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IMPACT OF HYDROCARBON REFRIGERANTS TYPE ON LEAKAGE RATE AND RESULTING FLAMMABILITY RISK

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ABSTRACT

The adoption of flammable natural refrigerants is increasing due to their low global warming potential and favorable thermodynamic properties. However, leaks involving these flammable refrigerants can present significant safety risks. This paper investigates how different refrigerants influence leakage rates during accidental releases, challenging the assumption in some previous research and standards that all refrigerants leak at the same rate. A Computational Fluid Dynamics (CFD) model, validated through experiments, is used to simulate the dispersion of refrigerants in a confined space. The differences in leakage rates are then incorporated into the CFD simulations, which analyze the flow dynamics and concentration profiles of R290 and R600a within a typical room setting. The results demonstrate significant differences in leakage rates between R290 and R600a. Additionally, the CFD simulations reveal distinct dispersion patterns for each refrigerant. By showing that refrigerant type affects both leakage rate and dispersion, this study highlights the necessity for safety protocols that consider the specific properties of different flammable refrigerants. This is crucial for the safe use of these environmentally friendly yet flammable refrigerants.

Keywords: Refrigeration, Leakage, Flammability, CFD, Propane, Isobutane, Safety standards

1. INTRODUCTION

Refrigeration systems typically consist of mechanical moving parts, extensive piping, and numerous small components. Over extended periods of operation, various factors can contribute to refrigerant leakage into external spaces. These factors include continuous pipeline vibration, internal refrigerant corrosion, external pipeline wall corrosion, mishandling, and the loosening of small components. Consequently, the likelihood of leaks is closely associated with the construction and operational characteristics of the system. Factors influencing refrigerant concentration after leakage can be categorized into internal and external factors. Internal factors originate within the refrigeration system and primarily impact the leakage process. These include refrigerant charge, leakage hole size, back pressure, and the physical properties of the refrigerant. External factors exist in the surrounding environment and directly affect the diffusion process of the leaked refrigerant. These include the installation position and height of the refrigeration system, the geometric structure of the system housing, ventilation conditions and obstacles in the external space, and the temperature and humidity of the leakage environment (Y. Li et al., 2023).

Most safety standards do not consider internal influencing variables beyond the refrigerant charge and its LFL. For instance, according to standards EN 378-1 (2020), IEC 60335-2-40 (2022), and ISO 5149-1 (2003), the maximum allowable charge for air conditioning systems or heat pumps for human comfort is calculated using Eq. (1):

$$M_{max} = 2.5 \times LFL^{\frac{5}{4}} \times h_0 \times A^{\frac{1}{2}} \qquad \textit{Eq. (1)}$$

Where:
M_{max} is the allowable maximum charge in a room in kg;
A is the room area in m^2;

LFL is the Lower Flammable Limit in kg/m^3;
h_0 is the lowest installation height of the appliance.

This equation was originally proposed based on the four-minute leak duration on the observation that 150g of CO_2 would leak through a capillary tube in that time, representing a catastrophic leak (Kataoka et al., 2000). Since saturation pressure significantly influences the leakage rate and varies greatly among different refrigerants, it is important to consider this factor when calculating the maximum allowable charge.

Furthermore, after determining the leakage rate, the use of Computational Fluid Dynamics (CFD) simulations to study dispersion offers several advantages. The complex fluid dynamics involved in refrigerant leakage events, including diffusion, mixing, and transport, require a sophisticated approach to accurately model these behaviors. CFD provides the capability to simulate these processes with high fidelity, enabling detailed analysis and prediction of leakage scenarios. By applying CFD simulations, it is possible to gain a comprehensive understanding of refrigerant leakage behaviors and flammability risks, leading to more effective safety measures and standards for the use of flammable refrigerants.

Researchers have conducted various experimental and numerical studies on internal factors influencing dispersion during refrigerant leakage. Some of these studies are summarized below. Li (2014) measured the concentration distribution of R290 in a room under various leak scenarios to assess compliance with safety standards. Their findings suggest that the current IEC 60335-2-40 standard may be overly restrictive for wall-mounted units, as the concentration levels typically remain below the LFL. The study indicated that the leak rate significantly influences concentration. It was also found that under a high leakage rate, a high refrigerant concentration was more likely to form below the leakage hole, resulting in a more uneven distribution. Tang et al. (2018) examined the impact of refrigerant charge and leakage hole size on the distribution of R290 concentration in a room following a leak. The results indicate that fire hazards are primarily a concern during the rapid leakage phase, with the area directly beneath the leak being the most at risk. The study showed that the size of the leakage hole significantly influences the distribution of R290 concentration. A 1.0 mm diameter hole results in the longest residence time of the combustible zone, whereas a larger hole (4.37 mm) creates a more extensive combustible zone but with a shorter residence time. A smaller hole (0.5 mm) leads to a lower leak rate, making it more difficult for the R290 concentration to reach the LFL. A leakage hole with both a prolonged leak duration and a sufficiently high leak rate posed the greatest danger when using R290 in split-type household air conditioning systems. Nagaosa (2014) investigated the influence of gas density on the concentration profiles of flammable gas spread. The findings revealed that gas flow velocities are significantly influenced by gas density, with higher spread velocities occurring due to the greater density difference between the leaked gas and ambient air. Colbourne and Suen (2015), compared the risk associated with using of R290 in split air conditioners to R600a in domestic refrigerators through quantitative risk assessment methods. The results indicated that while domestic refrigerators using R600a present a higher ignition risk due to their design and operational conditions, split air conditioners using R290 have significantly lower ignition frequencies and overall risks.

It is evident that the existing research and standards do not sufficiently address the influence of internal factors on leakage and diffusion, especially for R600a. The aim of this paper is to explore the impacts of using different natural refrigerants on leakage and subsequent dispersion through CFD simulations. These findings offer valuable insights for the safe use and risk mitigation of these refrigerants. The results have been validated for certain cases by comparison to experimental studies found in the literature.

2. SIMULATION APPROACH

1.1. Leakage Rate

Almost in all the published literatures, the leakage of the refrigerant gas in refrigeration system was approximately simplified as the gas leakage in pressure pipeline. Based on this, the classical Eq. (2) for choked mass flow through an orifice shall be used. According to IEC 60335-2-89 (2022) this formula is also used and considered representative of any leak that occurs from a part that contains two phases or liquid.

$$\dot{m} = 0.06\, C_d A_0 \sqrt{k\rho_0 (p_0 - p_{atm}) \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \qquad Eq.\ (2)$$

Where:
$\dot{m}$ is the mass flow in g/min;
C_d is the discharge coefficient (set to 0.61);
A_0 is the leak hole area;
k is the ratio of specific heats of refrigerant vapour at the applicable dew point temperature;
ρ_0 is the density in kg/m^3 of refrigerant vapour at the applicable dew point temperature;
p_0 is the vapour pressure in Pa of refrigerant vapour at the applicable dew point temperature;
p_{atm} is the atmospheric pressure 1.0132 5 $\times 10^5$ in Pa.

1.2. Numerical Solution Method and validation

The numerical simulations were carried out using ANSYS FLUENT (ANSYS, 2023), employing the finite volume method with a second-order upwind scheme for discretizing the governing equations. Pressure-velocity coupling was addressed with the COUPLED algorithm, and boundary conditions were carefully defined. Turbulence was modeled using both the standard k-epsilon (kε) and the SST k-omega (kω) models. Upon validation against experimental data, the SST k-omega model was selected for its better performance in the validation process. The validation of the simulation model was carried out using experimental data from Colbourne (2020), as detailed in our previous work (Esmaeelian et al., 2024).

1.3. Simulation Conditions

To examine the effects of various parameters on refrigerant dispersion during unintentional leakage, simulations were conducted in a small room equipped with an air conditioner, as illustrated in Fig. 1. The room was assumed to be adiabatic, meaning no heat transfer occurred through the walls or other components, and it had no ventilation or infiltration. During the simulations, refrigerant concentrations from the leakage were measured at several locations within the room. Most measurement points were positioned 10 cm above the floor to account for the refrigerant's tendency to settle near the ground due to its higher density. These control points were spaced evenly in the horizontal plane.

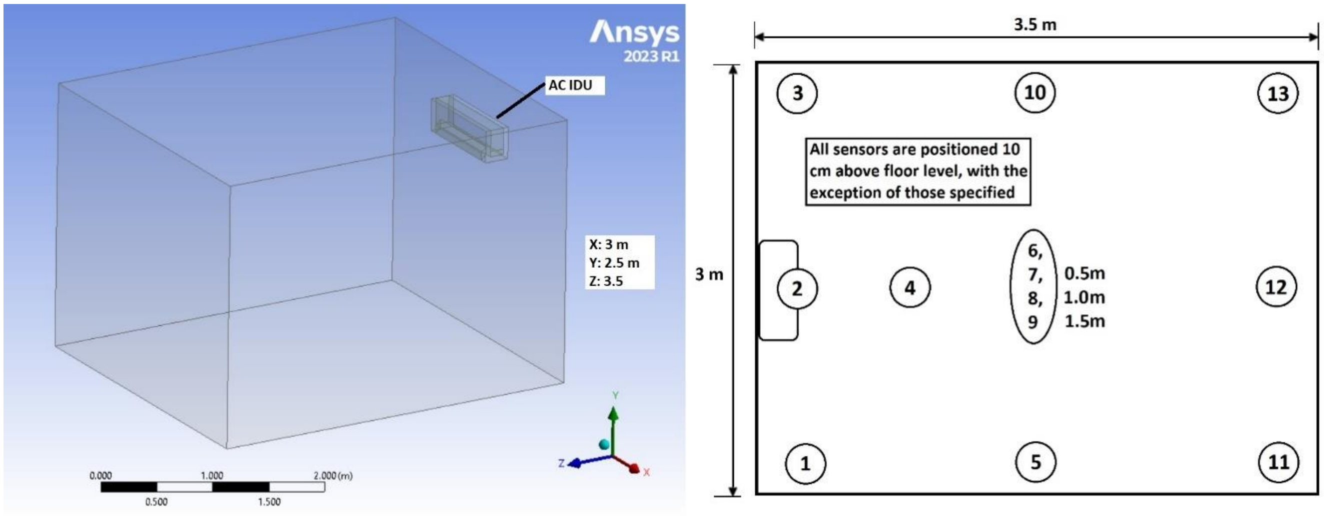

Figure 1: Geometry of simulation domain (left) and location of virtual sensors (right)

A test matrix, outlined in Table 1, was used to explore the impact of different parameters. Scenario S1 served as the reference, with the air conditioner installed at a height of 1.8 m from the floor. The leakage of R290 from a hole on the right-hand side bend of the AC indoor unit (IDU) coil was assumed to occur at a constant mass flow rate, similar to the study by (Colbourne & Suen, 2018). The leaked refrigerant mixed with the return air inside the IDU, and the resultant mixture was expelled through the IDU exit, dispersing into the room at a 45-degree angle with an average velocity of 1.3 m/s and a flow rate of 0.053 m^3/s. For this scenario, the maximum allowable charge for R290, calculated using Eq. (1), was found to be 244 g. Leak tests prescribed in IEC 60335-2-40 stipulated that the entire refrigerant charge must leak within 4 minutes. Thus, the leak rate for this scenario was fixed at 60 g/min for a total charge of 240 g.

Scenario S2 is identical to Scenario S1, except that R600a is used instead of R290. According to Eq. (1), the charge for R600a is calculated as 280 g because the LFL of R600a is higher than the LFL of R290 (0.043 kg/m^3 vs. 0.038 kg/m^3). Using Eq. (2), the leakage rates for both refrigerants and the leakage ratio of R290 to R600a are shown in Fig. 2 for different saturation temperatures. As illustrated, the leakage rate of R290 is consistently higher than that of R600a across all temperature ranges. According to IEC 60335-2-89, a temperature of 35°C is considered as the saturation temperature. At this temperature, the leakage rate of R290 is 2.73 times that of R600a. Therefore, for Scenario S2, the leakage rate is considered to be 22 g/min, resulting in the entire refrigerant charge being discharged in 763 seconds.

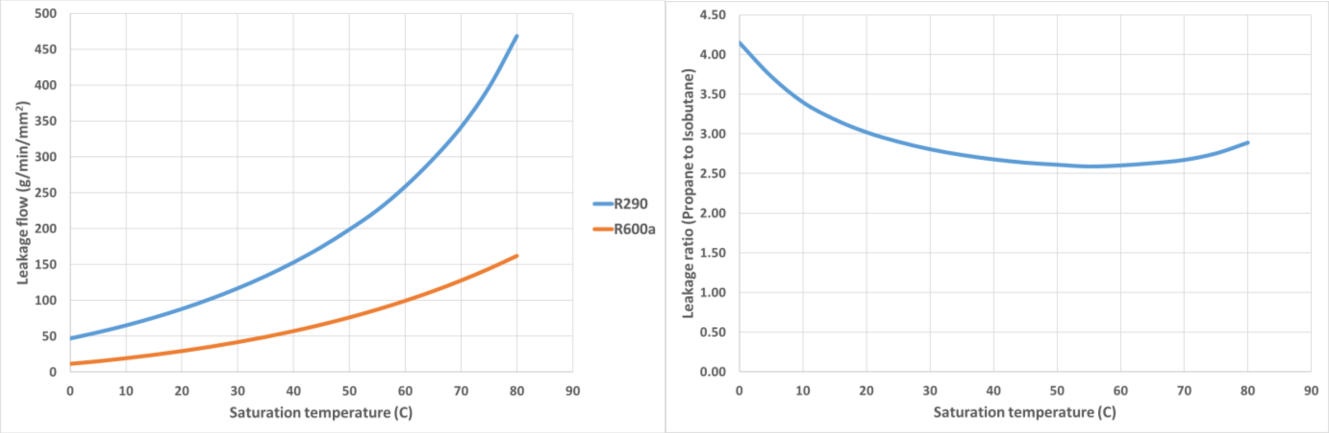

Figure 2: leakage fluxes (left) and leakage ratio (right) of R290 and R600a

For scenarios S5 and S6, the IDU is installed at the floor level, so according to EN 378-1 the allowed charge without safety measures for R290 and R600a are 152g and 172 g respectively. The leakage rate for R290 is 38 g/min according to 4 min release and is 14 g/min for R600a for the same hole size. For these scenarios, the mixture exits the IDU horizontally into the room. For other scenarios, simulations were conducted with the same conditions but with AC fan off, as detailed in Table 1.

Table 1. Different simulation scenarios

Test	Refrigerant	Charge (g)	Rate (g/min)	Duration (s)	Height (m)	AC fan condition	**AC fan** direction
1	R290	240	60	240	1.8	ON	45^{o}
2	R600a	280	22	763	1.8	ON	45^{o}
3	R290	240	60	240	1.8	OFF	---
4	R600a	280	22	763	1.8	OFF	---
5	R290	152	38	240	0.1	ON	0^{o}
6	R600a	172	14	763	0.1	ON	0^{o}
7	R290	152	38	240	0.1	OFF	---
8	R600a	172	14	763	0.1	OFF	---

3. RESULTS AND DISCUSSIONS

The flammable volume inside the room is defined as the volume where the refrigerant concentration falls between the lower flammability limit (LFL) and the higher flammability limit (HFL). This volume was recorded during the simulations, with the maximum values shown in Fig. 3.a. Across all similar scenarios, the maximum flammable volume is significantly higher for R290 compared to R600a. Furthermore, the operation of the IDU fan has a substantial impact on mixing within the room, as seen in scenarios S1-S2 compared to S3-S4, and S5-S6 compared to S7-S8. Scenarios S7 and S8, where the fan is not operating and the IDU is installed at floor level, exhibited the worst cases with the highest flammable volume. However, in these scenarios, the ratio of maximum flammable volume between R290 and R600a is lower than in other scenarios. This is because, in the absence of fan operation or a high installation position, R600a has more time to mix with the air inside the room, but the only mixing mechanism available is diffusion

The impact of leakage duration is another critical factor in assessing the flammability risks associated with refrigerant leaks, as shown in Figure 3.b. Flammable volume-time is the integral of flammable volume over the time during and after leakage. While the maximum flammable volume (Fig. 3.a) is significantly higher for R290 across all scenarios, the flammable volume-time in Figure 3.b provides additional insights. Since R600a has a longer leakage duration compared to R-290, the overall difference in flammable volume-time between the two refrigerants is less pronounced than the difference in maximum flammable volume. However, the trend remains consistent, and R-290 exhibits a higher flammable volume-time across all scenarios, indicating a greater sustained risk of flammable conditions.

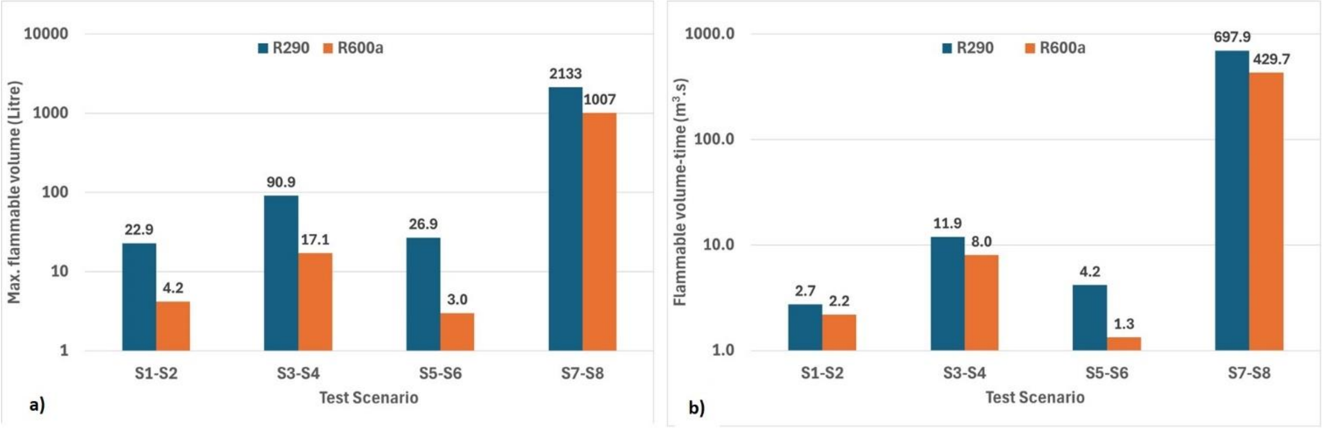

Figure 3: Maximum flammable volume (a) and flammable volume-time inside the room

To provide a comprehensive understanding of the simulation results, Fig. 4 presents concentration contours for the refrigerants across all scenarios, illustrating the conditions after the entire charge has leaked. The middle plane of the room is chosen for presenting the results, even though the refrigerant concentration is higher in the leakage plane which is located on the right-hand side of the evaporator. This selection provides a more comprehensive representation of the conditions within the room. Additionally, although some regions have concentrations exceeding 100% of the LFL, the 0-100% range was used to facilitate comparison across all scenarios and ensure the visibility of concentration gradients. Thus, the deepest shade of red indicates concentrations exceeding 100% of the LFL.

Across all pairs, it is evident that R290 results in higher concentrations compared to R600a under similar hole size. This is obvious in scenarios S1, S3, S5, and S7 where the color gradients for R290 are consistently more intense and cover a larger volume of the room. Additionally, the scenarios where the fan is operational (S1, S2, S5, S6) demonstrate a more dispersed refrigerant concentration, with lower overall percentages of LFL compared to scenarios where the fan is off (S3, S4, S7, S8). The operational fan aids in mixing the leaked refrigerant with the room air, reducing the concentration near the source and spreading it more evenly throughout the room. However, when the fan is off, the refrigerant tends to accumulate near the floor, leading to higher concentrations in localized areas, as seen in S3, S4, S7, and S8. Furthermore, Scenarios S7 and S8, where the IDU is installed at floor level and the fan is off, exhibit the highest flammable volumes. The refrigerant tends to settle near the floor due to its higher density, leading to more significant accumulation and elevated flammability risks. In contrast, when the IDU is installed at a standard height (S5, S6), the refrigerant disperses more before settling, resulting in lower flammable volumes. This highlights the importance of installation height in mitigating flammability risks.

For a better understanding, Fig. 5 illustrates the changes in R290 and R600a concentrations at defined points during the leakage period and for the subsequent 4 minutes in Scenarios S3 and S4. R600a demonstrates higher concentrations at floor level but lower concentrations at higher levels in the room. This is because R600a has more time to diffuse and disperse throughout the room, resulting in a more gradual concentration gradient compared to R290. However, it should be noted that the flammable volume persists for a longer duration with R600a.

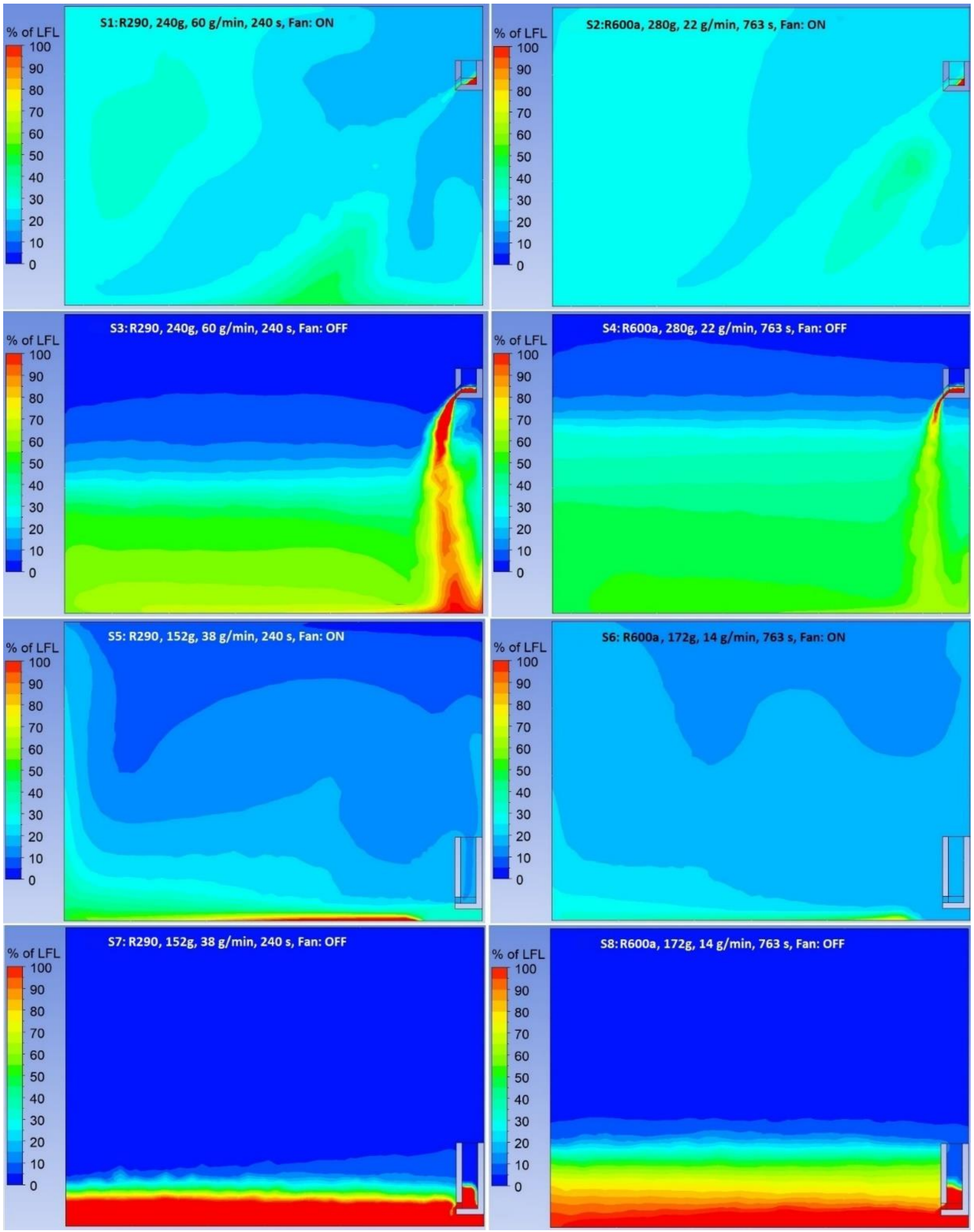

Figure 4: Concentration of refrigerants at the middle plane of the room for all scenarios

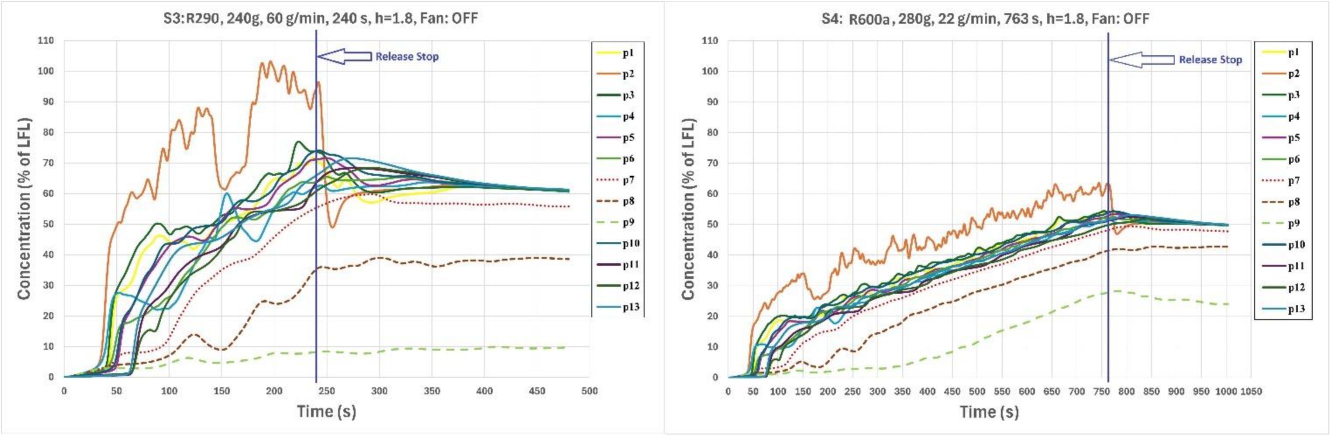

Figure 5: Concentration of R290 and R600a during leakage and afterward for selected scenarios

Fig. 6 shows the volume where the concentration of the refrigerant exceeds 100% of LFL for scenarios S7 and S8. These visualizations underscore the heightened flammability risk in scenarios where the fan is not operational and the IDU is installed at floor level, with the potential for significant volumes of flammable mixtures to form. R290 demonstrates a larger flammable volume in Scenario S7 compared to R600a in Scenario S8.

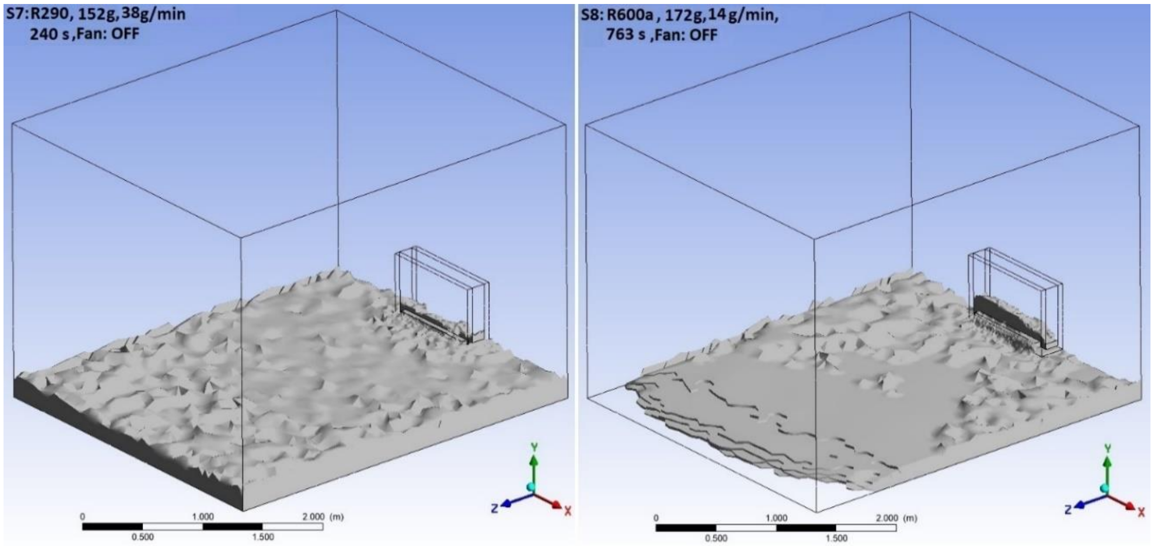

Figure 6: Volume with concentration over 100% of LFL for selected scenarios

4. CONCLUSIONS

This study investigated the impact of different refrigerants on leakage and subsequent dispersion within a controlled environment using Computational Fluid Dynamics (CFD) simulations. The findings reveal that R290 consistently results in a higher flammable volume than R600a, primarily due to its higher saturation pressure, which causes a more rapid leak rate and leads to higher concentrations within the room. On the other hand, R600a, with its slower leak rate, allows for more uniform diffusion, producing lower concentration gradients and reducing the immediate flammability risk. However, it is important to note that while R600a has a lower flammable volume, its longer leakage duration results in a more extended presence of flammable conditions over time. Despite this, R600a still presents a lower overall flammability risk compared to R290, underscoring its potential as a safer, environmentally friendly refrigerant for refrigeration and heat pump systems. The results emphasize the need for safety standards to account for both internal and external factors to more accurately predict and mitigate risks associated with refrigerant leaks.

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NOMENCLATURE

A	room area (m^2)	AC	air conditioner
CFD	computational fluid dynamics	h_0	height from floor level (m)
LFL	lower flammable limit	IDU	indoor unit
P_{atm}	atmospheric pressure (Pa)	M_{max}	allowable maximum charge (kg)
$\dot{m}$	mass flow (g/min)	C_d	discharge coefficient
A_0	leak hole area (m^2)	k	ratio of specific heats
ρ_0	density (kg/m^3)	p_0	vapour pressure (Pa)

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