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CONCENTRATIONS OF HYDROCARBON REFRIGERANT EXITING FROM RACHP EQUIPMENT ENCLOSURES

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ABSTRACT

Previous studies involving simulated leaks of hydrocarbon refrigerants from refrigeration, air conditioning and heat pump equipment found that the concentration of mixture exiting the equipment enclosure had a strong influence on the evolution of room concentrations. The present work investigates factors that affect these exiting concentrations, using wall type split air conditioner enclosures and a so-called variable enclosure, where the configuration may be changed to mimic different types of equipment. Important variables were found to include release position, size and number of openings and layout of internal components. These findings can be employed to assist with the design of equipment to help further minimise room concentrations in the event of a refrigerant leak.

Keywords: Hydrocarbon refrigerant, flammable refrigerant, R290, safety, exiting concentration, enclosure

1 INTRODUCTION

Recent work (Colbourne and Suen, 2016; 2018; 2021) identified that room floor concentrations (C_f) arising from R290 (propane) releases from within refrigeration, air conditioning and heat pump (RACHP) enclosures was strongly dependent upon the maximum concentration of the mixture exiting (C_{exit}) from that enclosure. It was also observed that C_{exit} could vary widely, depending upon the internal location of the release and the size and configuration of the enclosure and number and dimensions of its openings. It is therefore pertinent to investigate this aspect further with the intention that the findings can be used to help design RACHP equipment to encourage lower C_{exit} and thus C_{floor} in the event of a leak. A further use of this data is as a boundary condition for computational fluid dynamics (CFD) models, to avoid the time-consuming and resource-intensive tasks of modelling the release jet and subsequent impingement and mixing within the enclosure; instead of simply assigning an opening with an expected C_{exit}.

Other work related to this topic within the literature is sparse. Perhaps the closest is that dealing with dispersion of hydrogen in closed spaces, such as garages, where small openings are used to mimic the effects of natural ventilation, e.g., Pitts et al. (2011) and Giannissi et al. (2016) and more specifically Ghatauray et al. (2016), where effects of different sized and alternate positioned vent openings were considered. Cleaver and Cumber (2001) describe a similar study using natural gas. Whilst these studies examined concentrations within rooms and similar enclosures, no consideration was given to concentrations exiting those spaces.

2 METHODOLOGY

2.1 Experimental arrangement

Tests were conducted to measure C_{exit} arising from releases from within various RACHP enclosures, within a sealed room. Room air speed was checked with an omnidirectional hot wire anemometer to confirm all readings were less than 0.02 m s^{-1} before starting the measurements, to ensure that measurements were not being influenced by extraneous air currents. Multiple aspirated gas sensors (pellistors with a range of 0-5% R290 and infra-red type with a range 0-100% R290; accuracy within ± 3% of the reading) were positioned at various height increments at or near enclosure openings, in a formation appropriate for the test objective and enclosures used. All sensors were subject to regular re-calibration. Experiments were carried out when the room temperature was at 25°C ± 2 K.

To correspond to practical scenarios, release mass flow of R290 vapour was set mostly within the range of 10 g min^{-1} to 60 g min^{-1} (Colbourne et al., 2021). R290 was released through a fixed orifice with diameters selected to ensure choked flow delivered at a fixed velocity for the selected release mass flows; a mass flow controller was used with an accuracy of ± 1%.

Measurements were carried out on two wall-type air conditioner (AC) indoor unit (IDU) enclosures and a "variable enclosure" (VE) that could be modified to simulate the constructional characteristics of common commercial refrigeration (CR), AC IDUs and HP housings.

2.2 Wall type AC IDU

Two IDUs were used, of 8 kW ("large") and 2.5 kW ("small") nominal capacity and were positioned about 1.5 m above floor level, so that the quantity of R290 used for each test would not form a stratified layer approaching the apparatus and thus influence the measurements. IDUs were fitted with several frusta, sealed to the discharge grille (Figure 1), extending downwards for >0.5 m. They were used to channel refrigerant-air mixture exiting the IDU openings with the aim of obtaining steadier readings (as opposed to the erratic readings experienced with direct measurements at the outlet openings). Additional casing (indicated) was attached around the perimeter of the inlet grille to collect mixture exiting the top opening. Sampling points were positioned at the base of individual frustum channels. Prior measurements with multiple sensors across the base of the frustra indicated effectively homogeneous distribution at this point.

R290 was released at constant mass flow rates from positions about the return bends of the IDUs (with fan de-energised). The arrangement is illustrated in Figure 1; the schematic shows the casing and positioning of sensors used to capture exiting concentration. Leak positions (LP) within the end segment of the IDU are indicated. Other leak positions along the coil were previously found to result in substantially lower room concentrations (Colbourne and Suen, 2018) so were neglected for the present work. Approximately 80 sets of measurements were conducted across the range of variables.

Figure 1: Diagram and photographs of the test arrangement: construction of the frusta and sampling points (left), photograph of the frusta (centre) and selected leak positions (LP) within the IDU right end.

2.3 Variable enclosure

Similar measurements were carried out with the variable enclosure (VE), which was constructed of wooden panels and sealed with plastic sheeting to enable external dimensions and number and size of front openings to be changed (Figure 2). Thereby a variety of different RACHP enclosures and housings could be mimicked. VE base was 0.5 m above the floor so as to avoid stratified refrigerant-air layers affecting the results. Approximately 160 sets of measurements were conducted.

Sensors were positioned just on the inside of the VE envelope to capture C_{exit} at various horizontal and vertical intervals across the opening(s) as shown in Figure 2. Opening heights ranged from 0.1 m to 1.3 m. Releases were made from different positions within the enclosure, generally at the centre of the rear wall at three different heights and also at the left rear-side corner. Releases closer to the opening yielded lower C_{exit} so such positions were neglected. Sometimes two openings were used; one at the lower front section and a second at the upper. The width of the VE was 1.8m, halved (0.9 m) and quartered (0.45 m). Internal height was 1.5 m, but was also reduced to 0.85 m and 0.5 m. Mostly the VE was empty, although some tests employed "congestion" in the form of the internal parts of large wall type AC units, exemplifying pipework, coils, control boxes, etc. reaching an internal height of 0.6 m.

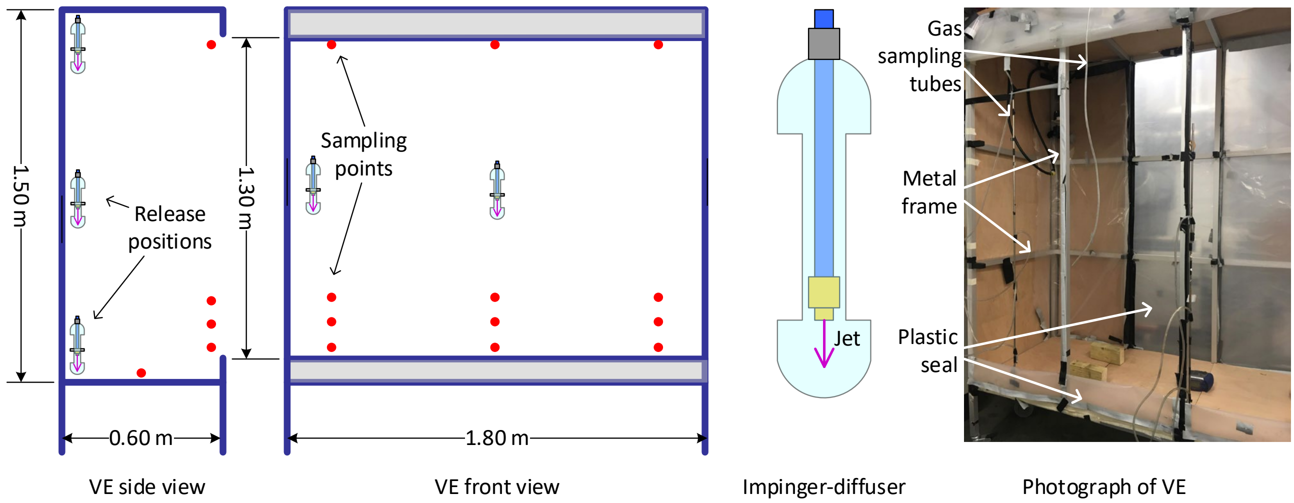

Figure 2: Test arrangement for variable enclosure (example of 1.8 m length and with a 1.3 m high opening) and locations of sampling and release positions.

An "impinger-diffuser" (Figure 2) was designed and used to mimic practical situations where a high velocity jet impinges on a nearby surface and thus reduces the momentum of the refrigerant jet, in a consistent manner. Comparisons between a downward jet release and the impinger-diffuser found results with the "free" jet – both C_{exit} and C_{floor} – were about half those from the impinger-diffuser.

Table 1 summarises the ranges of variables used for the VE tests.

Table 1: Range of variables used for VE tests

R290 mass released	100 g – 300 g
R290 mass flow	10 g min^{-1} – 90 g min^{-1}
Number of (front) openings	1, 2
Opening height (relative to VE base)	0.1 m – 1.3 m
Release height (relative to VE base); position	0.15 m – 1.3 m; rear-centre, rear-left corner
Enclosure depth; length	0.6 m; 0.45 m, 0.90 m, 1.80 m

Data was extracted from each test for the 1 – 2 minutes prior to cessation of the release, once steady concentrations had established; this dictated the duration of each release. Concentrations measured during that period (for each sampling point) were then averaged.

3 RESULTS

3.1 Wall type air conditioner IDU

Results for the small IDU are given in Figure 4, according to a sequence of mass flow rates, with values for each successive linear location along the outlet (left) and inlet grille (right) openings. The release position is indicated by an arrow on the x-axis. Data shows for lower mass flow rates, a higher proportion of the mixture exiting closer to the release point, but as release mass flow increases, a more even distribution develops and eventually the greater proportion exits at the opposite end from the release. Across mid to high mass flow rates, the centre location tends to show lowest C_{exit}. Nevertheless, all mass flows result in at least one location exhibiting a flammable C_{exit} (i.e., above lower flammability limit, LFL = 38 g m^{-3}). The direction of the release also has an influence on C_{exit} distribution. For example, other tests (not shown) with a different release orientation (but same location) resulted in the pattern being the reverse of Figure 4, where highest values occurred at the release (right) end of the IDU. Refrigerant is also forced upwards, out of the inlet grille, but C_{exit} are much lower than with the outlet and mixtures are always below LFL, even at highest mass flow rates.

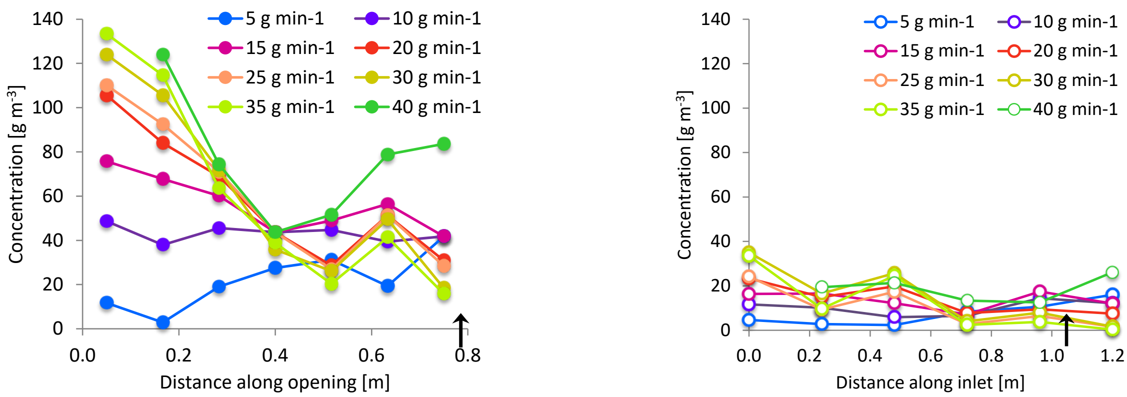

Figure 3: Example C_{exit} profiles for small IDU at outlet (left) and inlet (right) for leak position (i) as indicated by the upward arrow on the x-axis.

Figure 5 shows maximum C_{exit} for four different leak positions (see Figure 1), again, for the outlet and inlet grilles. Lowest C_{exit} are from LP (iii), which is at the top-front position. For the inlet grille, the majority of C_{exit} are below LFL, although those arising from leak position (ii), at the top-rear position, exceeds LFL for the majority of the opening length.

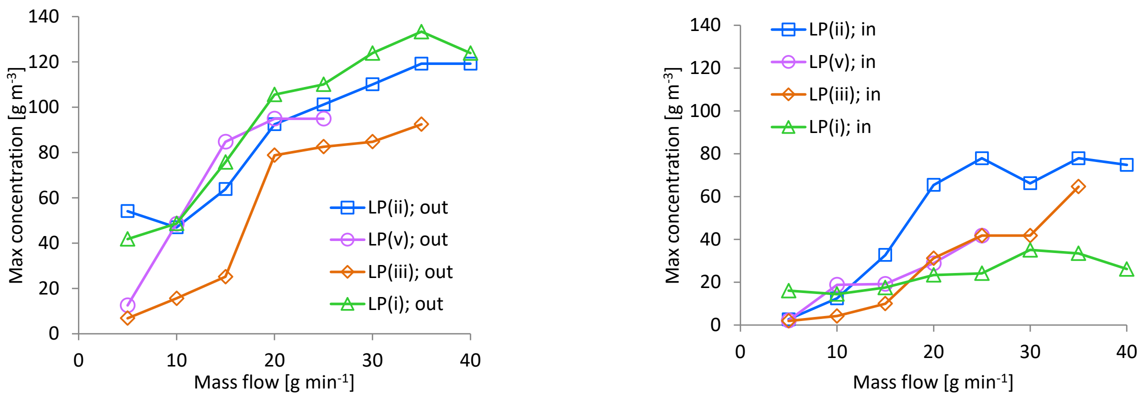

Figure 4: Maximum C_{exit} of R290 for the outlet (left) and inlet (right) of the small IDU for four different leak positions.

Measurements for the large IDU, using leak position (i) are shown in Figure 6. C_{exit} distribution is more even than with the small IDU; the profile of the 100 g min^{-1} is similar to the 10 g min^{-1} release, always tapering off towards the left end. The difference in behaviour between the small and large IDUs is likely due to the effect of the internal volume, where in the larger space the release momentum has a lesser influence over the distribution of the mixture. A similar trend was seen with the other leak positions.

In terms of the flow from the inlet grille, C_{exit} was lower than with the small IDU, about one quarter of the values, again due to the larger internal volume. Once there is sufficient volume of refrigerant vapour to act against the negative buoyancy of the mixture within the IDU, it will be forced up and out of the inlet; this was found computationally in previous work (Colbourne and Suen, 2014). However, the refrigerant mixture can only flow upwards from a proportion of the inlet opening area given that fresh air must be simultaneously drawn downwards through the opening to enable the mixture to flow from the outlet in the base. Crucially, this phenomenon should assist with the dilution process as it increases the area of the plume-air interface.

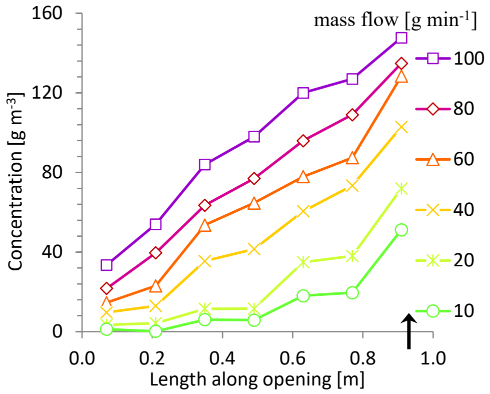

Figure 5: R290 concentrations at different mass flow rates along large IDU discharge opening length. Arrow on x-axis indicates position of release.

Experiments were carried out to investigate the effect of reducing the size of the IDU openings, where both the inlet grille and the outlet were partially blocked to 50% of the original opening areas. Results show that with a blocked outlet, C_{exit} was lower, at least for moderate release mass flows and leak position (i). For another release position (v), C_{exit} tended to be higher with the outlet blocked. Results for the inlet grille C_{exit} shows the blocking appeared to have an indistinguishable impact.

3.2 Variable enclosure

Results for the various VE configurations are detailed.

3.2.1 Sealed enclosure

To help understand the mixing process within an enclosure, tests were first carried out to observe mixture distribution whilst the VE was sealed. Releases were at three different mass flow rates and from three heights (indicated with arrows on the y-axis in Figure 7). Concentrations were measured at 0.1 m vertical increments at the centre of the VE. Results in Figure 7 show a marked difference between the vertical distributions particularly with release height.

For higher release positions, vertical distribution is effectively identical for all mass flow rates. With the release at 0.75 m, there is a slight departure from homogeneity. Concentrations falls off about four-fifths of the distance towards the top of the VE and the lower mass flow yields a higher concentration than higher mass flows from the release height through to the base. Releases close to the base result in the most pronounced differences, where concentrations at the VE floor are two to three times higher than with the other release heights. Also, the mixture layer height never extends above half the VE height.

Particularly significant is the impact of mass flow, where a smaller mass flow release tends to give much higher concentrations at the VE base, whereas the greater release mass flow rates results in lower concentrations. This is somewhat counter-intuitive to observations for releases in larger spaces (rooms) where higher mass flows lead to higher C_{floor}. In the present case, the greater momentum of the release relative to the VE internal volume generates more turbulent mixing than if it was in a large space; this phenomenon was also reported by Cleaver et al. (1994). Such an effect would be more pronounced in cases where the VE was smaller and/or the mass flow was higher.

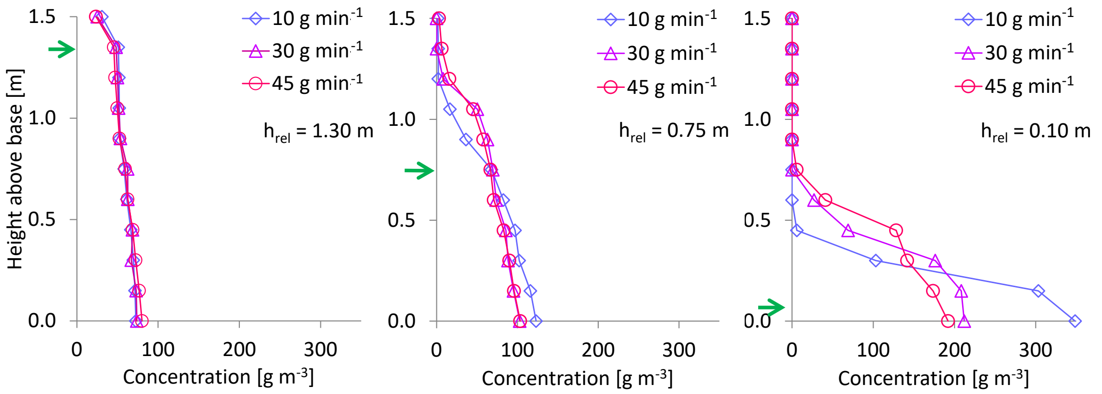

Figure 6: HCP within sealed VE at 135 g into a release from three different release heights and three different mass flow rates. Greater than 135 g, some sensors went beyond their measuring range.

Were there openings within the VE, it can be expected that for releases close to the VE base, C_{exit} would be much higher than with releases occurring from the mid-height or top. It may also be anticipated that for releases at higher positions, mass flow should not result in a significant variation in C_{exit} but the closer the release is towards the base, the more pronounced the variation would become.

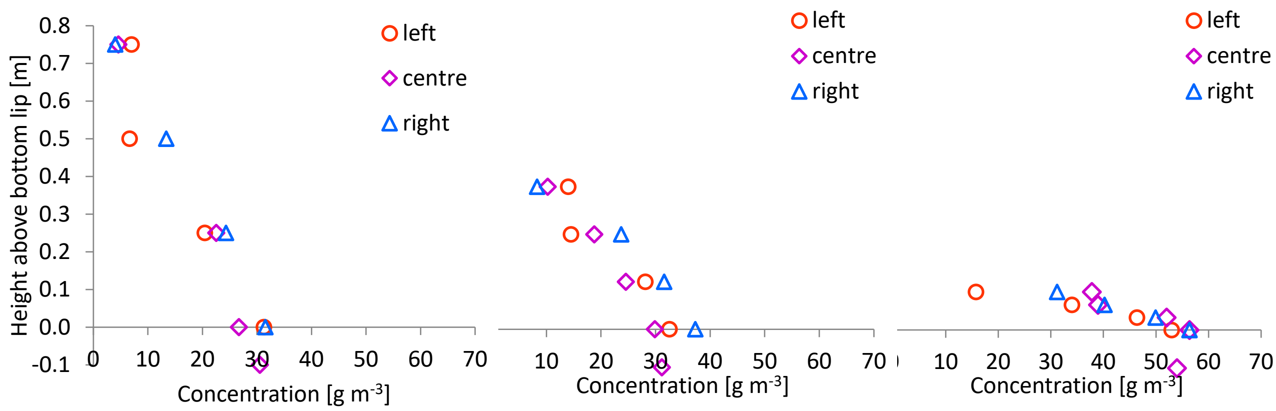

Figure 7: C_{exit} for VE across length and height of opening; configuration: length = 1.8 m, release height = 1.3 m above base, lower lip = 0.1 m from base, opening = 0.10 m (left), 0.38 m (centre) and 0.75 m (right), release location = rear centre, mass = 250 g, mass flow = 30 g min^{-1}, congestion: none.

3.2.2 Local distribution of C_{exit} from VE openings

C_{exit} data for three different opening sizes is given in Figure 8, including values for sensors to the left, centre and right of the opening (see Figure 1), all for four equally incremented positions on the vertical axis. An additional sensor was located at the centre of the VE on the base (i.e., below the “lip”); the concentration here is evidently always mirrored by the concentration at the centre of the VE opening lip. For C_{exit} across the openings, it can be seen that there is an approximately linear decline from the lower to the upper lip. At a given height and any horizontal positions, C_{exit} tend to be similar. The highest value of C_{exit} is always at the lower lip. In other tests, where the release occurred at heights below the upper lip of the opening, concentrations at the opening above the release height were at or close to zero. Otherwise, where release positions are higher, concentration at the lower part of the opening is usually about double that at the upper part of the opening. Nevertheless, the position just above the lower lip is the most important location to consider for C_{exit}. Smaller openings (0.10 m opening height) result in higher C_{exit} than the larger (0.38 m, 0.75 m) openings. This arises because smaller openings hinder the outflow of the mixture, thus enabling more time for backed-up mixture to become richer.

3.2.3 VE opening height and release height

Figure 9 provides data for tests involving incrementally lower release heights and a range of opening heights. Key observations are that higher mass flow tends to lead to slightly higher C_{exit}, except for the lowest release height (0.10 m), where the effect of mass flow seems indistinguishable. Nevertheless, lower release heights always give higher C_{exit}. Also, for a given release height, smaller opening heights tend to result in higher C_{exit}, although again, this is be contradicted for the lowest release height (0.1 m), where a 1.3 m opening has higher C_{exit} than 0.75 m; there is no obvious explanation for this.

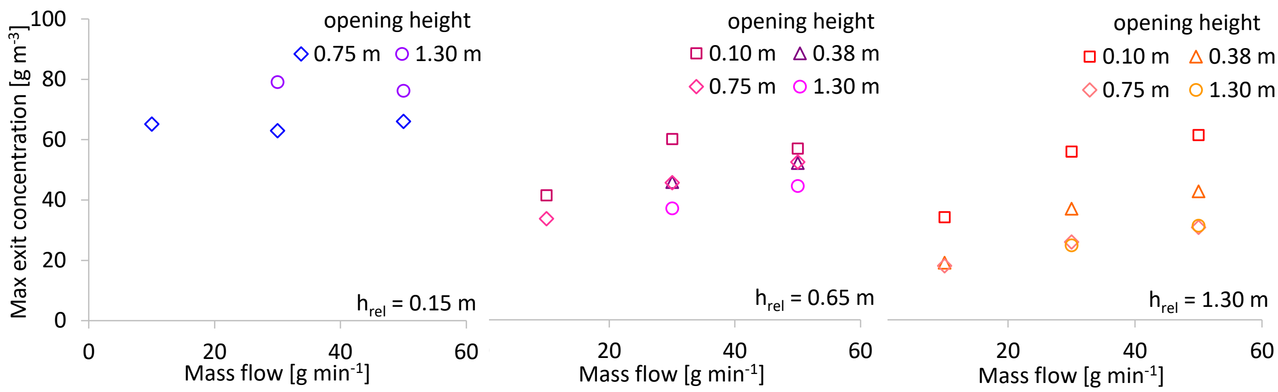

Figure 8: Maximum C_{exit} for VE; configuration: length = 1.8 m, release height = 0.15 m (left), 0.65 m (centre) and 1.30 m above base (right), lower lip = 0.10 m, release location = rear centre, mass = 250 g, congestion = none.

3.2.4 VE with two openings

Tests were carried out with a second opening towards the upper part of the VE. Figure 10 displays results (with congestion; see section 3.2.7) where a second opening of 0.10 m was introduced. This resulted in almost identical C_{exit} as with no second opening. Whilst it may be expected that a second upper opening should assist the outflow of the mixture and thus result in lower C_{exit}, since the lower opening was already quite large, significant fresh air is probably already induced into the plume so any additional openings are unlikely to contribute much. (The congestion evidently does not have a notable influence here.)

In contrast, Figure 11 shows results for the VE with a 0.10 m opening at the base and a second 0.10 m opening at 0.75 m. Here, C_{exit} is significantly lower when the second opening is present. This is likely due to the effect of the volume below of second opening being filled with a relatively dense mixture which is able to induce more air in and down from the upper second opening and thereby dilute the mixture further before it flows out of the lower opening.

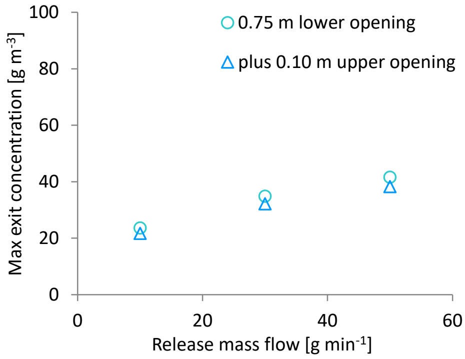

Figure 9: Effect of second upper opening on C_{exit} for VE; configuration: length = 1.8 m, release height = 1.3 m above base, release location = rear centre, opening = 0.75 m, second opening = 0.10 m at 1.3 m, mass = 250 g, congestion = yes.

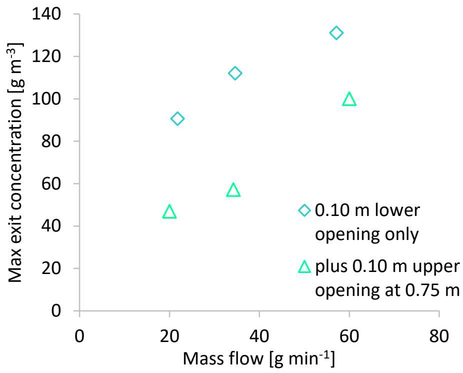

Figure 10: Averaged C_{exit} for VE; configuration: length = 0.45 m, VE height = 0.85 m, release height = 0.7 m above base, release location = rear centre, mass = 200 g, lower lip = none, lower opening height = 0.10 m, congestion = none.

3.2.5 Lip below VE opening

Whilst most tests were carried out with a lower "lip" present (rising 0.1 m above the VE base), some were conducted without. Figure 12 shows a major reduction in C_{exit} when no lip is present. This is believed to be due to the mixture flowing out of the VE unimpeded, as opposed to the lip holding back a proportion of the mixture which can be further enriched with refrigerant entering this "dead-space". Since the height of the opening was fixed, the "no lip" case effectively had a 25% larger opening area; whilst this enlargement of the opening will have provided some benefit to lowering C_{exit}, based on observation of other data (e.g., Figure 9) the majority of the effect is believed to be due to the absence of the lip.

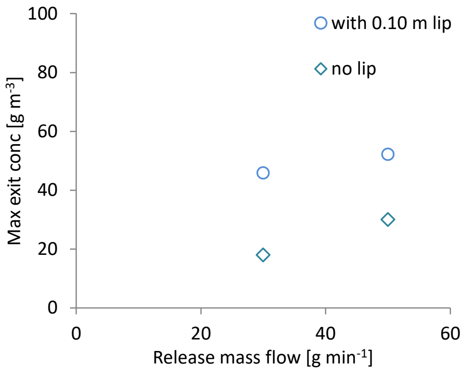

Figure 11: Effect of presence of lower lip on C_{exit} for VE; configuration: length = 1.8 m, release height = 0.65 m above base, release location = rear centre, opening = 0.38 m with lip and 0.48 with no lip, mass = 250 g, congestion = none.

3.2.6 Lateral position of release within VE

A comparison has been made for releases that occur at the far left (front view) of the VE against the centre position. The results can be seen in Figure 13, which includes 0.65 m and 1.30 m release heights. The data shows that irrespective of the release height, the maximum C_{exit} when using the far end release position is about double C_{exit} when using the central release position. This is expected since more of the plume perimeter is prevented from entraining fresh air as it flows out of the VE, as opposed to a centre release where it has a greater interface area to mix across.

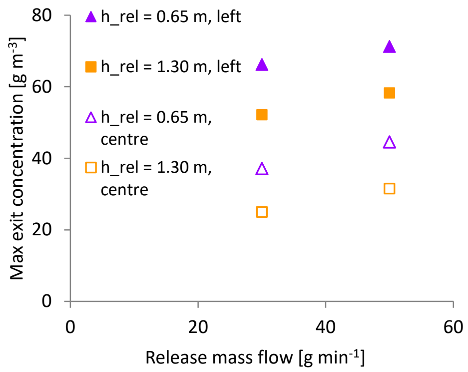

Figure 12: Maximum C_{exit} for VE, comparing releases from centre and releases at far left; configuration: length = 1.8 m, mass = 250 g, lower lip = 0.10 m, opening = 1.3 m, congestion = none.

3.2.7 VE internal congestion

Usually, RACHP enclosures will contain congestion: piping, heat exchangers, control boxes, wires and so on. The range of combinations is infinite, but an attempt was made to mimic such congestion expected in some RACHP equipment. This was in the form of finned-tube heat exchanger blocks, coils of copper pipe and several electrical boxes and wires, altogether extending across the VE base and rising to about 0.6 m. Figure 14 shows the influence of the congestion when a release is made from the top of the VE and with a 0.75 m opening. Here, there is a small but notable increase in C_{exit} due to the congestion, which is expected since it displaces the free volume available for dilution of the release. However, in the case of a lower release position, C_{exit} is substantially lower when (the same) congestion is present. Whilst this may not ordinarily be anticipated, it is likely that the congestion generates additional turbulence and thus mixing as the refrigerant plume passes through the congestion. A further observation is the near absence of increase in C_{exit} at higher mass flow rates.

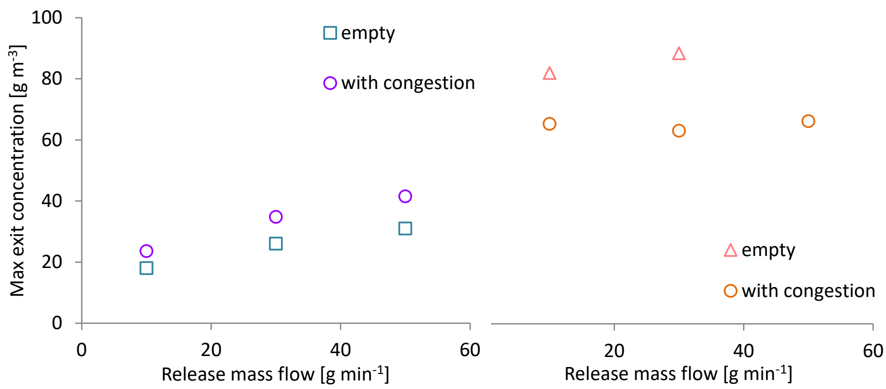

Figure 13: Effect of congestion in VE on C_{exit} for VE; configuration: length = 1.8 m, release height = 1.3 m (left) and release height = 0.15 m (right) above base, release location = rear centre, opening = 0.75 m, mass = 250 g.

3.2.8 VE base area

Lastly, C_{exit} has been compared for the different sized VEs expressed in terms of base area; 0.45 m × 0.6 m, 0.9 m × 0.6 m and 1.8 m × 0.6 m. Figure 15 shows how C_{exit} is smaller with larger VE base areas. This can be attributed to the same phenomenon as when a release occurs in a room, where the mixture disperses more effectively over a larger floor area. This was previously observed when comparing large and small CR cabinets (Colbourne and Suen, 2016). In Figure 15, whilst a lower release height leads to greater C_{exit}, the rate at which C_{exit} diminishes with larger base area is greater than with the higher release height.

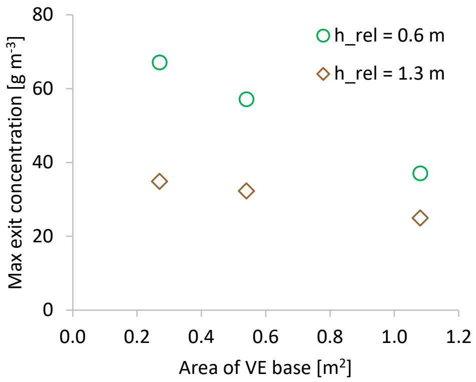

Figure 14: Maximum C_{exit} for different size of VE base; configuration: mass = 150 g, mass flow = 30 g min^{-1}, lower lip = 0.10 m, opening = 1.3 m, congestion = none.

4 CONCLUSIONS

Experiments have been carried out in order to characterise C_{exit} arising from a simulated leak of R290 from within RACHP equipment enclosures. The work focussed on two enclosure types: AC IDUs and other RACHP enclosures, by means of a VE. It links to other studies (e.g., Colbourne and Suen, 2021) which identified that the exiting concentration has a strong influence on C_{floor} (where the equipment is located). It therefore provides a better understanding of how to control C_{exit} to help in the design of safer equipment for use with flammable refrigerants.

For AC IDUs:

- C_{exit} profile is different for "small" and "large" IDUs; the smaller IDU exhibited wider variations across the outlet as mass flow changes, whereas the larger IDU gave a fairly consistent C_{exit} profile across openings. This is likely related to the momentum of the release in relation to the available internal free volume.
- Smaller IDUs tend to have higher C_{exit} from the inlet grille (for the same mass flow) due to the smaller volume filling with vapour sooner and thus "overflowing".
- Whilst the return bend segment of the IDU has a small volume relative to the overall IDU, the release position and direction within that segment has a strong influence on C_{exit}, especially at the outlet opening.
- Changing the size of the outlet openings can have a notable effect on C_{exit}, but whether it is a positive or negative effect is dependent upon the leak position.

It is unlikely that changes can be made to IDU design to guarantee substantially lower C_{exit} (other than physical volume), that would not impact on the thermal performance and efficiency. For instance, providing channels from the return-bend segments into the main part of the IDU could help reduce C_{exit}, but this could diminish airflow across the heat exchanger during fan operation.

For the VE:

- Observations in mixture distribution for the sealed enclosure were not always reflected in the measurements of C_{exit}. For instance, different mass flow in releases at higher positions did not result in corresponding changes in C_{exit} and smaller mass flows at lower positions did not lead to higher C_{exit}. These may be attributed to the dynamic influence of continual outflow of the mixture, whereas steady conditions are different to those of a sealed enclosure.
- Across all tests, C_{exit} was between around one-third of the LFL and almost eight times the LFL and this will be reflected in C_{floor}. This indicates the potential usefulness of configuring enclosures to achieve as lower C_{exit} as possible to minimise flammable mixtures within the room.

- For a given opening, the highest concentration tends to be at the lower lip, declining linearly towards the upper lip of the opening or the release position, whichever is the lower height.
- Depending upon the release conditions and the geometry of any lower opening, a second upper opening can greatly reduce C_{exit}, particularly when the enclosure is smaller.
- Generally, the larger the opening, the lower the C_{exit}, provided the release occurs from a height greater than the top lip of the opening.
- Releases from the rear centre of the VE give lower C_{exit} compared to releases from the rear corners. This is due to the smaller area available for the refrigerant to entrain air before the flow reaches the opening.
- Congestion within the VE can be beneficial or detrimental for lowering C_{exit}, largely depending upon the height of the release. Where the release occurred above the congestion, C_{exit} was about 25% higher than a release occurring within the congestion. However, a single (random) arrangement for congestion was used and other arrangements may yield different findings.
- Presence of a bottom "lip" of 0.1 m increases C_{exit} by up to 50% in the cases studied, which occurs due to the lip obstructing the outflow of released refrigerant, allowing it to be enriched.
- Smaller VE (in terms of base area) lead to higher C_{exit}, whilst a larger VE provides greater area across which the release can mix before exiting.

Whilst the tests described above employed enclosures whose base was well above floor level; it is expected that for cases where the base is at or is close to the floor C_{exit} would be higher since the outflowing mixture would persist locally. The extent of increase in C_{exit} would in addition be dependent upon the space floor area.

These experiments provide a good indication as to constructional changes that may be implemented into the design of RACHP enclosures to minimise C_{exit} and thus C_{floor}. Broadly, refrigerant-containing parts – or at least connections/joints – should be limited as far as possible to the upper parts of the enclosure, lower openings should be as large as possible and if the volume of the enclosure is relatively small, a second upper opening can provide benefit.

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