early stages of developing low-GWP refrigerant mixtures that prioritize minimizing GWP.

Because refrigerants transport heat through phase changes during evaporation and condensation, they must possess thermophysical properties such as a normal boiling point and critical constants that are suitable for the operating temperature range of the equipment in which they are used. Safety, including flammability, toxicity, and decomposition reactions, is an important evaluation item that is being comprehensively examined in collaboration with other groups. In the initial screening of candidate refrigerants, 13 refrigerants were selected based on the research results reported by McLinden et al. at NIST, supplemented by the measured data and experience accumulated by Japanese researchers. These refrigerants include HFOs such as R-1132a, HFO-1123, R-1132(E), and R-1234yf; HFCs such as R-32 and R-152a; and hydrocarbons such as R-290 and CO₂ (R-744). However, because satisfying all the requirements related to performance, safety, and environmental impact for a single substance is difficult, its use as a refrigerant mixture is assumed.

Among these candidate refrigerants, HFO-1123 and R-1132(E) are regarded as promising first-component refrigerants because their GWP values are extremely low (1 or less), and their thermodynamic properties are close to those of existing refrigerants. However, concerns regarding self-decomposition reactions make their use as single-component refrigerants difficult, and they are expected to be useful as components of refrigerant mixtures. For the second and third components, R-1234yf, R-1234ze(E), R-32, and R-152a are selected as the leading candidates, considering their availability and practicality. Natural refrigerants such as propane (R-290) and CO₂ (R-744) are also considered under the limited conditions of use.

At Kyushu University, thermodynamic property measurements were conducted on several candidate refrigerant mixtures. As of March 2026, data on the PVT properties, saturated density, critical points, and vapor–liquid equilibrium were acquired for binary and ternary systems, as summarized in Tables 2.2-1 and 2.2-2. PVT measurements were performed by the isochoric method using a pressure vessel placed in a thermostatic bath, and data were acquired with high accuracy: ± 5 mK for temperature, ± 1 kPa for pressure, and $\pm 0.15\%$ for density. The saturated densities and critical points were determined by direct observation of meniscus disappearance. Efficient measurements using small sample quantities were achieved by combining multiple vessels. The vapor–liquid equilibrium was measured using the circulation method, and the compositions were determined using a TCD gas chromatograph. These measurement apparatuses have extensive track records, and their reliability has been sufficiently verified.

Specifically, PVT_x data were first obtained for the R-32/1234yf refrigerant mixture, and the existing REFPROP mixture model, namely the Akasaka model, was compared with the new Bell model. The R-32/1234yf mixture is the most widely used binary refrigerant mixture among the ternary mixtures that have obtained ASHRAE R-number designations, and this binary mixture is also registered in the R-454 series. Equipment using R-454B (68.9 mass% R32) and R-454C (21.5 mass% R32) has begun to enter the market. In the present evaluation of the R-32/1234yf system, the original Akasaka model in REFPROP 10.0 was confirmed to exhibit reduced accuracy in the high-density region. In contrast, the Bell model reproduced the experimental data well over a wide range. Therefore, the Bell model is strongly recommended for future calculations.

Detailed measurements were also conducted for the R-1132(E)/1234yf system, showing that, except near the critical point, the density can be reproduced with high accuracy within a deviation of 0.5%. These results clarify the importance

of the equations of state and mixture models based on reliable measured data. Measurements were also conducted for several ternary refrigerant mixtures, and the corresponding evaluations are presented in the figures.

This study addresses the selection of candidate substances, precise thermodynamic property measurements, and verification of REFPROP calculation models, all of which are indispensable for the practical application of low-GWP refrigerant mixtures. The results constitute foundational achievements that will contribute substantially to future refrigerant development and database enhancement.

Table 2.2-1 Binary refrigerant mixtures measured at Kyushu University (as of March, 2026).

Binary blend	Composition [mass%]	PvT	Saturated density	Critical point	Critical locus	VLE
R-1132(E)/1234yf	23/77 (R-474A)	✓	N/A	N/A	✓	✓
	30/70	✓	✓	✓		
	50/50	✓	✓	✓		
	70/30	✓	✓	✓		
R-1132(E)/32	20/80	✓	✓	✓	✓	✓
	50/50	✓	✓	✓		
	80/20	✓	✓	✓		
R-32/1234yf	7/93	✓	N/A	N/A	✓	✓
	10/90	N/A	✓	✓		
	20/80	✓	✓	✓		
	21.5/78.5 (R454C)	✓	N/A	N/A		
	43/57	✓	N/A	N/A		
	50/50	✓	✓	✓		
HFO-1123/1234yf	30/70	✓	✓	✓	✓	✓
	50/50	✓	✓	✓		
HFO-1123/32	40/60	✓	✓	✓	✓	✓
	60/40	✓	✓	✓		
R-1132(E)/290	60/40	✓	✓	✓	✓	✓
	80/20	✓	N/A	N/A		
HFO-1123/290	65/35	✓	✓	✓	✓	✓
	80/20	✓	✓	✓		
R-1132(E)/744	90/10	✓	N/A	N/A	N/A	N/A
	60/40	✓	N/A	N/A		

(*) Check mark indicates that the measurement has been completed, whereas “N/A” indicates that it has not yet been measured.

Table 2.2-2 Ternary refrigerant mixtures measured at Kyushu University (as of March, 2026)

Ternary blend	Composition [mass%]	PvT	Saturated density	Critical point	Critical locus	VLE
R-32/1132(E)/1234yf	10/30/60	✓	✓	✓	N/A	✓
	21.5/28.0/50.5 (R-479A)	✓	✓	✓		
	22.0/19.5/58.5	✓	✓	✓		
	44/23/33 (R-479B)	✓	N/A	N/A		
R-32/1123/1234yf	10/40/50	✓	✓	✓	N/A	✓
	21.5/40.0/38.5	✓	✓	✓		

3. Acquisition of Speed-of-Sound Data for Low-GWP Refrigerant Mixtures (Research Institute for Engineering Measurement, National Institute of Advanced Industrial Science and Technology)

At the Research Institute for Engineering Measurement, National Institute of Advanced Industrial Science and Technology, precise gas- and liquid-phase measurements of the speed of sound and density were conducted for various refrigerant mixtures, mainly composed of HFO-1123 and R-1132(E). These measurements provide the thermodynamic data required to develop highly accurate equations of state for next-generation refrigerants. As several thermodynamic properties are derived from the derivatives of the equations of state with respect to temperature and density, the reliability of the underlying measured data is critical. In particular, the speed of sound strongly affects the calculation accuracy of properties that are important for refrigeration-cycle evaluation, such as enthalpy and entropy. It therefore contributes substantially to improving the equations of state. In this study, two measurement apparatuses originally developed by the institute were used to acquire highly accurate speed of sound and density data over wide ranges in both gas and liquid phases.

In the gas phase, the speed of sound and density were measured simultaneously using acoustic and microwave resonance methods with a cylindrical cavity. The speed of sound was determined by generating acoustic resonance in a cylindrical resonator filled with the sample gas and measuring the resonance frequency. Because this apparatus also measures the microwave resonance, the cavity dimensions can be determined from the microwave resonance frequency measured under vacuum conditions. A key feature of this apparatus is its ability to perform absolute measurements of the speed of sound in gases, without calibration using a reference fluid. Using this method, the speed of sound in gases can be measured with an expanded uncertainty of approximately 0.04%. The measurement reliability of the method was confirmed through validation experiments using argon, for which the speed of sound is well established. In addition, the dielectric constant can be measured simultaneously from the microwave resonance frequency of the cylindrical resonator filled with the sample gas. By analyzing the measured dielectric permittivity data using the dielectric-virial equation, the sample-gas density can also be determined. The gas density can be measured with an expanded uncertainty of approximately 1 %, and its reliability was confirmed through validation experiments using argon. The gas-phase speed of sound and dielectric permittivity data also enable the derivation of the fundamental properties required to construct the ideal gas term of the equations of state, including the ideal gas isobaric heat capacity, polarizability, and

dipole moment.

In the liquid phase, an apparatus for the simultaneous measurement of the speed-of-sound and density was developed by combining an ultrasonic-pulse propagation speed-of-sound sensor with an oscillation U-tube densimeter. For the speed-of-sound measurements, the propagation time of a 4 MHz ultrasonic-pulse through the sample liquid was measured, and the speed-of-sound was obtained using the temperature and pressure correction parameters for the sensor. A pressure-resistant oscillation U-tube densimeter was used for the density measurements, and the density was determined from the vibration period of the U-tube filled with the sample liquid. The apparatus was calibrated using pure water and R1336mzz(Z), for which the speed-of-sound and density are well established. The expanded uncertainties of the speed of sound and density measurements in the liquid phase were estimated to be 0.17% and 0.08%, respectively. By simultaneously acquiring the speed of sound and density data under identical temperature and pressure conditions, adiabatic compressibility can also be derived, establishing a system for the comprehensive evaluation of liquid-phase properties.

Using these apparatuses and methods, the speed of sound and density data were acquired over wide temperature and pressure ranges for binary and ternary refrigerant mixtures mainly composed of HFO-1123 and R-1132(E) in combination with R-1234yf and R-32. The measurement data obtained for each refrigerant accurately described the temperature and pressure dependence and provided valuable information for evaluating the thermodynamic properties of the refrigerant mixtures. In particular, systematically clarifying the changes in the speed-of-sound and density resulting from differences in refrigerant composition is expected to contribute substantially to the validation of mixing rule models and the development of new equations of state.

4. Development of Equations of State and Mixture Models for Low-GWP Refrigerant Mixtures (Kyushu Sangyo University)

The R&D item “Characterization of low-GWP refrigerant mixtures” aims to rapidly screen candidate low-GWP refrigerant mixtures and establish a highly reliable thermophysical property basis that can be commonly used for equipment and system evaluations. Kyushu Sangyo University is responsible for (1) developing a Helmholtz-type equation of state for the low-GWP pure refrigerant R-1132(E) and (2) constructing mixture models for R-32/R-1132(E) and R-1132(E)/R-1234yf based on the Kunz–Wagner multifluid approximation. The resulting models serve as a common foundation for an integrated R&D process, from refrigerant candidate screening (Refrigerant A-1) to cycle evaluation (refrigerants D-1 and D-2) and equipment evaluation, with future implementation in NIST’s thermophysical property calculation database REFPROP.

First, for R-1132(E), a Helmholtz-type equation of state was developed using existing experimental data, including vapor pressure, saturated liquid and vapor densities, the (p, ρ, T) relationship, gas-phase speed of sound, and ideal-gas isobaric heat capacity. The vapor pressure was reproduced with an average deviation of 0.08% over the range from 240 K to near the critical temperature and within approximately 0.05% at temperatures above 275 K. The single-phase density was reproduced with an average deviation of 0.03% in the liquid phase and 0.17% in the gas phase, which are comparable to the measurement uncertainties. In contrast, the gas-phase speed of sound was reproduced with an average deviation of 0.04%. However, in the critical region, the density deviations reach approximately 2.9% at some points, indicating that additional data near the critical point are required to further improve the equation of state. To avoid unphysical behavior in the extrapolated regions that may arise from a model based on limited data, thermodynamic soundness was verified using virial coefficients, isochoric heat capacity, speed of sound, and the phase identification parameter (PIP), confirming that no anomalous behavior occurred over wide temperature and pressure ranges.

Next, using the above pure-substance Helmholtz equation, multifluid mixture models based on the KW model were

constructed for the binary systems R-32/R-1132(E) and R-1132(E)/R-1234yf. The mixture parameters, consisting of four parameters related to reducing temperature and reducing density and coefficients that adjust the contribution of the excess term, were optimized by nonlinear least-squares fitting to single-phase (p , ρ , T) relationship data and vapor–liquid equilibrium data, including saturated density and bubble-point pressure, obtained in Refrigerant A-1. Weighting by data type was introduced into the objective function to emphasize the reproducibility of the liquid-phase density. In contrast, quantities with relatively large uncertainty, such as the saturated vapor density, did not dominate the optimization. To avoid numerical instability in vapor–liquid equilibrium calculations and physical inconsistencies caused by overfitting, the behavior of vapor–liquid equilibrium curves, heat capacities, speed of sound, and related properties was monitored in the critical and extrapolated regions during optimization, and the final parameters were determined by adjusting the data points and weights, as necessary. As a result, the bubble-point pressures were reproduced within a relative deviation of 1% for both systems, and the saturated-density reproducibility was improved compared with that obtained using the REFPROP estimation parameters. In the R-1132(E)/R-1234yf system, deviations of approximately 3–5% were observed for the saturated vapor density, suggesting limitations in applying the generalized departure function of the KW0 model. Introducing a system-specific departure function and expanding the high-pressure data remain future tasks for improving the behavior near the critical region.

In summary, this study established a pure-substance Helmholtz-type equation of state and mixture models for refrigerant mixtures, both of which are indispensable for the evaluation and design of candidate low-GWP refrigerant mixtures. The study constructed thermophysical property foundation information that is common to cycle evaluation and equipment design. Additional data acquisition, including data near the critical region, further model advancement, and rapid feedback to other R&D items through implementation in REFPROP will be pursued in future studies to accelerate the screening and practical evaluation of low-GWP refrigerant mixtures.

5. Evaluation of Safety Characteristics for Screening Low-GWP Refrigerant Mixtures

(Research Institute for Sustainable Chemistry, National Institute of Advanced Industrial Science and Technology)

This R&D task was undertaken to quantitatively evaluate the combustion characteristics of candidate refrigerants and obtain data supporting the screening of refrigerant mixtures, thereby advancing the development of next-generation refrigerants that combine a particularly low GWP with high safety.

Candidate refrigerants were primarily examined in ternary mixture systems containing low-GWP fluoroethylene-based refrigerants. The dependence of the combustion characteristics on the mixing ratio and refrigerant concentration was evaluated to identify the composition ranges that satisfied domestic and international refrigerant safety criteria. Specifically, the study aimed to determine mixture compositions that provide safety equal to or greater than that of gases classified as “lower flammability class (Class 2L)” under the international standard ISO 817 and designated as “specified inert gases” under Japan’s High Pressure Gas Safety Act (HPGSA). Among the evaluation indices, particular emphasis was placed on the flammability limits and burning velocity, which are essential parameters for defining the lower flammability class.

The combustion characteristics of R-1132(E)/R-32/R-1234yf and CO₂/HFO-1123/R-290 systems were evaluated. Where necessary, the combustion characteristics of the corresponding binary mixtures and pure components required to assess the ternary systems were examined. For refrigerants with extremely low flammability, which are difficult to evaluate under normal gravity, microgravity experimental apparatus and lightweight quenching distance measurement devices were used to enable accurate measurements of the burning velocity and quenching distance. In addition, for

the explosion limits of the two candidate refrigerants narrowed down by the Group for Refrigerant Property Evaluation, evaluations were conducted not only using the HPGSA method but also using the flammability-limit measurement method required under ISO 817, namely, the ASHRAE method. The results provided data that can serve as a basis for domestic and international registration under ASHRAE 34, ISO 817, and the HPGSA.

First, the combustion characteristics of the R-1132(E)/R-32 (fixed at 10 wt. %)/R-1234yf mixture system, which was selected as a candidate refrigerant by the Group for Refrigerant Property Evaluation, were evaluated. The combustion characteristics of pure R-1132(E), which have not been previously clarified, were examined under various conditions, revealing that its burning velocity and quenching distance were nearly equivalent to those of R-290. The binary R-1132(E)/R-1234yf mixture was then evaluated under standard conditions, and the relationship between the combustion characteristics and mixing ratio was obtained. Based on this, the dependence of the combustion characteristics of the R-1132(E)/R-32 (fixed at 10 wt%)/R-1234yf system on the mixing ratio was clarified. In particular, when the R-1132(E) fraction was 61 wt% or less, the maximum burning velocity was 10 cm s⁻¹ or less, corresponding to the lower flammability class. In addition, for the two candidate compositions narrowed down by the Group for Refrigerant Property Evaluation, namely, 30/10/60 and 40/10/50 wt%, the flammability limits were measured using the ASHRAE method specified in ISO 817, and data sufficient for applications for domestic and international standards registration were obtained. The values evaluated using the HPGSA and ASHRAE methods were in close agreement, and both candidates fall within the lower flammability class.

The combustion characteristics of the ternary CO₂/HFO-1123/R-290 system were also evaluated. First, the combustion characteristics of the required binary CO₂/R-290 system, including the flammability limits, burning velocity, heat of combustion, and quenching distance, were evaluated under standard conditions. By formulating these results based on the theory of thermal dilution by CO₂, combustion characteristic data could be obtained for arbitrary mixture compositions ranging from non-flammable to highly flammable conditions. The ternary mixture system was subsequently evaluated, and the mixture conditions corresponding to the lower-flammability class were clarified. It was found that even a small addition of R-290 to HFO-1123 substantially increased the amount of CO₂ required to reduce flammability and that achieving lower flammability requires a large amount of CO₂, comparable to that required for the CO₂/R-290 system.

The consistency between the measured quantities, such as burning velocity and quenching distance, and theoretical models was also examined. Even in these mixed systems, an approximately inversely proportional relationship was observed between burning velocity and quenching distance. Therefore, this study advances efforts to improve reliability and establish methods for estimating flammability. Based on these results, a comprehensive refrigerant evaluation aimed at practical applications in actual equipment will be pursued through collaboration with the Group for Refrigerant Property Evaluation and other development groups.

6. Cycle Characteristics of Low-GWP Refrigerant Mixtures and Performance Evaluation

Using a Refrigeration-Cycle Model Test Apparatus (Kyushu Sangyo University)

This section compares the cycle characteristics of the existing refrigerant R-32 and the low-GWP refrigerant mixture R-474B using a refrigeration-cycle model test apparatus for residential air conditioners. It examines the differences in performance and applicability. The primary objective is to identify the differences between the two refrigerants under identical apparatus and operating conditions. Another objective is to clarify the equipment-related and thermodynamic factors responsible for these differences. The evaluation indices include the overall system coefficient of performance, the coefficient of performance of the refrigeration cycle itself, heat-exchanger temperature distributions, compression ratio, irreversible losses, and compressor efficiency, which extend beyond a simple capacity comparison to the internal

loss structure of the refrigeration cycle.

The test apparatus consisted of a refrigerant loop comprising a compressor, cross-fin tube condenser, electronic expansion valve, and cross-fin tube evaporator, along with heat-source water loops connected to the condenser and evaporator sides. This configuration enables a comparison of the cycle behaviors of R-32 and R-474B under both heating and cooling conditions. Thus, rather than merely comparing the thermophysical properties of refrigerants, this study experimentally investigated how each refrigerant behaves in an actual refrigeration cycle and where the losses are amplified.

The experimental results showed that R-474B exhibited a lower COP than R-32 under both heating and cooling conditions, with a more pronounced difference during heating. One important factor is the difference in the operating pressure. Because R-474B operates at a lower pressure than R-32, the refrigerant velocity tends to increase to compensate for its lower vapor density and obtain a comparable heat exchange rate. Consequently, the pressure losses in the piping and heat exchangers increase, causing the compressor inlet pressure to decrease. This decrease increases the compression ratio and the work required for compression, making it a major factor in the COP reduction. In particular, under heating conditions, the evaporator side is exposed to severe low-temperature conditions. Therefore, the effect of this decrease in the inlet pressure becomes more significant and is considered to further increase the disadvantages of R-474B.

The temperature glide arising from the zeotropic nature of R-474B is also an important factor affecting the performance difference. In R-32, the temperature remains nearly constant in the two-phase region, whereas in R-474B, it changes continuously during condensation and evaporation. As a result, the temperature difference between the refrigerant and heat-source water tends to become locally larger within the heat exchanger, increasing the heat-exchange irreversibility. This effect is particularly pronounced on the condenser side during heating, where an increase in the irreversible loss directly reduces the heating performance. Thus, the performance degradation of R-474B can be attributed not only to the increased compressor load but also to the thermodynamic mismatch within the heat exchangers.

Compressor compatibility is also important. Irreversible losses in the compressor are particularly large under heating conditions. As the compression ratio increases, the adiabatic compression work and losses associated with internal leakage and friction increase. In addition, although no major difference was observed in the inverter efficiency, differences were confirmed in the compressor and volumetric efficiencies, suggesting the possible involvement of refrigerant properties, compatibility with lubricating oil, required torque, and cooling conditions. Thus, the performance issues associated with R-474B are not confined to the heat exchanger side but are related to the compatibility design for the entire system, including the compressor and lubricating oil.

However, R-474B is not entirely disadvantageous. Under cooling conditions, the difference in performance is smaller than that under heating conditions, and the volumetric efficiency does not necessarily degrade. Hence, the applicability of R-474B strongly depends on operating conditions and equipment matching. Moreover, R-474B exhibits a low GWP, which gives it considerable value in the context where further reductions in environmental impact are increasingly required. Although challenges remain for direct substitution into current R-32 systems, R-474B should be reevaluated as a refrigerant for next-generation systems specifically designed for low-pressure-loss heat exchangers, heat-exchanger designs that account for temperature glide, and compatible compressors and lubricating oils.

In summary, this study clarified the current performance of R-474B in comparison with R-32 and identified the causes of its performance degradation in terms of pressure loss, temperature glide, irreversible loss, and compressor compatibility, thereby indicating areas of improvement. Although R-474B currently presents challenges as a simple drop-in refrigerant, it has the potential for use in next-generation low-environmental-impact systems with a dedicated design. Further investigations are required to clarify its effectiveness and applicable conditions.

7. Analysis of Losses in Cycle Components for Low-GWP Refrigerant Mixtures (Nagasaki

University)

In this study, compressor efficiency measurements using a 2 kW-class vapor-compression experimental apparatus and cycle simulations based on the resulting data were conducted to evaluate the performance of air-conditioning refrigeration cycles using low-GWP refrigerants. The experimental apparatus consisted of a compressor, two cross-fin tube heat exchangers, and an electric expansion valve. Heat exchange with the heat-source water in a water tank was used to simulate an air heat source. The temperature and pressure were measured at each measurement point, and the refrigerant state properties were calculated using REFPROP, with fluid files optimized based on the measured data and circulating refrigerant composition. The adiabatic, mechanical, volumetric, and inverter efficiencies were evaluated. Experiments were conducted using R-32, R-1234yf, and their respective refrigerant mixtures.

The measurements showed no significant difference in adiabatic efficiency among the refrigerants, and the results agreed well with the existing correlations. In contrast, the mechanical and volumetric efficiencies varied depending on the refrigerant type. These differences are considered to originate from the differences in miscibility between the POE oil and refrigerants. For R-1234yf, high solubility reduces oil viscosity and increases leakage loss, thereby decreasing mechanical efficiency. In the case of R-32, which has a high vapor density, the required torque is large, but the leakage loss is small, resulting in a tendency toward a high inverter efficiency. Using these measurement results, the compressor characteristics were modeled, and a cycle simulation incorporating segmented calculations inside the heat exchangers was developed. A comparison of the experimental and simulation results on the P - h diagram showed good agreement, confirming the validity of the model.

Performance predictions were conducted for ternary refrigerant mixtures in R-32/HFO-1123/R-1234yf and R-32/R-1132(E)/R-1234yf systems under a cooling capacity condition of 2.0 kW. The maximum COP values were 3.4 and 4.1, respectively. The COP decreased, whereas the required heat-transfer area increased as the temperature glide increased. The maximum volumetric capacities were 7500 kJ m^{-3} for the R-32/HFO-1123/R-1234yf system and 6500 kJ m^{-3} for the R-32/R-1132(E)/R-1234yf system, which reversed the ranking observed for the maximum COP. The maximum volumetric capacity was observed for the compositions with a smaller fraction of R-1234yf. It was also confirmed that the maximum COP and volumetric capacity were strongly affected by the composition regions constrained by GWP limits and the risk of disproportionation reactions.

8. Development of LCCP Evaluation Methods and AI Analysis for Air-Conditioning Equipment Compatible with Low-GWP Refrigerant Mixtures (Aizoth)

This study aims to evaluate the nationwide environmental impact in Japan associated with the diffusion of air-conditioning equipment using low-GWP refrigerant mixtures. Specifically, life cycle assessment (LCA), life cycle climate performance (LCCP) evaluation, and future demand projections were integrated to comprehensively analyze the environmental impacts of equipment manufacturing through operation and disposal. An evaluation framework that accounted for safety and social acceptability was constructed, and the findings were fed back to research institutions and companies to support the advancement of research and business strategies.

LCA/LCCP evaluation was used in this study to assess both the environmental impact per residential air conditioner and the nationwide environmental impact in Japan. In the LCCP evaluation, analyses were conducted using Japanese standard coefficients within the LCCP evaluation framework and combined with an LCA evaluation of refrigerant production based on patent information and estimates of power consumption obtained from cycle simulations.

The LCA evaluation of refrigerant production revealed that the environmental burden during production depends

strongly on the raw materials and process yield and that this burden increases particularly when the yield is low. Natural refrigerants such as propane and CO₂ have relatively small production-stage burdens, whereas some synthetic refrigerants have high environmental impacts.

The cycle simulation results showed that the annual electricity consumption of air conditioners differs depending on the refrigerant and that single-component refrigerants tend to require less electricity than refrigerant mixtures.

The LCCP evaluation showed that most of the environmental impact arises from electricity consumption during operation and that even when the refrigerant itself has a low GWP, the LCCP increases if the energy efficiency decreases. Therefore, refrigerant selection must account not only for GWP, but also for impacts over the entire life cycle. Overall, R-1132(E), R-1234ze(E), and R-290 were identified as promising refrigerants capable of achieving both low GWP and LCCP, although safety concerns, such as flammability, remain important considerations.

Future demand projections for air conditioners in Japan indicate that small-capacity models account for a large share, and that the number of operating units is expected to decrease with population decline. In the future, these demand projections will be combined with the environmental impact per unit to evaluate the nationwide environmental impacts in Japan under diffusion scenarios.

Finally, AI-based analyses were performed. A machine-learning model was developed to predict the GWP of refrigerants with high accuracy. This model estimated the GWP from the molecular structure information and improved the efficiency of screening for new refrigerants and refrigerant mixtures. This tool is expected to accelerate the search for refrigerants with superior environmental performance and optimization of air-conditioning equipment design.

Volume 3 Development of Component Technologies Compatible with Low-GWP Mixed Refrigerants

1. R&D Overview and Outcomes (Saga University)

The research reported in this volume aims to support the practical application of next-generation low-GWP refrigerant mixtures in response to the Kigali Amendment. Component technologies for heat exchangers and compressors were advanced in an integrated manner to overcome heat-exchanger and compressor performance degradation. Through collaboration among multiple institutions, this task comprehensively addressed research and development on (1) elucidation and mitigation of heat-transfer degradation mechanisms in refrigerant mixtures, (2) heat-exchanger design and performance evaluation, (3) measurement and modeling of refrigerant transport properties, (4) prediction using heat-transfer databases and machine learning, (5) evaluation of refrigerant–oil system characteristics in compressors and clarification of compression characteristics of refrigerant mixtures, (6) improvement of compressor mechanical efficiency, and (7) material development for compressor components.

First, heat transfer degradation caused by mass diffusion resistance was shown to occur during the condensation and evaporation of refrigerant mixtures, resulting in heat transfer coefficient reductions of approximately 30–40% during condensation and 15–50% during evaporation compared with pure refrigerants. The flow patterns, void fraction, pressure loss, and nucleate boiling characteristics in microchannels were also systematically evaluated, showing that refrigerant mixtures exhibited a reduced void fraction, an increase in boiling incipience superheat of approximately 22 K, and a reduction in heat-transfer coefficient of up to approximately 40%. Furthermore, the effects of flow instability and oscillatory flow in parallel channels on heat-transfer characteristics were clarified, indicating the possibility of heat-transfer enhancement through a rewetting effect.

A performance evaluation was conducted through experiments and numerical analyses of heat exchangers composed of flat multiport tubes and corrugated fins. The limitations of applying the conventional logarithmic mean temperature difference (LMTD) method were demonstrated, and a segmented analysis method that accounted for the local heat transfer was established. Heat transfer degradation was also mitigated through optimization of the surface and channel structures; heat transfer enhancement of approximately 10–15% by porous surfaces and 1.3- to 2.7-fold enhancement by microfin channels were confirmed. Simultaneously, practical challenges, such as the difficulty of applying uniform surface treatment to the inner walls of multiport tubes, were clarified. A database consisting of approximately 97,000 heat transfer and pressure loss data points (RECDB) was constructed, while correlation-evaluation functions were developed. Furthermore, a heat-transfer coefficient prediction model using machine learning was established, achieving higher accuracy than conventional correlations.

For refrigerant transport properties, high-accuracy measurements of viscosity and thermal conductivity, combined with modeling based on the extended corresponding states (ECS) principle, enabled the construction of models capable of predicting measured values for new refrigerants and refrigerant mixtures with errors of approximately ± 1 –2%.

Concerning compressor technologies, the solubility characteristics, compositional changes, and oil-return characteristics of refrigerant-refrigeration-oil mixtures have been clarified, revealing that composition segregation and liquid-film transport behavior specific to refrigerant mixtures affect compressor performance. The friction and wear characteristics of the sliding components were also evaluated experimentally, showing that the friction coefficient varies with the dimensionless bearing number. The friction characteristics were also shown to substantially affect the mechanical efficiency under high-speed operating conditions. Although the application of composite materials indicated the potential for increasing the rolling contact and reducing wear, issues such as abnormal wear originating

from the internal structure of the materials were also identified.

Aluminum matrix composite materials intended for compressor components have been developed as compressor material technology. A density of 2.73 g/cm^3 was achieved, corresponding to a weight reduction of approximately 60% compared with conventional cast iron. Moreover, a tensile strength of 360 MPa, Young's modulus of 120 GPa, and fatigue strength of 133 MPa were obtained, confirming improved mechanical properties. The machinability evaluation also showed that the tool wear could be reduced by approximately 30%. However, the cutting resistance increased, thereby clarifying its applicability from the perspectives of machinability and wear resistance.

Based on these outcomes, progress has been made in establishing an evaluation framework that integrates heat transfer phenomena, flow characteristics, thermophysical properties, data science, materials, and mechanical elements as foundational technologies required to design heat exchangers and compressors compatible with new low-GWP refrigerant mixtures. The research outcomes promote the development and dissemination of refrigeration and air-conditioning equipment using low-GWP refrigerant mixtures, reduce the use of HFC refrigerants, and support high-efficiency operation and energy savings for refrigeration and air-conditioning equipment.

2. R&D on Heat-Exchanger Component Technologies for Suppressing Heat-Transfer Degradation in Low-GWP Refrigerant Mixtures (Saga University)

This study aims to advance heat-exchanger component technologies that account for heat-transfer phenomena specific to refrigerant mixtures to address heat-transfer performance degradation. Specifically, an integrated investigation was conducted from four perspectives: (1) heat exchanger design and performance evaluation, (2) measurement and modeling of refrigerant transport properties, (3) construction of a heat transfer database equipped with correlation-evaluation functions, and (4) prediction of heat transfer coefficients using machine learning.

First, the heat exchange characteristics of zeotropic refrigerant mixtures were examined. In refrigerant mixtures, temperature glide occurs during the phase-change processes, producing temperature distributions and heat-transfer characteristics that differ from those of pure refrigerants. For example, in R-454A, R-454B, and R-454C, which are mixtures of R-32 and R-1234yf, the temperature glide varies within a range of approximately 1–5°C depending on composition. For these three mixtures, the GWP decreases as the proportion of R-1234yf increases, whereas temperature glide tends to increase. In addition, temperature changes caused by frictional pressure loss occur inside heat exchangers, particularly during condensation, which acts in the same direction as the temperature glide, leading to heat transfer performance degradation and increased compressor power requirements. Therefore, air-conditioning equipment using refrigerant mixtures requires heat exchangers that can achieve efficient heat exchange with small temperature differences.

To address this issue, a heat exchanger performance evaluation apparatus was constructed using a temperature- and humidity-controllable wind tunnel. Evaluation experiments were conducted on heat exchangers using refrigerant mixtures. First, heat exchangers employing flat multiport tubes as heat-transfer tubes and fins on the air side were investigated, and the air-side pressure loss and the condensation and evaporation heat-transfer characteristics were measured. The experiments confirmed the general tendency of the air-side pressure loss to increase with the Reynolds number. In contrast, the friction factor decreased, indicating that the experimental data could be reproduced well by modifying the coefficients of existing correlations for louver fins. In condensation tests, evaluating the KA value, an index of heat-exchanger performance, revealed that the conventional logarithmic mean temperature difference (LMTD) method was difficult to apply to refrigerant-mixture systems in which the state continuously changed from superheated vapor to a subcooled liquid. To address this limitation, a numerical analysis method in which the heat exchanger was divided into small segments was introduced, and evaluations consistent with the experimental results were achieved by iteratively calculating the local heat-transfer coefficients and temperature distributions.

Refrigerant transport properties, namely viscosity and thermal conductivity, are essential for heat exchanger design and system simulation, and high-accuracy measurements and modeling are required for new refrigerants. In this study, the viscosity was measured using the tandem capillary tube method, and thermal conductivity was measured using the transient hot-wire method. Subsequently, the accuracy of the calculation model based on the extended corresponding state (ECS) principle incorporated in REFPROP was improved. As a result, even for new refrigerants for which sufficient accuracy cannot be obtained using the existing REFPROP model, measured values were reproduced with an accuracy of approximately $\pm 1\text{--}2\%$ through parameter fitting. In addition, a framework for the parameter fitting of the ECS model, which estimates the properties of a target fluid using the equation of state and transport properties of a reference fluid, was established, and its applicability to new pure refrigerants and refrigerant mixtures was confirmed.

In this study, a heat transfer database (RECDB) was constructed to enable the integrated use of heat transfer data. This database contains experimental data obtained in the current NEDO project as well as literature data on evaporation and condensation heat transfer and pressure loss in circular tubes, flat multiport tubes, and plate heat exchangers. As of March 2026, more than 97,000 data points had been accumulated. In addition to functions for data search, visualization, and condition extraction, the RECDB is equipped with a correlation evaluation tool that enables purpose-specific data

selection and evaluation of correlation applicability. This database is expected to systematize knowledge across diverse refrigerants and heat transfer conditions, and support the advancement of design guidelines.

Using the large-scale data accumulated in the RECDB, a machine-learning-based model for predicting the heat transfer coefficients was developed. First, approximately 22,000 flow-boiling or evaporation data points for 18 pure refrigerants were used to compare the predictive performances of 28 models, including linear regression, wide neural networks, and support vector machines. The bagged-tree model exhibited the best predictive performance, achieving high accuracy with an RMSE of 1.97. SHAP analysis further revealed that the refrigerant type and tube geometry were the most important factors, followed by the wall temperature and mass flux as dominant influences. These results demonstrate that the nonlinear and multivariate effects that conventional empirical correlations cannot fully capture can be accurately represented.

In summary, this study established a comprehensive evaluation framework that integrates experimental heat exchanger evaluation, measurement and modeling of transport properties, database construction, and machine-learning analysis as foundational technologies for heat exchanger design compatible with new low-GWP refrigerant mixtures. The methods established in this study will be extended to other refrigerant systems and heat exchanger configurations, thereby contributing to the development of high-efficiency refrigeration and air-conditioning technologies for the practical application of next-generation low-GWP refrigerants.

3. Basic Research on Suppression of Heat-Transfer Degradation in Low-GWP Refrigerant Mixtures and Development of Heat-Exchanger Application Technologies (Tokyo University of Marine Science and Technology)

Many low-GWP refrigerant mixtures currently under development are zeotropic, and heat-transfer performance degradation in heat exchangers caused by mass-transfer resistance during condensation and evaporation has become a major issue. This R&D study aims to clarify the mechanisms of heat transfer degradation in refrigerant mixtures and establish technologies for suppressing such degradation using surface-treated heat transfer surfaces and microchannel structures, thereby contributing to the development of heat exchangers compatible with low-GWP refrigerant mixtures. In this study, the flow patterns and liquid-film structures during the phase change in horizontal parallel microchannels simulating flat multiport tubes were visualized, the evaporation and condensation heat-transfer coefficients were evaluated, and the effects of heat-transfer surface treatment and channel geometry on the suppression of heat-transfer degradation were verified.

- Clarification of evaporation and condensation heat-transfer characteristics of low-GWP refrigerant mixtures

Using parallel microchannels simulating flat multiport tubes with a hydraulic diameter of 1.0 mm, flow patterns and heat transfer characteristics in the condensation and evaporation flows were visualized and evaluated. The heat transfer coefficients of the refrigerant mixtures were confirmed to be lower than those of pure refrigerants, with particularly significant degradation under low-mass-flux conditions. The heat-transfer coefficient of R-474A was 30–40% lower during condensation and 15–50% lower during evaporation than that of the pure refrigerant R-1234yf under the same mass flux and quality conditions, and this degradation was identified as being caused by mass diffusion resistance.

- Heat transfer enhancement based on surface characteristics

Currently, there is limited knowledge regarding the influence of surface characteristics on the evaporation heat-transfer characteristics of refrigerant mixtures in microchannels. In this study, heat transfer coefficients were measured using surface-treated aluminum alloy channels with porous layers (anodized surfaces), and the heat transfer enhancement associated with the surface characteristics was evaluated. Compared with the smooth surfaces, the anodized surfaces generated finer and more numerous bubbles, confirming that the porous layer promoted bubble nucleation. In particular, under relatively high heat-flux conditions, heat-transfer enhancement by the anodized surfaces was obtained; the heat-transfer coefficient improved by approximately 15% compared with that on the smooth surface, and a heat-transfer coefficient exceeding that of the pure refrigerant R-1234yf was obtained.

- Heat-transfer enhancement through channel geometry

To promote flow agitation and disrupt boundary layers, channels equipped with numerous inclined microfins (hereafter referred to as microfin channels) were fabricated, and their effects on suppressing heat transfer degradation and enhancing heat transfer were investigated. Even under a low-mass-flux condition ($G = 50 \text{ kg m}^{-2} \text{ s}^{-1}$), the microfin channels achieved heat-transfer coefficients 1.3–2.7 times higher than those of the parallel microchannels, confirming that microfin-induced flow agitation is effective for suppressing heat-transfer degradation and enhancing heat transfer in zeotropic refrigerant mixtures.

This study demonstrated that porous-layer formation and microfin-induced flow agitation are effective in enhancing heat transfer and suppressing heat-transfer degradation. In the future, evaluations will be conducted for low-GWP refrigerant mixtures, including other candidate refrigerants. In collaboration with other R&D items, component technologies for suppressing heat transfer degradation and enhancing heat transfer will be further developed for applications in heat exchangers.

4. R&D on Improving Evaporation and Condensation Performance of Refrigerant Mixtures by Controlling the Surface Structure of Aluminum and its Application to Heat-Transfer Tubes (UACJ)

Aluminum multiport tubes have been increasingly adopted as heat exchangers for stationary air-conditioning systems because they offer advantages in terms of space savings and weight reduction. Owing to the surface-tension effects in the gas–liquid two-phase flow within the microchannels, these tubes exhibit higher heat-transfer coefficients than circular channels. With the tightening of environmental regulations, low-GWP zeotropic refrigerant mixtures are considered promising; however, a major challenge is the degradation of in-tube heat-transfer performance when such mixtures are used. Component separation can occur because of the biased flow distribution caused by gravity and surface tension, and the preferential evaporation of low-boiling components causes high-boiling components to concentrate near the surface, resulting in nonuniform liquid films and reduced heat-transfer efficiency. Therefore, new measures are required to address these issues.

In this project, component technologies are developed to suppress heat-transfer performance degradation specific to refrigerant mixtures and to maximize heat-exchange performance. Specifically, this project examines an approach in which nanoscale porous structures are formed by anodization on aluminum surfaces used as heat-transfer tubes, thereby improving the boiling characteristics. As the final target for FY2027, the project aims to develop and evaluate a prototype heat exchanger that combines surface-treatment technology, which is effective in suppressing heat transfer degradation, with an optimized channel structure.

To verify the heat transfer enhancement by surface treatment, a porous oxide film with numerous pores, approximately 700 nm in thickness and 70 nm in pore diameter, was successfully formed on aluminum surfaces by constant-current anodizing and chemical dissolution treatment. The boiling heat-transfer characteristics of the specimens with this porous surface were evaluated using the refrigerant mixture R-454C. As a result, bubble nucleation was promoted, finer bubbles were generated, and the heat-transfer coefficient improved by approximately 13% compared with that of an untreated channel. These results demonstrate that controlling the surface microstructure is effective for enhancing boiling heat transfer in refrigerant mixtures.

The applicability of the anodizing treatment to the inner channel walls of multiport tubes was also investigated. When a multiport tube was immersed in an electrolyte and energized, ion diffusion became rate-limiting, causing a thick oxide film to form mainly on the outer surface of the tube. In contrast, the film formed on the inner channel walls was extremely thin. Even when the outer surface of the tube was masked or an auxiliary electrode, namely a platinum wire, was inserted inside the tube, the reaction was concentrated near the channel entrance, causing localized dissolution and preventing uniform film formation. These results highlight the limited throwing power of the treatment for closed, long channels.

Based on the results obtained to date, the formation of a uniform porous structure on the inner channel walls of multiport tubes requires a specialized surface treatment process that incorporates, for example, forced liquid flow inside the channels rather than simple immersion. In the latter half of the project, efforts will be focused on establishing a surface treatment method with an improved throwing power. In parallel with surface treatment, heat transfer enhancement through optimization of the cross-sectional geometry of the multiport tubes will also be pursued to continuously supply the liquid phase to the dryout regions and maintain an optimal liquid film. Finally, a prototype heat exchanger integrating these findings will be fabricated, and a comprehensive heat-exchange performance evaluation through wind tunnel experiments is planned.

5. Elucidation of Thermal-Fluid Mechanisms of Low-GWP Refrigerant Mixtures and R&D on Heat-Transfer Enhancement Technologies (Kobe University)

HFO-based refrigerants currently being developed as low-GWP refrigerants have low heat transport capacity when used as single-component refrigerants; therefore, practical application generally requires their use as mixtures with HFC-based refrigerants. In zeotropic mixtures, temperature glide occurs during phase change even under equilibrium conditions, and interfacial-temperature changes caused by nonequilibrium at the gas–liquid interface reduce the evaporation heat-transfer coefficient. Meanwhile, improving the coefficient of performance of air conditioners is strongly required from the viewpoint of energy saving, and increasing the KA value, namely the product of the overall heat-transfer coefficient K and the heat-transfer area A , is necessary to reduce the size and weight of heat exchangers. Because increasing K is difficult for zeotropic refrigerant mixtures, increasing A becomes unavoidable. To meet this requirement, increasing the heat-transfer area density by reducing the diameter of refrigerant channels is effective, and the use of aluminum flat multiport tubes is considered indispensable in refrigerant–air heat exchangers.

Accordingly, Kobe University conducted single-channel experiments to elucidate the thermal-fluid characteristics of refrigerants in microchannels, experiments on oscillatory flow in parallel channels aimed at promoting liquid-phase mixing in zeotropic refrigerants, and experiments on boiling incipience superheat and nucleate boiling heat transfer to enhance liquid-phase mixing through nucleate boiling within liquid films. The research outcomes are summarized below.

- Thermal-fluid and void-fraction characteristics of refrigerant two-phase flow in microchannels

Horizontal gas–liquid two-phase flow experiments were conducted in a circular channel with an inner diameter of 1 mm using the pure refrigerant R-1234yf and the zeotropic mixture R-454C. Flow pattern, void fraction, and pressure loss were evaluated. Slug flow, semi-annular flow, annular flow, and undisturbed annular flow were observed as flow patterns. A flow-pattern map organized using the Weber numbers of the gas and liquid phases, We_G and We_L , generally agreed with the flow-pattern transition model of Akbar and Ghiaasiaan. However, for R-454C, the transition to annular flow tended to occur at a slightly higher We_G , namely at a higher vapor quality. The volume-averaged void fraction measured using a capacitance sensor with flat-plate electrodes is plotted against vapor quality in Fig. 3.5-1. Although the trend was almost the same as that predicted by the correlation of Cioncolini and Thome, the measured values were lower than the correlation. R-454C showed slightly lower values than R-1234yf. Because the measurements were performed immediately downstream of the heated section, the actual vapor quality for R-454C may have been lower owing to delayed phase change. Frictional pressure loss was organized using the Lockhart–Martinelli method as shown in Fig. 3.5-2. The two-phase multiplier for R-454C showed lower values than those predicted by the correlation of Kim and Mudawar, suggesting that the large temperature variation at low quality may have influenced the results.

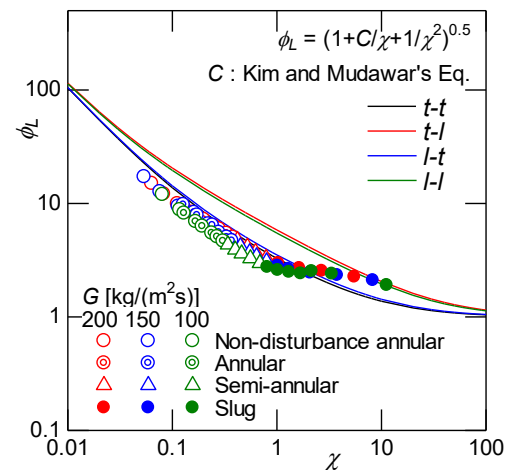
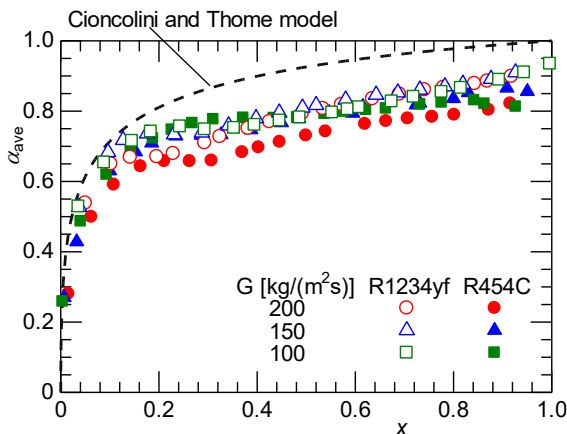


Figure 3.5-1 Average void fraction of R1234yf and R454C. Figure 3.5-2 Frictional pressure loss arranged by L-M method.

- Oscillatory flow in refrigerant evaporation within parallel channels and its influence on heat-transfer characteristics

Evaporation heat-transfer experiments were conducted in horizontal parallel channels simulating flat multiport tubes, and the effects of inlet-header volume on flow behavior and heat-transfer characteristics were evaluated. When a constant mass flow rate was supplied by a mechanical gear pump and the pump inlet pressure was held constant, no significant oscillatory flow or maldistribution was observed in the parallel channels. In contrast, when the pressure at the inlet of the parallel channels was held constant by using a thermal accumulator to simulate a practical heat exchanger, the flow became unstable as the inlet-header volume increased, and backflow from the parallel channels into the inlet header was also observed. The header volume was controlled by installing an aluminum porous metal plate in the header and varying the distance Δh between the plate and the parallel-channel inlet. The measured heat-transfer coefficients for $\Delta h = 0, 2$, and 4 mm are shown in Fig. 3.5-3. These values are local heat-transfer coefficients measured over a heated length of 200 mm, and the measured results obtained at three points in the flow direction under the same conditions are connected by solid lines. Conditions in which oscillatory flow was observed are indicated by filled symbols, whereas those without oscillatory flow are indicated by open symbols. At low quality, the value for 4 mm was the lowest because nucleate boiling was suppressed by oscillatory flow. At high quality, however, the average heat-transfer coefficient increased owing to the rewetting effect on dry patches.

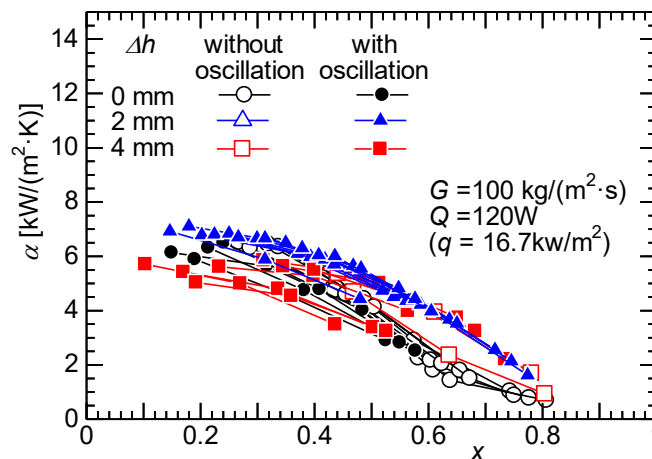


Figure 3.5-3 Local heat-transfer coefficient.

- Identification of boiling incipience superheat and effects of zeotropic refrigerant-mixture composition

In pool-boiling experiments, boiling incipience superheat and nucleate boiling heat-transfer characteristics were evaluated. Compared with pure refrigerants, R-454C exhibited a high wall superheat at the onset of nucleate boiling (ONB) of 22.24 K, corresponding to 1.17 times that of R-1234yf. The heat-transfer coefficient of R-454C in developed nucleate boiling decreased by approximately 40% relative to that of the pure refrigerant. The rate of change with respect to heat flux was almost the same as that for the pure refrigerant. Experiments were also conducted on zeotropic refrigerant mixtures composed of R-1234yf and R-32 by varying the R-32 composition ratio. The influence of composition ratio on the boiling curve is shown in Fig. 3.5-4. The ratios in the figure indicate the R-32 composition ratio. A larger wall superheat indicates a lower heat-transfer coefficient. These results show that the influence of mixing ratio on wall superheat at ONB was small and that the value was nearly equivalent to that of the pure high-boiling component R-1234yf. However, the nucleate boiling heat-transfer coefficient decreased substantially as the R-32 composition ratio decreased. Although a large decrease was observed at 10%, the heat-transfer coefficient improved as the R-32 fraction increased, reaching a level comparable to that of R-1234yf at 50%. The deterioration in the nucleate

boiling heat-transfer is caused by a decrease in the evaporation rate during bubble growth while rising. Therefore, if nucleate boiling becomes dominant in forced-flow evaporation inside small tubes, the reduction in heat-transfer coefficient is expected to be suppressed by liquid-film mixing.

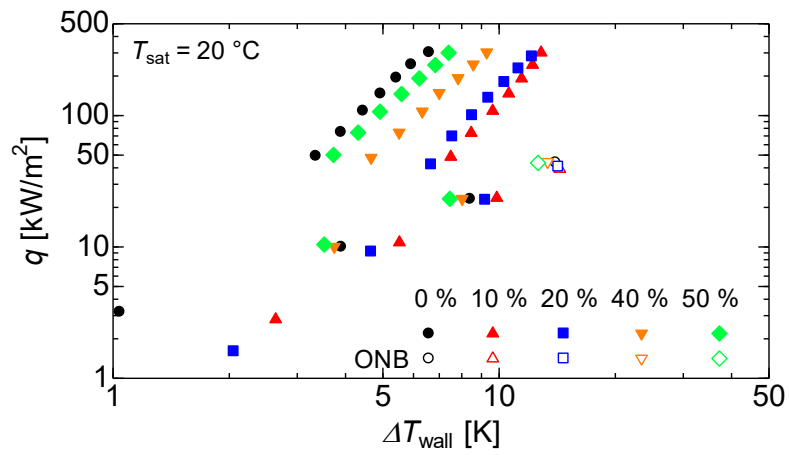


Figure 3.5-4 Boiling curves for refrigerants with several mixing ratios at $T_{\text{sat}} = 20^\circ\text{C}$.

6. Refrigerant Dissolution Behavior in Refrigeration Oils, Compatibility Evaluation, and Elucidation of Compression Characteristics of Low-GWP Refrigerant Mixtures in Compressors (Shizuoka University)

Refrigerant compressors play a major role in refrigeration cycles, and the development of compressors compatible with low-GWP refrigerants is essential. For compressors using low-GWP refrigerant mixtures, ensuring performance and reliability requires developing and evaluating refrigeration oils suitable for such mixtures, clarifying the dissolution behavior of zeotropic refrigerant mixtures in refrigeration oils, and understanding their compression characteristics. Against this background, this study was divided into the following research areas:

- Solubility behavior of refrigeration oil–refrigerant mixtures: solubility, property measurements, and volume change
- Solubility behavior of refrigeration oil–refrigerant mixtures: dissolved components and solubility prediction
- Formulation of oil return characteristics based on oil film measurements in a vertical upward tube
- Development of a compressor performance prediction model considering compositional changes in refrigerant mixtures and evaluation of its applicability to alternative refrigerants
- Establishment of design guidelines for high-speed compressors using low-GWP refrigerants and testing of prototype compressors

Tests were conducted from FY2023 to FY2025 using currently available zeotropic refrigerant mixtures, and their basic characteristics and properties were clarified. For compressor development and practical applications, compressor calculation models incorporating these characteristics were constructed and used for model calculations. Furthermore, compressor design guidelines were examined, and preparations for prototype compressor testing were advanced. An outline of each research item is provided below:

- Solubility behavior of refrigeration oil/refrigerant mixtures: solubility, property measurements, and volume change

In refrigerant compressors, refrigeration oils that are generally miscible with refrigerants are used. Inside the compressor, the refrigerant dissolves in refrigeration oil, and various properties change depending on its solubility. Therefore, when selecting refrigeration oil for a refrigeration cycle, it is important to understand not only the refrigerant solubility in refrigeration oil under various temperature and pressure conditions, but also the changes in the mixture properties associated with solubility. In addition, the low-GWP zeotropic refrigerant mixtures targeted in this project consisted of multiple pure refrigerants with different boiling points, and their dissolution behaviors may differ from those of pure refrigerants. In this study, the solubilities of POE or PVE mixtures with the refrigerant R-454C and its components R-32 and R-1234yf were measured, and the refractive index was measured as one property. Measurements were conducted by varying temperature from 30 to 90°C and refrigerant concentration from 0 to 100%. In addition, the volume of the refrigeration oil/refrigerant mixtures was measured to investigate the volume changes caused by mixing.

In zeotropic refrigerant mixtures, the dew point and bubble point pressures at a given temperature differ, and the gas–liquid equilibrium may be established in a state different from that of a pure refrigerant within the pressure range above the dew point pressure and below the bubble point pressure. Therefore, solubility was calculated by considering only the refrigerant dissolved in the refrigeration oil, in addition to the general method for calculating solubility. The two methods exhibit almost the same tendencies. For the POE/R-454C mixture, the pressure increased with the refrigerant mass fraction. Up to a mass fraction of approximately 0.5, the pressure increased sharply, whereas above approximately 0.5, the increase was more gradual within the range between the dew point and bubble point pressures. The mass fraction at which the pressure change became gradual increased with temperature and was approximately 0.4 at 30°C.

For the refractive index of the refrigeration oil/refrigerant mixture, the POE/R-454C mixture showed that the refractive index decreased as refrigerant concentration in the refrigeration oil increased at temperatures from 30 to 70°C; at nearly the same refrigerant concentration, the refractive index decreased slightly with increasing temperature.

However, two-phase separation occurred at 90°C, and the refractive index exhibited minimal change at refrigerant concentrations of 60% or higher.

Regarding the volume changes caused by mixing refrigerant into refrigeration oil, the mixture volume became the smallest at a mass fraction of approximately 50% of the liquid volumes of the pure refrigerant and oil before mixing. At this mass fraction, the volume reduction during mixing increased with the temperature.

- Solubility behavior of refrigeration oil/refrigerant mixtures: dissolved components and solubility prediction

Because zeotropic refrigerant mixtures consist of multiple pure refrigerants with different boiling points, each component may exhibit different dissolution behaviors in refrigeration oil. In this study, the selective dissolution of each component constituting a refrigerant mixture into refrigeration oil was experimentally investigated for zeotropic refrigerant mixtures containing HFO.

The dissolved composition in the saturated dissolution state of the refrigeration oil/refrigerant mixtures was measured for the PVE/R-454C mixture. At 20°C, the dissolved composition was almost identical to the charged composition, and selective dissolution was hardly observed. In contrast, at 60°C, when the refrigerant mass fraction was 30–60%, the dissolved composition of R-32 was slightly lower than the charged composition, indicating slight selective dissolution of R-1234yf relative to R-32 in this region.

- Formulation of oil return characteristics based on oil film measurements in a vertical upward tube

For the practical use of new refrigerants, the oil return characteristics of the refrigeration cycle piping must also be evaluated. In the piping that leads to a compressor, the flow generally takes the form of an annular two-phase flow, and it is necessary to determine how the refrigerant flow transports the high-viscosity refrigeration oil. In this study, flow patterns were observed by visualization, and temporal changes in the oil film thickness were measured using a liquid-film sensor to examine the measurement parameters required for prediction.

In these experiments, the liquid film thickness was measured using water and two aqueous glycerol solutions of different viscosities. Based on equations derived by Inoue and Maeda (Phys. Fluids, 2021), the basal liquid film observed in the experiments was accurately predicted when the Wallis equation was used as the interfacial friction factor. In contrast, when the Blasius equation was used as the interfacial friction factor, the basal liquid film thickness could not be predicted from the present experimental results, particularly in the low liquid film Reynolds number region, where the deviations were large (i.e., for high-viscosity liquids). The amount of liquid film transported by the basal liquid film can also be estimated from the linear velocity distribution.

Regarding the transport mechanism of liquid films in an annular gas–liquid two-phase flow, a limiting value determined by the gas flow rate in the tube was inferred to exist for liquid transport by the basal liquid film. It was also inferred that the excess liquid was transported by surface waves instead of the basal liquid film.

- Development of a compressor performance prediction model considering composition changes in refrigerant mixtures and evaluation of applicability to alternative refrigerants

Zeotropic refrigerant mixtures are promising alternatives to low-GWP refrigerants. However, because the thermophysical properties of refrigerant mixtures vary with composition, they can substantially affect compressor performance and loss characteristics. Therefore, prediction models must be constructed to predict compressor characteristics for various compositions.

The measured data obtained using R-22 as the refrigerant were compared with those obtained using the constructed compressor model. For all evaluated quantities, including refrigerant mass flow rate, compressor power, volumetric efficiency, and overall efficiency, the calculated values generally agreed with the measured values within $\pm 10\%$, demonstrating the validity of the compressor model.

Using the constructed compressor model, the refrigerant mass flow rate, compressor power, volumetric efficiency, and overall efficiency were predicted by varying the compositional ratio of the R-32/R-1234yf refrigerant mixture. As the mass fraction of R-32 increased, the refrigerant flow rate decreased monotonically, and the volumetric efficiency decreased correspondingly. By contrast, the compressor power and overall efficiency tended to decrease gradually with

increasing R-32 mass fraction. In addition, composition changes exhibited almost no influence on the indicated, leakage, or mechanical losses.

- Establishment of compressor design guidelines and prototype compressor testing

Many low-GWP refrigerant mixtures currently under consideration tend to exhibit lower volumetric refrigeration capacities than conventional refrigerants. To secure the required refrigeration capacity, increasing compressor size or operating speed may be considered. However, from a practical application perspective, increasing compressor speed is an effective approach for achieving refrigeration capacity equivalent to that of current refrigerants. Therefore, theoretical investigations in this study were conducted on rotary compressors to identify the significant loss factors during high-speed operation. Based on these results, improvement measures for the compressor design were examined, and a prototype compressor was fabricated.

Challenges associated with increasing the compressor speed and corresponding countermeasures were examined, and the effects of each measure were evaluated based on theoretical considerations. Based on these results, a prototype compressor was fabricated using a 2.8 kW-class two-cylinder rotary compressor manufactured by a domestic compressor manufacturer as the base model. In the prototype, the motor was replaced with a motor capable of high-speed operation, and lightweight components developed by the subcontractor were applied to the vane and piston. The completed prototype compressor was connected to a test refrigeration cycle and its operating performance was measured.

7. Elucidation of Friction, Wear, and Lubrication Characteristics in Low-GWP Refrigerant Mixture Atmospheres for Improving Compressor Mechanical Efficiency (Osaka Electro-Communication University)

For compressors using low-GWP refrigerant mixtures, an increase in compression displacement is required to maintain a performance equivalent to that of current systems and achieve further improvements. This can be accomplished either by enlarging the compressor or increasing its operating speed to increase the amount of compression per unit time. Because the compressor body should not be made larger than that at present, a high-speed operation is required. Under such conditions, it is essential to prevent an increase in friction losses at the sliding parts of each mechanism, which would otherwise reduce the mechanical efficiency.

In this study, the friction characteristics of the composite materials developed in Equipment C-3 were evaluated under low-GWP refrigerant-mixture atmospheres to support the development of compressors capable of operating at higher speeds than conventional compressors. In particular, the friction, wear, and lubrication characteristics of the mechanical components of the compressor, which are closely related to the mechanical losses, were examined in detail. The findings support the formulation of design guidelines for high-performance compressors using low-GWP refrigerant mixtures, as investigated for Equipment C-1.

In rotary compressors, mechanical efficiency is affected by the sliding and rolling behavior between the vane and cylinder groove, the vane and rolling piston, and the rolling piston and cylinder. To clarify the friction characteristics at these locations, test rigs reproducing the sliding conditions of actual compressors were fabricated, and the friction and oil-film forces in a refrigerant atmosphere were measured experimentally.

For the friction coefficient between the vane and cylinder groove, the friction coefficient was confirmed to remain almost constant when the dimensionless bearing number, defined as the product of viscosity and velocity divided by the pressing force per unit length, was smaller than approximately 5×10^{-7} . The use of composite materials resulted in a slightly higher friction coefficient than the combination of cast iron components. In addition, combinations of the composite materials tended to yield slightly lower friction coefficients than combinations of a composite material and cast iron.

When the cast iron components were combined, the friction coefficient between the vane and the rolling piston remained almost constant at dimensionless bearing numbers below approximately 5×10^{-5} . However, the friction coefficient tended to decrease gradually at dimensionless bearing numbers of approximately 5×10^{-5} or higher. When a composite material was combined with cast iron, the friction coefficient tended to decrease gradually at dimensionless bearing numbers of approximately 1×10^{-4} or higher. However, when composite materials were combined, no reduction in the friction coefficient was observed within the present test range.

To examine the material wear characteristics, the wear volume loss was measured using a confocal microscope and organized according to the specific wear rate. The effects of surface roughness and contact pressure are currently being analyzed, and the detailed results will be reported separately.

The friction coefficients measured in this study were similar to the values reported in previous studies; however, notable differences were also observed. These differences are due to factors such as the refrigerant type, lubricating oil, and material combinations. A sharp decrease in the friction coefficient was also observed in the high-bearing-number region. This finding is particularly important for simulating the compressor performance during high-speed operation because the bearing number increases under such conditions. Calculations are also underway to determine appropriate dimensional specifications for maximizing the mechanical efficiency when composite materials are used for moving parts in high-speed rotary compressors. The results of these analyses will be reported separately.

8. Development of Metal-Matrix Composite Materials Suitable for Compressor Components and Evaluation of their Basic Properties (Advance Composite)

Compressor performance substantially affects the efficiency and reliability of refrigeration cycles using low-GWP refrigerants. Simultaneously, low-GWP refrigerants may reduce refrigeration capacity and compensating for this reduction may require higher compressor speeds or larger compressor sizes. However, increasing the compressor size requires more installation space. It increases the weight, whereas higher-speed operation may increase the loads on the motor shafts and sliding components and reduce durability. Therefore, reducing weight, increasing rigidity, and improving reliability of the compressor components are important technical challenges in realizing compressors that are compatible with low-GWP refrigerants.

In this study, Advance Composite Corporation utilized its metal-matrix composite material technology to develop and evaluate lightweight, high-rigidity materials suitable for compressor components compatible with low-GWP refrigerant mixtures. Cast iron FC250, which is commonly used for rotating compressor components and related parts, was used as the reference material, and aluminum matrix composite materials capable of replacing it were designed, prototyped, and evaluated. The development targets were set at a density of 3.0 g/cm³ or less, tensile strength of 200 MPa or higher, Young's modulus of 110 GPa or higher, coefficient of thermal expansion of 14 ppm/K or less, fatigue strength of 100 MPa or higher, and Brinell hardness of 120 HBW or higher, to develop a material that simultaneously achieves light weight and sufficient mechanical properties.

In FY2023, the materials used for the compressor components were surveyed, and the basic design of the metal-matrix composite materials was conducted. Because cast iron FC200 or FC250 is often used for compressor components, particularly rotating parts, the development was conducted using mechanical properties equivalent to those of FC250 as the benchmark. In material design, the rule of mixtures is used to estimate the density, coefficient of thermal expansion, elastic modulus, and related properties. However, because the strength, elastic modulus, and thermal properties are strongly affected by the reinforcement particle shape, particle size, dispersion state, and interfacial state of the matrix, the rule of mixtures was used only as a design guideline. In the initial investigation, strength improvement was attempted by changing the matrix alloy based on the existing material AC-Albolon®. The developed material exhibited a density of 2.79 g/cm³, tensile strength of 240–260 MPa, Young's modulus of 110–115 GPa, coefficient of thermal expansion of 11–12 ppm/K, fatigue strength of 105 MPa, and Brinell hardness of 129 HBW, thereby generally satisfying the development targets. Although the fatigue strength exceeded the target value, further improvements in the reliability were possible. Fracture surface observations confirmed that the matrix material was distributed in the linear regions surrounding the reinforcement and that cracks propagated along these regions. Variations were also observed in the reinforcement shape and particle size, suggesting that these factors may affect variations in material strength and fatigue properties.

In FY2024, the particle shape and size of the reinforcement were reviewed based on the FY2023 results, and the composite material was redesigned. The developed material '24_MMC02N exhibited a density of 2.73 g/cm³, tensile strength of 360 MPa, Young's modulus of 120 GPa, coefficient of thermal expansion of 12.5 ppm/K, fatigue strength of 133 MPa, and Brinell hardness of 174 HBW. Thus, while achieving a substantial weight reduction compared with FC250, the material exhibited mechanical properties exceeding those of FC250 in terms of tensile strength, Young's modulus, and fatigue strength. In particular, revising the reinforcement structure was shown to be effective in improving the mechanical properties compared to changing only the matrix. The fracture surface observations exhibited clear radial patterns, indicating fracture origins in the tensile specimens, and the fracture morphology appeared macroscopically brittle. Microscopic observations using SEM also revealed dimples, which were traces of ductile fractures. In the fatigue specimens, smooth fracture-surface morphology characteristics of the metal-matrix composites were observed, and fine pore-like features considered to originate from the shape of the reinforcement were also

confirmed. Inclusions were observed in some regions, indicating that suppressing foreign matter contamination during reinforcement processing and stabilizing quality will be important for future mass production.

In FY2025, machinability was evaluated with a view to the practical application of the developed material '24_MMC02N. In milling, MMC02N tended to exhibit a higher cutting resistance and cutting-edge temperature than the conventional AC-Albolon. This tendency can be attributed to the higher mechanical strength of the developed material. Although no major difference in tool wear was observed between the two materials in the early stages of machining, the wear progression in MMC02N became more gradual as the machining distance increased. Ultimately, MMC02N caused less tool wear than the conventional material, confirming that despite its high strength, it has potential for practical application in terms of machinability. The tool wear, cutting resistance, and post-machining surface roughness of the carbide and diamond tools were compared. The results showed that carbide tools tended to exhibit higher cutting resistance and greater tool wear, whereas diamond tools exhibited less tool wear, particularly during finishing, which enabled stable machining. Increased surface roughness was observed under some conditions, presumably owing to initial wear or aluminum adhesion; however, the roughness also tended to stabilize with increasing machining distance. These results indicate that optimization of the tool material and machining conditions is important for machining MMC02N and that the use of diamond tools may be effective.

Through these outcomes, the developed material '24_MMC02N achieved an approximately 62% reduction in density compared with FC250, while improving tensile strength by 44%, Young's modulus by 20%, and fatigue strength by 18.8%. The coefficient of thermal expansion was also maintained at a value close to that of FC250, indicating its promise in terms of the dimensional stability required for compressor components. These results suggest that the material can contribute to the objective of this study, namely compressor weight reduction, particularly the target of a 10% reduction in the compressor weight. In addition, machinability evaluation showed that although the developed material has a high cutting resistance, it tends to cause less tool wear, demonstrating that practical machining is feasible through appropriate tool selection and machining condition settings.

Future development will be advanced from the perspectives of productivity, quality, stability, and cost, based on the mechanical properties and machinability results obtained to date. In particular, controlling the reinforcement particle shape and size, suppressing inclusion contamination, reducing quality variations in mass-production processes, and establishing optimal machining conditions are important. By resolving these issues, the developed material is expected to be commercialized and deployed as a lightweight, high-rigidity metal-matrix composite material for compressors compatible with low-GWP refrigerants.

Volume 4 Safety and Performance Evaluation of Low-GWP Mixed Refrigerants

1. R&D Overview and Outcomes (Central Research Institute of Electric Power Industry)

HFCs, which are alternatives to CFCs and HCFCs, have a high global warming impact, and substantial reductions in their production and consumption are required under the Kyoto Protocol, Paris Agreement, and the Kigali Amendment to the Montreal Protocol. Accordingly, the early development of low-GWP refrigerants and equipment using such refrigerants has become an important issue for residential and commercial air-conditioning equipment, as well as small refrigeration and cold storage equipment. In particular, for residential air conditioners and related equipment for which alternative refrigerants have not yet been finalized, an integrated approach is required from refrigerant-candidate selection to equipment design and evaluation. HFO-1123 and R-1132(E) have attracted significant attention as next-generation low-GWP refrigerants. These refrigerants have thermophysical properties similar to those of R-32, which is the current major refrigerant, and are promising candidates for residential and commercial air conditioning, electric vehicle air conditioning, refrigeration, and cold storage applications. However, because these refrigerants may undergo self-decomposition reactions, safety evaluations that address their chemical stability are required in addition to conventional flammability and toxicity assessments. Self-decomposition reactions strongly depend on the high-pressure and high-temperature conditions, refrigerant composition, and externally supplied energy. In particular, if high-temperature and high-pressure conditions occur inside a compressor owing to abnormal operation and discharge, a self-decomposition reaction may be induced as a result of electrical insulation failure. Because this reaction is exothermic, the resulting increase in pressure and temperature can lead to severe accidents, such as compressor rupture.

Based on these considerations, the Group for Safety Evaluation is advancing research and development on the following major tasks: (1) identifying factors that induce self-decomposition reactions and developing energy evaluation methods, (2) developing methods for evaluating self-decomposition reactions, (3) narrowing down refrigerant compositions, (4) conducting risk assessments, and (5) promoting international standardization (Figure 4.1-1). Together with the Japan Refrigeration and Air Conditioning Industry Association, the group has organized a study group on self-decomposition reactions and is conducting risk investigations within an industry–government–academia framework.

This study evaluates the risk of self-decomposition reactions by comparing the discharge energy corresponding to various short-circuit modes in actual residential air-conditioning equipment with self-decomposition reaction-propagation boundary data. It also enables the identification of refrigerant compositions judged to be safe from the perspective of self-decomposition reactions, the presentation of requirements for safe refrigerants and equipment, and the incorporation of these findings into international standards. By integrating the outcomes of safety, environmental, and performance evaluations conducted by other groups, this study will accelerate the practical application and international standardization of next-generation HFO refrigerants, contribute to achieving the goals of the Paris Agreement and the Kigali Amendment, and support commercialization by refrigerant and equipment manufacturers.

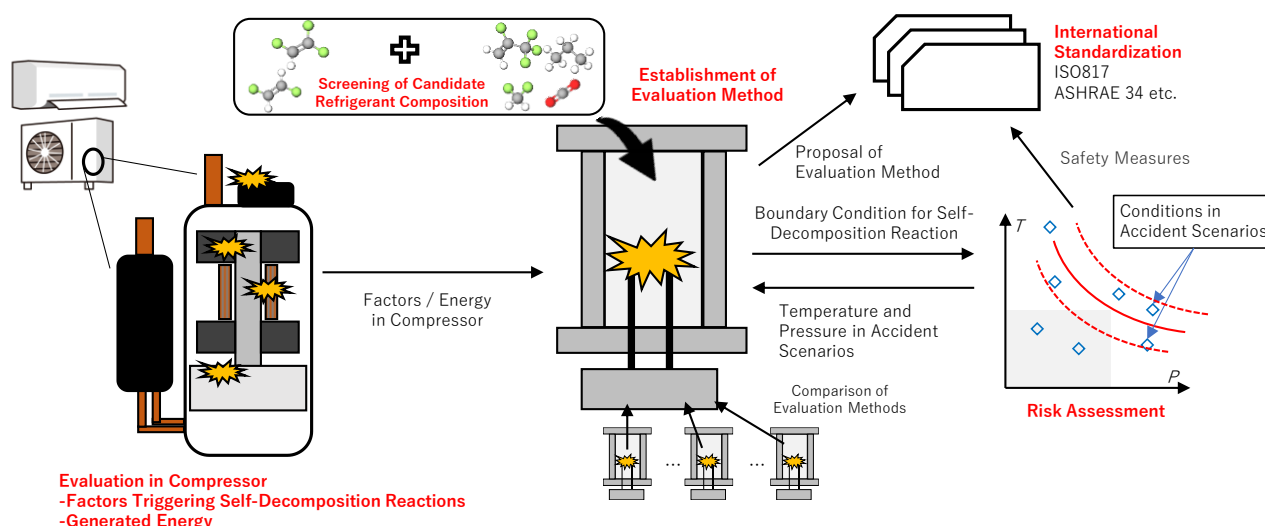


Figure 4.1-1 Overview of research and development items of Group for Safety Evaluation

2. Safety Study on Self-Decomposition Reactions of HFO Refrigerants (Central Research Institute of Electric Power Industry)

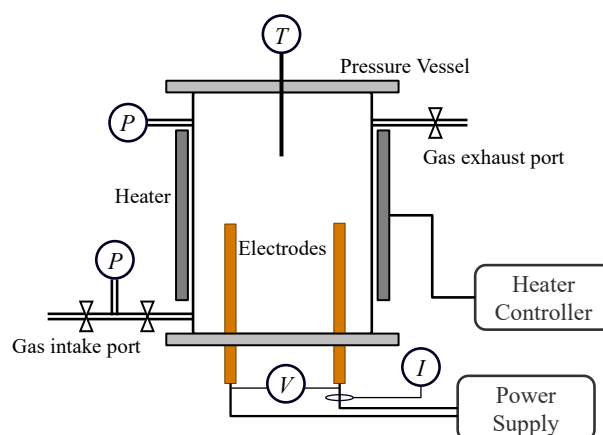
Although HFO-1123 and R-1132(E) exhibit extremely low GWP values, safety concerns associated with their self-decomposition reactions have hindered their practical application and dissemination. In addition to low GWP and safety, these refrigerants must satisfy sufficient cycle performance requirements. In previous NEDO projects, the conditions for the self-decomposition reactions of HFO refrigerants and their mixtures were investigated. However, the test methods were not standardized, and differences in the reaction boundaries depending on the evaluation method remained an issue. Therefore, the standardization of evaluation methods, including test methods and judgment criteria, is indispensable for international standardization.

Current refrigerant safety classifications are defined in ISO 817:2024, based on flammability and toxicity. However, stability-related issues such as self-decomposition reactions have not been addressed. In response to the emergence of next-generation low-GWP refrigerants with self-decomposition reactivity, TF3 (Refrigerant Stability Classification) was established under Japanese leadership within ISO/TC86/SC8 (Refrigerants and refrigeration lubricants), and work was initiated to revise ISO 817 by adding refrigerant stability classifications. As of March 2026, classifications under consideration include Class α for refrigerants with sufficient stability, Class β for refrigerants with sufficient stability under controlled conditions, and Class γ for unstable refrigerants that cannot be used. This study aims to develop the test apparatus and evaluation methods required for the revision of these standards.

In self-decomposition reaction evaluation tests, the reaction propagation is evaluated by applying externally supplied energy to a high-pressure, high-temperature refrigerant sealed in a reaction vessel. The test apparatus is illustrated in Figure 4.2-1. To standardize the self-decomposition reaction evaluation, it is necessary to specify not only the configuration of the test apparatus but also the test conditions, including the temperature, pressure, and ignition method (i.e., the method for supplying energy to the refrigerant). Among these, the ignition method, which supplies the energy required to initiate the reaction, is important.



(a) Appearance



(b) Schematic diagram

Figure 4.2-1 Self-decomposition reaction evaluation apparatus

Regarding ignition methods, multiple existing methods have been reviewed, including the melting, discharge (movable electrode, spiral electrode, and dielectric breakdown), and hot-spot methods. The comparison revealed that even for the same refrigerant under identical conditions, the reaction boundary varied substantially depending on the method, indicating the need for an evaluation method that provides reproducibility, simplicity, controllability of the input energy, and stable discharge characteristics in a high-pressure refrigerant atmosphere. Based on these requirements, the fusing wire and discharge method was selected as a promising method for international standardization. In this method, a metal wire placed between electrodes is fused by energization, and the resulting metal vapor is used to stably form an arc discharge, thereby supplying energy to the refrigerant (Figure 4.2-2).

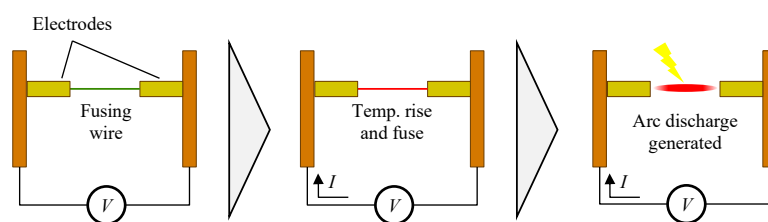


Figure 4.2-2 Fusing wire and discharge method

For the fusing wire and discharge method, the wire fusing and arc discharge processes were evaluated separately, and the predictability and controllability of the input energy were examined. The energy required for wire fusion can generally be predicted from the physical properties of the wire and the energy required to melt the wire completely. In contrast, the input energy during arc discharge can be quantified using the arc voltage, current, and energization time. The arc voltage can also be organized as a function of the electrode gap, gas density, and gas species, demonstrating that the input energy can be predicted and controlled based on these parameters. Through these investigations, test parameters suitable for evaluating the refrigerant self-decomposition reactions were selected.

To verify the validity of the fusing wire and discharge method, interlaboratory comparison tests were conducted at three institutions: CRIEPI, AGC, and Daikin Industries. R-1132a was used as the target refrigerant, and the reaction-boundary pressures were compared under conditions of 150°C, an input energy of 25 J, and an electrode gap of 1 mm. The reaction boundary pressures obtained by the three institutions were within approximately $\pm 5\%$ of the average value. These results confirm that the fusing wire and discharge method is valid for evaluating self-decomposition reactions and provides consistent results across different testing institutions (Figure 4.2-3).

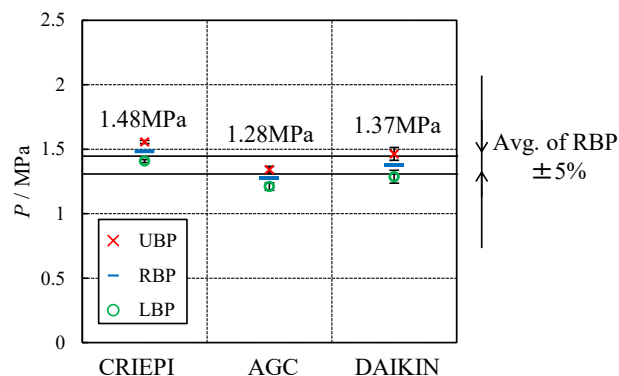


Figure 4.2-3 Comparison of results obtained by three organizations

*: UB: Upper Bound Pressure, RB: Reaction Boundary Pressure, LB: Lower Bound Pressure

Based on these results, this study proposes an outline, test procedure, and the main test conditions for a self-decomposition reactivity evaluation method for the revision of ISO 817. The dependence on additional parameters that may affect the results, such as the input energy, input duration, and vessel volume, will be clarified. In addition, the safety evaluation of next-generation low-GWP refrigerants using the developed evaluation method, narrowing down refrigerant compositions, and risk assessment under assumed practical use conditions will be advanced. These efforts will contribute to the establishment of an environment in which next-generation low-GWP refrigerants can be used safely and will form the basis for practical applications and international standardization.

3. Development of Self-Decomposition Reaction Evaluation Methods and Study of HFO-1123 Refrigerant Mixtures (AGC)

In recent years, growing concerns regarding environmental issues, including global warming, have led to increasingly stringent environmental regulations in the refrigeration and air-conditioning sectors, thereby increasing the demand for the transition to environmentally friendly next-generation refrigerants. Among the HFO refrigerants, HFO-1123 and R-1132(E) contain carbon-carbon double bonds and are therefore chemically unstable, posing risks associated with self-decomposition reactions. When these compounds reach certain conditions, such as specific temperatures, pressures, and input energy levels, self-decomposition reactions are known to propagate in a chain-like manner to the surrounding region. If such propagation occurs inside the refrigerant compressor of the actual equipment, the interior may reach high-temperature and high-pressure conditions, potentially leading to accidents. Therefore, a risk assessment is required to ensure safety before HFO refrigerants with such characteristics can be widely adopted as next-generation refrigerants. However, evaluation methods for determining the conditions under which self-decomposition reactions propagate have not yet been established. Furthermore, tests are currently being conducted by individual companies and research institutions using different apparatus and methods. Consequently, different laboratories may obtain different results. Therefore, the international standardization of evaluation methods is indispensable for the dissemination of these refrigerants. In this study, foundational data supporting the validity of the test methods and apparatuses essential for the international standardization of self-decomposition reaction evaluation methods were obtained.

First, improvements to the existing ignition method for AGC were investigated. Although the existing ignition method can closely reproduce the discharge phenomena that occur in actual equipment and act as inducing factors, it has limitations in reproducing quantitative discharge energy, requiring an extremely large number of test points and making it unsuitable for international standardization. By changing the existing ignition method from an alternating-current

discharge method to a direct-current discharge method and improving the electrode structure, an ignition method that can reproduce discharge patterns with different energy densities and amounts occurring in actual equipment was developed. Figure 4.3-1 shows the resulting discharge energies for R-32 at 3.0 MPa.

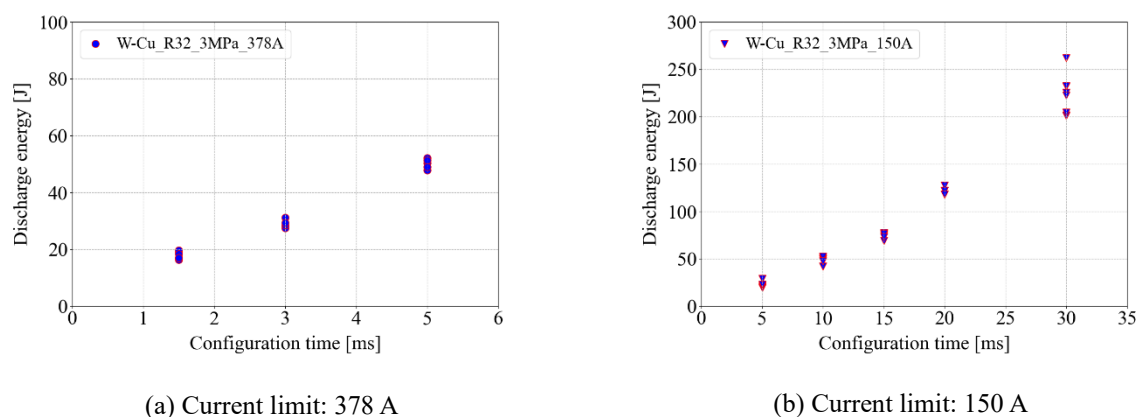


Figure 4.3-1 Quantification of discharge energy in R-32 at 3.0 MPa under different current limiters

Based on the TDG method, the Group for Safety Evaluation proposed a fusing-wire arc method as an ignition method that satisfies both the reproducibility of the discharge phenomena, which can act as inducing factors in actual equipment, and the simplicity of testing. Because the international standardization of this ignition method requires foundational test data to support its validity, basic investigations were conducted. To confirm the consistency of the evaluation results, interlaboratory comparison tests were conducted among three organizations within the Group for Safety Evaluation—CRIEPI, AGC, and Daikin Industries—using R-1132a (vinylidene fluoride) as the reference substance. The boundary pressures for propagation of self-decomposition reactions obtained by each organization at 150°C, an electrode gap of 1 mm, and discharge energy of 25 ± 5 J were within an acceptable error range, thereby verifying the consistency of the evaluation method.

To validate the ignition method, various factors affecting the boundary pressure for the propagation of self-decomposition reactions under different ignition methods were investigated. The results showed that heat transfer through the electrode structure contributed significantly. Even when the same amount of input energy was supplied, the amount of energy transferred from the ignition point to the surrounding gas differed because of heat diffusion into the electrode structure. The fusing-wire arc method proposed for international standardization readily transfers energy to the surrounding gas and may, therefore, overestimate the propagation risk of self-decomposition reactions in actual equipment. These results suggest that an appropriate risk assessment requires the consideration of the thermal environment around the location where the discharge phenomenon occurs inside the refrigerant compressor of the actual equipment.

To acquire the data required for an efficient risk evaluation, room-temperature evaluation is desirable as a substitute for high-temperature testing. In this study, the temperature dependence of the boundary pressure for the propagation of self-decomposition reactions obtained using the fusing-wire arc method was found to be small. As the temperature increased, the molecular collision frequency and the reactivity consequently increased. Conversely, because the tests were conducted at the same pressure, the molecular density decreased at higher temperatures, lowering the collision frequency and reactivity. Nearly identical boundary pressures were obtained because these two effects offset each other.

In response to the demand for low-GWP refrigerants, the maximum mixing ratio of HFO-1123 in the ternary HFO-1123/R-32/R-1234yf refrigerant mixtures was investigated to develop a refrigerant mixture containing HFO-1123 with a GWP of 150. The test conditions were set at 130°C and 4 MPa, assuming normal operating conditions for residential air conditioners. Figure 4.3-2 shows the test results. Under these assumed normal operating conditions, when an energy of up to 30 J was supplied, self-decomposition reactions did not propagate for compositions with an HFO-1123 mixing

ratio of up to 50 mass%. These results can be used for composition development aimed at improving the cycling performance of refrigerant mixtures containing HFO-1123.

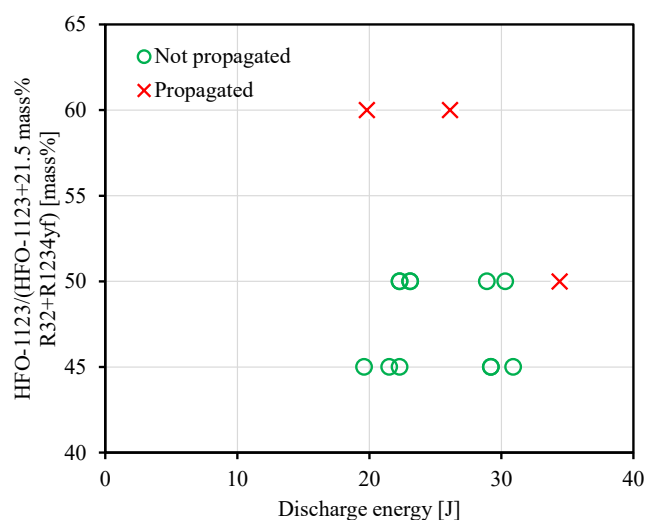


Figure 4.3-2 Experimental results for varying HFO-1123 concentration and discharge energy

4. Development of Self-Decomposition Reaction Evaluation Methods and Safety Verification of Refrigerant Mixtures Containing R-1132(E) (Daikin Industries)

A discharge test apparatus capable of operating under high gas pressures was developed to establish a test method suitable for evaluating self-decomposition reactions in air-conditioning equipment, and standardized investigations were conducted. Using the developed test method, the limiting R-1132(E) mixing ratio, or boundary, for self-decomposition reactions in mixed systems with R-1234yf and other refrigerants was examined. The mechanism of the self-decomposition reactions was investigated, and the risks anticipated when these refrigerants were used in air-conditioning equipment were evaluated, thereby providing information for determining whether equipment-level countermeasures are necessary.

The developed fusing-wire discharge method was shown to ensure a reproducible discharge energy while maintaining a lower input voltage than conventional methods, thereby simplifying the apparatus configuration and improving the ease of handling. The discharge characteristics were evaluated using the maximum electrode distance over which the discharge could be established. Furthermore, the effects of the apparatus and test parameters, including the metal wire material and diameter, gas/refrigerant pressure and temperature, applied voltage, and electrode distance, on the discharge behavior were systematically examined. The results suggest that the maximum discharge distance depends strongly on pressure, density, and inter-electrode voltage. The discharge behavior changes as pressure increases, and temperature has a relatively small influence within the present test range. In addition, the effects of differences in the metal wire material, including the melting point, boiling point, work function, and wire diameter, were organized as factors reflected in the discharge-establishment conditions, providing parameter design guidelines for use as an evaluation method.

Regarding the evaluation or test, conditions for self-decomposition reactions, temperature, and pressure were established by referring to the method presented in the United Nations Recommendations on the Transport of Dangerous Goods (TDG), while also considering the high-temperature and high-pressure abnormal states expected in

refrigerant equipment. This method is a candidate safety evaluation method for ISO 817. The validity of the apparatus and method was confirmed through an interlaboratory comparison (ILC). In verification tests using R-1132a, the boundary conditions for self-decomposition reactions, namely the relationship between pressure and discharge energy, were captured at approximately 1.3–1.5 MPa, and consistent trends were obtained among tests. In the evaluation of vessel dependence, the boundary was examined by varying the vessel volume, and changes owing to vessel size were found to be limited, at least within the evaluated range of conditions.

For refrigerant mixtures containing R-1132(E), the R-1132(E)/R-1234yf system was examined with a particular focus on R-474B. No self-decomposition reaction occurred under the test method proposed by ISO 817. The verification will be extended to other mixture compositions to clarify the boundaries of the self-decomposition reactions. Compared with the existing dielectric breakdown method, the boundary conditions were also confirmed to remain unchanged in the low-gas-pressure region. Regarding the mechanism of self-decomposition reactions, hypotheses concerning the reaction pathways have been formulated, and energy evaluations using computational chemistry methods, such as Gaussian, are being conducted to assess the validity of the candidate pathways. These efforts have established a basis for developing explanations that are consistent with experimental results.

This study provided foundational data and evaluation methods for the practical implementation and standardization of safety measures against self-decomposition reactions during the dissemination of next-generation low-GWP refrigerants. Issues anticipated at the dissemination stage were organized, including mechanisms to ensure that equipment patents held by multiple companies do not become barriers to adoption; frameworks for sharing and utilizing know-how related to design, manufacturing, and maintenance; and the importance of international standardization and public communication through public–private promotional collaboration. The results indicated that under domestic and international collaboration frameworks, such as NEDO projects, efforts are needed to propose and incorporate the findings into ISO, ASHRAE, and related standards. In particular, expert interviews and related investigations were summarized regarding mechanisms to ensure that equipment patents held by multiple companies did not become barriers to adoption.

5. Identification of Factors Inducing Self-Decomposition Reactions in Compressors and Development of Energy Evaluation Methods

(Suwa University of Science)

This study quantitatively identifies energy sources that may arise under abnormal conditions inside compressors for residential air-conditioning equipment through investigative, theoretical, computational, and experimental approaches. Based on these outcomes, this study also develops an estimation model capable of quantitatively predicting energy values from compressor operating conditions and related parameters. From FY2023 to FY2025, this study focused on the arc discharge associated with short circuits between windings and between windings and the ground as energy-generation sources under abnormal compressor conditions. An apparatus capable of experimentally reproducing such phenomena was developed, and current and voltage waveforms during short circuits, high-speed images of the discharge luminescence behavior, and emission spectra were obtained under various operating and environmental conditions. Based on these data, the discharge energy was estimated, and the effects of environmental conditions on the estimated energy were investigated. In addition, to establish an energy prediction method that does not rely solely on experiments, a computational method using numerical simulations was developed, and simplified theoretical equations were derived.

In the experiments, the power supply and motor wiring of commercially available single-phase 100 V and 200 V inverter-driven residential air-conditioner compressors and a single-phase 100 V constant-speed compressor were

branched and connected to short-circuit electrodes installed inside a cylindrical vessel capable of reproducing an environment of 6 MPa and 150°C, and one of the electrodes was short-circuited. First, in the interphase short-circuit test using the single-phase 200 V inverter-driven unit, the current rose instantaneously after the short circuit, and an arc discharge lasting approximately 12 μ s occurred at approximately 20 V. The discharge was essentially a single event because the operation of the inverter protection circuit limited its duration. The discharge energy, obtained by integrating the product of the voltage and current over the discharge duration, was approximately 2.5–4 mJ, and differences in the power supply specifications and short-circuit phases had minimal influence on the discharge energy. This value was almost independent of the ambient temperature and pressure and remained nearly constant. By contrast, the light-emitting region produced by the discharge, namely the plasma, expanded as the pressure and ambient temperature increased. Spectroscopic analysis of the emission spectra confirmed that, assuming that only the plasma center reached thermal equilibrium, the energy was of approximately the same order as the discharge energy described above. The limited influence of ambient pressure, temperature, and power supply specifications on the discharge energy is considered to result from the fact that, in arc discharge, thermionic emission from the electrodes is the principal factor sustaining the discharge, and the electrode temperature is the dominant factor.

In the experiments using a constant-speed compressor, in contrast to the inverter-driven unit, the discharge waveform differed among the trials, and multiple discharges were observed. In some cases, the discharge duration was approximately 10 ms. This behavior is attributed to the constant-speed unit operating while being directly connected to the commercial power supply. In particular, a large energy release was observed when a short circuit occurred at a high voltage instant, corresponding to a power supply phase of approximately 90–120°. The average discharge energy was approximately 1.9 J. Analyses conducted using commercial numerical simulation software also yielded results consistent with the experimental results in terms of order of magnitude.

These results provide a basis for establishing methods for predicting the discharge energy caused by short circuits inside inverter-driven and constant-speed compressors. In the future, prediction models will be developed, particularly for discharge energy during ground faults in inverter-driven and constant-speed compressors and during interphase short circuits. Other possible energy-generation mechanisms will also be investigated.

APPENDIX Safety Evaluation for Practical Use of Refrigerants with Potential Self-Decomposition Reactivity (Japan Refrigeration and Air Conditioning Industry Association)

The Self-Decomposition Reaction Risk Study Working Group of the Japan Refrigeration and Air Conditioning Industry Association (hereinafter, JRAIA) conducted a safety evaluation for the practical use of refrigerants with potential self-decomposition reactivity that are under examination as NEDO green refrigerants. The purpose of this study is to establish conditions under which self-decomposition reactions can be avoided, and equipment safety can be ensured by conducting risk assessments for refrigerant mixtures containing ethylene-based HFOs that may undergo self-decomposition reactions when used in refrigeration and air-conditioning equipment and by examining the measures required to ensure safety. Another objective was to disseminate the prospect that NEDO green refrigerants can be used while avoiding self-decomposition reactions, thereby enabling stakeholders in the refrigeration and air-conditioning fields to begin evaluating these refrigerants at an early stage.

In FY2022, JRAIA established and conducted activities through the “Preparatory Working Group for Self-Decomposition Reaction Risk Study” to examine risk assessment methods for refrigerants with potential self-decomposition reactivity. Subsequently, while building on the knowledge obtained by the predecessor working group, full-scale activities were launched in December 2023 as the “Self-Decomposition Reaction Risk Study Working Group,” in cooperation with the NEDO Study Group on Self-Decomposition Reaction.

To ensure safety, the JRAIA Self-Decomposition Reaction Risk Study Working Group examined scenarios in which

the boundary conditions for the onset and propagation of self-decomposition reactions could be exceeded in actual equipment as well as the probabilities of such events. The examination was based primarily on the temperature–pressure relationship lines representing these boundary conditions, which were provided by the NEDO Study Group on Self-Decomposition Reaction and refrigerant manufacturers (hereinafter referred to as the self-decomposition reaction limit lines).

As a basic concept for evaluating the self-decomposition reaction risks, the self-decomposition reaction limit line depends on the energy applied to the refrigerant that induces the reaction (hereinafter referred to as the input energy) and on the composition ratio of R-1132(E) in the refrigerant mixture. As numerous combinations of these factors can be assumed, the evaluation becomes highly complex. Moreover, obtaining self-decomposition reaction limit lines requires several tests to determine the boundary at which self-decomposition reactions occur. Therefore, to simplify the judgment based on self-decomposition reaction limit lines, refrigerant manufacturers estimated the limit lines by fixing the applied energy and varying the R-1132(E) composition ratio in increments of 5%.

The input energy was considered to be generated primarily by the discharge that occurs when a short circuit arises in the motor section of the compressor. This energy varies depending on the power-supply specifications used to drive the compressor, and is expected to differ, particularly between inverter-driven and constant-speed systems. Even among inverter systems, the input energy varies depending on the power-supply specifications and output power. In this study, the power supply specifications were limited to the inverter systems, and the input energy was fixed at the maximum value by estimating the maximum possible input energy. By measuring the maximum discharge energy of inverters for residential air conditioners (RACs) used by the participating companies, the maximum input energy for single-phase 100 V RAC inverters was derived. Based on these results, the maximum input energy applicable to other power supplies, such as three-phase and 200 V systems, as well as inverters for large air-conditioning equipment, was established.

For refrigerants with a temperature glide, the composition ratio of R-1132(E) in the refrigerant mixture may deviate from the charged composition during the operation of the actual equipment. As an initial assessment of the possibility of self-decomposition, the R-1132(E) composition ratio was fixed at the maximum possible value. As a simplified method for estimating the composition, the entire refrigeration cycle was represented by an accumulator and all other components. Furthermore, the composition changes were assumed to depend on the amount of liquid refrigerant retained in the accumulator. Based on this assumption, the maximum R-1132(E) composition ratio was derived using the ratio of the amount of liquid refrigerant that could be retained in the accumulator to the amount of charged refrigerant (hereinafter referred to as the proportion of the accumulated refrigerant) as a parameter.

Regarding the temperature and pressure conditions that may occur in actual equipment, the working group identified scenarios that could lead to high-temperature and high-pressure states, and conducted verification tests for the self-decomposition reaction occurrence scenarios considered likely to reach particularly severe temperature and pressure conditions.

Based on these results, the self-decomposition reaction occurrence limit lines for each R-1132(E) composition ratio and the reachable pressure and temperature conditions for the self-decomposition reaction scenarios were plotted on a temperature–pressure map, and the possibility of self-decomposition reaction occurrence was evaluated. Overall, the equipment conditions under which self-decomposition reactions could occur were considered fairly limited. However, to communicate these results clearly, the findings are presented in the following form:

First, the maximum R-1132(E) composition ratio at which the currently assumed reachable conditions for self-decomposition reaction scenarios do not exceed the self-decomposition reaction limit line was defined as the “R-1132(E) limiting composition ratio” for each refrigerant. The limiting composition ratios were 45% for R-474A and R-474B, and 55% for R-479A. Next, based on the data for the maximum R-1132(E) composition ratio derived from the proportion of accumulated refrigerant in the accumulator described above, the avoidance of self-decomposition reactions was determined for each refrigerant as a function of the proportion of the accumulated refrigerant.

To widely disseminate the judgment results regarding the possibility of avoiding self-decomposition reactions,

presentations were given at the “Activity Report Meeting of the NEDO Project ‘Development of High-Efficiency Refrigeration and Air-Conditioning Technologies toward the Practical Application of Next-Generation Low-GWP Refrigerants’ ” and at the “International Symposium on New Refrigerants and Environmental Technology 2025.” These presentations explain the prospects of using these refrigerants while avoiding self-decomposition reactions, and clarify the applicable range of equipment specifications.

Volume 5 Development of System Evaluation Methods for Low-GWP Mixed Refrigerants

1. R&D Overview and Outcomes (Waseda University)

The objective of this project was to develop technologies for accurately evaluating the performance of equipment using next-generation refrigerants through both theoretical analysis and experimental validation. Specifically, this project has the following objectives:

- ① First, to develop general-purpose heat exchangers and refrigeration-cycle simulators that can be applied not only to existing refrigerants but also to various newly developed next-generation refrigerants.
- ② Second, to establish internationally applicable performance evaluation standards and methods based on these simulators and the performance evaluation apparatus developed by FY2022.

To achieve these objectives, R&D activity was conducted using the following research items:

(1) Evaluation A-1-1: R&D in simulation technology

A general-purpose refrigeration cycle simulator capable of handling both existing refrigerants and various next-generation refrigerants is currently being developed.

(2) Evaluation A-1-2: R&D of optimization technology

A heat exchanger simulator is being developed to investigate the refrigerant distribution paths to ensure that an optimal heat exchanger can be designed for each refrigerant.

(3) Evaluation A-1-3: R&D on refrigeration cycle system evaluation technology.

To verify the validity of calculation results obtained using the heat-exchanger and refrigeration-cycle simulators, experimental validation is conducted using an “optimization validation apparatus,” and the accuracy of the simulation calculations is confirmed.

(4) Evaluation A-2: Development of AI optimization algorithms for refrigeration cycle simulators (Subcontracted Research)

Algorithms are developed to search for the optimal refrigerant distribution paths corresponding to each refrigerant for implementation in a heat-exchanger simulator.

This study aims to establish a system evaluation platform that enables the performance of diverse refrigerants, including low-GWP refrigerant mixtures, to be evaluated fairly and with high accuracy at the actual equipment level, which has been difficult using conventional methods. For example, in drop-in evaluations, in which refrigerants such as R-454C are evaluated using heat exchangers designed for a specific refrigerant such as R-32, it is difficult to assess the inherent performance of each refrigerant.

Accordingly, the basic objective of this study is to evaluate the performance under heat-exchanger conditions suitable for each refrigerant. However, if a complete optimal design, including heat exchanger dimensions and structures, is considered, the number of design degrees of freedom would become extremely large, making it difficult to unify the evaluation conditions for comparing the refrigerant performance. Therefore, this study defines an “optimal heat exchanger for each refrigerant” as one in which only the refrigerant flow path arrangement is optimized. In contrast, the basic structure, such as the heat exchanger size and number of stages, is fixed. Based on this policy, this study aims to establish an evaluation platform that enables a fair comparison of refrigerant performances while considering practicality and potential standardization. This evaluation concept has also been discussed with the Japan Refrigeration and Air Conditioning Industry Association, an industry association of equipment manufacturers, and a certain level of consensus has been obtained regarding its validity.

In this study, refrigerant flow path arrangements were optimized using a heat exchanger simulator, and the performance of each refrigerant was compared and evaluated through refrigeration-cycle simulations that incorporated the optimization results. These activities are not intended to optimize the heat exchanger design method itself; rather, they aim to establish a system evaluation platform that enables fair performance comparisons among refrigerants. Figure 5.1-1 shows the overall R&D structure of this study.

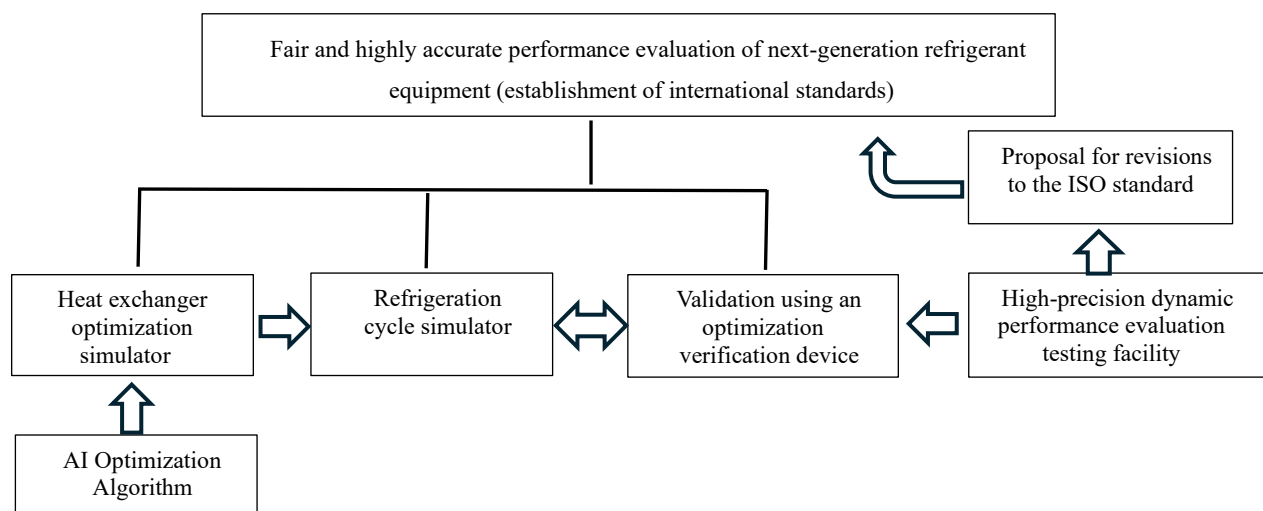


Figure 5.1-1 Overall structure of research and development in this study

This study achieved the following outcomes:

- (1) Establishment of a fair performance comparison and evaluation method considering the characteristics of each refrigerant.
- (2) Construction of a highly reliable evaluation platform integrating simulations and experiments.
- (3) Establishment of a practical design-level heat exchanger optimization technology using AI.

These outcomes constitute foundational technologies that enable the performance design, optimal design, and environmental impact assessment to be implemented in an integrated manner for equipment development using next-generation refrigerants. In particular, the concept established in this study—evaluating the performance under conditions optimized for each refrigerant—will serve as an important guideline for developing international performance evaluation standards.

This R&D work enables the following:

- (1) Advancement of design guidelines for next-generation refrigerant equipment
- (2) Contribution to the standardization of international performance evaluation standards
- (3) Acceleration of social implementation of low-GWP refrigerants

Through these outcomes, the project advances the design guidelines for next-generation refrigerant equipment, supports the standardization of international performance evaluation methods, and accelerates the social implementation of low-GWP refrigerants. The results also directly enhance the reliability of equipment performance evaluation during the transition to next-generation refrigerants.

2. R&D on Performance Evaluation of Refrigeration Cycles Using Next-Generation Refrigerants (Waseda University)

(1) Evaluation A-1-1: R&D in simulation technology

Objective: To develop a refrigeration cycle simulator capable of predicting actual equipment performance with an accuracy of approximately 5%.

Outcome: By incorporating device models, including an accumulator model, the simulator accurately reproduced both refrigerant charge and cycle behavior. A general-purpose analytical platform applicable to both pure refrigerants and zeotropic refrigerant mixtures was developed. Consequently, a simulator capable of predicting the actual performance of conventional refrigerants with an error of approximately 5% was constructed. Figure 5.2-1 shows a schematic of the accumulator as an example of a device model.

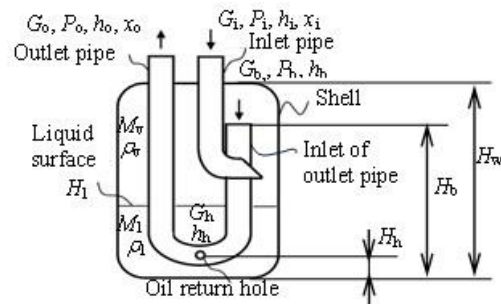


Figure 5.2-1 Schematic structure diagram of accumulator

(2) Evaluation A-1-2: R&D of optimization technology.

Objective: To establish a method for optimizing the refrigerant circuitry in heat exchangers that reflects the characteristics of each refrigerant.

Outcome: A detailed heat-exchanger simulator for evaporators and condensers was developed using a genetic algorithm to optimize the design elements, including branch structures for flow distribution, pressure-loss control, and circuit arrangements for optimizing temperature and phase distributions, while accounting for conditions feasible in actual equipment. As a result, optimal circuit configurations, such as cross-parallel and cross-counter arrangements, can be automatically derived according to the operating conditions, enabling designs that account for the effects of the temperature glide characteristics of zeotropic refrigerant mixtures. Figure 5.2-2 shows a conceptual diagram of the evolutionary process of the path generation algorithm.

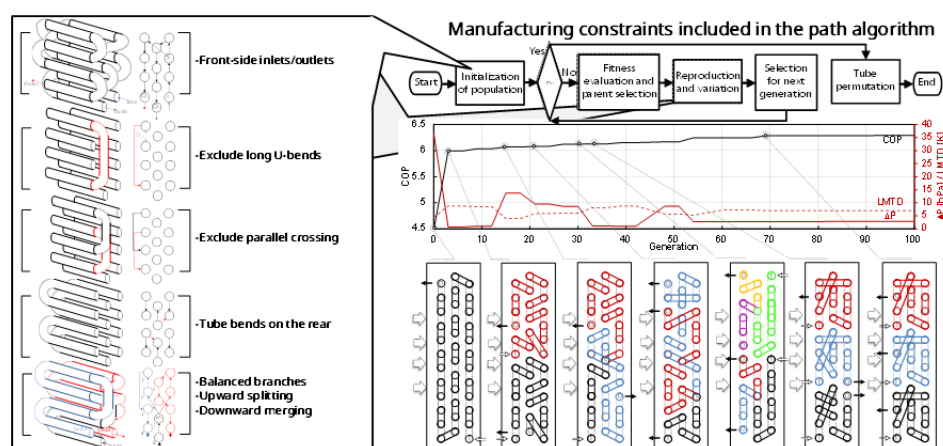


Figure 5.2-2 Conceptual description of the evolutionary progression of the path generation algorithm

(3) Evaluation A-1-3: R&D of refrigeration cycle system evaluation technology

Objective: To construct an evaluation and validation platform for experimentally verifying simulation results.

Outcome: To confirm the applicability of conventional refrigerants, validation tests were conducted for R-32 and R-

454C using an optimization validation apparatus. The simulation results agreed well with the experimental results, confirming the validity of the optimization method. The COP was also shown to improve by up to 20% through evaporator optimization, by up to 11% through condenser optimization, and by up to 23% through simultaneous optimization of the evaporator and condenser. Furthermore, the optimal solution differed depending on the operating conditions. These results indicate that heat-exchanger optimization can improve the performance of R-454C to a level close to that of R-32 and that, for zeotropic refrigerant mixtures, condenser-side characteristics as well as evaporator-side characteristics are important. Figure 5.2-3 compares the cycle performance of R-454C and R-32 when the heat exchanger paths are optimized. These results established an integrated method that enabled a fair performance comparison among refrigerants, which was previously difficult.

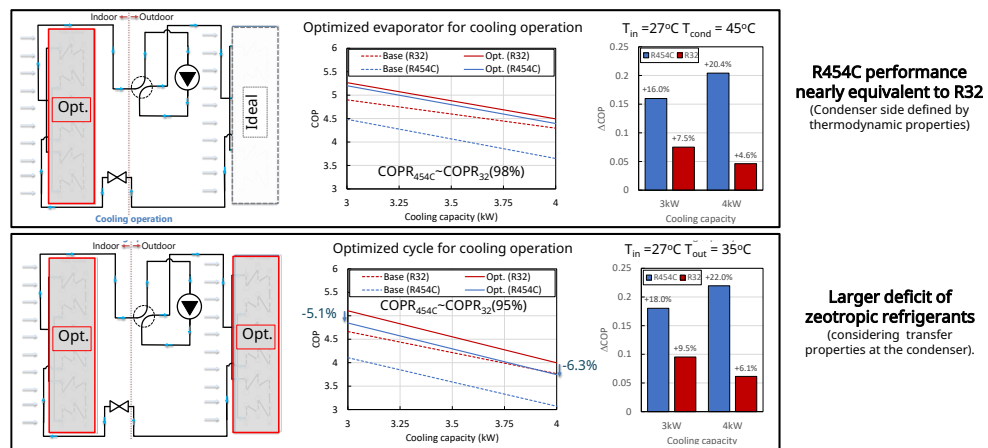


Figure 5.2-3 Optimized cycle performance comparison for different refrigerants

Furthermore, as an extension of the LCCP evaluation, the simulation results were compared with the performance evaluation results obtained in practice. The results showed that heat exchanger optimization can reduce the LCCP of R-454C to a level comparable to that of R-32, demonstrating the possibility of achieving both environmental and energy performance for low-GWP refrigerants. Figure 5.2-4 shows the calculation results for an air conditioner with a rated cooling capacity of 4 kW. It was confirmed that the heat exchanger optimization reduced the LCCP of R-454C to a level comparable to that of R-32.

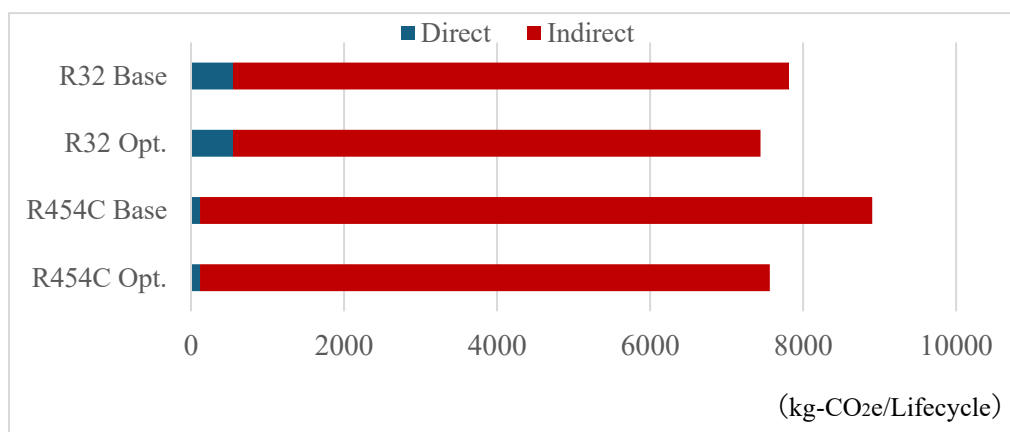


Figure 5.2-4 LCCP calculation results based on heat exchanger optimization (air conditioner with cooling capacity of 4 kW for residential buildings)

3. Development of AI Optimization Algorithms for Refrigeration-Cycle Simulators (The University of Electro-Communications)

(1) Evaluation A-2: Development of AI optimization algorithms for refrigeration-cycle simulators

Objective: To develop AI optimization algorithms that account for manufacturing constraints.

Outcome: A practical algorithm that can handle more than 2,000 combinations of constraint conditions was developed by modeling piping structures as directed acyclic graphs (DAGs) while accounting for manufacturing constraints. The implemented functions include constraint-embedded optimization, an automatic repair mechanism, acceleration through evaluation caching, improved search efficiency by eliminating structural duplication, and enhanced local search using a swap function. Consequently, high-speed optimization limited to manufacturable designs was realized, and the search efficiency was substantially improved compared with conventional methods. This made it possible to quantitatively and automatically optimize the heat-exchanger circuit design, which had previously depended on designer experience. The visualization program is illustrated in Figure 5.3-1.

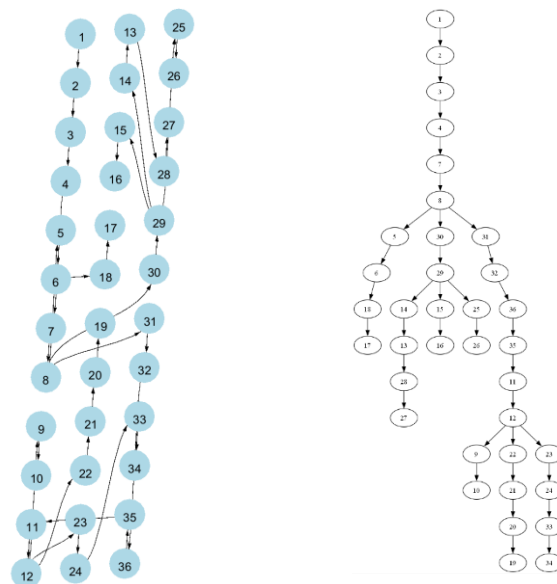


Figure 5.3-1 Examples of structural visualization
Left: Visualization maintaining physical spatial relationships
Right: Visualization of the flow from entrance to exit

Volume 6 Development of Equipment Compatible with Low-GWP Refrigerants

(Residential and Commercial Air Conditioners, Refrigerated and Frozen Showcases)

1. Development of a Condensing Unit Using Green Refrigerant (Hitachi Global Life Solutions)

Under the Kigali Amendment, developed countries are required to reduce their HFC consumption by 85% on a GWP-weighted basis by 2036. The transition to low-GWP refrigerants has become an important societal requirement in the refrigeration and cold storage sectors. Condensing units used in refrigerated and frozen showcases and refrigerated warehouses operate for long periods after installation. As such, refrigerant leakage during operation can affect the environment for extended periods. Therefore, reducing the environmental impact of the refrigerant itself is required in addition to improving equipment efficiency. This study aims to develop a condensing unit that uses a green refrigerant with a GWP below 10 while achieving performance equal to or higher than that of the current model using R-448A, with an initial installation cost at a comparable level.

This study was led by Hitachi Global Life Solutions in collaboration with manufacturers of refrigerants, refrigeration oil, and showcases. A distinctive feature of the study is that it was not limited to the performance evaluation of a stand-alone unit but also included evaluation in a system configuration that assumed actual store operation. The refrigerant selection, material and oil compatibility evaluation, compressor and unit design, prototyping, and demonstration testing were conducted in an integrated manner. By establishing a feedback loop from desk-based studies to actual equipment verification, this study aims to identify and resolve technical issues through practical implementation.

The R&D work consists of seven items. ① “Performance evaluation and selection of HFO refrigerant mixtures through simulation,” refrigerant properties provided by refrigerant manufacturers were incorporated into the company’s simulation tools, and refrigerants were selected while considering unit performance. ② “Evaluation and selection of refrigeration oils and materials,” the thermochemical stability of refrigeration oils and material compatibility were evaluated for the selected refrigerant, issues related to long-term reliability were identified, and appropriate oils and materials were selected. ③ “Compressor design,” ④ “Condensing-unit design”. The validity of the design was then verified through ⑤ “Compressor prototyping and performance/reliability evaluation,” and ⑥ “Condensing-unit prototyping and performance evaluation.” As the final stage, ⑦ “Monitor evaluation equivalent to actual store operation,” is conducted in an actual-store-simulated test room connected to showcases. Performance and reliability were comprehensively evaluated, and the findings were fed back into design improvements to establish specifications capable of withstanding actual operating conditions.

The objective is to clarify a pathway for developing elemental and peripheral equipment technologies that enable a performance equal to or higher than that of the current model. Specifically, the technical targets were defined as follows: (1) selection of refrigerant type and composition; (2) evaluation of oil and material compatibility; (3) formulation of performance improvement measures; and (4) design, prototyping, and evaluation of the compressor and unit, with long-term reliability equivalent to that of the current model and a COP of 100% or higher relative to the current model.

In this study, R-474B was selected as the low-GWP refrigerant suitable for refrigeration unit applications in terms of environmental performance, safety, energy efficiency, and economic feasibility. Compatibility evaluations of the

refrigeration oils and materials indicated the prospect of ensuring long-term reliability equal to or higher than that of the current model. Furthermore, an R-474B-compatible compressor and condensing unit were prototyped and evaluated, achieving a COP equal to or higher than that of the current model. These results indicate that the R-474B condensing unit is highly compatible with the current model and can contribute to achieving carbon neutrality through further dissemination of equipment using low-GWP refrigerants.

Using the refrigeration-cycle simulation technology of the company, the performance and safety of the candidate refrigerants were examined through desk-based studies. Consequently, R-474B was selected as the refrigerant to satisfy the target conditions. Thermal stability tests of refrigerated oils and material compatibility evaluations were conducted, and the oils and materials were selected to ensure long-term reliability. The compressor was designed to increase the circulation rate through high-speed operation without changing the external dimensions. The operating range and reliability were confirmed through component and stand-alone tests. For this unit, the factors causing the COP during the drop-in operation to decrease to approximately 94% of that of the current model were analyzed. Improvement measures, including reducing low-pressure-side pressure loss by adding a subcooling circuit, reducing accumulator pressure loss, and reducing fan input through fan geometry optimization, were applied to improve the COP, achieving 100.5% relative to the current model. In the evaluation under conditions equivalent to the actual store operation, changing the refrigerant from the current R-448A to R-474B reduced the annual electricity consumption to 95.4% of that of the current model, and the application of the prototype compressor and adjustment of the refrigerant charge further reduced it to 89.1%.