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Leakage of Mildly Flammable Refrigerants into a Room

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Simulation of leakage of mildly flammable refrigerants

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ABSTRACT

The use of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) has been widely restricted. They have been replaced with hydrofluorocarbons (HFCs) in order to protect the ozone layer. However, the leakage of refrigerant into the air from active or end-of-life air conditioners is a serious environmental issue owing to the high global warming potential (GWP) of HFCs. Therefore, replacing HFCs with low-GWP refrigerants has been recognized as a reasonable solution to the problem. In Japan, low-GWP refrigerants such as R1234yf, R1234ze, and R32 have been considered as alternatives to conventional HFC refrigerants. However, these low-GWP refrigerants are often flammable.

When refrigerants leak into a space, they tend to accumulate above the floor if they are heavier than air. The refrigerant may ignite if the refrigerant concentration is higher than the low flammable limit (LFL), there is an ignition source, and the air velocity is lower than the burning velocity. When leakage occurs from an air conditioner, there is always a region where the refrigerant concentration is higher than the LFL because the refrigerant concentration is 100% near the outlet from the air conditioner. Thus, understanding the refrigerant diffusion phenomena of low-GWP refrigerants is important to acquiring sufficient information for developing safety standards to assess the risks of using these refrigerants. Numerical analysis is an effective tool because it is very difficult to measure the diffusion of a refrigerant in a large space. In this study, diffusion phenomena were numerically analyzed when a refrigerant leaked slowly from a room air conditioner (RAC) and package air conditioner (PAC) and rapidly from a chiller into a large space. Based on the calculation results, the refrigerant concentration distributions, the volumes and positions of the flammable regions, and their changes in time were examined.

1. INTRODUCTION

According to the Kyoto Protocol, emissions of greenhouse gases such as hydrofluorocarbons (HFCs) should be reduced. Therefore, refrigerants with low-global warming potential (GWP) such as R32 and R1234yf are expected to be the next generation of refrigerants. However, these low-GWP refrigerants are often flammable. Table 1 lists the physical and flammability properties of typical refrigerants (Takizawa, 2012; JFMA, 2012). Here, LFL is the lower flammability limit, UFL is the upper flammability limit, BV is the burning velocity, and MIE is the minimum ignition energy.

To obtain the information needed to assess the risks of using these refrigerants, the leakage of mildly flammable refrigerants was simulated in this study. When refrigerants leak into a space, they tend to accumulate above the floor when they are heavier than air (Kataoka *et al.,* 1996). As shown in Fig. 1, the refrigerant may ignite when the refrigerant concentration is greater than the LFL, there is an ignition source, and the air velocity is lower than the burning velocity. When leakage occurs from a room air conditioner (RAC), there is always a region where the refrigerant concentration is higher than the LFL because the refrigerant concentration is 100% near the outlet of the leakage port. Thus, appropriate safety standards must be prepared for air-conditioning equipment containing flammable refrigerants because of the risk of explosion.

Understanding refrigerant diffusion phenomena is important to preparing safety standards. The effects of parameters on the diffusion phenomena of refrigerants that are heavier than air must also be clarified.

Table 1 Physical and flammability properties of low-GWP refrigerants (Source "Takizawa, 2012; JFMA, 2012")

Refrigerant	GWP[*1]	LFL[*2]	UFL[*3]	BV[*4]	MIE[*5]
R290 (propane)	< 3	2.1 vol.%	9.5 vol.%	38.7 cm/s	0.246 mJ
R717 (ammonia)	< 1	15.5 vol.%	27 vol.%	7.2 cm/s	380–680 mJ
R32	675	13.3 vol.%	29.3 vol.%	6.7 cm/s	15 mJ
R1234yf	4	6.2 vol.%	12.3 vol.%	1.5 cm/s	200 mJ
R1234ze(E)	4	7.0 vo.l%	9.5 vol.%	—	—

*1 GWP: Global warming potential
*2 LFL: Lower flammable limit
*3 UFL: Upper flammable limmit
*4 BV: Burning velocity
*5 MIE: Minimum ignition energy

Numerical analysis is an effective tool for this purpose because measuring the diffusion of a refrigerant in a large space is very difficult. Goetzler and Burgos (2014) numerically simulated the leakage of class 2L flammable refrigerants into a residential space to evaluate the viability of using these refrigerants in heating, ventilation, and air conditioning (HVAC) systems and refrigeration systems. In this study, diffusion phenomena when a refrigerant leaks into a large space from a room air conditioner (RAC), variable refrigerant flow (VRF), and chiller were numerically analyzed. Based on the calculation results, the refrigerant concentration distributions, the volumes and positions of the flammable regions, and their changes over time were determined. For the RAC, the calculation results were verified by using the results of a refrigerant leakage experiment.

2. CALCULATION METHOD

Table 2 lists the leakage scenarios considered in this study. The commercial computational fluid dynamics (CFD) program STAR-CD was used to simulate refrigerant diffusion phenomena. The advection–diffusion problem for a mixture in a three-dimensional space was governed by the continuity, Navier–Stokes, energy conservation, and convective diffusion equations.

Both the air and refrigerant were assumed to be ideal gases, and the density was calculated by using the equation of state of an ideal gas. PISO or SIMPLE was used for the pressure–velocity coupling scheme, and UD and MARS were employed for the discretization scheme. Standard and realizable k–ε turbulence models were used in cases 1–22 (RAC and VRF) and 23–32 (chiller), respectively (Table 2). For the boundary conditions, a constant flow at the inlet boundary was assumed, and a constant pressure corresponding to the amospheric pressure or a free outflow condition at the outlet boundary was assumed. The law of the wall was assumed at the wall boundary.

3 ANALYTICAL MODELS

Figure 2 shows the analyzed geometries. The details of these geometries are described below.

(a) Leakage from a Wall-mounted Indoor RAC Unit

The refrigerant was modeled as leaking from a wall-mounted indoor RAC unit into a space with dimensions of 2.8

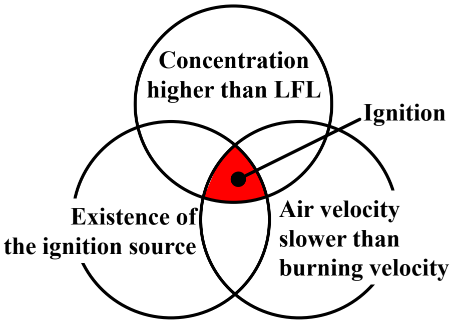


Fig. 1 Ignition mechanism

Table 2 Leakage scenarios

case No.	Type	Refrigerant	Charged amount	Leakage velocity		Ventilation air flow	Air vent
1	wall-mounted indoor unit of RAC	R32	1.0 kg	125 g/min		0 m^3/h	exist
2				250 g/min		0 m^3/h	exist
3				1000 g/min		0 m^3/h	exist
4		R1234yf	1.4 kg	175 g/min		0 m^3/h	exist
5				350 g/min		0 m^3/h	exist
6				1400 g/min		0 m^3/h	exist
7		R290	0.2 kg	50 g/min		0 m^3/h	exist
8			0.5 kg	125 g/min		0 m^3/h	exist
9	floor-mounted indoor unit of RAC	R32	1.0 kg	250 g/min		0 m^3/h	exist
10		R1234yf	1.4 kg	350 g/min		0 m^3/h	exist
11	outdoor unit of RAC	R32	1.0 kg	250 g/min		0 m^3/h	(outdoor)
12		R1234yf	1.4 kg	350 g/min		0 m^3/h	(outdoor)
13	VRF	R32	26.3 kg	10 kg/h		0 m^3/h	none
14						0 m^3/h	exist
15						169 m^3/h	exist
16						0→169 m^3/h	exist
17				10→0 kg/h		0 m^3/h	exist
18		R1234yf	29.4 kg	10 kg/h		0 m^3/h	none
19						0 m^3/h	exist
20						169 m^3/h	exist
21						0→169 m^3/h	exist
22				10→0 kg/h		0 m^3/h	exist
23	water-cooled chiller	R32	23.4 kg	75 kg/h	(burst leak)	0 m^3/h	exist
24				10 kg/h	(rapid leak)	0 m^3/h	exist
25						545 m^3/h	exist
26		R1234yf	23.4 kg	70 kg/h	(burst leak)	0 m^3/h	exist
27				9 kg/h	(rapid leak)	0 m^3/h	exist
28						545 m^3/h	exist
29		R1234ze(E)	23.4 kg	54 kg/h	(burst leak)	0 m^3/h	exist
30						545 m^3/h	exist
31				7 kg/h	(rapid leak)	0 m^3/h	exist
32						545 m^3/h	exist

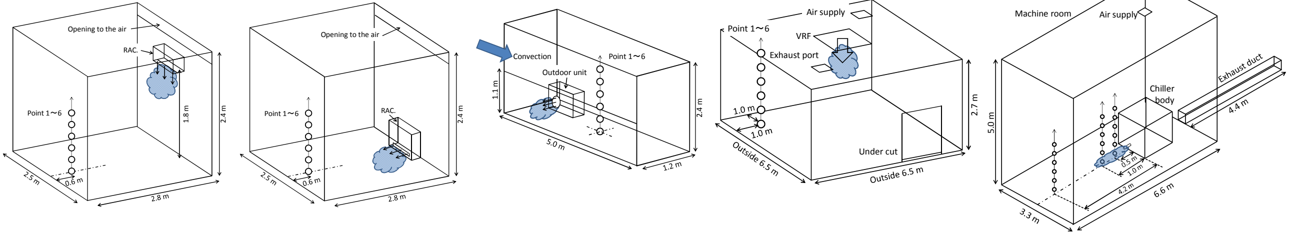

(a) wall-mounted indoor unit of RAC (b) floor-mounted indoor unit of RAC (c) outdoor unit of RAC (d) VRF (e) water-cooled chiller

Fig. 2 Analytical geometries

m × 2.5 m × 2.4 m. The indoor unit was located 1.8 m above the floor at the center of one of the walls. The dimensions of the indoor unit were 0.6 m × 0.24 m × 0.3 m, and the indoor unit had an air outlet with dimensions of 0.6 m × 0.06 m. The refrigerant leaked from this air outlet. Approximately 200,000 non-equidistant mesh points were used to discretize the governing equations. The refrigerants considered were R32, R1234yf, and R290 (propane).

(b) Leakage from a Floor-mounted Indoor RAC Unit

Refrigerant was modeled as leaking from a floor-mounted indoor RAC unit into a space equal in size to that used for leakage from the wall-mounted indoor RAC unit.

The size of the space where the refrigerant leaked from the floor-mounted indoor unit was equal to that where the refrigerant leaked from the wall-mounted indoor unit. The indoor unit was located on the floor at the center of one of the walls. The dimensions of the indoor unit were 0.7 m × 0.21 m × 0.6 m, and the indoor unit had an air outlet with dimensions of 0.46 m × 0.045 m. The refrigerant leaked from this air outlet. Approximately 240,000 non-equidistant mesh points were used to discretize the governing equations. The refrigerants considered were R32 and R1234yf.

(c) Leakage from an Outdoor RAC Unit

Refrigerant was modeled as leaking from an outdoor unit placed on a balcony with dimensions of 5.0 m × 1.2 m × 1.1 m. The outdoor unit was located on the floor at the left side of the balcony. The dimensions of the outdoor unit were 0.77 m × 0.29 m × 0.68 m, and the outdoor unit had a fan with a diameter of 0.4 m. The refrigerant leaked from the fan. In addition, wind with a velocity of 0.5 m/s was assumed to be blowing around the balcony. Approximately 350,000 non-equidistant mesh points were used to discretize the governing equations. The refrigerants considered were R32 and R1234yf.

(d) Leakage from a Variable Refrigerant Flow

Refrigerant was modeled as leaking from a VRF placed in an office with dimensions of 6.5 m × 6.5 m × 2.7 m. The indoor unit of the VRF was located on the ceiling at the center of the office. This indoor unit had an air outlet with dimensions of 0.45 m × 0.0645 m and a suction opening that was 0.37 m in diameter. The refrigerant leaked from the air outlet and suction. The office also had an air supply with dimensions of 0.2 m × 0.2 m and exhaust grills, and the gap under the door was 1.5 m × 0.01 m. Approximately 200,000 non-equidistant mesh points were used to discretize the governing equations. The refrigerants considered were R32 and R1234yf.

When the leakage velocity is higher than the burning velocity, there may be no flammable volume. Therefore, for the calculations of (a)–(d), the leakage flows were set to be very slow to consider high-risk situations.

(e) Leaks from Water-cooled Chiller

Refrigerant was modeled as leaking from a water-cooled chiller placed in a machine room with dimensions of 1.28 m × 1.28 m × 1.28 m. The chiller was located 1.01 m from the wall and was assumed to have a nozzle-shaped leakage port 100 mm in length located 150 mm from the floor. The inner diameter of the nozzle depended on the type of leakage: $\varphi = 4.0$ mm for rapid leakage and $\varphi = 8.0$ mm for burst leakage.

The air inlet and exhaust duct inlet were located on the ceiling above the chiller and at the bottom of the machine room, respectively. The areas of the air inlet and exhaust duct inlet were calculated as follows.

The velocity and openness at the air inlet and exhaust port were as follows:

- (at air inlet) velocity: $v_{in} = 2.0$ m/s , aperture ratio: $\alpha_{in} = 0.7$
- (at air exhaust duct) velocity: $v_{out} = 4.0$ m/s, aperture ratio: $\alpha_{out} = 0.3$

The air ventilation volume per hour q was calculated from the following equation.

- Air ventilation volume: $q = XV$ ($\mathrm{m^3/h}$)

where X and V are the number of air vents and volume of the machine room ($\mathrm{m^3}$), respectively.

The areas of the air inlet A_{in} and exhaust duct inlet A_{out} were obtained from the following equation.

$$q = \alpha_{in} v_{in} A_{in} = \alpha_{out} v_{out} A_{out}$$

where α_{in} and α_{out} are the aperture ratios of air inlet and air exhaust duct, respectively. The refrigerants considered were R32, R1234yf, and R1234ze(E).

For the calculation of the case with the chiller, the leakage speed was assumed to be that of a burst leakage or rapid leakage from the hole, like a nozzle; therefore, the leakage velocity was much higher than those in the case of RAC and VRF. This is why a different type of turbulence model was selected from those used for RAC and VRF. Here, the realizable k–ε turbulence model was used because Pattamatta and Singh (2012) reported that the near wall velocity profile captured using the realizable k–ε turbulence model showed the best agreement with the experimental data compared to other models.

4 RESULTS AND DISCUSSION

Table 3 presents the calculation results. The term $\Sigma(V{\cdot}t)$ represents the product of the flammable gas volume and presence time. This value is associated with the risk of combustion and is called the flammable volume time (FVT). The term V_{FL} represents the flammable gas volume, and the term V_{BVFL} represents the flammable gas volume with an air velocity lower than the burning velocity.

(a) Leakage from the Wall-mounted Indoor RAC Unit

The calculation results in Table 3 for cases 1–8 represent the leakage from the wall-mounted indoor RAC unit. Case 1 is shown in Figs. 3 and 4 as a representative result. Fig. 3 shows the LFL isosurface when V_{FL} reached its maximum value, and Fig. 4 shows how $\Sigma(V_{FL}{\cdot}t)$ and V_{FL} changed with time. The FVT was very small, even if a mildly flammable refrigerant leaked from the wall-mounted indoor unit. As shown by the results for cases 1–6, the FVT values determined while considering the burning velocity were equal to zero. These results suggest that ignition does not occur, even if an ignition source exists, because of the convection caused by the refrigerant leakage. Therefore, no combustion occurs if no ignition source exists inside the indoor unit. For case 7, although the calculated value was higher than the maximum allowable fill ratio of propane, the refrigerant leakage represented a large hazard because the FVT value was very high compared to the other cases. For case 8, the MIE of propane was lower than that of R32 and R1234yf, and the quenching distance of propane was very narrow. Therefore, the leakage of propane is a hazard because the flame is easily transmitted.

(b) Leakage from the Floor-mounted Indoor RAC Unit

The calculation results in Table 3 for cases 9 and 10 represent the leakage from a floor-mounted indoor RAC unit. Case 10 is shown in Figs. 3 and 4 as a representative result. According to Table 3, both the terms $\Sigma(V_{FL}{\cdot}t)$ and $\Sigma(V_{BVFL}{\cdot}t)$ were very similar. These results suggest that the air velocity is lower than the burning velocity in the combustion region. Therefore, if an ignition source exists in the combustion region, there is a risk of combustion throughout much of the combustion region. In addition, because the LFL of R1234yf is lower than that of R32, the presence time of R1234yf is longer than that of R32. Thus, the risk with R1234yf is higher than that with R32. Therefore, safety regulations are required when flammable refrigerants are used in air conditioners because the risk of leakage from a floor-mounted indoor unit is higher than that from a wall-mounted indoor unit.

(c) Leakage from the Outdoor RAC Unit

The calculation results in Table 3 for cases 11 and 12 represent the leakage from the outdoor RAC unit. Case 12 is shown in Figs. 3 and 4 as a representative result. The results in Table 3 show that the flammable gas volume existed for a long time for the same reason as explained for the floor-mounted indoor unit. Therefore, a balcony with drains and undercuts is preferred for safety because an outdoor unit has a fan near the floor level, which may lead to the flammable region spreading over the entire balcony area.

(d) Leakage from the Variable Refrigerant Flow

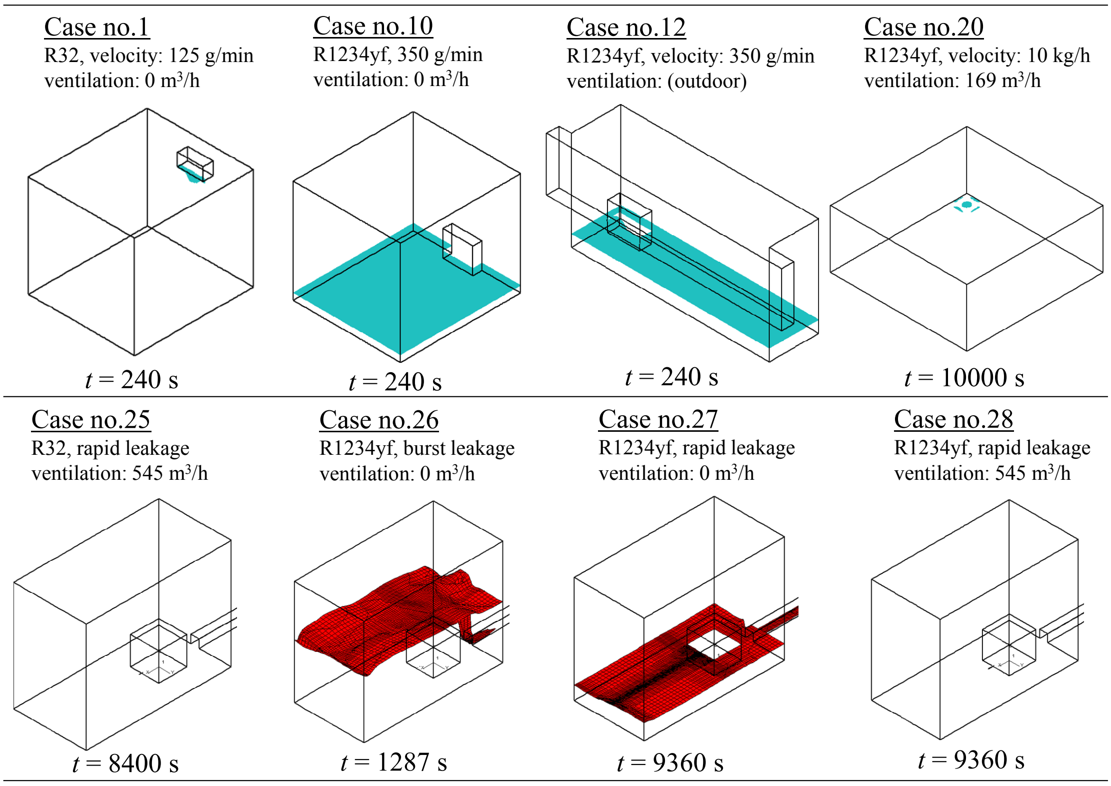
The calculation results in Table 3 for cases 13–22 represent the leakage from the VRF. Case 15 is shown in Figs. 3 and 4 as a representative result. According to Table 3, the existence of an air vent as an air supply source affects the FVT and presence time. In addition, the release period of the VRF was more than 150 min because of the large amount of refrigerant leaked. Therefore, although the flammable gas volume is small, the FVT ($\Sigma(V_{FL}{\cdot}t)$) is longer than that for leakage from a wall-mounted RAC unit. On the other hand, the FVT decreases significantly when the air velocity is considered. For R1234yf, the risk of ignition is very low because the burning velocity is low. For R32, safety regulations pertaining to, for example, a refrigerant leakage sensor, alarm, and ventilation are required when flammable refrigerants are used in air conditioners.

Table 3 Predicted $\Sigma(V_{FL}\cdot t)$ and $\Sigma(V_{BVFL}\cdot t)$

case No.	Presence time, min	$\Sigma(V_{FL}\cdot t)$, m^3min	$\Sigma(V_{BVFL}\cdot t)$, m^3min
1	4.01	1.18×10^{-2}	0
2	4.01	1.23×10^{-2}	0
3	8.01	9.79×10^{-3}	0
4	8.01	1.07×10^{-2}	0
5	1.03	3.73×10^{-2}	0
6	1.05	4.34×10^{-2}	0
7	1473.00	7689	7688
8	4.73	0.258	0.161
9	111.00	136.83	136.81
10	309.00	507.82	507.50
11	45.00	43.01	42.50
12	93.00	62.54	61.53
13	157.85	1.622	0.021
14	157.82	0.831	0.011
15	157.82	0.702	0.014
16	157.82	0.725	0.011
17	8.36	3.14×10^{-2}	0
18	176.47	2.152	0
19	176.42	0.661	0
20	176.41	0.583	0
21	176.41	0.592	0
22	10.25	2.14×10^{-2}	0
23	18.72	0.013	0
24	140.40	0.599	0.000022
25	140.40	0.002	0
26*1	up to22.62	up to 127.84	up to 3.449
27*1	up to 157.67	up to 1108.44	up to 44.15
28	156.00	0.008	0
29*1	up to 27.67	up to 361.62	0 *2
30	26.00	0.014	0 *2
31	200.58	16.352	0 *2
32	200.58	0.009	0 *2

*1 Calculation was stopped at 100 second after refrigerant leaked out completely.

*2 R1234ze(E) is non-flammable when relative humidity is zero.



Case no.1
R32, velocity: 125 g/min
ventilation: 0 m³/h
t = 240 s

Case no.10
R1234yf, 350 g/min
ventilation: 0 m³/h
t = 240 s

Case no.12
R1234yf, velocity: 350 g/min
ventilation: (outdoor)
t = 240 s

Case no.20
R1234yf, velocity: 10 kg/h
ventilation: 169 m³/h
t = 10000 s

Case no.25
R32, rapid leakage
ventilation: 545 m³/h
t = 8400 s

Case no.26
R1234yf, burst leakage
ventilation: 0 m³/h
t = 1287 s

Case no.27
R1234yf, rapid leakage
ventilation: 0 m³/h
t = 9360 s

Case no.28
R1234yf, rapid leakage
ventilation: 545 m³/h
t = 9360 s

Fig. 3 LFL isosurface when V_{FL} reached its maximum value

(e) Leakage from the Water-cooled Chiller

The calculation results in Table 3 for cases 23–32 represent the leakage from the water-cooled chiller. Cases 25–28 are shown in Figs. 3 and 4 as representative results. For cases 26, 27, and 29, the calculation was stopped 100 s after the refrigerant had leaked out completely, although there was a flammable region at that time. Therefore, the actual existence time and FVT must be larger than the values listed in Table 3. In addition, although humidity was not considered in this study, humidity should be considered for leakage of R1234ze(E) because this refrigerant is non-flammable when the humidity is zero.

These results indicate that the ventilation air flow has a large effect on the FVT, similar to the VRF results. For example, the effects of enough air ventilation volume ($X = 5$) on the rapid leakage of R32 and R1234yf are evident for cases 24 and 25 and cases 27 and 28, respectively. According to the results, for rapid leakage of both R32 and R1234yf, $\Sigma(V_{FL} \cdot t)$ is very small and $\Sigma(V_{BVFL} \cdot t)$ equals zero. This is because the ventilation air makes the refrigerant flow through the exhaust duct to the outlet. This result may be attributed to the enough air ventilation volume. On the other hand, for the non-ventilation case, the FVT of R1234yf was larger than that of R32 because the former has a lower LFL and longer presence time than the latter, as noted previously.

Furthermore, the leakage velocity was assumed to be much higher than that for leakage from an RAC or VRF; this leads to a zero or very small $\Sigma(V_{BVFL} \cdot t)$, even if $\Sigma(V_{FL} \cdot t)$ increases. However, if there is no ventilation air flow and there is a high-concentration region after the refrigerant leaks out completely, as in cases 26, 27, and 29, $\Sigma(V_{BVFL} \cdot t)$ may increase.

The results for the leakage from the water-cooled chiller indicate that sufficient ventilation air flow is needed to keep the room safe when flammable refrigerants are used in chillers. A leakage sensor is also required.

5 EXPERIMENT ON REFRIGERANT LEAKAGE

(a) Experiment Method and Conditions

The refrigerant concentration was measured in an experimental room with the same dimensions as that used in the numerical calculation of RAC. Figure 5 shows the diagram of the experiment system. Refrigerant from the gas cylinder was cooled by evaporative latent heat and raised to the prescribed temperature through a thermostat bath. The mass flow rate was controlled by the mass flow controller. Refrigerant was leaked into the experimental room,

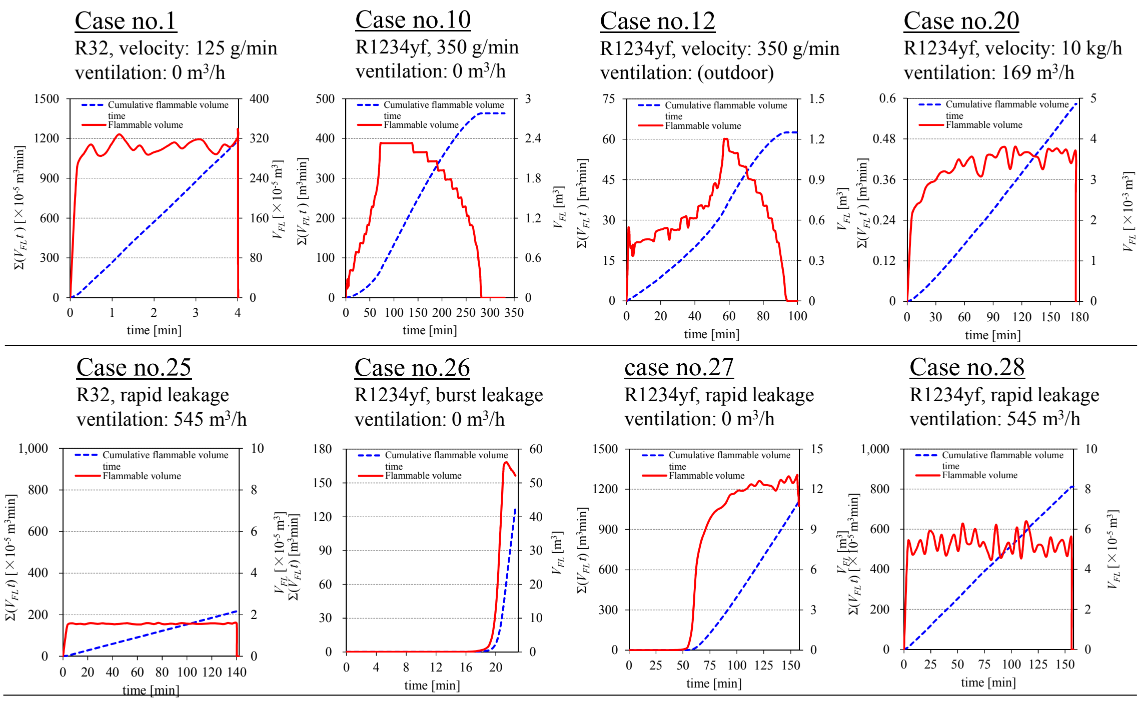


Fig. 4 $\Sigma(V_{FL} \cdot t)$ and V_{FL} changes with time and the refrigerant concentration was measured by the concentration sensor. The experiment was carried out under the same conditions as those used for cases 1, 3, and 9; these are listed in Table 2.

(b) Results and Discussion

Figure 6 compares the experimental and calculation results. The experimental leakage from the wall-mounted indoor unit at low measurement points indicated a higher refrigerant concentration, while the refrigerant arrival time also showed a positive inclination relative to the calculation results. However, for the wall-mounted indoor unit, the refrigerant concentration at low measurement points was lower than the calculated results when the leakage ended; thus, the experimental results indicated that the wall-mounted indoor unit was safer than the calculation results.

For the experiment on leakage from the floor-mounted indoor unit, the measured refrigerant concentration on the floor was almost equal to the calculation results. However, the time before the concentration on the floor became less than the LFL was much shorter than that in the calculation results. This was caused by the imperfect experimental conditions without air flow. The exhaust duct equipped in the experimental room may have led to convection caused by the pressure difference between the experimental room and outdoor environment. Therefore, convection provided safer results, which is favorable for the risk assessment.

On the other hand, the experimental results showed that the refrigerant concentration on the floor, which was thought to be least affected by convection, did not reach the LFL during leakage from the wall-mounted indoor unit, and the refrigerant concentration exceeded the UFL when the leakage from the floor-mounted indoor unit ended. These tendencies were generally consistent with those of the calculation results. From a regulation standpoint, the CFD simulation is preferred for the development of strict regulations. However, the experimental results can be used to confirm the qualitative trend of the refrigerant concentration distributions.

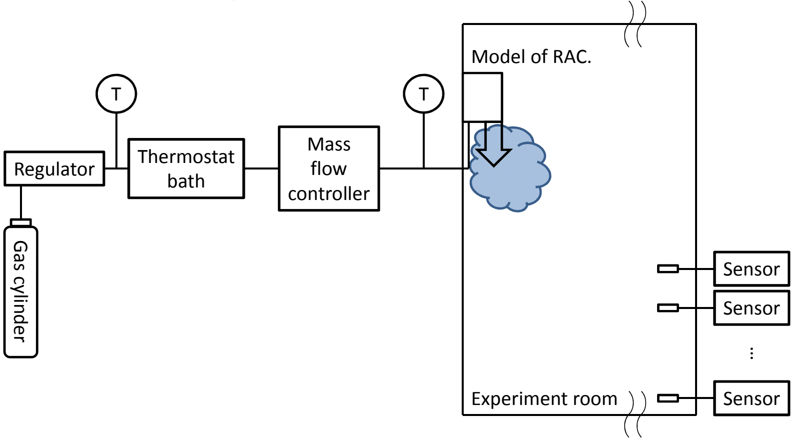


Fig. 5 Schematic diagram of experimental apparatus

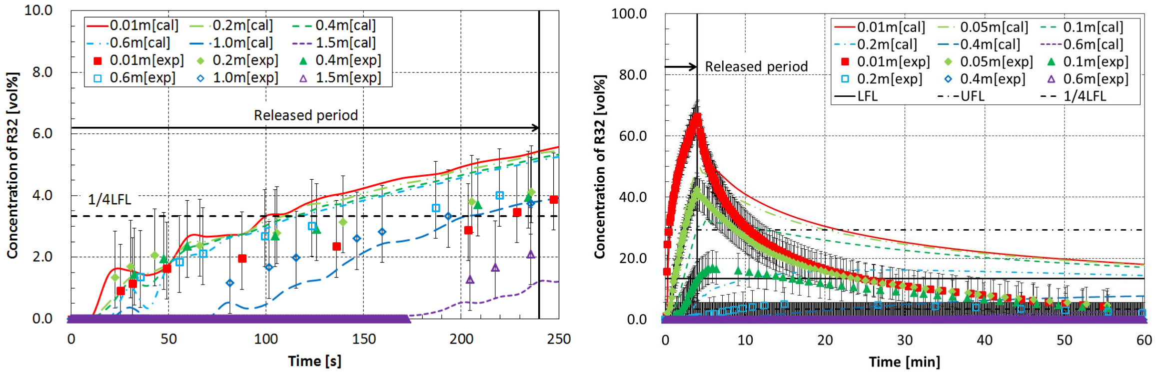


Fig. 6 Results of refrigerant leakage experiment
(right): Wall-mounted, R32, 1000 g, 250 g/min,
(left): Floor-mounted, R32, 1000 g, 250 g/min

6. Conclusion

The simulation and experiments conducted in this study on the leakage of refrigerants into a space yielded the following findings.

1. In the case of leakage from a wall-mounted indoor unit, combustion does not occur if an ignition source does not exist inside the indoor unit.
2. In the case of leakage from a floor-mounted indoor unit, safety regulations are required when flammable refrigerants are used in air conditioners.
3. In the case of leakage from a floor-mounted indoor unit or outdoor unit, the risk of combustion is higher with R1234yf than with R32.
4. In the case of leakage from an outdoor unit, a balcony with drains and undercuts is preferred because an outdoor unit has a fan near the floor level, which may lead to spreading of the flammable region over the entire balcony area.
5. In the case of leakage from a VRF, the FVT is much smaller when the burning velocity is considered.
6. In the case of leakage from a water-cooled chiller, the ventilation air flow has a large effect on the FVT. When there is no ventilation air flow and the velocity of the refrigerant leakage is high, the FVT may increase after the refrigerant leaks out completely.
7. The experiment confirmed that the refrigerant concentration on the floor does not reach the LFL in the case of leakage from a wall-mounted indoor unit and exceeds the UFL in the case of leakage from a floor-mounted indoor unit.

7. Future Works

Future works will involve the simulation of leakage from an air-cooled chiller. In addition, the analytical conditions for leakage from a water-cooled chiller—in particular, the ventilation time, shape of the exhaust duct, and area of the machine room—will be reconsidered.

NOMENCLATURE

A_{in}	area of air inlet	(m^{2})
A_{out}	area of air exhaust duct	(m^{2})
q	air ventilation volume per hour	(m^{3} h^{-1})
v_{in}	air velocity at air inlet	(m s^{-1})
v_{out}	air velocity at air exhaust duct	(m s^{-1})
V	volume of machine room	(m^{3})
X	number of air vents per hour	(h^{-1})
α_{in}	aperture ratio of air inlet	
α_{out}	aperture ratio of air exhaust duct	
φ	inner diameter of nozzle	(m)

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