

# ASSESSMENT OF FACTORS AFFECTING R290 CONCENTRATIONS ARISING FROM LEAKS IN ROOM AIR CONDITIONERS

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## ABSTRACT

Currently R290 is used to a small extent in room air conditioners, such as split, portable and window types. Products are limited to relatively small cooling capacities due to refrigerant charge sizes being constrained to around 300 – 400 g, on account of maximum charge formulae within standards IEC 60335-2-40, ISO 5149-1 and EN 378-1. This is especially challenging in warm countries where the cooling load is greater and charge sizes need to be larger. Work is underway to improve maximum charge size determination methods for a given room size. As a contribution to this on going process, further research has been carried out to understand the factors that affect development of flammable concentrations within rooms in event of a leak. Parameters related to the characteristics of room air conditioners and installations have been investigated experimentally by measuring R290 concentrations from releases and selected findings are described.

Keywords: Hydrocarbon refrigerant, R290, flammable, leakage, concentration, safety standards, air conditioner

## 1 INTRODUCTION

There is a need to enable larger quantities of R290 within room air conditioning systems (RACS) for a given room size than safety standards currently permit, if consumption and emissions of HFCs are to be reduced. In the event of a refrigerant leak from the indoor components of a RACS the conditions should be such that a substantial volume of flammable refrigerant-air mixture does not occur, which could otherwise lead to injury and/or damage if ignited. Charge size limits for hydrocarbons such as R290 in RACS are laid out in several safety standards including EN 378-1, ISO 5149-1 and IEC 60335-2-40. Determination of limits is partly through formulae intended to preclude the formation of large volumes of a flammable mixture. These have led to significant constraints for applicability of R290 as exemplified in Figure 1. Here, RACS of various efficiency levels from the Eurovent database are plotted against charge size, adjusted for R290-equivalent by using the ratio of R290 to the design refrigerant liquid densities at 45°C (GIZ, 2011). Charge limits for R290 are superimposed for three different classes of RACS indoor units (IDU), assuming a nominal cooling load of 150 W m<sup>-2</sup>. For R290 to be viable, the charge limit lines should be above the data-points so that the R290-charged RACS would be able to be installed in rooms of specific dimensions. This implies that current charge limits obstruct the selection of R290, especially for higher efficiency models; the consequence is even starker for applications with higher cooling loads. This observation is echoed in a recent report on significant barriers to the uptake of flammable refrigerants by the European Commission (2016).

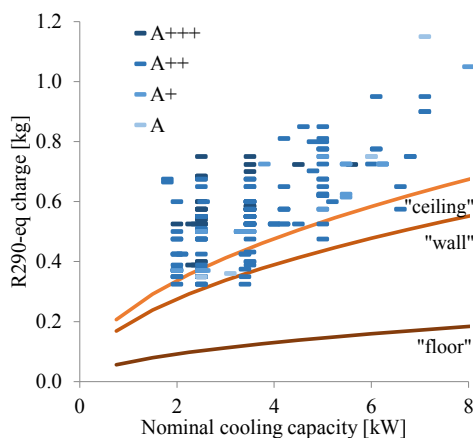


Figure 1: Comparison of RACS charge sizes (converted to R290-eq.) and current charge limits for a 150 W/m<sup>2</sup> cooling load

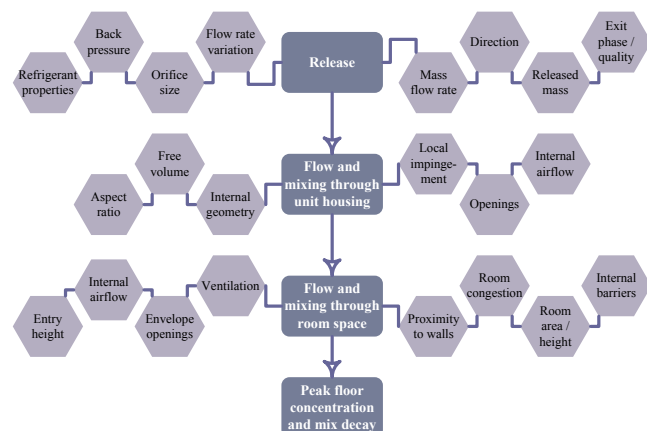


Figure 2: Main process from refrigerant release to peak concentration and eventual decay, identifying key influencing variables

The foundations and validity of the current formulae have frequently been questioned (e.g., Corberan et. al, 2008; Li, 2014; Vonsild, 2014; Zhang et. al., 2013) and thus highlighting the need to re-examine the previous approach and assumptions with respect to practical application. To this end, the three main stages that lead up to the formation of a peak floor concentration and the eventual decay of the mixture are identified in Figure 2, along with some key influencing variables that broadly apply to each of those stages. A change in any one of these variables could substantially affect the peak concentration. The implications of some of the variables have been addressed within the wider literature, for example, direction of a release and room ventilation. For those that have not, more practical evidence for the significance of their influence is useful for helping develop more inclusive methods for determining charge size limits. Accordingly the purpose of this present work is to examine the effect of important variables on maximum concentrations and thus maximum charge size determination, and of those to recommend which should be accounted for and how they may be incorporated in future measures and safety standards.

Concerning the measurements presented here, testing was carried out in a 14 m<sup>2</sup> laboratory. Refrigerant-grade R290 was used and supplied through hoses to a suitably sized release orifice or capillary tube to achieve choked flow. Flow meters and controllers employed include Omega FMA and Alicat MCR with cross-checking of cylinder weight. Sensors include Honeywell Micropel SR-W-MP75C, IR 2302B1082 and PID S4-W04, with regulator factory calibration and cross-calibration at the start and end of each day of measurements. RACS equipment included three wall and one floor type IDU, all of 8 kW nominal capacity, except for one 2.5 kW wall type.

## 2 RELEASE CONDITIONS

### 2.1 Leak mass flow rate

Assumed refrigerant leakage mass flow rate is perhaps the most critical of all parameters affecting the determination of charge limits. Historically the assumption used the entire charge being released within four minutes. The basis of this assumption is reported to be a measurement carried out according to a test described in IEC 60335-2-24 for determining the mass flow rate for a leak simulation test of domestic refrigerators, typically using R600a (Kataoka et al, 2000). This test passed 150 g of R744 through the specified capillary tube and was found to take four minutes and hence a four-minute leak time was established. Such an approach may be considered entirely invalid since the thermodynamic properties of R744 are completely different from R600a, R290 or indeed any of the other flammable refrigerants. Figure 3 compares the choked flow mass flux of R744 and selected flammable refrigerants. R744 exhibits a mass flux about 15 times that of R290 and over 40 times that of R600a, implying that the time for the latter two refrigerants to leak out would take substantially more time, as reflected within IEC 60335-2-24 that refers to 80% the refrigerant charge being release over one hour. Conversely, if a legitimate worst case leak rate were to be applied then values corresponding to charge mass divided by compressor mass flow rate should be adopted, as presented in Figure 4 for different flammable refrigerants. Here, the leak time ranges from ½ to 1½ minutes and there is a wide variation amongst different refrigerants.

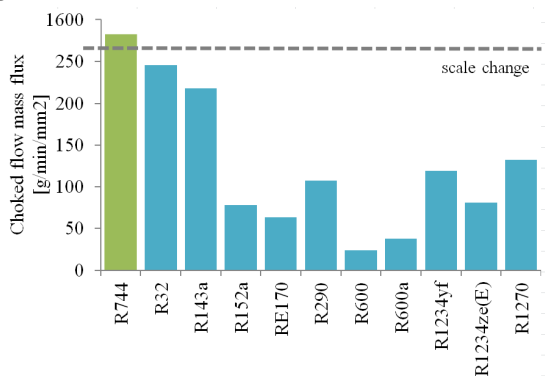


Figure 3: Comparison of mass flux at choked flow at saturated vapour pressure corresponding to 25°C for various flammable refrigerants and R744

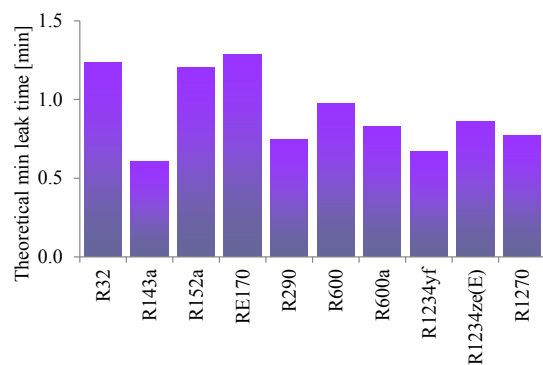


Figure 4: Comparison of theoretical minimum leak time for various flammable refrigerants in RACS

Critically, leak time or leak mass flow rate is rather sensitive to the refrigerant type as well as internal conditions (i.e. saturation temperature). They are also contingent upon the leak mechanism and the leak hole size. Thus adopting a single fixed leak time (such as 4 minutes) to cover all refrigerants and conditions is far

from appropriate, especially given the strong dependency of maximum charge to this assumption. Choice of leak time or mass flow rate must be carefully considered with respect to the refrigerant type, design and construction of the RACS as well as empirical leak data. Practical mass flow rates from real systems have been presented previously (e.g., Colbourne et al, 2013; Colbourne and Suen, 2016) along with approximation of actual potential leak rates based on leak hole sizes from field surveys. Applying those leak hole sizes to the critical mass flux of the various flammable refrigerants, the “expected” maximum leak rate is in the order of 5 to 10 g/min – a factor of about 100 times lower than if the fastest leak times would be used. Adoption of these expected leak rates would lead to maximum charge limits in the order of two to five times greater than those currently permitted and the majority of RACS within Figure 1 would be captured by the charge limits.

Examples of the influence of leak mass flow rate and released mass on developed concentrations (at the time of cessation of the release) when the fan is off are given in Figure 5 for an IDU at 0.5 m, 1.0 m and 1.5 m. For these measurements, a release was initiated and concentration was measured at sampling points at multiple heights at the centre of the room. Floor level sampling points were monitored once they approached LFL of R290 the flow terminated and released mass recorded. Figure 5 shows that as mass flow rate diminishes more refrigerant accumulates in the space between the horizontal plane of the IDU and the floor, allowing a greater mass of refrigerant to be released before LFL across the floor is reached. For the IDUs at higher positions, there is a more clearly defined homogenous layer extending some distance above the floor, before rapidly transitioning to much lower concentrations closer to the IDU height. Also for the higher IDU the release mass flow rate becomes as important as the installation height in determining maximum charge. Figure 6 compiles the data for all three IDU heights and mass flow rates. As the IDU is installed at higher levels, a greater charge can be released without reaching LFL at the floor and benefits more from a longer release time.

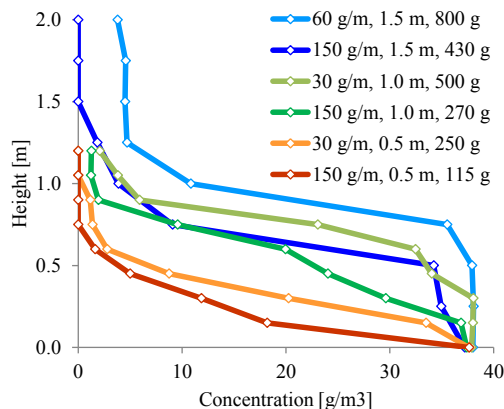


Figure 5: Effect of various release mass flow rate for IDU at 0.5 m, 1.0 m and 1.5 m

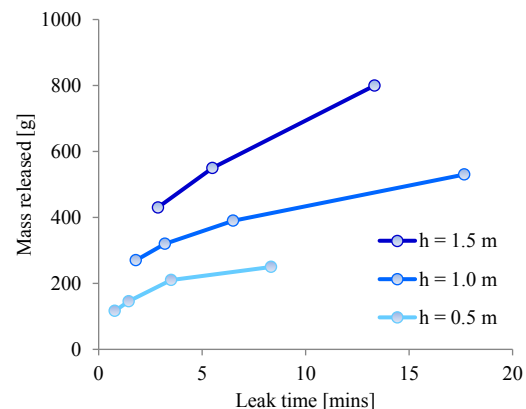


Figure 6: Effect of release time and IDU height on released mass upon reaching LFL at floor

## 2.2 Variable release rate

Both the tests involving concentrations measurements prescribed within safety standards and other studies (e.g., Colbourne and Suen, 2003; Kataoka et al, 2000, Li, 2014; Zhang et. al., 2013) employ a constant release mass flow rate. This assumption unlikely represents a “realistic” leak scenario, i.e., which may increase over time due to gradual enlargement of orifice size or which may diminish over time as system charge is depleted. On one hand, leak holes take time to develop; as the orifice area increases over time so will the mass flow (assuming a steady back pressure). Corrosion leaks evolve in the order of weeks, months or years (inferring that system charge will have been depleted at extremely small rates – <1 g/min – that do not pose safety concerns) whereas leaks due to fatigue cracking can develop in minutes; Figure 7 illustrates an example case for advancing leak rate from severe fatigue cracking, based on a system with 1000 g R290 at 25°C and a compressor rotating at 2900 rpm, using a simple model based on Fleck (1984). On the other, as a leak progresses boiling of the liquid refrigerant depress the backpressure so mass flow declines (Colbourne and Liu, 2012). An example of decaying leak rate due to an instantaneous 5 mm<sup>2</sup> hole at condenser outlet on an R410A window AC is shown in Figure 8, where the system had been off for 24 hours and also moments after the system had been continuously operating. In the former, a gradual decrease can be noted. In the latter case, the hot compressor imposes a higher saturated vapour pressure but prevents significant absorption of refrigerant in the oil, resulting in a higher initial flow rate and also a much steeper decay. Time for large hole to develop can be faster than time for charge to deplete with such a large hole – so it is probably reasonable to assume an instantaneous hole in parts of the system that are vulnerable to fatigue cracking. Depending on the particular circumstances, the variation in mass flow over time will consist of an increase as the hole size

develops and eventually a decay as the system pressure declines, with a middle period of steady release for which the duration depends upon hole size and pressure.

Overall, two cases may be identified. For “small and medium” leaks, it is reasonable to assume a fairly constant leak rate where the middle period accounts for the majority of the mass leaked. For “large” leaks, the decay period (e.g., Figure 8) is dominant as the leak hole must have developed due to mechanisms that cause near-instantaneous holes (such as external impact or fatigue cracking). Such flow rate profiles may lead to different maximum concentrations following a release of a certain mass.

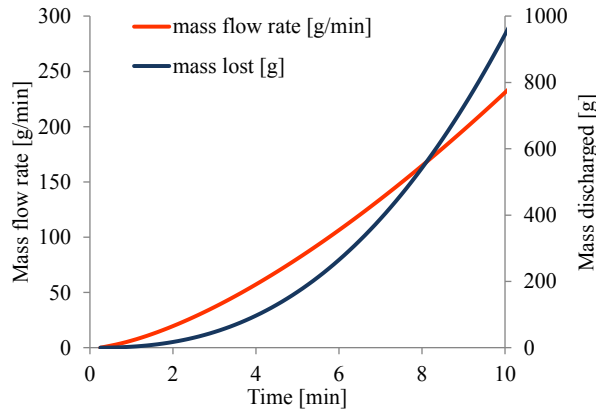


Figure 7: Approximated leak mass flow rate of R290 at the initial period of fatigue crack in pipe

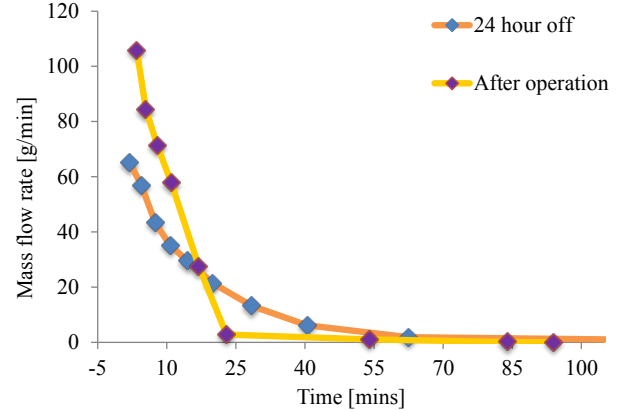


Figure 8: Measured instantaneous release mass flow rates from a window AC

Figure 9 and Figure 10 show floor concentrations with IDU fan off, arising from a rising release mass flow profile (broadly mimicking that in Figure 7) and a decaying release profile (as in Figure 8), respectively, and Figure 11 is a reference case using a constant flow rate. All tests involved a 300 g release of R290 over ten minutes from IDU right hand return bends at a height of 1.0 m. Whilst the test in Figure 11 used a constant 30 g/min, the variable mass flow tests used six increments of 50 g at mass flow rates ranging between 10 g/min and 100 g/min in 15 g/min graduations.

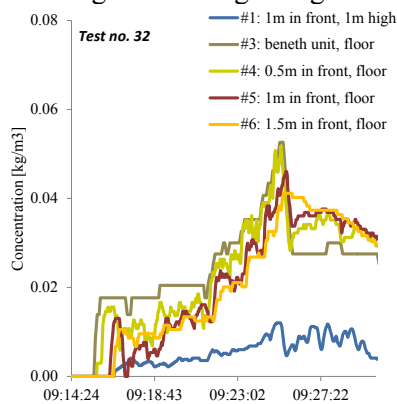


Figure 9: Rising release rate averaging 30 g/min for 10 mins

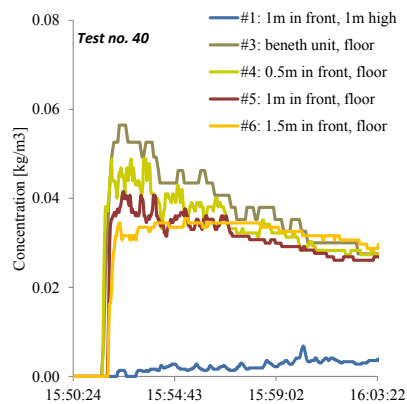


Figure 10: Decaying release rate averaging 30 g/min for 10 mins

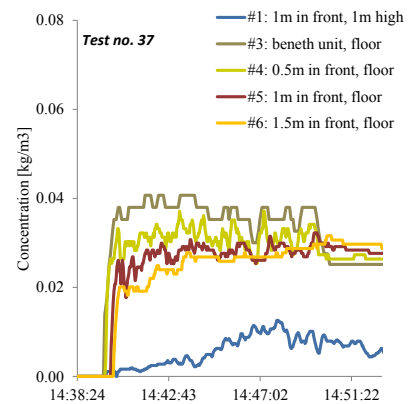


Figure 11: Constant release rate of 30 g/min for 10 mins

Results show three substantially differing concentration profiles. Rising leak rate shows gradual concentration rise until the maximum value. Decaying leak produces a significant initial “jump”, which for most sampling points represents the peak concentrations for the entire test. With both the variable leak rates, average floor concentration changes significantly over the test duration, compared to a relatively minor change with the fixed leak rate. Overall, the two variable rate cases produce a substantially higher maximum concentration than the fixed leak rate, although whilst the peak maximum is about the same for both yet the average maximum value for the decaying release rate is 10% lower than that of the rising release rate. This is due to the short period where the mass flow rate is several times higher than the constant 30 g/min case. Particularly for the decaying leak, the initially high leak rate seems to dominate the subsequent floor concentration. Concentration at 1 m above floor level supports this, as it is significantly lower than in the other two cases, where the higher mass flow occurring latterly seems to shunt more of the mixture from the floor upwards.

### 2.3 Release phase

Hitherto, most contributions to this subject have used vapour only releases. Primarily this is because the experimental procedure is much easier and mass flow can be controlled more consistently. Furthermore – at least for smaller RACS, “real” simulated leaks (i.e., from systems) have found that even if a release is created from a liquid or two-phase pipe, there is usually intermittent or cyclic “spitting” of liquid for the first tenth of the release duration and is then followed by continuous vapour.

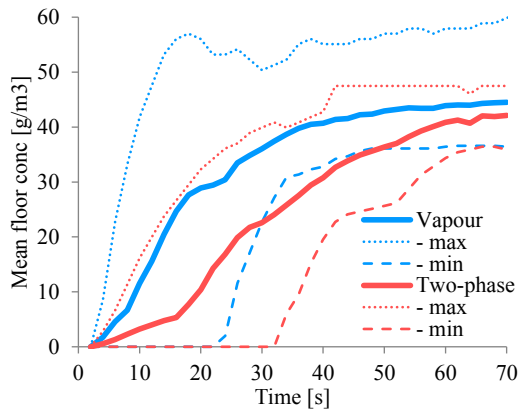


Figure 12: Comparison of average, maximum and minimum floor concentrations for vapour and two-phase release of 100 g/min from IDU at 1.0 m

initially, concentration development for the two-phase release tends to be more gradual and the final concentration is also marginally lower. This more gradual rise is likely due to the delay caused by the vaporisation of the liquid droplets. Average maximum concentration after a 120 g release is approximately 10% higher for the vapour-only release. In addition the variation across floor concentrations is substantially wider for vapour releases ( $\pm 11 \text{ g/m}^3$ ) than for the two-phase release ( $\pm 6 \text{ g/m}^3$ ). Overall two-phase releases seem to lead to more homogenous distribution, which is probably due to the additional convection generated by the flashing liquid and additional thermal gradients.

A number of tests were carried out in order to discern any significant difference between vapour only and two-phase where R290 was released at 100 g/min at the right hand return bends of an IDU positioned 1 m above the floor when IDU fan is off. Sampling points were located on the floor at 1 m increments away from the IDU. Refrigerant cylinder was cooled to about  $0^\circ\text{C}$ , the supply hose insulated and then cooled with liquid R290 to avoid pre-boiling of the liquid at the start of the test. It is estimated that the vapour fraction of the two-phase release during the test was 0.25.

Example results for averaged floor concentration are shown in Figure 12. Whilst the vapour release tends to create faster rate of concentration rise

## 3 UNIT HOUSING

### 3.1 Use of diffuser

Under quiescent conditions, entrainment of surrounding air into a jet or plume of dense refrigerant is strongly influenced by its momentum; a high velocity jet into free air can easily result in near-homogenous mixing within the space whereas a low velocity descending negatively buoyant plume will often establish a stratified layer on the floor (e.g., Webber et al., 2011). Recognising that almost all refrigerant-containing parts of RACS are encased to some extent, it is reasonable to assume that any leak will impinge upon an immediate surface, thus reducing momentum from the jet and leading to a plume sinking from the IDU. Development of the formula for maximum refrigerant charge within IEC 60335-2-40 employed a so-called “diffuser” device in an attempt to mimic this situation, where the release is fed through a sort of packed inverted funnel such that the exit velocity is in the order of millimetres per second (Kataoka et al, 2000).

Whether a diffuser suitably mimics a release from an IDU was examined by simulating releases from both a diffuser device and from within an IDU and comparing floor concentrations. Each test presented here used 310 g released at a constant 60 g/min via a 2 mm diameter capillary tube at various positions and orientations within the IDU (Figure 13), which was fixed 1.5 m above the floor and sampling points were positioned across the floor. Results for maximum mean floor concentration and “peak” concentration are given in Figure 14. Highest concentration amongst all of the releases originating from the base of the IDU right hand return bends. Crucially this is a fraction of the measured concentration using the diffuser. Values for all positions at the left or right return bends are comparable, whereas releases within the coil block and from the connector fitting are considerably lower. Implication is that the available internal volume within which the release can freely pre-mix before sinking out of the IDU has a strong effect on floor concentrations.



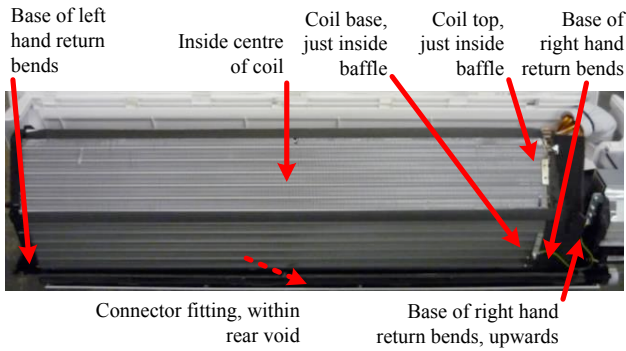


Figure 13: Comparison of theoretical minimum leak time for various flammable refrigerants

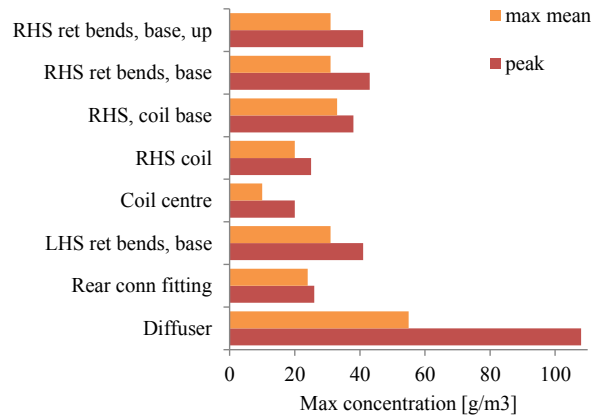


Figure 14: Comparing peak concentrations due to releases from positions within IDU and diffuser

Further tests were carried out to broaden the assessment of differences between use of a diffuser and a real IDU (with fan off), by varying release mass flow rate and release height but maintaining a fixed release position within the IDU at the base of the right hand return bends (since it led to the highest floor concentration). Figure 15 presents results for the diffuser only, with the outlet positioned at 1.0 m and 1.8 m, and results for the IDU at the same heights in Figure 16. Findings from Figure 14 are replicated, where across all release heights and mass flow rates, the diffuser produces approximately double the peak and maximum mean concentration than with the IDU. The wider difference between peak and max mean values for the diffuser is due to the axial variation throughout the plume not having had sufficient decent distance to become more homogenised. This is not seen with the IDU release because homogenisation has already occurred through mixing within the enclosure.

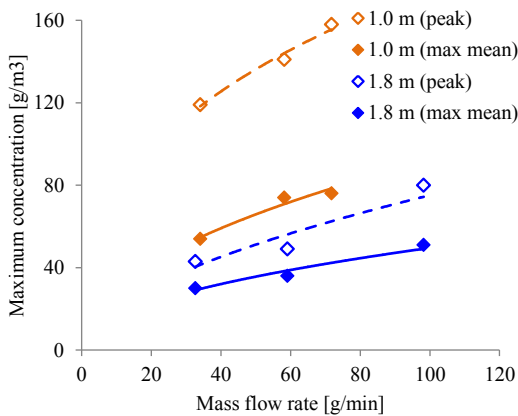


Figure 15: Floor concentrations arising from diffuser releases

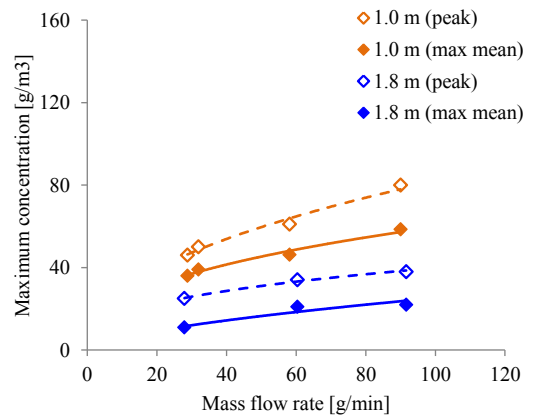


Figure 16: Floor concentrations arising from releases at IDU coil return bends

### 3.2 Outflow concentrations

Further insight to the condition of the mixture exiting the IDU is useful as it helps clarify the differences between releases from diffusers and IDUs. An IDU was prepared with several frusta sealed to the open discharge grille, extending downwards for 0.5 m so as to channel all refrigerant-air mixture that pours from the base. Addition casing was attached around the perimeter of the inlet grille to collect any mixture spilling out of the top opening. Sampling points were positioned at the base of each channel of the frusta. R290 was released at different constant mass flow rates from the base of the right hand return bends (with fan off).

Average concentrations for each of the mass flow rates at each successive linear location along the discharge opening are given in Figure 17, with the release position indicated by an arrow. (Corresponding graph for the inlet opening not shown.) Figure 18 summarises those results and also for the mixture flowing out of the top inlet opening. Local data in Figure 17 shows a significantly higher proportion of the mixture exiting closer to the release point than at the opposite end of the IDU (about 40 times higher at 10 g/min) but as release rate increases, a more even distribution develops (e.g., only four times higher at 100 g/min). It may also be noted that the direction of the release also has an influence on this distribution. For example, other tests (not shown) with a different release orientation (but same location) resulted in the pattern in Figure 17 being reversed,

where highest values occurred at the opposite end of the IDU; the momentum of the jet “pushed” the refrigerant away from the immediate openings. As seen in Figure 18, not-insignificant quantities of refrigerant migrate out of the top (inlet) of the IDU, once there is sufficient volume of refrigerant vapour to act against the negative buoyancy of the mixture within the IDU; this observation was found computationally in previous work (Colbourne and Suen, 2014). Refrigerant mixture must only be flowing upwards from a proportion of the inlet opening area given that fresh air must be simultaneously drawn downwards through the opening it to enable the mixture to flow from the base (exit). Importantly, this phenomenon should assist with the dilution mixing process as it increases the area of the plume-air interface. Figure 18 also includes data for a 2.5 kW IDU, which has an internal volume one-third of the 8 kW. Concentration at the 2.5 kW IDU outlet (for the same mass flow) is notably lower than the 8 kW yet two to three times higher at the inlet (top) opening. A higher ratio of R290 volume flow to internal enclosure volume means more gas is forced out of the top; this lower overall exiting concentration infers reduced values at floor (with same mass flow).

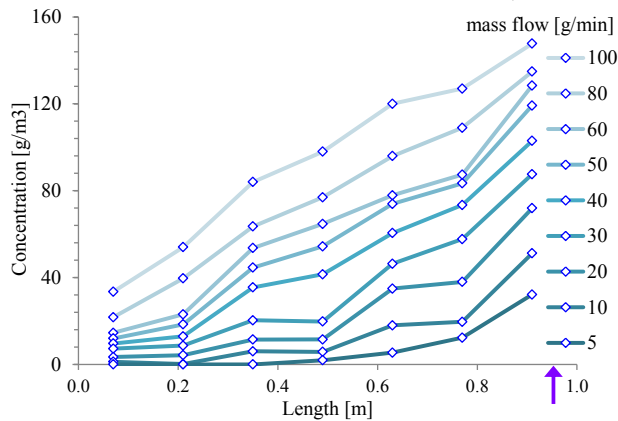


Figure 17: R290 concentrations at different mass flow rates along IDU discharge opening length

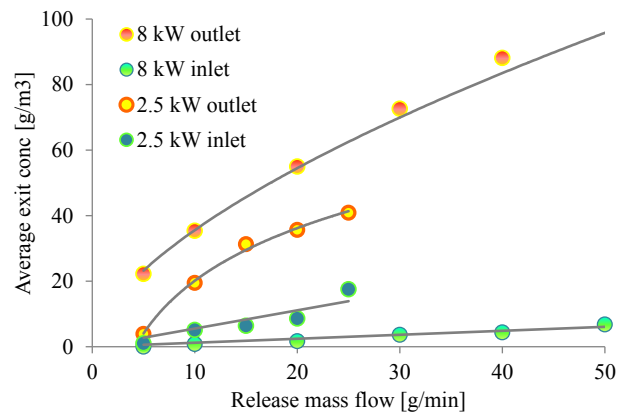


Figure 18: Average concentration of R290 exiting IDU

### 3.3 Unit housing geometry

To help understand the effect of IDU housing geometry on developed concentrations, a mock IDU was constructed to enable certain characteristics to be varied. External dimensions were 0.54 m long and 0.26 m × 0.26 m cross-section, with options to vary opening areas at the top, base and side, internal enclosure length and internal free volume. R290 was injected horizontally into a small compartment to mimic the void associated with coil return bends, the volume and baffle area of which was also changeable. Throughout the mass flow rate was fixed at 70 g/min with 200 g and with the enclosure fixed at 1.0 m above the floor and against a wall panel. No forced airflow was applied.

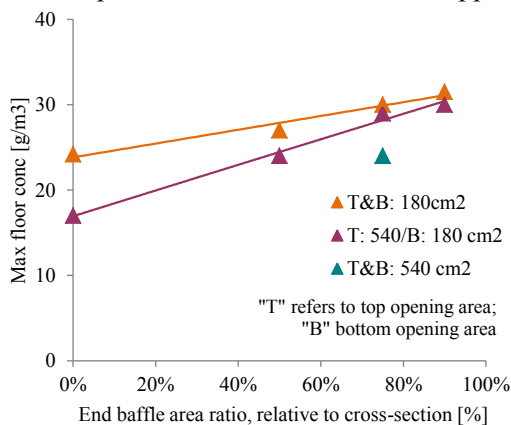


Figure 19: Effect of baffle area and top and base opening area on maximum floor concentration

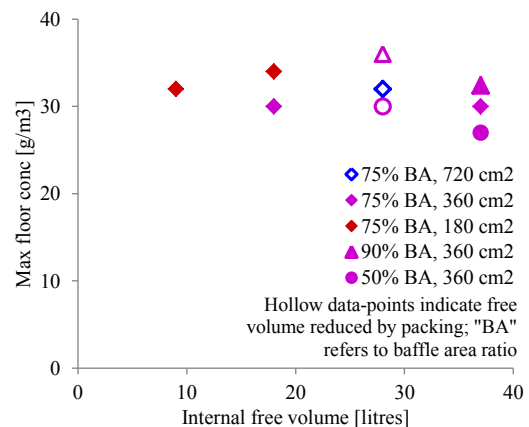


Figure 20: Effect of internal free volume and total opening area on maximum floor concentration

Figure 19 compares maximum concentration moments after cessation of the release across a range of end baffle to cross-sectional area ratios; a high ratio means that the end section is almost closed off and so restricts migration of the refrigerant to the rest of the enclosure volume. Generally, the more open the path is between the void containing the release and the remaining part of the enclosure, the better the pre-mixing appears to be based on lower floor concentration. Three sets are shown according to the area of the top (T) and bottom (B)

openings; again, more dilution of the initial release occurs with larger openings. The influence of IDU free volume is presented in Figure 20, along with baffle area ratio and opening area (equally divided between top and bottom). For fixed baffle area ratio and opening area, the effect of internal free volume on maximum concentration appears negligible. However, when the free volume is reduced by means of internal packing (whilst enclosure volume is fixed) there is a notable increase in maximum concentration. Whether or not free volume is displaced with internal packing, both reduced baffle area ratio and increased opening area help reduce floor concentrations.

## 4 ROOM SPACE

### 4.1 IDU location with respect to wall

Concentration measurements are typically carried out in empty rooms, with IDUs positioned centrally against one wall so as to be as symmetrical as possible and improve repeatability. In theory, a more pessimistic release position should be the corner of the room, inferring that the available surface area for plume entrainment would initially be reduced and thus higher concentrations. Measurements were made using a release of 440 g at 100 g/min from the right hand return bends of an IDU at 1.0 m above the floor and positioned at three alternate locations. Figure 21 compares concentrations at cessation of the release for the same unit being positioned at the mid-point of a “short” wall (3.3 m), mid-point of a “long” wall (4.6 m) and in the corner (against the long wall). There is variation of about  $\pm 10\%$  of the average maximum floor concentrations across the three positions, with the IDU at the corner leading to highest values and the short wall position giving the lowest. For the corner position, the plume spread at floor level is more constrained thus limiting dilution, whereas for the short wall position, the plume is given the longest flow path, likely to aid dilution. Having said this, consideration must also be given to the fixed position of the gas sensors and in relation to the local distribution of the mixture.

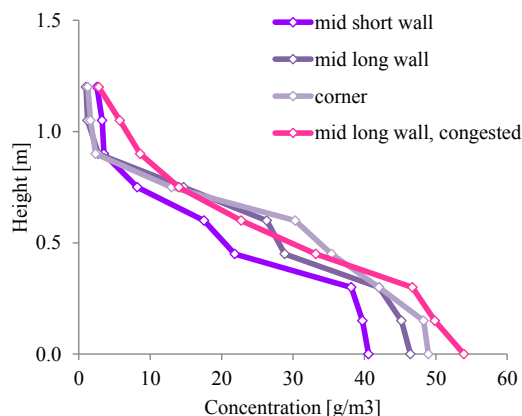


Figure 21: Effect of IDU position and congestion

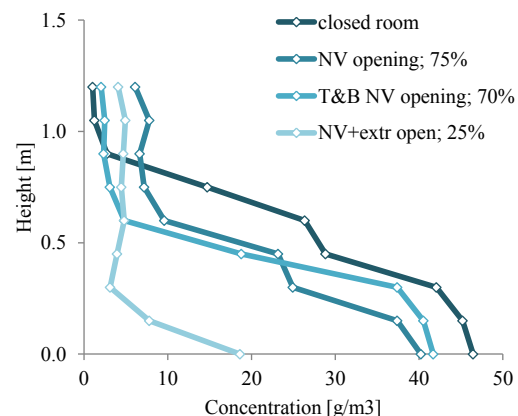


Figure 22: Effect of natural ventilation

### 4.2 Room congestion

Room concentration tests normally employ empty rooms to enable reproducible measurements. Since most rooms are seldom empty it is appropriate to consider the effects of congestion within a space. With respect to the dispersion of releases there are three “forms” of congestion: one which comprises large obstructions within the space, another where larger obstructions are present within the path of descent of the plume and a third which consists of many small items. Distributed large obstructions tend to have a detrimental effect on mixing since they not only displace free volume but also act as barriers inhibiting the spread of a plume. Where obstructions are present within close proximity of a release from above floor level, previous work with condensing units (Colbourne and Suen, 2016) found that despite displacing free volume, they help to enhance dispersion by means of forcing the plume to have a larger interface area across which more entrainment occurs. Theoretically, presence of many smaller objects can also help augment mixing since they can generate turbulence within a flowing mixture; investigating this case experimentally is potentially complicated and laborious given the infinite number of permutations. In order to attain a better insight of the implications of “extreme” congestion, a test was carried out by filling the room with as much clutter as practicable; tables, chairs, cupboards, boxes, cylinders, ladders, test rigs, etc., with the majority of objects exceeding the height of the IDU and covering 45% of the room floor area. Concentrations for this test are given in Figure 21 so that they can be gauged against results for the empty room. Peak floor concentration is between 10% and 30% higher than the empty room cases and showing a much more linear transition in concentration with height. If the maximum charge is determined for an empty room, it is probably reasonable to apply to a normally partially



congested room as one might encounter in practice; there is no need to apply an additional margin to account for room congestion.

### 4.3 Airflow

Airflow may originate from a number of different sources, as indicated in Table 1. For the frequently considered types of airflow such as natural and extract ventilation, there are extensive studies throughout the literature and for fan circulation, specific studies are cited. However, a brief mention on the effectiveness of the other forms of airflow is provided here.

Table 1: Different forms of airflow within a room

Type	Description	Reference
Natural/buoyancy ventilation	From thermal/wind pressure and openings	Ivings and Kelsey (2014); Figure 22
Extract ventilation	Mechanical/artificial airflow through fans	Ivings and Kelsey (2014)
Fan circulation	From IDU fan, ambient cooling fan, etc.	Colbourne and Suen (2008; 2018)
Physical movement	People walking, moving things	Figure 23
Thermal convection	Radiators, people, electrical equipment	Colbourne and Suen (2003); Figure 24

Figure 22 provides some example results for a 440 g release at 100 g/min from an IDU at 1.0 m under different natural ventilation conditions. “NV opening” is a single opening of 0.2 m × 0.8 m at floor level, “T&B NV opening” is the same but with an additional opening of the same size at ceiling height and “NV+extr opening” is the first opening but also an opening at the opposite end of the room that is ducted to the outside. Values shown in the legend refer to the percentage of refrigerant mass in the room relative to that present in the baseline closed room (as determined by integration of the vertical concentration profile). By the end of the release, both “NV opening” and “T&B NV opening” led to 10% to 15% lower floor concentration and 25% to 30% less refrigerant present in the room. Having the additional opening at ceiling level does not provide a significant benefit, despite the intention that it should accentuate the static pressure head and thus allow more mixture to flow out. Conversely the “NV+extr opening” case provides a major benefit, where floor concentration is reduced the two-thirds and mass present is only about one quarter of the closed room case. Velocity measurements across the outside air ventilation opening indicated a volumetric flow rate of about 6 air changes per hour.

Figure 23 shows the effect of gentle strolling through a stratified layer of R290 moments after cessation of the release. Within a few seconds of strolling the mixture had been diluted to below LFL (red line) and after a couple of minutes the concentration is below 25% of LFL, indicating the effectiveness of any physical movement on dispersing releases.

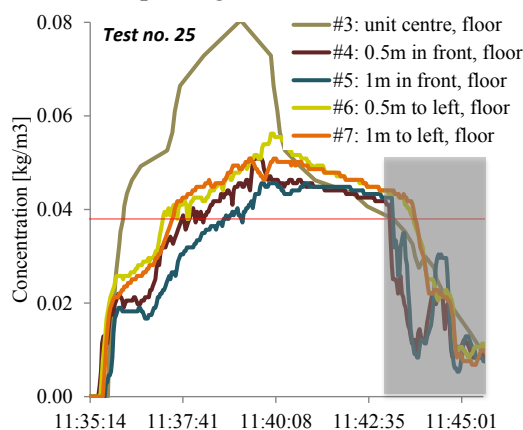


Figure 23: Effect of “strolling” through a stratified layer (during greyed duration)

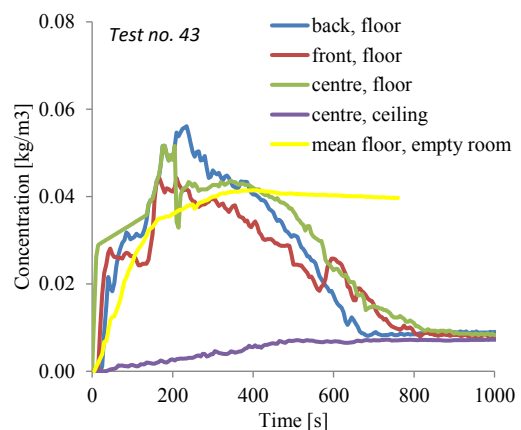


Figure 24: Effect of four thermal manikins and mock PCs on mixing of a release

From an earlier study (Colbourne and Suen, 2003), a test was carried out where 1.2 kg of CO<sub>2</sub> (to mimic R290) was released into a 40 m<sup>2</sup> insulated room, which contained four thermal manikins and four mock PCs, each emitting 100 W of heat. In Figure 24, whilst the peak concentration was not significantly affected, rapid homogenisation of the release can be seen to occur within a few minutes, which does not happen over the same timescales with an empty room (as compared with the mean floor concentration for a similar case of 1 kg CO<sub>2</sub> superimposed on Figure 24). This illustrates the effectiveness of common objects helping to disperse releases.

## 5 CONCLUDING REMARKS

Charge size limits within current safety standards are obstructive to the wider application of hydrocarbon refrigerants in RACS. Analysis of the assumptions associated with the current charge limit formula and exclusions from the background discussions have identified several areas where substantial refinements and corrections can be made. Breakdown of the process yields three main stages: release of the refrigerant, its flow through and mixing within the RACS housing and then mixing within the room space. Numerous variables affect each of these stages and it is important to understand their influence and if and how to introduce their effects into any improved method for maximum charge determination. For the three stages, several important findings should be accounted for.

### 5.1 Release of refrigerant

Maximum charge is highly sensitive to leak time or leak mass flow rate so appropriate consideration must be given to suitable values, dependent upon refrigerant (properties), operating conditions, likely leak mechanisms and hole sizes (which are as much as possible based on empirical field data). Adopting a single “blanket” leak time (such as 4 minutes) is not justified and fundamentally wrong. Further, for “large” leaks, adoption of a decaying leak profile is fitting whereas a constant mass flow is apt for “small” and “medium” leaks. According to measurements so far, assumption of a vapour-only release is likely to lead to more pessimistic floor concentrations and thus smaller charge limits (compared to a two-phase leak).

### 5.2 Mixing within RACS housing

Previously, the influence of the RACS housing on room concentration development was entirely neglected; releases were assumed to enter the room space as pure refrigerant and with minimal momentum. This work found that it was impossible to achieve IDU exit concentrations anywhere near pure refrigerant and in fact it is seldom richer than 10% (by volume with air); use of a “diffuser” device is by no means a reliable mimic for releases from actual IDUs. Maximum floor concentrations are substantially lower – and thus refrigerant charges could be higher – when a release is pre-mixed within IDU housing. Deeper investigations found that not only does the specific release position within the housing have a major effect on floor concentrations but that (with a fixed release position) the construction characteristics of the housing can also dictate the floor concentrations. Internal volume of the enclosure within which the release occurs and the sizes of transfer paths to other internal sections are some of the most important variables. Furthermore, effect of increasing release mass flow on floor concentrations can be partially offset where excess refrigerant pours out of the upper opening of the IDU, thereby assisting with the dilution mixing process as it increases the area of the plume-air interface. Effect of IDU internal pre-mixing alone infers around double the permitted refrigerant charge than at present.

### 5.3 Mixing within the room space

Apart from installation height of the IDU and to some extent the room size, many of the parameters associated with the room space that affect floor concentrations are awkward to quantify for practical situations. One group of parameters, i.e., those associated with air movement always assist with dilution of a release. For instance, openings in the room envelope and mechanical airflow but also gentle movement of occupants and presence of ordinarily insignificant thermal sources can have a major contribution on rapidly diluting and homogenising releases with a room. Another group of parameters involving positioning of IDUs in relation to walls and presence of objects contributing to congestion within the room tend to have a detrimental effect on floor concentrations. However, as far as congestion effects are concerned for typical environments, the negative effect on floor concentrations seems to be sufficiently small to neglect, especially when considering the abundance of the numerous parameters associated with air movement which are likely to offer an offset.

Implementing the aspects identified above is likely to help lead to more inclusive methods for determining maximum charge limits for hydrocarbon refrigerants.

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