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Indoor R-290 Heat Pump Safety Concepts: Development, Measurement and Evaluation

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Abstract

As part of the LCR290 project, R-290 heat pump solutions for multi-family houses were planned, simulated, tested, and evaluated. The project reports to an advisory board representing the housing industry as well as the heat pump manufacturing industry. One of the main areas of attention are safety concepts for indoor brine-to-water heat pump installations. As part of the project, a heat pump demonstrator was built to test different safety concepts by releasing R-290 into the enclosure located in a test room. The demonstrator represents a 30kW heating capacity heat pump with 800g refrigerant charge. The test room has controlled and varied air exchanges rates starting at around 0 up to 17. The test facilities enable the use of safety concepts without exchange to the ambient air and concepts with R-290 exhaust to the ambient. The developing R-290 concentrations in and around the heat pump enclosure were measured using concentration sensors. The measurement method used for testing the concentration includes the variation of (i) leakage mass flow rate, (ii) leakage position, (iii) enclosure tightness, (iv) room air exchange ratio and (v) enclosure air exchange ratio. This contribution presents the measurement methodology used. Different safety concepts have been tested, using the adaptive demonstrator. The results of a selection of these tests, resulting in time developing propane concentration measurements at multiple locations, are shown. The results have tangible value in quantitative risk assessment and are good candidates for improving existing safety concepts as well as the evaluation methods of R-290 outflow measurements.

Keywords: Propane; R290; Heat Pump; Safety Concept; CFD Simulation;

1. Introduction

R-290 (propane) offers a very low global-warming potential and is increasingly used as refrigerant in residential heat pumps, but it is flammable and therefore requires dedicated safety measures. This holds especially for indoor installations due to small installation rooms and risk of accumulation of R-290. Relevant standards that govern safe application and testing are EN 378 (refrigerating systems and heat pumps — safety and environmental requirements) and IEC 60335-2-40 with its normative annexes (e.g., Annex GG) that address A3 refrigerants and ventilation/mixing concepts. Indoor R-290 units are not yet widespread on the market; However, some manufacturers [1, 2] offer or have announced R-290 indoor ground source heat pumps with safety concepts, while other suppliers are still evaluating pathways for their R-290 indoor units. The LCR290 project [3] aims to close key knowledge gaps by providing experimental data for representative leakage scenarios and by testing practical safety concepts (reference, internal circulation, external exhaust) so that normative applicability, product design choices and CFD validation can be better supported.

2. State-of-the-art in studying release experiments of R-290

The current state of research on R-290 (propane) release and dispersion at installation locations shows CFD-based modeling studies and experimental leakage investigations and in rare cases both investigating approaches. Very central work for experimental investigations was initiated by Colbourne in his PhD thesis [4] and several dozens of publications not listed in this paper which also include good resources for CFD simulation approaches and results.

A recent study was done Guo et al. [5] employs Computational Fluid Dynamics (CFD) to simulate R-290 leaks from residential air conditioning units and compute evolving flammable volumes under varying conditions such as leak rate, release location, airflow velocity, room dimensions, and interior obstacles. This work integrates CFD dispersion results with quantitative risk assessment to estimate ignition event frequencies, concluding that under prescribed charge limits the ignition risk remains extremely low.

Several other research efforts leverage CFD to characterize indoor propane dispersion. For example, 3D CFD models using commercial solvers like ANSYS Fluent have been developed and validated against experimental data to predict concentration fields and identify critical flammable zones for different leak scenarios [6]. Independent academic work has used open-source platforms like OpenFOAM to simulate R-290 leaks and compare simulated concentration fields to controlled experimental measurements, supporting model validation [7].

On the experimental side, some more recent investigation was done by Ning et al. [8] directly measured R-290 concentration distributions in room leakage tests, documenting how leak rate, position, and indoor airflow influence spatial gas distributions. Combined experimental and numerical studies have produced measured concentration fields for R-290 leaks and compared these to numerical predictions, providing crucial data for model validation [8]. Additional experimental investigations have quantified mass distribution and dispersion characteristics for a range of RAC unit sizes, contributing empirical datasets that underpin risk assessments and safety standard development [9].

In summary, the research landscape comprises CFD efforts aimed at spatial-temporal prediction of flammable concentration fields and risk quantification, and experimental studies that generate ground-truth concentration measurements and validate numerical approaches. The integration of both methods continues to improve understanding of R-290 leakage behavior, informing safety standards and engineering practices for flammable refrigerants [5].

3. Test facility and Demonstrator

The experimental campaign was conducted in a purposebuilt- indoor test chamber coupled to an external emission area for selected exhaust tests. The indoor chamber represents the indoor installation room of the heat pump (e.g. a cellar) and its volume is 21,875 m³ and the room ventilation is fully controllable to cover air exchange ratios (AER) relevant for normative and practical scenarios. The ventilation system can be set from very low flows (≈0,3 m³/h, AER ≈ 0,015/h) up to high flows (≈650 m³/h, AER ≈ 30/h) and can generate a negative pressure up to ≈75 Pa. This wide range allows reproducing the AER values used in the campaigns (typical test points: ≈0; 2,2; 10,8; 17,2 m³/h) and investigating both naturaldecay and -forcedventilation- regimes. The device under test heat pump is positioned along the test chambers smaller side. See Figure 1 left side for details.

The chamber is instrumented with a dense array of calibrated, ATEX-rated concentration sensors and auxiliary instrumentation. The installed sensor types and locations are shown in Figure 1 right side and can be differentiated into:

- Room sensors: ~32 fixed concentration sensors arranged in three vertical layers (bottom ≈ 0,05 m; middle ≈ 0,45 m; top ≈ 0,85 m) and at multiple radial positions around the device under test (DuT). This geometry follows a normative inspiration (prEN 3781 surrounding concentration test) and enables capturing nearfloor pooling as well as vertical mixing effects where they occur.
- DuT sensors: 6 sensors mounted inside the DuT to monitor the enclosure interior.
- Exhaust / outdoor sensors: for tests guiding gas to the outside, a radial sensor array at the emission point and nearby outdoor positions records concentrations in the exhaust plume and ambient.
- Auxiliary instrumentation: multiple differential pressure sensors to monitor enclosure and piping pressure, and ATEX thermistors for temperature control and safety monitoring.

All channels are time-synchronized (typical common sample base 1–5 s) and sensors are calibrated prior to campaigns. Data acquisition records raw traces for post-processing (offset correction, basic low-pass filtering) and for event tagging (leak start, fan activation, purge start).

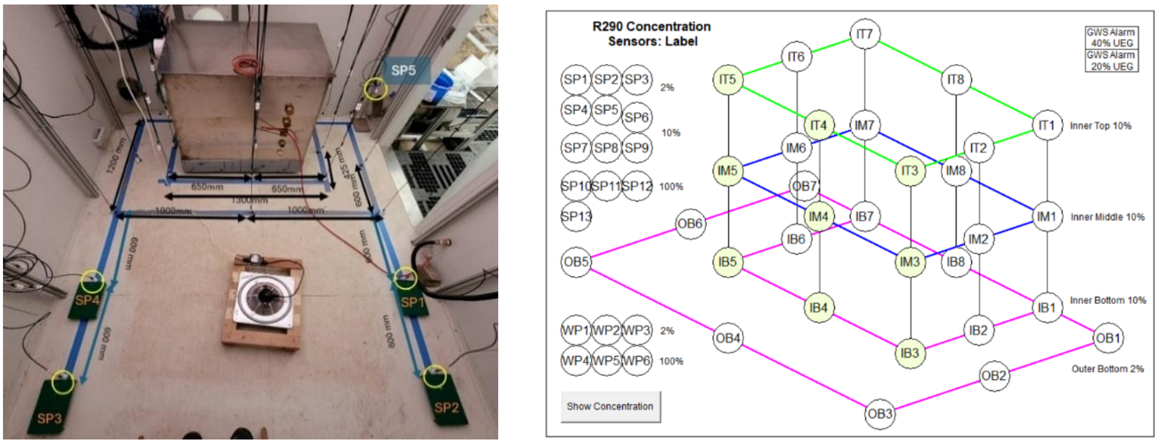

Figure 1. Overview of the sensor location in the test bench for indoor heat pumps

The chamber is coupled to a separate, regulated leakage dosing rig that supplies defined propane mass flows (typical set points used in the campaigns: 0,15 g/s; 1 g/s; 3,3 g/s) up to the tested maximum charge (800 g). The controlled feed enters the welded demonstrator through industrial cable/hose glands; a nitrogen purge line is installed to flush the enclosure and chamber after each test.

The primary evaluation tools are synchronized timeseries plots and distance/duration summaries derived from the sensor traces. Timeseries visualizations show layerresolved concentration traces at selected radial positions and mark key events (release start, fan activation, purge). From these traces the analysis extracts durations above relevant thresholds (e.g., LFL = 1,7 vol%), the effect of reaction times for leakdetectiontriggered fans, and decay rates under different AERs and fan settings. Figure 2 (see below) shows a representative multilayer timeseries example used repeatedly in the evaluation to quantify durations above thresholds and to compare parameter effects.

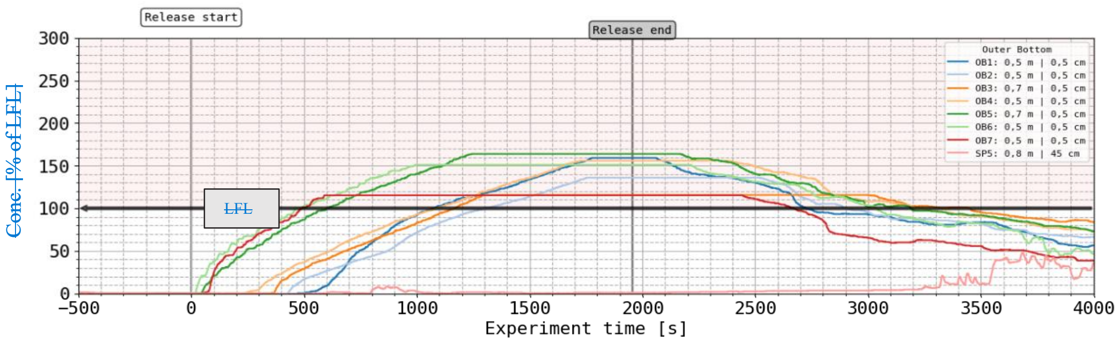

Figure 2. Example concentration time series for seven outer bottom sensors with 0.5 m to 0.7 m distance from DuT. Representative run with time periods of gas concentration above LFL. Vertical markers indicate controlled events (release start and end).

The demonstrator represents a centralized indoor brinetowater heat pump (nominally 30 kW) installed inside a purposebuilt, welded stainlesssteel safety enclosure. The enclosure is fabricated from 2 mm plates, the lid edges are flanged and sealed with a continuous gasket and bolted down. The tank is mounted on lockable casters and the clearance under the housing is closed with sealed panels to ensure gas tightness. An industrial cable/hose gland set feeds the controlled refrigerant line from the external dosing rig into the enclosure and a nitrogen purge line is provided to flush the enclosure after each test. To vary enclosure tightness, a 3Dprinted adapter with interchangeable gap inserts (0 / 0,5 / 1,0 mm) is mounted on one side, yielding cumulative leak cross sections of ≈ 0 / 2.5 / 5 cm². The DuT is elevated by 45 mm so that the slot outlet lies about 41.6 mm below the device underside — a placement chosen because propane is heavier than air and nearfloor behavior is critical.

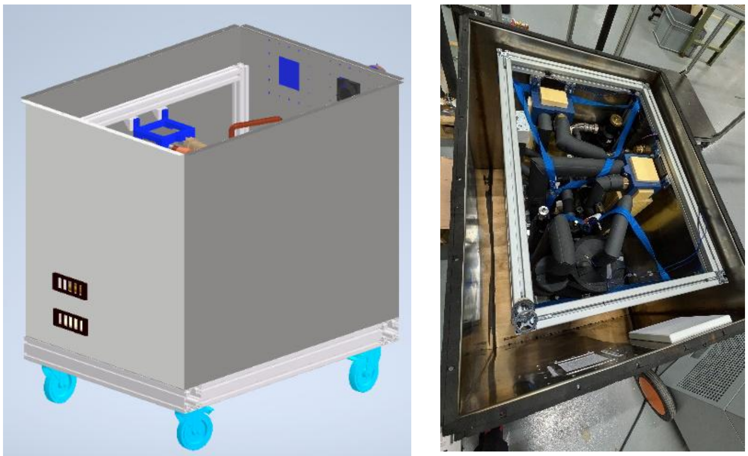

Figure 3. Heat pump demonstrator in enclosure. CAD view of the welding tank without cover (left); view inside the DuT with sealing surface of the cover (right). The wheels were covered such that this ground source heat pump unit style would behave as if the lower part is part of the heat pump's enclosure.

4. Experimental design, safety concepts and results

This section introduces the three experimental campaigns evaluated in this paper: Campaign 1 (Simple / Reference), Campaign 2 (In-room ventilation for internal mixing) and Campaign 3 (External ventilation according to norm). Figure 4 shows schematically the three campaigns.

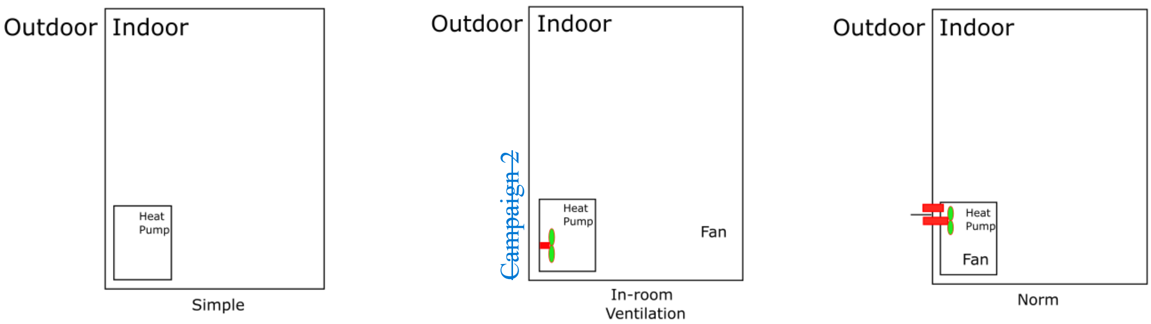

Figure 4: Conceptual layout of the three tested safety concepts. Left: Simple (reference) – leak into room. Centre: Inroom ventilation (internal mixing) – integral fan circulates housing/room air. Right: External ventilation (normative) – builtin exhaust to ambient

Each campaign uses the same demonstrator and sensor geometry; openings from the demonstrator to the room or outdoor are adapted for each campaign. The experimental parameter space was selected to cover normative and practical scenarios (see parameter overview in Table 1).

Table 1. Overview of test parameters and tested parameter space

Parameter	Parameter space	Unit
Air exchange ratio (AER)	0; 2,15; 10,75; 17,2	m^3/h
Refrigerant charge	300; 800	g
Leakage mass flow	0,15; 1; 3,3	g/s
Slot width	0,5; 1	mm

4.1. Campaign 1 - Reference

Campaign 1 established a conservative reference case by simulating outflow in the vicinity of the bottom plate while keeping the rest of the casing extratight to reproduce defined drainage conditions with cumulative leak -crosssections- of ≈0,12; 2,62 and 5,12 cm². The full set of runs (see Figure 5) covers the project parameter space (AER, charge, leak rate and slot geometry) and provides the baseline measurements used for CFD validation (CFD not part of this paper). Results consistently show strong nearfloor pooling: -bottomlayer- sensors recorded prolonged LFL exceedances in many 300 g tests. The impulse of the leak flow has a large impact on local mixing.

Experiment	Air exchange ratio	Refrigerant charge	Leakage mass flow	Slot width	Risk	Time in seconds > 100% LFL				
					Distance	0,1m	0,3m	0,5m	1,0m	1,5m
	m^3/h	g	g/s	mm		2	3	4	5	6
C1.23.unit	17,2	800	1	1	Shrinking risk	3752	3752	3752	3642	3518
C1.08.unit	0,5	300	0,15	1		3615	3615	3615	3388	3061
C1.14.unit	0,5	300	1	1		3372	3372	3372	3345	1397
C1.05.unit	17,2	300	0,15	0,5		3019	3019	3019	2617	1959
C1.09.unit	10,75	300	0,15	1		2980	2980	2980	2704	1981
C1.21.unit	10,75	300	0,15	1		2980	2980	2980	2704	1981
C1.04.unit	0,5	300	0,15	0,5		2959	2959	2959	2758	2372
C1.10.unit	17,2	300	0,15	1		2838	2838	2838	2590	2062
C1.06.unit	10,75	300	0,15	0,5		2600	2600	2600	2331	1756
C1.07.unit	0,5	300	0,15	1		1702	1702	1702	1427	1070
C1.24.unit	10,75	300	3,3	0		1325	1316	1316	589	585
C1.15.unit	10,75	300	1	1		1313	1313	1313	1100	802
C1.11.unit	0,5	300	1	0,5		1103	1103	1103	1101	909
C1.16.unit	17,2	300	1	1		1049	1049	1049	833	729
C1.13.unit	17,2	300	1	0,5		1001	1001	1001	733	435
C1.12.unit	10,75	300	1	0,5		870	870	870	830	645
C1.22.unit	17,2	300	3,3	1		613	603	603	453	330
C1.20.unit	0,5	300	3,3	1		536	511	511	408	328
C1.18.unit	10,75	800	3,3	0,5		304	275	275	231	143
C1.19.unit	17,2	300	3,3	0,5		296	266	266	135	107
C1.17.unit	0,5	800	3,3	0,5		281	261	261	218	213

Figure 5: Campaign 1 results table — test configurations (AER, refrigerant charge, leakage mass flow, slot width) and measured durations (s) with concentrations >100 % LFL at sensor distances 0,1; 0,3; 0,5; 1,0 and 1,5 m from the DuT.

Low leakage mass flow (0,15 g/s) with low momentum yields longer periods of gas concentration above LFL in the surrounding of the DuT. For higher leakage mass flow (3,3 g/s) dilution in the room is stronger and the critical time of gas concentration above LFL is significantly lower. In short, the simple enclosure without active dilution or controlled exhaust is not a viable standalone safety concept under the tested conditions; the Campaign 1 dataset therefore serves as conservative validation material for CFD and for assessing required mitigation measures.

4.2. Campaign 2 – In-room ventilation

In a closed room a heat pump with a sufficiently strong integral circulation airflow can also meet the safety requirements according to IEC 60335-2-40 Annex GG.2.3. In this case, the size of the room is limiting the allowable propane mass and therefore heat pump size. Therefore, it was tested to which extent this limit can be challenged. In compliance with the standard, only a mass of 350 g is allowed in the room. However, also cases with up to 800 g were tested. The concept is based on the idea that a strong impulse of the airflow, generated by a fan mounted to the housing, is sufficiently mixing the propane with the air in the room to keep the concentration in the near surrounding of the DuT permanently under the LFL. The required air flow rate according to the standard is 140 m³/h (see formula GG.15). In addition to 140 m³/h, values of 0 m³/h, 40 m³/h and 75 m³/h were also set for the air flow from the DuT into the room.

Results show that internal circulation can be an effective safety measure for reduced charges (≈300 g) when the fan provides sufficiently high volumetric flow and the enclosure tightness is adequate: in many 300 g runs with high fan flow no LFL exceedance was recorded at the instrumented positions. However, for high charge (≈800 g) combined with large rupture-rate leaks (3,3 g/s) internal mixing often failed to prevent prolonged near-floor LFL exceedances, even at maximum tested fan flow. Higher leakage mass flows tended to increase entrainment and momentum, producing stronger local mixing; in some cases this transient mixing reduced concentrations at specific sensor locations, but it did not reliably eliminate near-floor pooling across the domain.

Figure 6 displays SHAP values from a RandomForest model [10] visualizing the duration during which propane concentrations exceeded 100 % LFL at a distance of 0.5 m from DuT. The x-axis value of 0 represents the expectation value. In this case 1770 s along all 34 tests. From this value the 6 testing parameters (feature values) change the duration time in either longer duration (right part of the vertical zero line) or shorter duration (left part) dependent on their magnitude. The leakage mass flow is identified as the most influential input, followed by released refrigerant charge, airflow -fan and air exchange ratio, while bleed hole and slot width have smaller effects. As expected, high leakage mass flow rate, high amounts of released refrigerant charge, low air flow fan, low air exchange ratio yields the longest periods of concentration above LFL with around 3700 s.

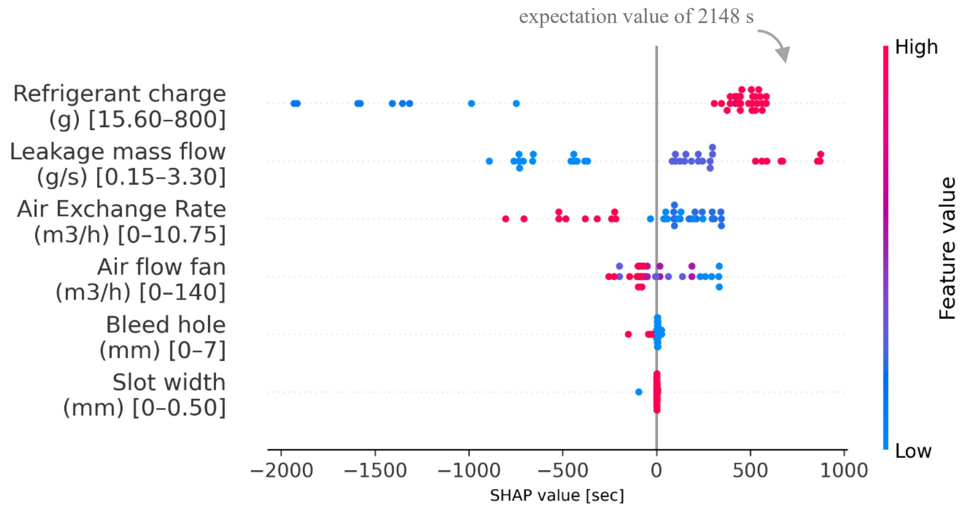

Figure 6: Campaign 2 results. SHAP beeswarm plot showing how six input parameters (units and defined ranges shown in the y-labels) contribute to the time above 100% LFL in a 0.5 m distance from DuT; the x-axis gives SHAP value in seconds (positive → increases predicted time), each dot is one experiment and color encodes the feature value (red=high, blue=low).

4.3. Campaign 3 – External ventilation

Campaign 3 examined the externalventilation concept in which enclosed gas in the DuT is actively removed to the outside via a coaxial duct (inner exhaust channel with annular supply air). Results demonstrate that external exhaust is a robust mitigation approach when the exhaust flow and termination are properly designed: with higher exhaust flow (27 m³/h) and/or a functioning check valve, LFL exceedances within the instrumented domain were typically eliminated for a wide range of leak and charge combinations. By contrast, lower exhaust flow (9 m³/h) combined with a 0.5 mm slot width and high leak rate (3,3 g/s) could still produce measurable LFL. However, only 6 tests out of 29 tests showed a time period with measured gas concentration above 20%LFL at 0.5 m distance from DuT. Measurements at the exhaust and in the outdoor plume confirmed effective dilution for the favourable configurations.

Additional tests with a leakage detection system (LDS) and a drain check valve have been performed. Reaction time is one critical parameter for the LDS in order to start increasing the exhaust fan speed. The “simulated reaction time“ is the delay between the start of a leakage event and the detection of a LDS. Typical delays were tested to test the system under conditions closer to a real-world example. Moreover, not only conventional two-duct systems but also single-ducted enclosures were tested with a back-flow flap (drain check valve) to use the room air for dilution purposes. Operation of a suitable LDS and check valve yielded a safe environment around the DuT in the tests performed, but introduces additional complexity and maintenance requirements.

5. Conclusions

Across the three campaigns, indoor R-290 hazards are governed by nearfloor propane accumulation which is of no surprise due to the heavy gas flow behavior of this refrigerant. How air is routed and terminated – either through inroom circulation or, more decisively, exhaust to ambient – matters more than bulk room AER alone. Risk is driven foremost by the amount of released refrigerant charge and leak mass flow (including jet momentum), followed by the design of leak and air paths (slot/bleed geometry, flow rate, and termination), then room AER, and finally the reaction time of the leakage detection system (LDS).

The reference concept (Campaign 1) – a sealed enclosure without active dilution or exhaust – showed long periods of R-290-air mixture above lower flammability level (LFL) in the room around the heat pump. As expected, it cannot be used as standalone safety solution, but it serves as a good database for CFD simulation.

The internal circulation concept (Campaign 2) can be effective, but only within constrained parameter space: for reduced refrigerant charge (≈300 g) and verified, sufficiently high fan flows, internal mixing often prevented LFL exceedances at the instrumented locations. For high charge (≈800 g) combined with large rupture-rate leaks (3,3 g/s), internal mixing frequently failed to prevent prolonged near-floor LFL exceedances even at maximum tested fan capacity. Transient impulse/momentum effects from high leakage mass flows can increase local mixing and, in some cases, shorten measured LFL durations, but they do not reliably eliminate the generation of local flammable mixture volumes across the domain.

The external exhaust concept (Campaign 3) proved the most robust technical measure when exhaust flow and leakage detection system reaction time were properly designed (e.g., ≈27 m³/h).
Key drivers for safety are the released refrigerant charge, leakage mass flow (impulse/momentum), enclosure tightness, and fan/exhaust sizing and control (including reaction times). Measurement limitations – notably vertical blind zones between sensor layers – restrict full 3-D hazard quantification; reported values therefore represent conservative, point-based references. Some recommendations are:

- Minimize indoor-released refrigerant charge where possible and design enclosure tightness to limit uncontrolled leakage paths.
- If internal circulation is used, verify fan performance and enclosure sealing for the specific product and operating point; design for bleed/vent paths that avoid protected local hotspots.
- For modelling and standardization, include impulse/momentum as a modelling parameter and expand vertical sensor density in future tests;

The presented dataset provides conservative validation cases useful for CFD model development, quantitative risk assessment, and the refinement of practical normative guidance for indoor R-290 heat pumps.

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References

[1] ait, 2025. [Online]. Available: https://www.alpha-innotec.com/de/produkte/erdwarmepumpe/wzsv-63.

[2] Vaillant, 2025. [Online]. Available: https://www.myvaillantpro.de/aktuell/neuheiten-2025.

[3] ISE, 2025. [Online]. Available: https://lcr290.eu/.

[4] Colbourne DH. *Methods for assessing environmental, safety and performance of alternative refrigerants*. PhD thesis, Department of Mechanical Engineering, University College London (UCL). June 2006.

[5] Guo C, et al. *Investigation of the application safety of R-290 in residential air conditioning systems.* Journal of Building Engineering. 2024;94:109999. DOI: 10.1016/j.jobe.2024.109999.

[6] Yadav P. *A study of R290 gas concentration in air in case of leakages from a refrigerating circuit of a heat pump unit.* Master thesis, Università degli Studi di Padova. 2023.

[7] Righetti G, Calati M, Longo GA, Mancin S, Zilio C. *CFD analysis of propane dispersion in an indoor environment.* Proceedings of 6th IIR Conference on Thermophysical Properties and Transfer Processes of Refrigerants. 2021-09-01. DOI: 10.18462/iir.TPTPR.2021.2181.

[8] Ning Q, He G, Fan M, Xiong J, Li X. *Flammable refrigerant leakage hazards control for split-type household air conditioners.* Int J Ref. 2022;144:188–201. DOI: 10.1016/j.ijrefrig.2022.08.009.

[9] Wang X, Li K, Liu J, Xie Y. *Analysis of leakage and diffusion of R290 in the engine compartment of electric vehicle.* Energy Proceedings. 2024;40.

[10] shap, 2025. [Online]. Available: https://shap.readthedocs.io/.