Risk Assessment of Mildly Flammable Refrigerants

2014 Progress Report Abstract

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ABSTRACT

1. Introduction

1.1 Trends in Refrigerant Regulation

The regulation regarding the use of stationary air conditioners is known as F-Gas Regulation (EC) No. 842/2006. The present regulation focuses on reducing refrigerant leakage from air conditioners and requires proper management; instructional courses for operators; the labeling of equipment containing F-gas; and reports by producers, importers, and exporters of F-gas. In January 2015, the European Union (EU) enhanced the existing regulations. The new amendment aims to reduce the leakage of F-gas to two-thirds of the present level and prohibits the release of equipment using F-gas in fields where an environmentally friendly refrigerant has been developed. To achieve this, a phase-down schedule has been determined that stipulates that the annual amount of hydrofluorocarbons (HFCs) sold in the EU be reduced to one-fifth of the present amount by 2030.

At the Conference of Parties, which was held with the aim of abolishing practices that damage the ozone layer, three North American countries (the United States, Canada, and Mexico) submitted a proposal to revise the Montreal Protocol and restrict the production and sale of HFCs. However, HFCs do not damage the ozone layer. The problem of global warming was caused by the replacement of prohibited chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which damage the ozone layer, with HFCs, which have a high global warming potential (GWP). The proposal suggests restricting the distribution of HFCs in a manner based on the framework of the Montreal Protocol.

In Japan, the "Law on the regulation of management and rational use of fluorocarbons" was established by the National Parliament on June 5, 2013, and took effect in April 2015. The name of the law was changed from the "Law for ensuring the implementation of the recovery and destruction of fluorocarbons in specific products." The new law requires the replacement of high-GWP HFCs, refrigerant management, and refrigerant recovery to reduce HFC leakage.

1.2 Research Trends of the Safety of Mildly Flammable Refrigerants

The low-GWP refrigerants R1234yf and R32 are promising candidates to replace conventional HFC refrigerants. However, these refrigerants are not very stable in air and are flammable. Therefore, it is essential to collect basic data on the flammability of low-GWP refrigerants and research their safety for practical use. With the objective of gathering essential data for the risk assessment of mildly flammable refrigerants, safety studies are currently being conducted by project teams from the Tokyo University of Science at Suwa, Kyushu University, the University of Tokyo, and the National Institute of Advanced Industrial Science and Technology. Since 2011, these institutions have been sponsored by the project "Development of Highly Efficient and Non-Freon Air Conditioning Systems" of the New Energy and Industrial Technology Development Organization (NEDO). In addition, a research committee was organized by the Japan Society of Refrigerating and Air Conditioning Engineers to assess the risks associated with mildly flammable refrigerants. The Japan Refrigerating and Air Conditioning Industry Association and the Japan Automobile Manufacturers Association are presently conducting risk assessments, and the results are being discussed by a research committee. The 2014 activities of the committee to assess the risks associated with mildly flammable refrigerants are compiled in this report. The committee members would be pleased if this report proved helpful to persons working in associated fields.

2. Fundamental Flammability

Because high-GWP compounds are stable in the atmosphere, less-stable compounds are now being considered as lower-GWP alternatives. The properties that cause these new compounds to have a higher reactivity in the atmosphere also make them more flammable. Considering this tradeoff in risks, low-GWP compounds with mild flammability appear to be alternatives that provide the optimum balance of acceptable safety properties and environmental performance. Thus, risk assessments of mildly flammable (2L) compounds must be conducted before they are used in practical applications.

In the risk assessment of flammable refrigerants, we should consider the combination of the probability of a fire occurring because of the leakage of the refrigerants and the severity of that fire hazard. Accordingly, it is important to collect a set of such indices that appropriately express these two factors. We present an interim report on the fundamental flammability of refrigerants, including flammability limits, burning velocity, minimum ignition energy, minimum quenching distance, extinction diameter, and thermal decomposition.

Many alternative refrigerants are multi-fluorinated compounds, and some are flammable. In particular, their flammability properties are sometimes strongly affected by the humidity conditions. In this study, the effects of humidity on various flammable and non-flammable refrigerants were investigated. The flammability limits of R1234yf and R1234ze(E) were found to be very sensitive to the humidity conditions. The higher the humidity, the wider the flammable ranges of these compounds. In particular, although R1234ze(E) is non-flammable in dry air, it becomes flammable when the humidity exceeds 10% corrected for 23 ºC. It was found that R410A, R410B, and R134a become flammable when the relative humidity exceeds 19%, 25%, and 38%, respectively, at 60 ºC.

Burning velocity measurements of HFO-1234ze(Z) were conducted in a microgravity environment to remove the effect of buoyancy. The maximum burning velocity was determined to be 1.9 cm s^{-1}, which is slightly higher than that of R1234yf. To confirm these results, the increases in the pressure of HFO-1234ze(Z) mixed with R32 and the burning velocities of HFO-1234ze(Z) in a variety of concentrations of O_2-enriched air were compared with those of HFO-1234ze(Z) isomers. It was found that the burning velocity of HFO-1234ze(Z) was lower than that of R1234yf and very similar to that of R1234ze(E).

To judge whether a refrigerant is flammable under practical conditions, information on the ignition energy of the refrigerant and the ignition source in the surrounding environment is necessary. In this study, quenching distance measurements, including its concentration dependence and the estimation of the minimum ignition energy, are updated. The values were compared with the energy of a static electricity spark from the human body.

In this study, an index called the extinction diameter is newly introduced to evaluate the flammability characteristics of 2L refrigerants. This index is expected to be used to judge whether an enclosure of electrical parts with openings, such as a magnetic contactor and socket, can become an ignition source for the refrigerants. We add new data on the extinction diameter of R1234yf as a function of the distance between the ignition source and the opening of the enclosure and provide a discussion on the extinction diameter.

Regarding the thermal decomposition of refrigerants, a comparison is made between 2L refrigerants and typical non-flammable refrigerants with and without moisture. Detailed analysis is performed on the onset of thermal decomposition, concentrations of toxic products, and the difference between the materials of the hot surface. We have not yet observed significant differences between 2L and conventional non-flammable refrigerants.

3. Physical Hazard Evaluation of A2L Refrigerants Based on Several Conceivable Accident Scenarios

3.1 Introduction

We conducted a series of experimental evaluations of the physical hazards associated with A2L refrigerants, assuming occasional accident scenarios in situations in which A2L refrigerants are likely to be handled, based on discussions with developers and associations dealing with air conditioning systems in Japan, such as the Japan Refrigeration and Air Conditioning Industry Association (JRAIA).

3.2 Physical Hazard Evaluation Details for Each Scenario

3.2.1 Scenario #1: Simultaneous use with a fossil fuel heating system

Even when all the refrigerant contained within a commercial room air conditioning system with an area of approximately 11 m^2 leaked into the general living space (7.8 m^2, approximately corresponding to the area of 4.5 tatami mats) where a fossil fuel heating system was in operation, ignition and flame propagation did not occur. The amount of

HF generated as a result of the thermal decomposition of the A2L refrigerant was equivalent to the amount of refrigerant present. When flows were present inside the space, the HF concentration increased.

3.2.2 Scenario #2: Service and maintenance situation

(1) Accident scenario (a): We evaluated the physical hazards of a commercial portable gas lighter used in a space where an A2L refrigerant leaked and accumulated. When a piezo gas lighter was used, no flame propagation was observed. Although ignition and small flame propagation was confirmed near the outlet of a turbo lighter, the flame quickly went out. Significant pressure rises from the blast wave or temperature increases were not observed. However, the ignition and flame propagation of accumulated R32 was confirmed for a kerosene cigarette lighter with a surrogate source of ignition replacing the usual generation by rubbing the flint wheel.

(2) Accident scenario (b): We assumed that the A2L refrigerant leaked from a fracture or pinhole formed in the pipes or hoses during service and maintenance. When the refrigerant leaked from a pinhole with a diameter of 4 mm to simulate a breaking pipe, a flammable zone only formed near the refrigerant outlet. Even when energy in excess of a conceivable ignition source in a realistic situation was provided to the refrigerant jet, ignition and flame propagation to the entire refrigerant jet were not observed.

(3) Accident scenario (c): We assumed that the A2L refrigerant leaked inside a device used for service and maintenance, such as a collection device. When there was no slit to diffuse the accumulated leaked refrigerant in the model collection device to the outside, the refrigerant ignited from an ignition source with very high energy, and the flame propagated to the entire refrigerant. However, the probability of generating an ignition spark above this high energy is extremely low in actual situations. If there is a slit of a suitable width in the model collection device, the accumulation of the refrigerant can be controlled in a very short period of time, and thus ignition can be averted.

(4) Accident scenario (d): We reproduced the diesel combustion that may occur during the pump-down of air conditioners by adiabatic compression of the air, refrigerant, and lubricating oil with the compressor. We determined that the combustion accidents that may occur during pump-down are caused by the diesel combustion of the oil resulting from the air entering the refrigerant tube. At this time, the refrigerant itself burns, which causes the intense pressure rise and the production of HF. It was revealed that the tendency of conventional A1 refrigerants to combust is similar to that of A2L refrigerants in the flammable range.

4. Physical Hazard Assessments

To utilize mildly flammable refrigerants, such as R32, R1234yf, and R1234ze(E), it is important to evaluate the combustion safety of these refrigerants in the event of leakage into the atmosphere from accidents during installation and operation. In this study, the fundamental flammability characteristics of refrigerants were experimentally evaluated using a large spherical combustion vessel, and their safety was assessed. Flammability was investigated in terms of various parameters, such as the flame speed, burning velocity, and deflagration index K_G, under the influence of elevated temperature and moisture and the uplift behavior due to buoyancy arising from the slow burning velocity. The obtained flammable characteristics were compared with those of other flammable gases. Reduced pressure effects due to an opening were considered based on a vent design.

Mildly flammable refrigerants have such a low burning velocity (≤10 cm/s) that a lifting of the flame front due to buoyancy significantly affects their combustion behavior, and they are categorized into the A2L class according to ASHRAE. In this study, a large-volume spherical vessel was prepared to observe and evaluate the effect of buoyancy on the flammable properties of R32 and R1234yf; the flame propagation behaviors of these two refrigerants were observed using a high-speed video camera, and the internal pressure in the vessel was measured using a pressure sensor. In addition to R32 and R1234yf, R1234ze(E) was included in the assessment medium, and the flammability of these A2L refrigerants in the presence of elevated temperatures and moisture was experimentally investigated considering the conditions of a hot and humid summer.

The deflagration index K_G is commonly used to estimate and design the area of the explosion vent of an enclosure to release the internal pressure and protect structures where internal explosions may occur. The deflagration indices K_G for each refrigerant were evaluated along with other properties, such as peak pressure P_{max}, flame speed S_f, and burning velocity S_u. As an implicit but useful reference, explosion characteristics, such as the minimum ignition energy (MIE), detonation limit, and K_G, of other flammable gases were listed with reference to K_G and were compared with those of A2L refrigerants obtained under elevated temperature and wet conditions. It is scheduled to make a comparison with A2L refrigerants and ammonia, which exhibits flammability similar to that of A2L refrigerants, under the same experimental condition.

A study on the severity evaluation method of combustion and explosion of A2L refrigerants under realistic situations has been promoted with the help of K_G value. An evaluation procedure to estimate the reduction effect of the severity of deflagrations caused by combustible A2L refrigerants in a full-scale environment has been developed by defining the relationship between reduced pressure and venting space in a room with the help of the venting design. According to the venting design for explosion protection, the reduced pressure effect due to the presence of an opening in the room was studied, and the effective venting area was experimentally evaluated. Venting area A is assumed to be circular or square-shaped. If the area is rectangular, the desirable ratio of the long side (L) to the short side (D) should be within 2. In an actual situation in the room, L/D may exceed 2, and the effective venting area Av in this case was experimentally evaluated. A cubic vessel with sides measuring 50 cm was prepared for the test. A refrigerant was leaked into the vessel at a rate of 10 g/min and was premixed to a stoichiometric air–fuel ratio. The gas concentration was measured at a point 15 cm from the bottom. The flammable behavior and reduced pressure were observed under the presence of various vent shapes—circles, squares, and rectangles—with different ratios of long and short sides. The reduced pressure effect was summarized according to the vent area and aspect ratio of the rectangles. The effect of decreasing explosion severity due to the presence of the venting will be assessed by determining the relationship between the reduced pressure, the vent area, and the vent shape (L/D). The effect of the vertical concentration gradient of the A2L refrigerants on the explosion severity will be also examined in the next fiscal year (FY).

5. Risk Assessment Procedure for Mildly Flammable Refrigerants

5.1 Introduction

The risk assessment of mildly flammable refrigerants, such as R32, R1234yf, and R1234ze(E), was promoted by the sub-working groups (SWGs) of the JRAIA. In this chapter, the activity of these SWGs is described. Figure 5.1 shows the procedure for the risk assessment of mildly flammable refrigerants, with steps added from IEC Guide 51.

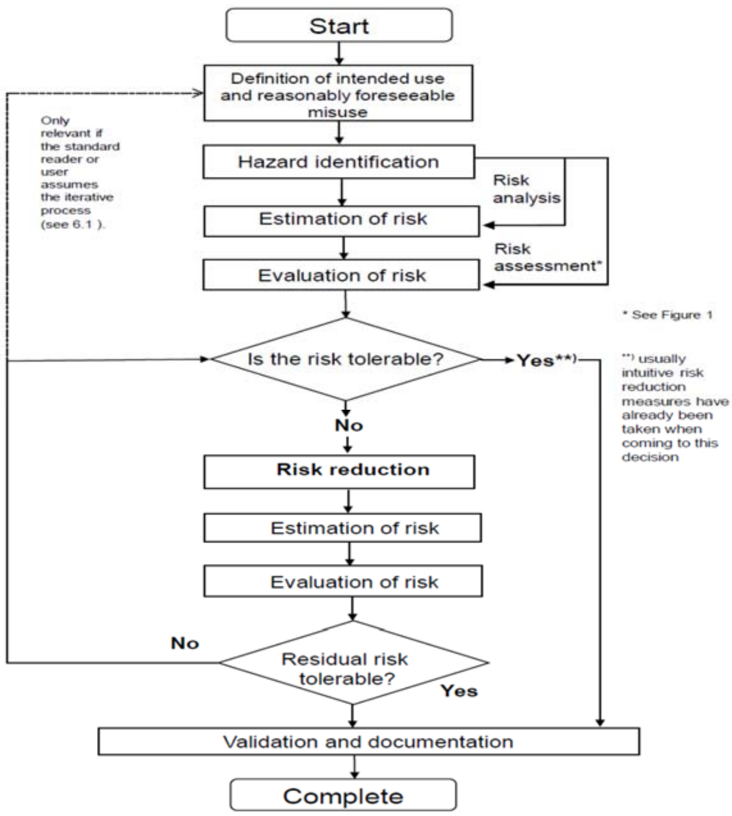

Fig. 5.1 Iterative process of risk assessment and reduction. (*Steps are described later)

In general, risk assessment was performed using such methods as fault tree analysis (FTA), event tree analysis (ETA), and failure mode effects analysis (FMEA). The risk assessment of flammable refrigerants considers two individual phenomena: the presence of an ignition source and the generation of a flammable volume. Thus, we choose FTA to determine the individual phenomenon because it allows for easy calculation. We also referred to Risk-Map (R-Map). For the target setting of the equipment in the risk assessment, the product committee in JRAIA considered a household air conditioner, a building with multiple air conditioners, and a chiller.

5.2 Risk Assessment Method for Mildly Flammable Refrigerants

To implement the specific risk assessment methods, it is necessary to clarify the following terms. According to the National Institute of Technology and Evaluation (NITE), the tolerance for a home electronics unit owned by an ordinary consumer is 10^{-8} accidents/year (based on 1 million sets sold). In other words, a product is regarded as safe if a fatal accident occurs once in 100 years for 1 million sets in circulation for air conditioners and once in 10 years for a chiller. Taking household air conditioning as an example, the leakage term was set to the total amount of leaks in 4 min based on the IEC standard. The time integral of flammable volume was calculated in a 7 m^2 room with computational fluid dynamics (CFD) by the University of Tokyo. In addition, an open flame was used as the ignition source, and human error was set to 10^{-3}. With all of these terms set, FTA was conducted.

This FTA was expanded in detail for each stage, and the values for transport, storage, installation, usage, service, and disposal were calculated. If the obtained value was less than the tolerance value, the risk assessment ended, and the products proceeded to commercialization and release to market.

If the calculated risk exceeded the tolerance value, the review took one of two paths. One was to reduce the risk by reviewing the measures. The other was to determine an event in the critical path that raises the risk value in the FTA. If the risk of hypothesized events was roughly assumed, more accurate risk was obtained through the analysis of the information or more detailed experiments. The calculated values from the review loop of this FTA were repeated until the tolerance value was achieved. Several measures can be considered to lower the risk to below the tolerance value.

5.3 Summary of Risk Assessment

The risk assessment procedure was conducted by the mini-split risk assessment SWG (I) based on the risk assessment advanced at JRAIA through a collaboration between the University of Tokyo, Tokyo University of Science at Suwa, and the AIST Chemical Division.

A risk assessment is a preliminary evaluation of a product for future commercialization. It is only a tool to determine what hazards are present in the product. Each hazard must be addressed if it is harmful. Product engineers master this tool well; it is mandatory to provide safe equipment with a reasonable social cost. Active disclosure of residual and unexpected risks must be continued.

In general, because the risk of an air conditioner increases with the refrigerant amount and the equipment size increases with the voltage source capacity, the risk tends to be high in FTA analysis. Some countermeasures include reducing the amount of refrigerant leakage by providing a shutoff valve, diluting the concentration by adding a high-speed fan, a dispersal fan and an exhaust, eliminating the ignition source by a power-interrupting device located outside the installation compartment, and installing an alarm device. There are many options to avoid risks. These include confirming a seal during installation, reporting safety checks, and regular equipment inspections. Risk can also be avoided by enforcing regulations and standards. The characteristics, installation conditions, usage conditions, convenience, and cost of each device should be chosen to align with the best approach.

The steps are as follows:

a) Select risk assessment method
b) Select evaluation region for the product
c) Select stages of the air conditioner's life cycle
d) Investigate the air conditioner's installation circumstances
e) Determine severity of hazard
f) Set tolerance levels
g) Investigate refrigerant leak rate, speed, and amount

h) Use CFD and calculate time integral of flammable volume
i) Consider ignition sources.
j) Develop FTA and calculate probability, followed by inspection
k) Compare risk (consistency with tolerance)
l) Evaluate risk (consistency with tolerance)

If the evaluated risk is lower than tolerance, go to step p).

m) Reduce risk (measures include the implementation of equipment, a manual, and regulations)
n) Redevelop FTA and recalculate probability
o) Compare risk (consistency with tolerance)
p) Commercialize (confirm important topics) and release to market.

6. Risk Assessment of Mini-Split Air Conditioners

6.1 Introduction

The risk assessment of mini-split air conditioners, which started in 2011, has been completed for all applicable products. Consequently, this is scheduled to be the final progress report. For the assessment of the flammability risks of residential air conditioners (RACs), we reduced the risk probability by performing a refrigerant leak simulation and ignition source evaluation.

The following is a brief summary of the FTA results for wall-mounted air conditioners, one-to-one connection floor standing housing air conditioners, and multi-connection floor standing housing air conditioners, for which data were obtained during the risk assessment undertaken in this project.

6.2 Risk Assessment Procedure

According to the literature released by the NITE, products that are distributed at a rate of 1 million units a year are considered safe if a fatal accident occurs once per 100 years. The total number of RACs (including mini-split air conditioners) in Japan is approximately 100 million sets, so the target value in the calculation is 10^{-10} or fewer sets/year. An indoor space 2.4 m in height and with 7 m^2 of floor area using an air conditioner was used as the leakage space. The installation position of the indoor wall-mounted unit was set at a height of 1.8 m from the floor, and the floor standing unit was set on the floor. To generate the flammable region, which is important when performing a risk assessment of mildly flammable refrigerant, the values of R32 and R1234yf were obtained using the same technique for the data given in earlier literature, and the simulation results were performed at the University of Tokyo. Referencing the reports of Imamura in the Tokyo University of Science at Suwa, Takizawa in AIST, and DOE/CE/23810-92 from ADL, Inc., in 1998, the SWG describes the items that are assumed to be ignition sources as follows. Low-voltage electrical equipment in Japanese homes does not ignite. Ignition does not occur with burning tobacco that does not emit a flame. Static electricity caused by the human body within the living space does not ignite. The ignition sources of outdoor and indoor units of R32 or R1234y RACs were assumed to be open flame, and the risk assessment was conducted. We also investigated leakage conditions and human error probability, thus obtaining the ignition probability by FTA using the above items.

6.3 Summary of Fault Tree Analysis

The results of the risk assessment for RACs in the configurations outlined above are described in Table 6.1. In the case of the one-to-one connection normal wall-mounted air conditioner, the hazard occurrence probability (ignition rate) in the revised risk assessment was almost 10^{-10} during use and was below 10^{-9} during logistics, installation, service, and disposal. Because each value was below the tolerance value, no further risk assessment was performed.

To achieve equivalent performance and efficiency for R1234yf when applying mildly flammable refrigerants to conventional R410A RACs, the heat exchanger must be increased to approximately 1.4 times its size, and a new large-size compressor must be developed and its reliability ensured. While looking at Table 6.1, it is necessary to keep in mind that the values have been slightly revised from the previous progress report.

Table 6.1 Ignition probability of various refrigerants (normal wall-mounted air conditioner)

Risk: Ignition probability			
Life Stage	R32	R1234yf	R290
Logistic	4.1×10^{-17}	4.5×10^{-17}	1.9×10^{-8}–5.0×10^{-6}
Installation	2.7×10^{-10}	3.1×10^{-10}	1.5×10^{-6}–1.7×10^{-5}
Use (Indoor)	3.9×10^{-15}	4.3×10^{-15}	5.9×10^{-9}–1.1×10^{-4}
(Outdoor)	1.5×10^{-10}	2.1×10^{-10}	9.7×10^{-13}–1.9×10^{-8}
Service	3.2×10^{-10}	3.6×10^{-10}	9.3×10^{-6}–1.7×10^{-5}
Disposal	3.6×10^{-11}	5.3×10^{-11}	1.8×10^{-5}–1.3×10^{-4}

However, the values for single and multi floor standing air conditioners are larger than the tolerance values, even in the reviewed risk assessment. Therefore, research into the installation and actual service conditions and investigation of door clearances were conducted, primarily in Japanese-style houses, to achieve risk assessment values closer to those of actual usage. We also reviewed whether the same tolerance values could be applied for normal wall-mounted air conditioners. The latest risk assessment results, which are very important, are given in Table 6.2.

The tolerance value for single floor standing air conditioners was 10^{-9} during use and 10^{-8} during logistics, installation, etc., which almost satisfies the allowable values.

Table 6.2 Ignition probability of various RACs

Risk: Ignition probability			
Life Stage	Normal wall-mounted R32	Single floor standing R32	Multi floor standing R32
Logistic	4.1×10^{-17}	3.6×10^{-11}	1.1×10^{-9}
Installation	2.7×10^{-10}	4.0×10^{-11}	9.0×10^{-9}
Use (Indoor)	3.9×10^{-15}	4.1×10^{-10}	4.7×10^{-10}
(Outdoor)	1.5×10^{-10}	8.6×10^{-11}	1.1×10^{-9}
Service	3.2×10^{-10}	2.6×10^{-10}	4.3×10^{-9}
Disposal	3.6×10^{-11}	2.5×10^{-11}	4.1×10^{-10}

6.4 Summary

In the mini-split risk assessment SWG, we performed risk assessments of R32 and R1234yf in wall-mounted small-size commercial use air conditioners (which are substantially the same as RACs) and confirmed that there are no problems upon use. We also conducted a risk assessment of RACs using R32 and confirmed that they can be used without problems if certain measures are adhered to. To lessen the risks, we also revised the installation and service manuals for the SWG. More precisely, in the “Piping construction manual for RACs using R32 refrigerant” (internal industrial society material) issued by the JRAIA, we added caution reminders to service and installation manuals, among other materials, and proposed suggestions and manuals for measures that can be carried out when using R32.

Finally, from the results of the analysis carried out at the Tokyo University of Science at Suwa and the National Institute of Advanced Industrial Science and Technology, which participated in the project for the risk assessment of mildly flammable refrigerants, the revision of the FTA resulted in significant improvements

. In the future, we expect that once the level of harm becomes clear, we will be able to use R32 and R1234yf air conditioners with even greater safety and contribute to the prevention of global warming. This concludes our present risk evaluation of mini-split air conditioners.

7. Risk Assessment of Split Air Conditioners (Commercial Package Air Conditioners)

By comparing split air conditioners (commercial package air conditioners, C-PACs) with mini-split air conditioners (RACs) and variable refrigerant flow (VRF) air conditioners for buildings from the perspective of a risk assessment as with A2L, we conducted a risk assessment of C-PACs by the same methodology. First, we set the allowable risk level of a C-PAC as the target of the risk assessment. The allowable level was set as the probability of a serious accident occurring in the market once every 100 years. Because research on the degree of a hazardous ignition accident has not yet been completed, all ignitions were treated as serious. The probability of an ignition accident was multiplied by the leakage probability, the probability of generating a flammable region, and the probability of the presence of ignition sources. For each life cycle stage (logistics, installation, usage, service, and disposal), the ignition probability was calculated using FTA based on the assumed risk scenario. We assessed C-PAC systems in three categories.

First category – Typical C-PAC models: ceiling cassette indoor unit in an office, less than 14 kW outdoor unit installed at ground level without additional charge, and bulk storage at a warehouse.

Second category – Severe models for systems of less than 14 kW, excluding floor standing indoor units. The maximum piping length and charge amount were assumed. Indoors: kitchen with many ignition sources, airtight karaoke room. Outdoors: each floor, semi-underground, and narrow space installations. Logistics: small warehouse storage and minivan delivery.

Third category – Severe models for all C-PACs of less than 30 kW, including floor standing indoor units. The maximum piping length and charge amount were assumed. Indoors: floor standing where the leaked gas remains at a high concentration, ice thermal storage indoor unit (ceiling type), and the same outdoor models as the second step.

For the typical normal models of a C-PAC system, the ignition probability using R32 satisfied the allowable risk without additional safety measures. However, safety measures were needed to satisfy the allowable level for some severe cases included in the second and third categories.

For some stages of outdoor semi-underground installation and narrow space installation, the ignition probability did not satisfy the allowable level. The dominant risk factors during the service stages were the result of human error, such as improper refrigerant recovery, which generates a flammable region, and improper wiring of power supply, which may cause a spark, in addition to the probability of the presence of the open flame of a gas burner during welding. Thus, we proposed education for workers and carrying a leak detector, as necessary safety measures.

For the usage stage, we proposed a reduction in the probabilities of the presence of ignition sources and the generation of a flammable region as follows. Semi-underground: prohibit installation near a boiler and mechanical ventilation or the unit's fan operating with a leak detector. Narrow space: an opening of 0.6 m or more for one side or prohibit installation near a boiler.

In the case of an indoor floor standing unit, the probability of generating a flammable region was too high because the leaked gas tended to remain near the floor at a high concentration. The safety measure taken during the usage stage was to force the unit's fan to be on with a leakage detector near the floor. For the service stages, the measures of education for workers and carrying a leak detector were effective.

We plan to introduce the safety measures to the installation manual for C-PACs using R32. When additional studies (on the flammability of A2L refrigerants other than R32 for varying levels of humidity and the degree of a hazardous ignition accident with A2L) are conducted in the near future, we plan to include the latest information in our risk assessments to achieve a more practical assessment.

8. Risk Assessment of Variable Refrigerant Flow Systems

8.1 Introduction

The purpose of this risk assessment is to accurately evaluate the risk of VRF systems using mildly flammable low-GWP refrigerants and establish safety standards based on those results to ensure a sufficient level of safety in the market. To slow the advancement of global warming, these products must gain market acceptance. This will require progress in the development of viable safety standards that eliminate the need for excessive regulations. To propose safety regulations that are compatible with commercialization, the probability of fire accidents was estimated, including installation cases that are close to actual market situations, and safety standards were proposed to reduce the probability to allowable values. In this risk assessment, R32 was used as a representative mildly flammable refrigerant.

8.2 Risk Assessment Results

First, installation cases that include significant risk were identified for each of the life cycle stages of transportation and storage, installation, operation, repair, and disposal. Next, an FTA was created for each identified case, and the probability of fire accidents for each stage was obtained. At that time, installation cases were assumed with no measures taken outside of replacing the current refrigerant R410A with R32, and the values for the probability of fire accidents were set with no measures taken. When those values exceeded the established allowable values, the execution of safety measures became necessary. When the incidence of a fire accident was less than 1 in 100 years, it was considered to be socially acceptable, and the allowable values for the probability of fire accidents were set to be equivalent to that frequency.

Tables 8.1 and 8.2 indicate the probability of fire accidents during indoor and outdoor operation, respectively. Each assumed installation case is listed vertically in the tables, and the installation site, unit type, constituent ratio of the market for each installation case, and allowable probability are indicated horizontally. Furthermore, the probability values of fire accidents occurring when no measures are taken are indicated for cases with no mechanical ventilation and for cases with mechanical ventilation in the amount specified by the Building Standards Act. Additionally, each probability of fire accidents for cases in which safety measures were implemented is indicated when the values without mechanical ventilation exceeded the allowable values. Cases exceeding the allowable values are indicated by white spaces. In the last column of each table, the probability of fire accidents is indicated for the market overall. This was obtained by multiplying the market constituent ratio by the fire probability of each installation case.

For installation cases excluding ceiling spaces, the probability of fire accidents occurring during indoor operation without mechanical ventilation was higher than the allowable values, and thus safety measures are necessary. Specifically, when ventilation is turned off at night in an

Table 8.1 Probability of fire accidents during indoor operation

In each installation cases [time/(unit・year)] Not allowable | Allowable

Installation case					Fire accident probability A		
					Without measures		With measures
Site		Type	Constituent ratio P	Allowable probability	No vent	Vented	
Indoor	Karaoke	Ceiling	2.1E-03	1.0E-09	1.8E-07	4.4E-11	0.0E+00
	Restaurant	Floor	2.0E-02		3.8E-07	5.4E-09 *1)	2.6E-10 *2)
	Hair salon	Ceiling	1.6E-03		1.3E-09	1.2E-10	6.8E-12
	BBQ restaurant	Ceiling	7.8E-04		2.8E-09	4.4E-10	1.5E-11
	Ceiling space	Ceiling concealed	1.0E-00		3.0E-10	-	3.0E-11

Ventilation turned off at night

Installation case					Fire accident probability A		
					Without measures		With measures
Site		Type	Constituent ratio P	Allowable probability	No vent	Vented	
Indoor	Office	Ceiling	3.8E-01	1.0E-09	7.6E-09 *3)	3.5E-12	3.5E-12

Total in market

Total＝Σ(P＊A)	4.0E-01	1.0E-09	1.1E-08	1.1E-10	3.7E-11

*1) Supply and exhaust on the ceiling surface cannot dilute refrigerant gas leaked from floor unit.
*2) Measures are mechanical ventilation with a vent opening near the floor, or , agitation by the indoor fan.
*3) Ventilation turned off 18:00 to 09:00. Ignition sources are smoking by overtime people and water heater driving after people left from office.

Table 8.2 Probability of fire accidents during outdoor operation

In each installation cases [time/(unit・year)] Not allowable | Allowable

Installation case				Fire accident probability A		
				Without measures		With measures
Site		Constituent ratio P	Allowable probability	No vent	Vented	
Out-door	Usual	9.4E-01	4.0E-09	1.9E-11	—	—
	Each floor	5.0E-02		3.0E-09	—	—
	Semi-underground	1.0E-04		1.1E-07	—	2.5E-13 *1)
	Machinery room	6.0E-03		6.1E-08	—	3.2E-09 *2)

Total in market

Total＝Σ(P＊A)	1.0E+00	4.0E-09	5.4E-10	—	1.9E-11

*1) Mechanical ventilation with suction duct
*2) Mechanical ventilation, 2times/h*2syetem

Table 8.3 Probability of fire accidents during each work stage

In each installation cases [time/(unit・year)] Not allowable | Allowable

Installation case					Fire accident probability A					
					Installation		Repairing		Disposal	
			Constituent ratio P	Allowable probability	Without meas.	With meas.	Without meas.	With meas.	Without meas.	With meas.
In-door	Office	Ceiling	3.8E-01	1.0E-08	1.9E-09	—	8.7E-11	8.8E-12	2.9E-14	2.9E-15
	Restaurant	Floor	2.0E-02		1.9E-09	—	1.2E-08	3.9E-11	3.4E-12	3.4E-13
	Karaoke	Ceiling	2.1E-03		-	—	-	—	-	—
Out-door	Usual	–	9.4E-01	1.0E-08	1.9E-09	—	1.4E-09	1.4E-10	2.4E-10	3.2E-11
	Each floor	–	5.0E-02		1.9E-09	—	3.1E-09	3.1E-09	1.0E-09	1.4E-10
	Semi-underground	–	1.0E-04		1.1E-08	1.9E-09	3.6E-07	2.1E-09	3.3E-08	4.8E-10
	Machinery room	–	6.0E-03		1.1E-08	2.1E-09	8.6E-07	5.4E-09	2.2E-08	3.3E-10

Total in market

			Without meas.	With meas.
Indoor total＝Σ(P＊A)	4.0E-01	1.0E-08	1.0E-09	4.1E-12
Outdoor total＝Σ(P＊A)	1.0E+00	1.0E-08	9.0E-09	3.7E-10

office where the constituent ratio is high, oil cigarette lighters can be ignition sources, and the fire probability exceeds the allowable values.

In outdoor operation, safety measures, such as a combination of mechanical ventilation and an outdoor unit fan, must be implemented because the probability of fire accidents exceeds the allowable values for semi-underground and machinery room installations.

In Table 8.3, the probability of fire accidents is indicated for each work stage, such as transportation and storage, installation, repair, and disposal. In semi-underground and machinery room installations, the probability of fire accidents when the burner acted as an ignition source during brazing operation exceeded allowable values. Leak detection devices are essential countermeasures to check leakage. Sufficient mechanical ventilation is necessary when repairing equipment at restaurants where floor standing units are installed.

8.3 Analysis of Probability of Fire Accidents

Figure 8.1 indicates the probability of a fire occurring during indoor operation when using refrigerants R32 and R290 in RACs and refrigerant R32 in VRF systems. The vertical axis expresses the probability of fire accidents and was derived by analyzing the probability of a flammable region (cloud) emerging from a refrigerant leak and the probability of the refrigerant leak encountering an ignition source. The probability that the flammable region encounters an ignition source is higher when using R290 than when using R32, and if a rapid R290 refrigerant leak occurs, it is thought that this can easily become the cause of a fire accident. This is due to the fact that R290 generates a large flammable region even if the leakage amount is relatively small because its lower flammability limit (LFL) is low, and one of many electrical components found indoors, such as an electrical outlet, light switch, or electric lighter, can easily become an ignition source. Because VRF systems using R32 have a greater amount of refrigerant than do RAC systems, the flammable region is large and continues to exist for a long time. For this reason, the probability of it encountering an ignition source becomes substantial.

To lower the probability of fire accidents to below the allowable values in R290 RACs and R32 VRF systems, safety measures are necessary. Lowing the probability below approximately 1/1,000,000 in R290 RACs requires the implementation of safety measures, including refrigerant charge amount regulations, explosion proofing, and ventilation. Safety measures are necessary to reduce the probability of fire accidents to approximately 1/10 in R32 VRF systems; however, options are not limited to regulatory control but also include official and industrial standards. Although ventilation, leak detection and warnings, and refrigerant shut-off devices have been considered as safety measures, the probability of fire accidents can be expected to fall below 1/10 by incorporating main unit safety functions.

Product	Residential	←	VRF
Refrigerant	R32	R290	R32
Charge [kg]	1.0	0.5	88.1
Installation site	Living room (7m²)	←	Office (40.3m²)
Ventilation	None	←	Off at night

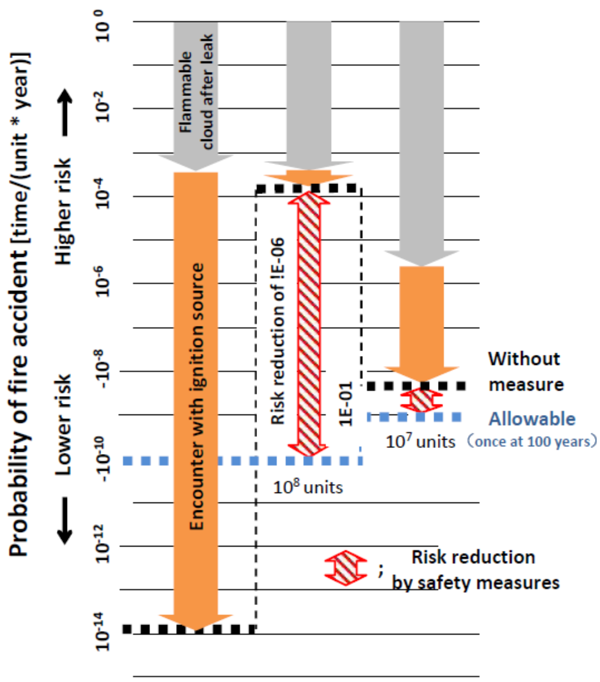

Fig. 8.1 Probability of fire accident with R290 (RAC) and R32 (RAC and VRF)

8.4 Summary

Risk assessment was performed for VRF systems using the mildly flammable refrigerant R32, which has a low impact on global warming. Safety measures were proposed for stages during indoor and outdoor operations, installation, repair, and disposal to lower the probability of fire accidents for each installation case to 1 in 100 years, including even the most difficult cases. Furthermore, an estimate was performed for the probability of fire accidents occurring during use in the market overall, and it was clarified that the incidence of a fire accident can be lowered to 1 in 100 years by incorporating main unit safety measures.

From this point forward, it is desirable to gather these safety requirements as technical standards and establish industrial safety measures that are incorporated as functions of the main unit instead of regulations, such as prior application at the time of installation.

9. Risk Assessment of Chillers

9.1 Introduction

Heat source systems supplying hot or cold water to central air conditioning systems use R410A or R134a hydrofluorocarbon refrigerants. Both refrigerants have a GWP exceeding 1000 and thus could contribute to climate change. Therefore, it is necessary to ultimately replace them with low-GWP alternatives. R1234yf, R1234ze(E), R32, and mixtures thereof have been evaluated in drop-in, retrofit, and performance tests. All of these low-GWP refrigerants are mildly flammable. Risk assessments for burn injury and fires in chiller systems using these mildly flammable refrigerants have been undertaken since the 2011 FY. The scope of this study includes air-cooled heat pumps installed outdoors and water-cooled chillers installed in machine rooms and used as a central air conditioning heat source with a cooling capacity ranging from 7.5 to 175,000 kW. This year, the chiller sub-working group (chiller SWG) executed (a) a risk quantification based on the results of a refrigerant leak analysis conducted jointly by the University of Tokyo and the chiller SWG, reviewing the probability of ignition and the associated risk, (b) RAs based on the requirements for chiller design and the conditions of the facilities that incorporate the measures and the actions, (c) the drafting of JRAIA guidelines (GLs) for the generalization of technical requirements.

9.2 Risk Assessment Procedure

Risk assessments are executed according to the following procedure, which follows the basic risk assessment flow.

(1) The basic specifications of the chiller of an RA are defined according to its application, cooling capacity, structure, and installation location.

(2) The life cycle of the chiller is separated into six life stages (LSs), from the logistics stage to the disposal stage, and the risks associated with each stage are then analyzed.

(3) The relationships between probable ignition sources and the cases of refrigerant leakage are clarified using the FTA method, and then the probability of the occurrence of burns and fire accidents is calculated by considering the ignition source density, leak probability, and the flammable space volume integrated with respect to the time of the leak. Because each accident or case is an independent event, the combined probability of each case indicates the annual probability of the occurrence of accidents per unit.

(4) Safety requirements for the chiller and the facility are established to reduce high-risk hazards, and then GLs for their technical requirements are drawn up.

9.3 List of Risk Assessment Conditions

For the current calculation of the risk of burn injury and fire accidents, the time-dependent volume of the flammable space for a burst and rapid leak was calculated along with the probability of the presence of each ignition source during that time. The calculation conditions are defined as follows, and it is assumed that each of the six LSs has different ignition sources.

(1) Four pieces of equipment that comprise the heat-source system are installed, and the startup/shutdown cycles of adjacent pieces of equipment are considered.

(2) The ventilation of the equipment is to be (2 air changes/h) × (2 lines) = 4 air changes/h, and the failure rate of the duct fan is estimated to be 2.5×10^{-4}/(unit·year).

(3) The probability that the equipment is not ventilated at all is 1%, and at the LSs of the installation and disposal it is assumed to be 50%.

(4) For each LS, logistics and disposal without the direct contact of a user are excluded from the probability of accidents while the values are specified.

(5) The probability of the existence of a flammable space when there is no ventilation is defined as same as the probability of refrigerant leakage.

(6) When the machine room is ventilated, the probability of a small leak existing is 0 because the existence of a flammable space is not considered.

(7) The probability of the existence of a flammable space is given as the time-dependent volume of the flammable space [m^3 min]/(target space [m^3] × 8760 h × 60 min). The target space of an air-cooled heat pump is defined as the area surrounded by soundproof walls.

(8) Ignition sources are assumed to exist throughout the flammable space, including the floor surface. For example, the existence of a lighter flame at the ground level is not excluded.

(9) The time-dependent volume of R1234ze(E) is applied for a water-cooled chiller, and R32 is applied for an air-cooled heat pump.

9.4 Probability of Fire Accidents

The probabilities of fire accidents for each LS in the case of chillers both with and without countermeasures are listed in Table 9.1. A previously measured value describes the risk with no ventilation and shows the probability of a fire accident based on the existence of an ignition source, the occurrence of low-flammability gas leaks, and whether the concentration of the refrigerant is within the flammable range. During the LSs under the management of a user, the probability of bursts, rapid leaks, and slow leaks are summed to yield 1.32×10^{-4} accident/(unit･year), which is larger than the actual value. For example, if the machine room is narrow and without ventilation at 1% of constituent ratio, the probability is 1.32×10^{-6} accident/(unit･year), which is not acceptable. The probability of a fire accident when countermeasures have been taken is calculated from the probability of the flammable space for a standard chiller model with ventilation and a standard machine room. The probability during the LSs under the management of a user is 3.90×10^{-12} accident/(unit･year), which is evaluated as being "improbable."

Table 9.1 Probability of fire accidents

	LS	LS ratio	Without ventilation [1/(unit･year)]		With ventilation [1/(unit･year)]	
			LS	LS under user's management	LS	LS under user's management
Suppliers	Logistics	0.0517	4.28×10^{-6}	-	1.51×10^{-13}	-
Operator	Installation [carry-in]	0.0517	4.67×10^{-6}	1.32×10^{-4}	2.40×10^{-12}	3.90×10^{-12}
	Installation [trial]	(0.0023)				
	Usage [machine room]	0.2144	6.19×10^{-5}		4.97×10^{-13}	
	Usage [outdoor]	0.5002				
	Repair	0.1207	6.52×10^{-5}		1.00×10^{-12}	
	Overhaul	0.0098				
Suppliers	Disposal	0.0517	1.72×10^{-5}	-	9.23×10^{-12}	-

9.5 Technical Requirements for Safety

This section describes the safety requirements and compares them with KHKS0302-3, ISO5149-3 (2014), and the Japanese domestic legal standards and requirements for the reference of this risk assessment.

(1) Ventilation of machine room: Mechanical ventilation must be required at all times. The baseline air change rate for a machine room should be 2–4 air changes/h, depending on the size of the machine room. The ventilation system should consist of two lines. The exhaust port should be installed close to the floor where the refrigerant tends to settle, such that it can be discharged directly through a duct. Ventilation equipment should be operable from outside the machine room.

(2) Refrigerant detector and refrigerant leakage alarm: One or more instruments that can detect refrigerants and have a sensor at an undisturbed position should be installed. The sensor should be positioned where the refrigerant will tend

to collect. The refrigerant detector and refrigerant leakage alarm should operate using an independent power supply, such as an uninterruptable power supply (UPS). The instrument is to be linked to an alarm (e.g., both audible and visible) that is noticeable from outside a machine room.

(3) Prohibition of open flame: Any apparatus with an open flame (e.g., heating apparatus, water heater, or stove) should be prohibited in a machine room.

(4) Smoking and other uses of fire should be strictly prohibited.

(5) Inspection: The machine ventilation, refrigerant detector, refrigerant leak alarm, and UPS should be periodically inspected during installation, and the air change rate should be as recommended by the manufacturer; all inspection records should be stored.

(6) Instrument protection: The normal operation of the refrigerant detector and the mechanical ventilation of the machine room should be configured to be interlocked with the startup of the chiller.

9.6 Conclusions

The risk assessments performed by the chiller SWG confirmed that the frequency of fire accidents and burns was sufficiently low for water-cooled chillers and heat pumps using low-flammability refrigerants when considering the probabilities of refrigerant leakage and the existence of ignition sources. In addition, it was confirmed that the probability of an accident occurring was smaller than once every 100 years in the machine room with appropriate machine ventilation (2–4 air changes/h with two ventilation lines). The general safety requirements determined through the risk assessments are: (1) Guarantee mechanical ventilation with the required air flow rate in a machine room, (2) Monitor the refrigerant leakage using at least one refrigerant detector, (3) Interlock the chiller with the refrigerant detector and the mechanical ventilation system, and (4) Guarantee the refrigerant detector and the refrigerant leakage alarm device run on an independent power supply, such as a UPS. Furthermore, a draft of the GLs for the chilling equipment based on these technical requirements has been drawn up. In the next FY, the SWG will work towards the development of GLs and a general overview of risk assessments.

10. Thermophysical Properties and Cycle Performance of Newly Developed Low-Global Warming Potential Refrigerants

In the present study, the measurement of the thermodynamic properties of HFO-1243zf, the proposed equation of state for HFO-1243zf, measurements of the surface tension of some low-GWP refrigerants, measurements of the transport properties of HFO-1234ze(Z), and the cycle performance test for the binary refrigerants mixture of HFO-32 and HFO-1234yf were performed. The obtained results are as follows.

(1) The pressure–density–temperature ($P\rho T$) properties, vapor pressures, and saturated liquid and vapor densities of HFO-1243zf were measured using two types of isochoric methods. Then, the critical temperature T_c and the critical density ρ_c were determined from the present measured data. The critical pressure P_c and the saturated vapor pressure correlation were also determined for HFO-1243zf.

(2) A fundamental equation of state explicit in the Helmholtz energy was formulated for R1243zf using the critical parameters and saturated liquid and vapor densities obtained in the present study. It was confirmed that the thermodynamic properties predicted by the formulated equation of state agree with the existing experimental data. An FLD file for REFPROP based on the equation of state was also provided.

(3) The surface tensions of HFO-1243zf, HFO-1234ze(Z), and HCFO-1233zd(E) were measured using the capillary elevation method. Then, empirical correlations of the van der Waals type were proposed.

(4) The thermal conductivity of HFO-1234ze(Z) was measured using a transient hot-wire technique with two fine wires of different lengths for HFO-1234ze(Z) both in the saturated liquid and superheated vapor states in the temperature range of 280–350 K. The extended corresponding model to predict the thermal conductivity of HFO-1234ze(Z) was also developed based on the present study. It was confirmed that there was good agreement between the measured and predicted values.

(5) The viscosity thermal conductivity of HFO-1234ze(Z) was measured using the tandem capillary tubes method based on Hagen–Poiseuille theory in both the subcooled liquid and superheated vapor states. The extended corresponding model for predicting the viscosity of HFO-1234ze(Z) was also developed based on the present study. The predictions of the extended corresponding model were in good agreement with the experimental data.

(6) In the present study, the cycle performances of several refrigerants were evaluated using a water source heat pump loop. This year, binary zeotropic mixtures of HFC-32 and HFO-1234yf (42/58 mass% and 28/72 mass%) were tested. The cycle performance of the refrigerant mixtures of HFC-32 and HFO-1234yf (42/58 mass% and 28/72 mass%) was compared to that of HFC-32 and HFO-1234ze(E) mixtures (42/58 mass% and 28/72 mass%) and R410A. It was found that the coefficients of performance (COPs) of the HFC-32/HFO-1234ze(E) and HFC-32/HFO-1234yf mixtures were almost comparable when their compositions yielded the same GWP. For the compositions that yielded a GWP of 300, the COPs of these mixtures exceeded that of R410A.

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