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MINIMUM AIRFLOW RATES TO DILUTE R290 CONCENTRATIONS ARISING FROM LEAKS IN ROOM AIR CONDITIONERS

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ABSTRACT

Currently R290 is used to a limited extent in room air conditioners, such as split, portable and window types. The product standard IEC 60335-2-40 currently specifies requirements to limit the charge of flammable refrigerants in such a way that it obstructs the wider use of R290. This is particularly challenging in warm countries where the heat load is greater and thus charge sizes need to be larger for a given room size, inferring higher concentrations in the event of a leak. Relying on the airflow of an indoor unit can be used to dilute a refrigerant leak and thus prevent flammable concentrations forming, despite the charge quantity being substantially greater than that currently permitted in the current standard. Research has been carried out to determine the minimum airflow rate from an air conditioner necessary to achieve sufficient dilution. A numerical model based on entrainment theory was developed and supported by experimentally analysing the behaviour of releases under various conditions with RACS airflow.

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

1 INTRODUCTION

There is a need to enable larger quantities of R290 within room air conditioning systems (RACS) than safety standards currently permit. In the event of a refrigerant leak from the indoor components of a RACS, a substantial volume of flammable refrigerant-air mixture should not be allowed to build up, which could otherwise lead to injury and/or damage in the event of ignition. Various measures to mitigate such an occurrence are available (e.g., Colbourne et al., 2012), one of which is to use the forced airflow from the indoor unit (IDU) of the air conditioner itself to disperse the leaked refrigerant. RACS normally have a set airflow rate which is defined by the manufacturer to provide a given capacity, air throw, etc. and users usually have control to some extent by means of several incremental fan speed settings. It is necessary to identify whether the minimum airflow setting is adequate to dilute a release of refrigerant in case of a leak and thus whether the manufacturer would need to assign a higher minimum airflow rate to achieve dilution. Too low airflow will result in formation of a flammable mixture at the room floor (under a given leak condition), whereas a requirement for excessively high airflow may result in unwarranted equipment costs (large fan/motor and housing) and energy costs.

Various methods for determining minimum airflow rate for prevention of flammable mixtures have been proposed elsewhere. A formula is provided within IEC (2015) that can be transposed for minimum airflow rate of extract ventilation (equation 1), for the presumption that a given continuous release does not form a flammable mixture greater than 1% of the room volume.

$$\dot{V}_{min} = \frac{\dot{m}_{leak}}{\rho_g} - \frac{f \times \dot{m}_{leak}}{\rho_g \phi LFL_v} \tag{1}$$

where $\dot{V}_{min}$ is the minimum airflow rate (m^3 s^{-1}), $\dot{m}_{leak}$ is the release mass flow rate (kgs^{-1}), ρ_g is the gas density (kg m^{-3}), ϕ is a dimensionless multiplier for the lower flammability limit (LFL), dictating the ventilation outlet concentration (i.e., <1 to ensure the mixture is non-flammable), LFL_v is LFL as volume fraction and f is a factor used to account for the internal mixing efficiency that may range from 1 (e.g., an empty room) up to 5 (e.g., a highly congested room). Alternatively, Colbourne and Suen (2008) proposed an expression for determining maximum floor concentration arising from a refrigerant release due to several installation and equipment characteristics which can be transposed to estimate minimum airflow rate. More recently the proposal of IEC (2017) for “A2L” refrigerants defines a minimum airflow rate (equation 2) and discharge velocity of 1.0 m s^{-1}.

$$\dot{V}_{min} = 30 \times m_c / LFL_m \tag{2}$$

where $\dot{V}_{min}$ is the minimum airflow rate (m^3 h^{-1}), m_c is system refrigerant charge (kg), LFL_m is LFL as mass per volume (kg m^{-3}) and 30 is a constant relating to assumed refrigerant leak mass flow rate.

There are several short-comings with these approaches. IEC (2015) assumes infinite release duration and that the airflow removes some of the mixture from the room whilst replenishing with fresh air; this does not suitably represent the case of a RACS in a closed room. Colbourne and Suen (2008) is based on a variety of highly pessimistic assumptions, such as the release originating from outside the unit housing and at low momentum and very high release mass flow rates, and the application of the formula itself is possibly too unwieldly for use in a standard. IEC (2017) only accounts for a fixed and similarly high release rate but also neglects the effect of RACS discharge or room air speed on mixing. Thus there is a clear need for a broadly universal approach for determining the minimum airflow rate of RACS, taking account of the various construction and installation characteristics of RACS as well as being relatively simple to apply for non-specialists. In order to do this, the airflow conditions associated with a RACS are identified and the applicable principles for airflow mixing are introduced. This leads to the development of a general formula, which is then examined with respect to practicalities experimentally and eventually the formulae are adjusted to account for empirical findings.

2 CONCEPT DEVELOPMENT

2.1 Basic approach

When a jet of air (e.g., from a RACS outlet grille) discharges into a free volume it entrains air from the surroundings so that that total volumetric airflow rate of the field gradually increases (Figure 1). If that jet comprises a stream of leaked refrigerant then the concentration of refrigerant within the flow field should also gradually decrease as more air is entrained, assuming that the flow within the jet remains turbulent. Greater discharge volume flow rate increases rate of entrainment and therefore leads to more dilution. Eventually the flow will terminate, either at the opposite wall or on the room floor, depending upon whether the buoyancy effects or the momentum effects of the jet dominate; also indicated in Figure 1. Thus the maximum concentration observed at the opposite wall or floor would correspond to the mean concentration within the cross-section of that jet at the point that it terminates. If this maximum concentration at jet termination is set to refrigerant LFL, then the corresponding minimum airflow rate and jet outlet characteristics may be determined.

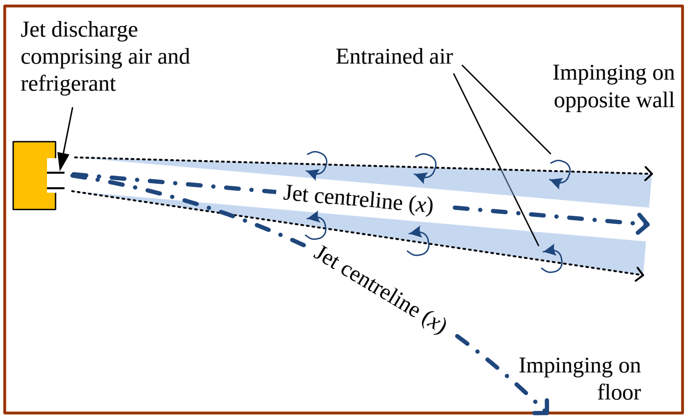

Figure 1: Schematic of entrainment process and jet termination

The analysis requires a number of assumptions: that there is negligible air exchange between the room and its surroundings, conditions are isothermal, .that the refrigerant vapour is denser than air, leak is of constant mass flow rate, negligible transit time for an element of refrigerant to flow from the IDU to the floor or wall, and – for the present work – the air discharge direction is horizontal.

2.2 Entrainment

Classical entrainment hypothesis is that the rate of entrainment of surrounding fluid across a jet or plume boundary is proportional to the average centreline velocity and perimeter of the flow field:

$$\frac{d\dot{V}}{dx} = P\alpha\bar{u}_c \tag{3}$$

where $\dot{V}$ is volume flow rate (m^3 s^{-1}), x is distance along the jet (m), P is perimeter around the flow field (m), α is entrainment coefficient and $\bar{u}_c$ is centreline velocity along x direction (m s^{-1}). From this, Etheridge and Sandberg (1996) derive closed equations for volume flow rate of neutrally buoyant jets at some distance from the jet exit. Since most RACS IDUs have high aspect ratio outlets, their model for plane jets is selected:

$$\dot{V}(x) = b\dot{V}_o\sqrt{\frac{\alpha x}{A_o}} \tag{4}$$

where the constant $b = 2^{5/4} \approx 2.4$ and A_o is the area of the jet outlet aperture (m^2).

At any distance x from the outlet, the flow rate $\dot{V}(x)$ is the sum of the outlet airflow rate ($\dot{V}_o$) and the additional airflow that has been entrained until distance x. Therefore the total entrained airflow, $\Sigma\dot{V}_e$ until x is $\dot{V}(x)$ minus that from the outlet:

$$\Sigma\dot{V}_e(x) = b\dot{V}_o\sqrt{\frac{\alpha x}{A_o}} - \dot{V}_o \tag{5}$$

2.3 Jet termination

A negatively buoyant jet is discharged horizontally comprising denser than air refrigerant will eventually impinge on the floor. From Etheridge and Sandberg (1996), using the constants for a plane jet with identical boundary for flow and concentration fields, the expression for the distance travelled until termination (x_T) along an unobstructed jet centreline is:

$$x_T = \left\{h_o\frac{3.75A_o}{f(I)Ar_o b\sqrt{\alpha}}\right\}^{0.4} \tag{6}$$

where Ar_o is the non-dimensional Archimedes number based on the outlet conditions, as given below, h_o is the centre height of the jet outlet (m) and $f(I)$ is a combination of volume, momentum, energy and buoyancy flux integrals determined analytically by Etheridge and Sandberg; $f(I)$ = 0.39. Archimedes number for the IDU discharge condition is:

$$Ar_o = g'\frac{\sqrt{A_o}}{u_o^2} \tag{7}$$

where g' is the reduced gravity (m s^{-2}) and u_o is the velocity at IDU air discharge (m s^{-1}).

Note that as the jet proceeds into the surroundings and more air is entrained the average concentration will reduce, so g' and thus Archimedes number become smaller; the result is the trajectory becomes less steep so lengthening x_T. Were this aspect to be accounted for in the model it forms an implicit solution and therefore difficult to compute. Since using Ar_o must produce a more pessimistic result (higher floor concentration) then it was opted to adopt this simplification of using IDU discharge Ar_o. Since $u_o = \dot{V}_o/A_o$:

$$Ar_o = g'\frac{A_o^{2.5}}{\dot{V}_o^2} \tag{8}$$

Since to be in a useable form g' must be based on the IDU discharge condition, i.e., at the start of the release where surrounding air is uncontaminated and discharge concentration (C_o) is known:

$$g' = g\left(\frac{\rho_m - \rho_a}{\rho_a}\right) \tag{9}$$

where g is gravity, ρ_m is density of the refrigerant-air mixture (kg m^{-3}) and ρ_a is air density (kg m^{-3}). The mixture density may be approximated as $\rho_m \cong C_o + \rho_a$, where C_o is refrigerant concentration (kg m^{-3}) in the discharged air.

For the time being, assuming that the release mixes homogenously with the entire airflow within the IDU housing, bulk mean concentration of the discharged jet would be:

$$C_o = \frac{\dot{m}_{leak}}{\dot{V}_o} \tag{10}$$

Substituting (10), (9) and (8) into (6), and combining the constants yields:

$$x_T = \left\{h_o\frac{9.6\dot{V}_o^3\rho_a}{g\dot{m}_{leak}A_o^{1.5}b\sqrt{\alpha}}\right\}^{1/2.5} \tag{11}$$

However, if the room is sufficiently small then the jet can impinge on the opposite wall of the room in which case termination distance is taken as the representative distance across the room:

$$x_T = \sqrt{A_{rm}} \tag{12}$$

where A_{rm} is the room floor area (m^2).

With higher refrigerant leak rates or lower airflow rates the distance to the floor is generally less than $\sqrt{A_{rm}}$. Therefore it is reasonable to use the approach for a negatively buoyant jet impinging on the floor for the analysis.

2.4 Dilution process

Refrigerant concentration within the IDU air discharge was defined in equation (10). At the time that the release begins (say, at time = $t1$) and assuming the jet enters an uncontaminated space and that the refrigerant continues to mix homogenously within the progressing jet, concentration at some distance (x) along the jet is:

$$\bar{C}(x) = \frac{\dot{m}_{leak}}{\dot{V}(x)} \tag{13}$$

Over time, the discharged refrigerant will mix within the room and therefore the entrained air comprises an increasingly richer mixture, peaking at cessation of the leak. Thus the total volume of air that has been entrained into the jet for the duration of the leak, or the volume of air within the room, whichever the smaller, is used to estimate the average concentration of the surrounding air at the time of cessation of the release (time = $t2$), i.e.:

$$\bar{C}_{sur,t2} = \frac{m_r}{min\{\Sigma\dot{V}_e t_{leak}, V_{rm}\}} \tag{14}$$

where m_r is the total mass of refrigerant released (kg) and t_{leak} is the time over which it is released (s), i.e., $t2 - t1$.

In practice, there is usually a minimum IDU airflow rate associated with a given capacity (typically in the order of 75 m^3 h^{-1} per kW) and thus room size on account of the associated heat load and a certain air discharge opening area to ensure the necessary air throw. Quantifying the term $\Sigma\dot{V}_e t_{leak}$ across a wide range of conditions, including leak time, indicates that V_{rm} will always be exceeded by up to a factor of five. Whilst this does not guarantee that the released refrigerant will be perfectly distributed throughout the entire room, it does provide some confidence that the term $min\{\Sigma\dot{V}_e t_{leak}, V_{rm}\}$ can simply revert to V_{rm}; thus $\bar{C}_{sur,t2}$ is the mean room concentration. This assumption has been further supported by CFD simulations over a wide range of scenarios (see Figure 3).

For any given time, the maximum concentration at floor level must correspond to the concentration within the jet as it approaches the floor or wall. At the beginning of the release ($t1$), that maximum concentration corresponds to the termination position of the jet as in equation (10), when setting $x = x_T$, i.e.:

$$\bar{C}_{max,t1} = \frac{\dot{m}_{leak}}{\dot{V}(x_T)} \tag{15}$$

As mentioned above, moments before cessation of the release the entrained air along the trajectory of the jet will also comprise refrigerant mixed within the room and in addition the refrigerant within the air drawn into the IDU suction. Thus, at cessation of the leak the maximum concentration will be:

$$\bar{C}_{max,t2} = \frac{\dot{m}_{leak} + \dot{m}_{sur} + \dot{m}_{suct}}{\dot{V}(x_T)} \tag{16}$$

where $\dot{m}_{sur}$ is the mass flow of refrigerant from the surroundings (kg s^{-1}), i.e. from the entrained mixture, is:

$$\dot{m}_{sur} = \bar{C}_{sur,t2}\Sigma\dot{V}_{e,t2} \tag{17}$$

And $\dot{m}_{suct}$ is the mass flow of refrigerant into the IDU suction (kg s^{-1}); since the volume flow of air into the IDU must be the same as that being discharged ($\dot{V}_o$), then:

$$\dot{m}_{suct} = \bar{C}_{sur,t2}\dot{V}_o \tag{18}$$

Substituting equations (14), (17) and (18) into (16), the maximum concentration at cessation of the release can be expressed as a function of exit airflow rate:

$$\bar{C}_{max,t2} = \frac{\dot{m}_{leak}}{\dot{V}(x_T)} + \frac{m_r}{V_{rm}} \tag{19}$$

Introducing equation (4) into (19) enables $\bar{C}_{max,t2}$ to be determined as a function of IDU airflow in the case of full room mixing (equation 20).

$$\bar{C}_{max,t2} = \frac{\dot{m}_{leak}}{b\dot{V}_o\sqrt{\frac{\alpha x_T}{A_o}}} + \frac{m_r}{V_{rm}} \tag{20}$$

By setting $\bar{C}_{max,t2} = LFL_m$ and rearranging, plus with the introduction of a new dimensionless term (R) to account for heterogeneity of the discharged refrigerant-air mixture (see section 3.1), equation (20) provides an explicit formula (equation 21) for determining minimum required airflow rate.

$$\dot{V}_o = \frac{\dot{m}_{leak}}{Rb\sqrt{\frac{\alpha x_T}{A_o}}\left(LFL - \frac{m_r}{V_{rm}}\right)} \tag{21}$$

Finally, equation (11) or (12) can be inserted into equation (21) and combining constants (including R = 1/3), yields equations (22) and (23), respectively.

$$\dot{V}_{o,min} = \frac{5.6\dot{m}_{leak}\sqrt{A_o}}{A_{rm}^{1/4}\left(LFL - \frac{m_r}{V_{rm}}\right)} \tag{22}$$

$$\dot{V}_{o,min} = \frac{4\dot{m}_{leak}^{3/4}\sqrt{A_o}}{h_o^{1/8}\left(LFL - \frac{m_r}{V_{rm}}\right)^{5/8}} \tag{23}$$

Under some situations, the jet will terminate on the opposite wall of the room, i.e., $x_T > \sqrt{A_{rm}}$, where equation (22) is applicable. When lower leakage mass flow rates are assumed (which implicitly results in lower $\dot{V}_{o,min}$) and the IDU is closer to the floor, the trajectory of the negatively buoyant jet veers towards the floor before reaching the opposite wall ($x_T < \sqrt{A_{rm}}$); in this case equation (23) needs to be applied. Through extensive evaluation of all applicable variables, equation (23) need only be applied when the R290 leak mass flow rate is less than, $\dot{m}_{leak} = m_r/(145 \times h_0 + 180)$.

Assessment of the approach was also carried out with CFD software (Simflow/OpenFOAM[1]), evaluating a range of conditions typical for RACS (airflow rate, discharge area, release mass and mass flow, unit height, discharge direction and room size). On average (e.g., over a several second duration to smooth out the "flapping" phenomenon), the trajectory of the jet was mostly less pronounced than equation (11) inferred. The exception was with units close to the floor where the Coandă effect helps draw the jet closer to the floor. But in all cases the extent of the LFL boundary was further from the floor or wall as anticipated by the model; examples are provided in Figure 2, Figure 3 and Figure 4..

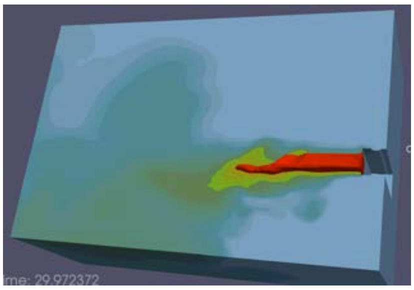

Figure 2: Contours showing trajectory, A_o = 0.20 m^2, 500 g at 141 g min^{-1}; x_T = 5.5 m*

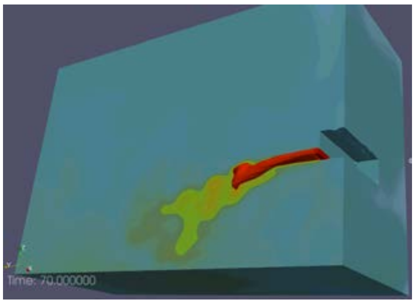

Figure 3:Contours showing trajectory, A_o = 0.05 m^2, 500 g at 141 g min^{-1}; x_T = 5.5 m; nearly all room air mixed within 70 s*

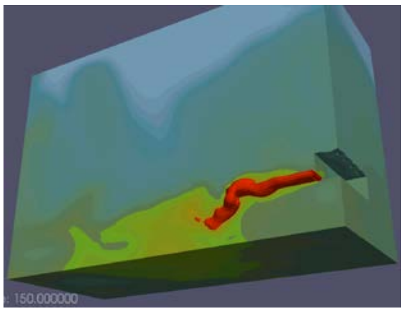

Figure 4: Contours showing trajectory, A_o = 0.05 m^2, 500 g at 141 g min^{-1}; x_T = 4.1 m*

* Red contour is region above LFL; green is 0.5×LFL to LFL; pale blue is <5% of LFL; room length = 4.5 m

[1] https://sim-flow.com/; solver: rhoreactingbuoyantFOAM, turbulence model: RANS RNG κ-ε; mesh: 0.015 – 0.06 m

3 MEASUREMENTS

A series of measurements were conducted to clarify several aspects, such as understanding the heterogeneity of the mixture at IDU discharge, the lateral distribution within the room and also a variety of different conditions to help validate the proposed formulae.

3.1 IDU exit condition

An initial assumption was that a release of refrigerant within an IDU is fully mixed within the airflow, before being discharged. Experiments were carried out in order to examine the validity of this assumption. Two types of IDU's were considered: three typical "wall" units and a "floor" unit. R290 releases of various constant mass flow rates were made from different positions within the IDUs over a range of airflow rate settings.

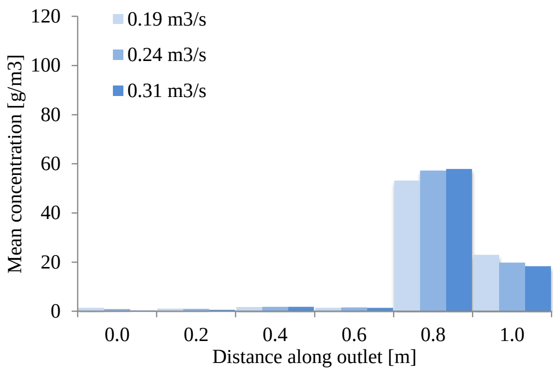

Figure 5: Measurements of R290 concentration within air discharged from an IDU at varying airflow rates

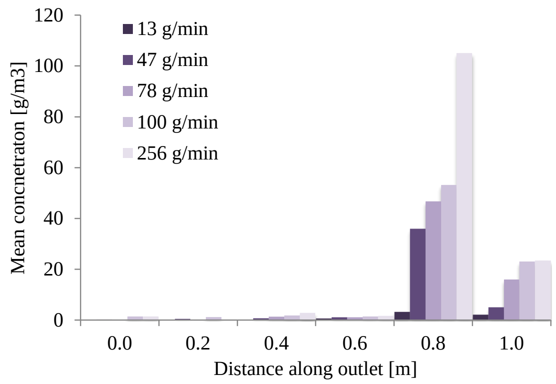

Figure 6: Measurements of R290 concentration within air discharged from an IDU at varying release mass flow rates

With the floor IDU R290 concentrations were measured at six equidistant positions along the centreline of the air discharge outlet. Figure 5 shows results with a 100 g/min release simulated from the coil right hand return bends and airflow rates of 0.19, 0.24 and 0.31 $m^3 s^{-1}$, whilst the results in Figure 6 used a fixed 0.19 $m^3 s^{-1}$ airflow and release rates ranging from 13 to 256 g min^{-1}. These indicate that irrespective of the conditions, refrigerant remains within about one-third of the discharged air, with the majority being within $1/5^{th}$.

Releases were simulated at four other locations, as indicated in Figure 7. Positioning and orientation of the releases were intended to create as much pre-mixing within the IDU as possible before the R290 was discharged with the air. Whilst most of these alternative release positions did lead to a wider distribution of refrigerant across the discharged air (Figure 8), full homogeneity could not be achieved.

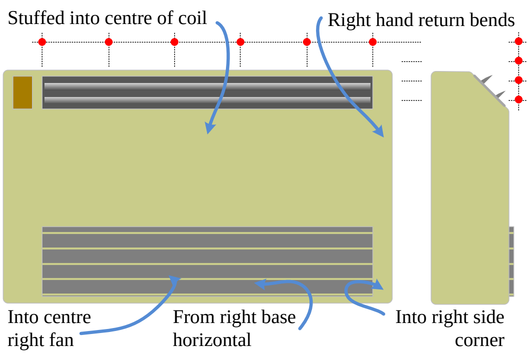

Figure 7: Positions/direction of additional release points and position of sampling points (red dots)

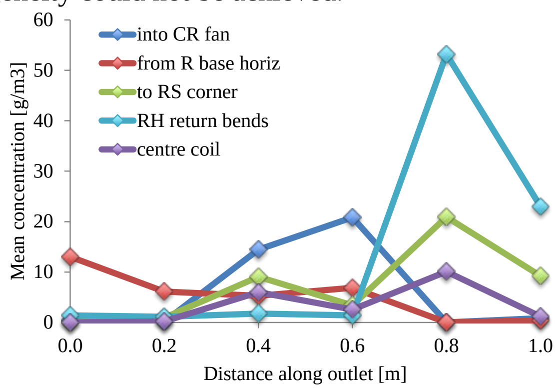

Figure 8: Average concentration at linear distances along air discharge arising from different release points

Further measurements were carried out on wall IDUs in a similar fashion, but with a finer distribution of sampling points (40 mm apart) and covering the width of the outlet at five angular locations relative to the horizontal (270°). Figure 9 and Figure 10 show local R290 concentrations for a low (480 $m^3 h^{-1}$) and high (1260 $m^3 h^{-1}$) IDU airflow rate arising from a 30 g min^{-1} release rate from the coil return. A similar tendency with the floor IDU is seen, where the majority of refrigerant is discharged from about half of the discharge opening (about 225° to 270°) and about one-quarter of the length. This pattern was replicated in both 2.5 kW and 8 kW IDUs and over several different leak positions and orientations about the right-hand return bends.

Maximum local values along the length are given in Figure 11 for four different airflow rates. As with the floor IDU, increasing airflow rate does not help homogenise the exit concentration. Comparing the peak concentrations against the bulk mean concentration (as expressed in equation 10) Figure 12 indicates a large discrepancy in the order of eight to 15, inherent in the assumption of homogenous mixing inside the IDU.

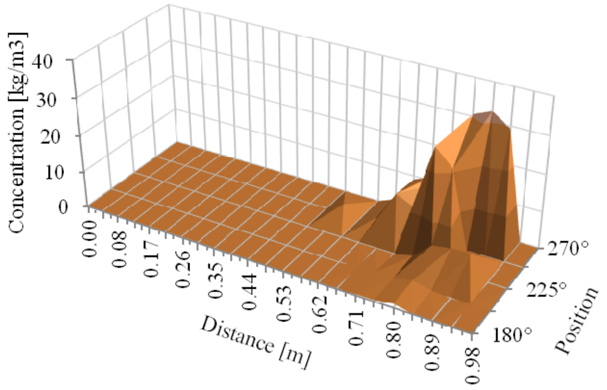

Figure 9: Local R290 concentration at wall unit discharge with 30 g/min and 480 m3/h airflow

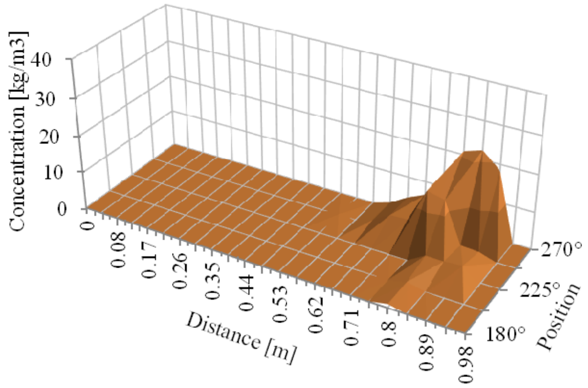

Figure 10: Local R290 concentration at wall unit discharge with 30 g/min and 1260 m3/h airflow

Based on these results, it is evident that the majority of the discharged air is not directly useful for dilution of a release. An approximation from these data suggests that broadly two-thirds of the discharged volume airflow may be neglected. Accordingly, the term applied to equation (21) was set at R = 1/3.

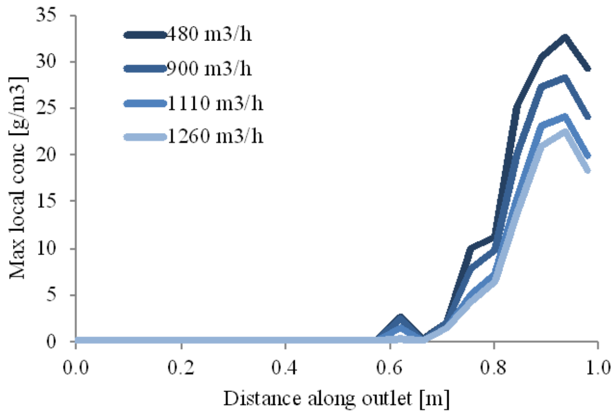

Figure 11: Maximum R290 concentration along discharge for different airflow rates

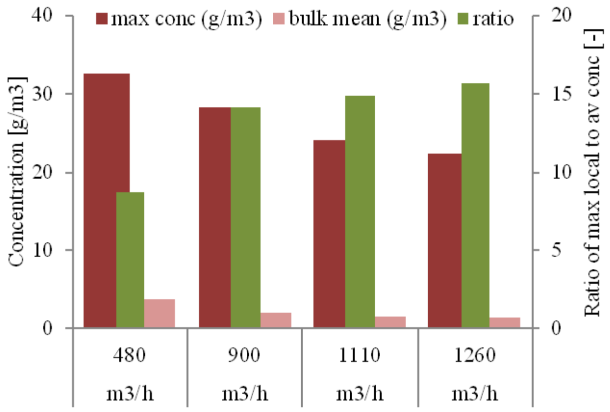

Figure 12: Comparison of maximum concentration and bulk mean concentration

3.2 Spatial distribution of discharged mixture

Whilst the measurements described above were made immediately after the IDU outlet, it may be possible that refrigerant mixing occurs across the entire jet prior to approaching the floor or opposite wall. Measurements were used to help provide confirmation of the validity of equation (11) for determining x_T and the usefulness of the term, R . Two arrangements were prepared to investigate this further. Figure 13 shows (a) incrementally spaced sampling points (purple) at floor level in order to indicate x_T and (b) a matrix of sampling points arranged at the same height as the IDU outlet ("h_H" in the graphs) and also at 0.15 m below ("h_L") to indicate both vertical and lateral distribution of the refrigerant within the discharged air.

Figure 14 plots local floor concentration (in line with the release position), with the respective coloured arrows indicating the result for x_T from equation (11). There is fairly good agreement, especially when considering the variability of the release conditions.

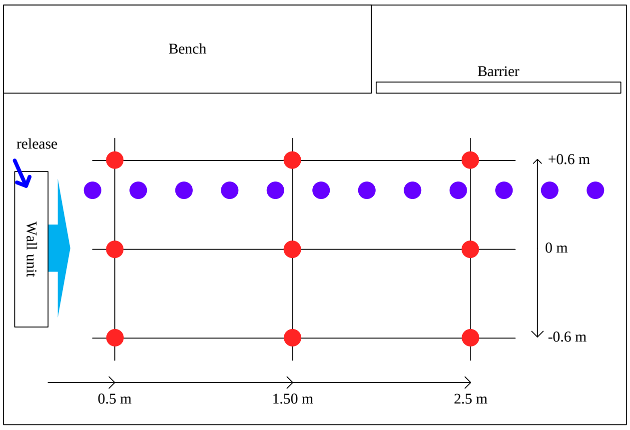

Figure 13: Layout of test room (3.5 m × 4 m) with sampling points indicated

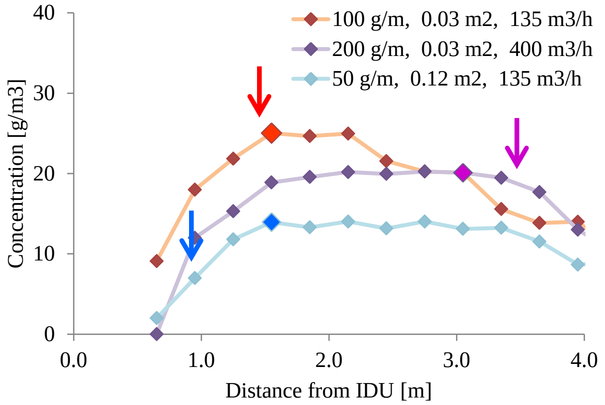

Figure 14: Floor concentrations during a release (g/min) within the IDU with outlet opening (m^2) and airflow (m^3 h^{-1}) at different conditions

Two sets of results are shown in Figure 15 and Figure 16, which are from identical test arrangements, except for different airflow rates. (Note data for -0.6 m is not included since it matches that of 0 m.) Concentrations along the 0 m line are about the same, irrespective of height and distance from the IDU and approximately correspond to mean room concentration. Concentrations directly in front of the release start at a high value and then decrease towards the background concentration at the far end of the room. Crucially, concentrations at 0.15 m below the plane of air discharge are found to be higher in the centre of the room, inferring a downward trajectory of the refrigerant-rich part of the jet. Results for the lower airflow rate suggest a steeper trajectory on account of the more pronounced decline in concentrations towards the far end of the room.

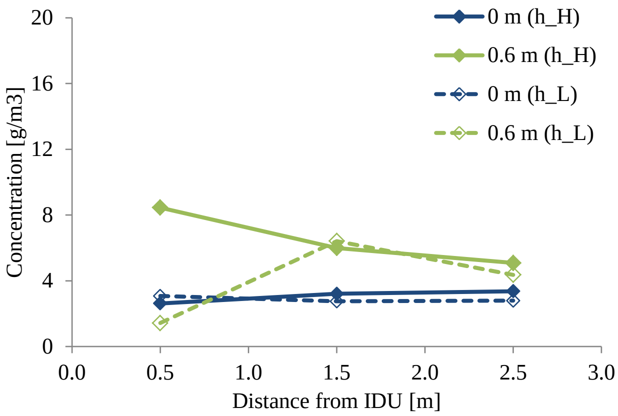

Figure 15: Local concentrations in front on air discharge; 1260 m^3 h^{-1}, 120 g min^{-1} and 200 g

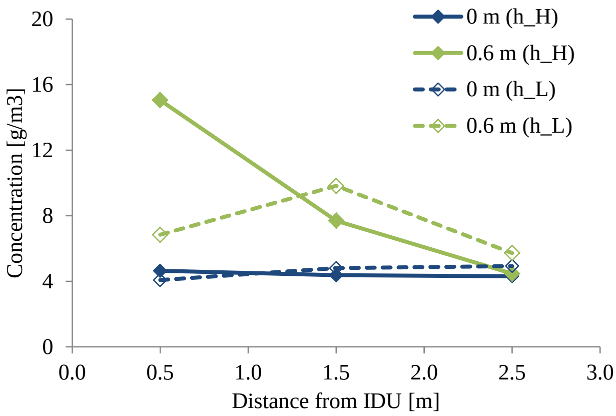

Figure 16: Local concentrations in front on air discharge; 480 m^3 h^{-1}, 120 g min^{-1} and 200 g

3.3 Validation

Equations (22) and (23) (rearranged as a function of $\bar{C}_{max,t2}$) were compared against maximum measured concentrations across a large number of experiments from our database, involving different RACS and also commercial refrigeration equipment (CRE). Across the database, tests used a wide range of variables, such as airflow rates, outlet areas, unit height/positioning, released masses and mass flow rates, room sizes and also density and distribution of sampling points. Figure 17 shows comparison between the measured and calculated values with approximately 250 data-points, which shows that the equations under predict in most cases. However, since the primary purpose of the task is to determine a minimum airflow rate to guarantee against a flammable mixture forming, a positive adjustment factor of 1.2 was applied to minimise the number of data-points remaining to the left of parity (Figure 18).

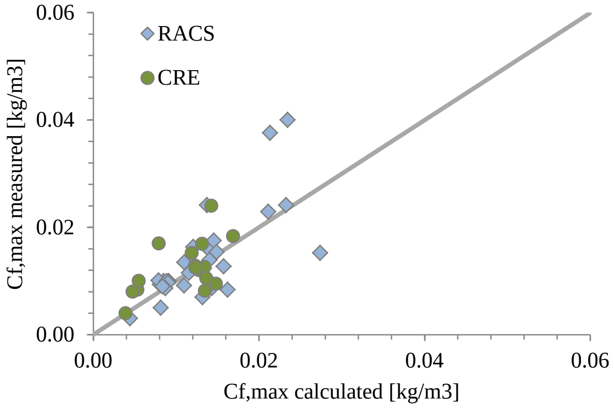

Figure 17: Comparison of measured maximum concentrations and unadjusted proposed formulae

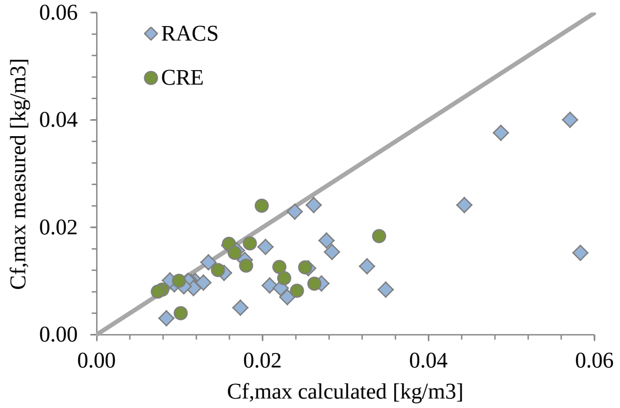

Figure 18: Comparison of measured maximum concentrations and proposed formulae adjusted to "catch all"

4 FINAL REMARKS

Usually, refrigerant charge amount for a RACS is determined according to the room size into which the IDU will be installed and the LFL of the refrigerant:

$$m_{max} = F \times LFL \times A_{rm} \times h_{rm} \quad \textbf{(24)}$$

where m_{max} is the maximum charge (kg), h_{rm} is the room height (m) usually assumed to be 2.2 m or 2.5 m and F is a non-dimensional limit intended to avoid the entire room approaching LFL; with typical values ranging from 0.1 to 0.5 according to how much refrigerant a given RACS requires.

In order to make equations (22) and (23) more directly and practically applicable, equation (24) is substituted in (and including the 1.2 adjustment factor), giving:

$$\dot{V}_{o,min} = \frac{6.8\sqrt{A_o}\,\dot{m}_{leak}}{m_c^{1/4}\,LFL^{3/4}}\left(\frac{F^{1/4}}{1-F}\right) \quad \textbf{(25)}$$

$$\dot{V}_{o,min} = \frac{5\sqrt{A_o}\,\dot{m}_{leak}^{3/4}}{h_o^{1/8}\,[LFL(1-F)]^{5/8}} \quad \textbf{(26)}$$

Using these formulae, some examples of minimum airflow rates according to the key variables are provided in Figure 19. It is seen that the minimum airflow is rather sensitive to the selected parameters, where for example, high leak rates increase airflow about proportionally, doubling charge amount increases airflow by a factor of three and increasing the outlet area by four (i.e., quartering discharge velocity) doubles airflow, assuming the other factors are kept constant. Also shown are typical values for high and low airflow setting on IDUs, assuming a specific heat load of 200 W m^{-2} of room area. Evidently, under some conditions IDU airflow may need to be raised to the high setting to ensure flammable mixtures are avoided and occasionally redesign of the RACS may be necessary.

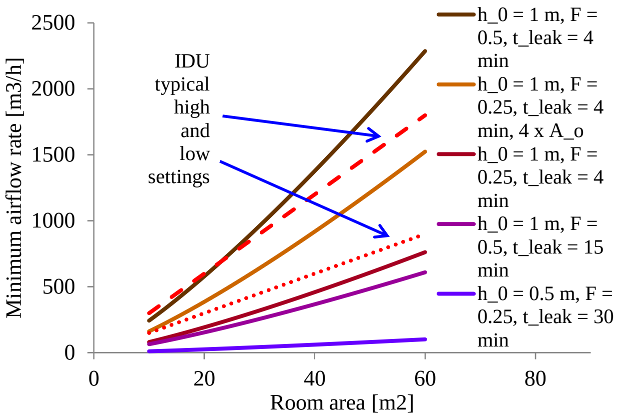

Figure 19: Example of airflow rate requirements with mean variables

Compared to the methods mentioned in the introduction, use of equations (22) and (23) are attractive in several respects. In particular, the need to make judgement on certain variables is eliminated, they account for discharge velocity of IDUs, absolute mass of releasable refrigerant charge and installation height of IDU (where applicable) as well as enabling the choice of assumed leak rate. Moreover, they have been extensively validated against database of measurements specifically using RACS and CRE.

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