Summary of background work, including research and testing, contributing to the revised requirements for A3 refrigerants within IEC 60335-2-40: 2022

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Contents

Executive summary

The 2022 edition of the IEC 600335-2-40 product standard for air conditioners and heat pumps includes important updates with regard to enabling the feasible, energy efficient, and safe market adoption of hydrocarbon (HC) refrigerants. The objective of this report is to provide an overview of the key subjects and sub-topics for safety research and testing that were considered by the responsible IEC working groups, IEC SC 61D WG16 and WG21. It includes the main discussion points and identification of further work that may help refine particular requirements or provide further validation for extension of the existing requirements and to better enable the applicable of HC refrigerants.

Nomenclature

A2	Safety class A2 refrigerant for lower toxicity (A), medium flammability (2)
A2L	Safety class A2L refrigerant for lower toxicity (A), lower flammability (2L)
A3	Safety class A2 refrigerant for lower toxicity (A) and higher flammability (3)
AC	Air Conditioner/Air Conditioning
ACL	Allowable Charge Limit
AQL	Allowable Quantity Limit
CF	Concentration factor
ETRS	enhanced tightness refrigeration system
EU	European Union
GB	Great Britain
HC	Hydrocarbon
HFC	Hydrofluorocarbon
HP	Heat pump
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JRECO	Japan Refrigerants and Environment Conservation Organis0ation
JSRAE	Japanese Society of Refrigeration and Air conditioning Engineers
LFL	Lower Flammability Limit
MSLR	Maximum Safe Leak Rate
MT	Maintenance Team
NC	National Committee
SC	Sub Committee
SEER	Seasonal Energy Efficiency Ratio
UCL	Upper Charge Limit
UQL	Upper Quantity Limit
WG	Working Group

1 Introduction

The prior editions of IEC 60335-2-40 employed highly obstructive requirements for the application of hydrocarbon (HC) refrigerants in split air conditioners (including reversible/heat pump systems). These obstructive requirements were primarily in the form of allowable charge limits, where the quantity of HC refrigerant permitted within a given space was typically far too small to enable most systems to achieve a cooling (or heating) capacity to satisfy the thermal load of a given space, thereby restricting commercial viability of designing most air conditioning (AC) and heat pump (HP) systems using HCs.

Figure 1 shows split AC/HP products for the European market[2], but with the refrigerant charge adjusted to the R290-equivalent using established approximations. The solid lines are the allowable charge limits for units installed on the floor (0.6 m), wall (1.8 m) and ceiling (2.2 m). The left graph in Figure 1 is based on the nominal refrigerant charge of the models, whereas the graph on the right includes additional charge which would be used were additional interconnecting piping (of 20 m) was installed.

What can be observed is that most units would not be permitted if they used R290. For floor units, it would be impossible in all cases. For wall units – which represents the vast majority of this product type (RTOC, 2022[3]) – only a handful of units would be viable, but not above a capacity of about 4 kW. For ceiling units, the potential is marginally better, but only up to a capacity of about 5 kW. Considering installation cases where the indoor unit is some distance away from the outdoor unit and additional refrigerant is needed for the extra lengths of piping, it would be extremely difficult to apply R290.

Product manufacturers do not want the uncertainty that their unit may not be allowed to be installed and moreover, where a manufacturer produces a range of units, perhaps from 2 kW to 10 kW, it is undesirable to have to switch refrigerant part-way through the range. Thus, these allowable charge limits imposed a significant technical and market barrier to the adoption of HCs.

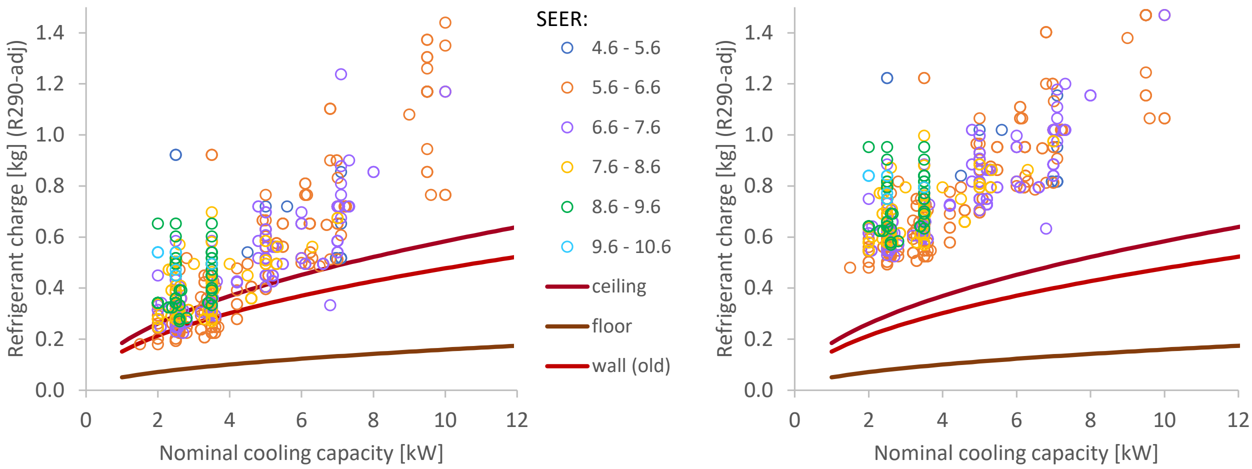

Figure 1: Comparison of R290 charge limits against HFC unit charges adjusted for R290, with nominal charge (left) and assuming an additional 20 m of interconnecting piping (right). Data is divided according to European seasonal energy efficiency ratio (SEER) bands.

As a further attempt to address this barrier, in June 2014, the British national mirror committee to IEC SC 61D (CPL61/4) issued a draft for comment (61D/303/DC) to IEC SC61D, comprising proposals to improve

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[2] Eurovent database, https://www.eurovent-certification.com/en/, August 2002.

[3] https://iifiir.org/en/fridoc/montreal-protocol-on-substances-that-deplete-the-ozone-layer-2022-146932

requirements within IEC 60335-2-40 specifically for A2 and A3[4] refrigerants. This draft for comment (DC) comprised proposals covering three elements:

i) Allowing a different means to determine refrigerant charge limit if the system utilises integral airflow to dilute the release of refrigerant.
ii) Allowing a different means to determine refrigerant charge limit if the only part of the system that is within the occupied space is the indoor unit and interconnecting piping.
iii) Permitting the charge amount to be based on the releasable charge if it can be demonstrated that the amount that will be released in the event of a leak is less than the total mass charged into the system.

Subsequently, a new working group, WG16, was set up and the development of new and revised requirements began. The work proceeded until 2019 when it was decided to include A2Ls in the revision process as well, since many of the topics under consideration were applicable to all flammable refrigerants, not only A2 and A3. This resulted in the formation of a new working group, WG21. Eventually, in 2022 the revised IEC 60335-2-40, containing requirements developed by WG16 (2015 – 2019) and WG21 (2019 – 2022), was approved and was issued in 2022.

Generally, member standards bodies are expected to adopt and publish an adopted IEC standard. There are three approaches possible: (i) reprint, (ii) translate and (iii) redraft, where national standards bodies opt for their preferred method. With IEC 60335-2-40 for example, China translates, Europe reprints (with deviations to harmonise with European regulations and directives) and North America redrafts. National adoption can take several years from the approval of the IEC standard, due to internal bureaucracy. Further details related to national adoption are included in the applicable ISO/IEC Guide 21-1[5].

The result is a new standard that allows the allowable charge size in an unventilated space for A2L, A2 and A3 refrigerants to be based on the “m2” upper charge limit (corresponding to 52 m^3 × LFL and 26 m^3 × LFL, respectively[6]) and minimum room size requirements. This enables practical application of air conditioning and heat pump systems using up to 988 g of R290 in direct systems[7].

The data in Figure 1 is repeated in Figure 2, but superimposed on some revised charge limits. It is observed that the majority of units are now captured with the revised limits and even with the assumption of additional interconnecting piping (although this is limited to 8 – 10 kW and does not quite extend to 12 kW, typical for this product category).

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[4] The standard ISO 817 classified refrigerant safety according to toxicity (A = lower toxicity, B = higher toxicity) and flammability (1 = non-flammable, 2L = lower flammability, 2 = flammable and 3 = higher flammability). Thus, all hydrocarbons, R290, R1270, etc. are class A3 refrigerants.

[5] https://www.iso.org/resources/publicly-available-resources.html?t=Ruvyk3OTE1FejG9wJie0LojrUDDf3weEqbMekT5NvH7ARf5jR7ng2dLlMyUmadiO&view=documents#section-isodocuments-top

[6] Lower Flammability Limit (LFL) is the weakest concentration that a refrigerant-air mixture can be ignited. It is usually expressed in terms of volume (m^3 of refrigerant vapour per m^3 of air) or mass-volume (kg of refrigerant per m^3 of air) or mass (kg of refrigerant per kg of air). HCs are generally in the order of 2% by volume, 0.04 kg/m^3 or 0.03 kg/kg. Many of the flammability safety requirements are linked to LFL.

[7] In this context, a “direct” system is considered equivalent to a “high probability” system under the ASHRAE-15 standard. Similarly, an “indirect” system would correspond to a “low probability” system.

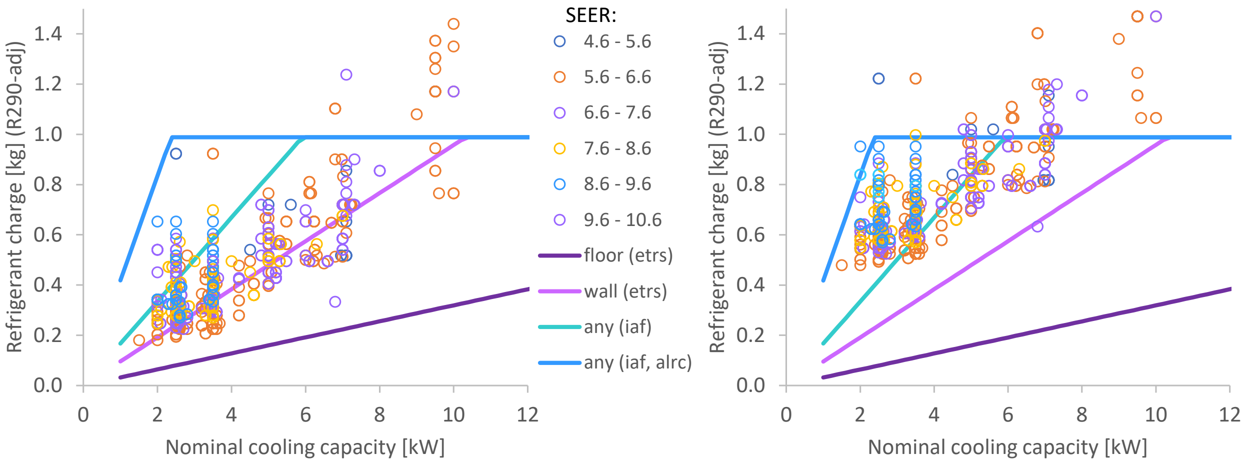

Figure 2: Comparison of revised R290 charge limits against HFC unit charges adjusted for R290, with nominal charge (left) and assuming an additional 20 m of interconnecting piping (right)

2 Task

During the process of developing new requirements for class A3 (and A2) refrigerants, a large number of technical matters were discussed in order to find conclusions to technical and safety issues and consensus on how to handle them. The work that went into this process involved reporting on experiences of manufacturers, information reported on the wider technical and scientific literature, testing, experimentation, technical analysis and numerical simulations carried out by WG members and associates. A summary of the key subjects that were handled by the WGs, related sub-topics and other aspects are summarised in Table 1. These items are addressed within the present report. Some of these sub-topics are directly related to specific requirements (such as releasable charge), some are indirectly related to specific requirements (such as leak hole sizes) and some only have some influence on specific requirements but are important in a general sense (such as room obstacle effects).

The importance is somewhat subjective, since different stakeholders have varying areas of interest, but those identified as "high" are those of most relevance to enabling use of HC refrigerants. The list of issues summarises the main consideration(s) for each sub-topic and lastly there is an indication of how the technical issues were tackled.

Table 1: Key subjects and sub-topics handled by WG16 and WG21

Key subject	Sub-topic	Importance	Issues	How handled
Max charge limits/ min room size	Leak hole sizes/ leak rates	High	Value is very significant for limits	Field study, discussion
	Dispersion quiescent room	High	Characterisation affects limits	Tests, discussions
	Dispersion under airflow	High	Characterisation affects limits	Tests, discussions
	Connected spaces	Low	One unit for two adjacent rooms	Tests, calculations
	Releasable charge	High	How much is retained, conditions	Tests, discussions
	Enclosure geometry	Medium	Characterisation affects limits	Tests, discussions
	Room obstacle effects	n/a	How they affect charge limits	Tests, calculations
	Upper charge limits	High	Exceeding 1 kg for HCs	Discussion
	Surrounding conc test	High	Accounts for lots of factors	Tests, discussion (no consensus)
Ducted systems	Charge limits	Medium	Mixing in ducts, room distribution	Tests, discussion (no consensus)

Key subject	Sub-topic	Importance	Issues	How handled
Sources of ignition	Potential and critical leak points	Medium	How to choose, define	Discussion, experience
Ventilated enclosure	Airflow rate and safety system	Medium	ETR systems	Manufacturer experience
Leak detection	Gas sensor requirements	Medium	Reliability, robustness	Manufacturer experience
	Detection using ultrasonics	Medium	General implications	Tests, trials
	Detection with sys parameters	Medium	General implications	Experience
Misc-ellaneous	Peripheral studies	n/a	Various	Presentation/ discussion/ noted

Eventually in 2022, the final draft international standard (FDIS) was approved unanimously by the SC61D member bodies and the standard was published soon afterwards.

The objective of this report is to provide an overview of the key subjects and sub-topics, what the main discussion points were and identification of further work that may help refine particular requirements or provide further validation for extension of the existing requirements.

3 Discussion

3.1 General

The hazard associated with a flammable refrigerant is that a leak could lead to the formation of a substantial flammable mixture, which when ignited, results in undesirable consequences that could harm persons and animals and damage property. Thus, if such refrigerants are to be used then the design of equipment should be such that:

- Leaks are, as far as possible, prevented.
- In the event of a leak, the size and persistence of a flammable mixture is very small or insignificant.
- No potential sources of ignition are within the proximity of a potentially flammable mixture.

None of these can be absolutely guaranteed, but design and construction features can be implemented to improve the probability that they will be ensured. Accordingly, various technical requirements are established that aim to achieve these targets and then supporting conditions are developed to help improve the level of confidence that they are achieved, regardless of the anticipated variation of external conditions.

Within this context, the most important subjects and related sub-topics with regards to extended application of A3 refrigerants are discussed and broken-down into several aspects, specifically:

- Issues – Identify the main issues involved with the topic, questions that needed answering, where contentions arose.
- Handling – Practical steps taken for addressing the topic, such as referring to the wider technical and scientific literature, testing, experimentation, technical analysis and numerical simulations.
- Outcomes – State the outcome as in the current edition of the standard, IEC 60335-2-40: 2022.
- Extensions – Identify whether requirements can be improved to help extend and revise the application of A3s refrigerants.
- Additional work – Suggestions for additional work, be it experimental, simulation or technical analysis, that could be beneficial to help develop further requirements for extending the application of A3s refrigerants.
- Literature – A list of publicly available material and IEC WG documents that relate to the key subject under discussion.

Specifically concerning output of the WGs, there were in total over 1000 documents. Excluding those dealing with administrative information (agendas, maps, hotels, details, etc.) as well as meeting reports, well over half were technical proposals and supporting technical documents. WG16 documents encompassed those from 2015-N001 to 2019-N209a and WG21 documents covered 2019-001 to 2021-297.

Across the recent scientific literature[8] covering relevant subjects, published in journals, conferences and reports of institutes, some is directly related to the activities associated with this standardisation process, some was carried out in parallel, either prompted by the interest in the technology or was carried out entirely independently and is thus coincidental.

3.2 Allowable charge/minimum room size

As mentioned in section 1, perhaps the most obstructive technical barrier to the uptake of HCs is the allowable refrigerant charge (or corresponding minimum room size). Essentially, if insufficient refrigerant is permitted for the system to provide the required amount of thermal capacity, it is not feasible to use that refrigerant. There are several elements that lead to the formulation of allowable charge limits, the most critical being assumed leak size, how that leak disperses in the space and the inclusion and effectiveness of any additional measures that can be applied to enhance that process[9].

3.2.1 Sub-topic: Leak hole sizes/leak rates

Issues

Assumed leak hole size and the corresponding leak mass flow rate is fundamental to many of the safety measures, such as:

- Minimum airflow rate calculations
- Implicit in concentration factors for refrigerant charge/quantity calculations
- Under certain conditions, the determination of releasable charge
- Leak detection response and sensor positioning tests
- Leak simulation test for ignition sources
- Calculation of ventilation rate for ventilated enclosure
- Calculation of extract ventilation rate
- Also, zoning calculations from IEC 60079-10-1, as invoked by certain industry guidelines

With all other conditions fixed, a larger leak hole results in a higher leak mass flow rate and a higher mass flow leads to higher concentrations and thus greater flammable volumes. It is simple to make an assumption that any leak hole will be as large as possible ("catastrophic"), but as a starting point this potentially conflicts with a reasonable outcome. By comparison, with reference to the "zoning" standard, IEC 60079-10-1, this recommends against use of catastrophic leak assumptions for determination of flammable zones. Due to catastrophic leak frequencies being so low, accounting for such a rare instance potentially leads to detrimental cost implications. Thus, it is necessary to suitably determine the appropriate size of a leak hole. With a robustly assumed leak hole size, all subsequent requirements can be developed.

Development of a previous edition of IEC 60335-2-40 (2003) involved an erroneous assumption of leak size.

[8] A fairly clear distinction may be observed across the literature related to this subject, being "progressive" or "regressive". The progressive literature generally strives to develop new methods and assess effectiveness of methodologies to enable safe application of HC refrigerants. Conversely, the regressive literature aims to identify "how dangerous" the use of HC refrigerants is, often without offering any means as to how to make its use less dangerous.

[9] Note that sub-topics are interrelated, closely linked with each other within the context of the overall outcome. Thus, it is sometimes not easy to isolate individual topics and the discussions should be considered in conjunction with the other topics.

Rather than a hole size, as such, a "leak time" was used and this was set at four minutes. This results in leak mass flow rates being determined by refrigerant charge divided by four minutes. Many experts regarded this approach as erroneous. Erroneous assumptions include:

- Presumption is that hole size differs according to refrigerant charge, but there is no technical basis for this.
- Inference is that higher pressure refrigerants use smaller hole sizes, which is counter-intuitive.
- Lower density refrigerants have larger hole sizes, which is not technically justifiable.
- Systems operating at higher temperature (pressures) have smaller hole sizes, which is counter-intuitive.
- Systems which are designed with better tightness, permanent connections, factory sealed and tested, etc. have the same hole sizes as systems that may be site-erected, use very many detachable joints, subject to high vibration, etc.
- Larger systems assumed to have huge leak rates (e.g., 130×LFL for A3 gives about 1250 g/min and 260×LFL of A2L gives about 20000 g/min) that can be physically impossible to achieve (i.e., required leak hole size larger than system pipe size).

More detailed discussions on the inconsistencies associated with this four-minute leak fallacy are detailed within the referenced literature.

Handling

The first step was therefore to find data on the size of actual leak holes. Such information is very difficult to obtain due to costs and (in)convenience, including complexities associated with gathering sections of leaking systems, not to mention industrial stakeholders' reticence to acknowledge that systems they are responsible for have leaks. From the literature, two studies (from Japan) were found which helped to provide some insight. In addition, a further study within Europe was initiated (EU Life Front) and data for over 1000 leak holes was compiled. This provided a distribution of leak hole sizes, indicating what a reasonable assumption could be. With an assumed leak hole, knowledge of the refrigerant (thermophysical properties) and operating temperatures of the systems, an assumed leak mass flow rate could be defined for each refrigerant.

Outcomes

A leak hole size of approximately 0.5 mm^2 was agreed upon, which (based on the selected conditions) provides a leak mass flow of around 60 g/min of R290. It is noted that this is approximately 10 times the size of about 98% of the leak holes measured in the EU Life Front and JARECO studies. Moreover, holes approaching and exceeding this size were due to corrosion or human intervention[10]. However, this was applied only to enhanced tightness refrigeration systems (ETRS) – which nowadays reflects a substantial proportion of systems, particularly small single splits, where the compressor is located out of the occupied space.

Extensions

The assumed hole size and corresponding leak rate based on refrigerant properties approach described above is currently only used for A2 and A3 refrigerants; for A2Ls (and ETRS) a fixed 167 g/min leak rate is used; whilst this also corresponds to a hole size of about 0.5 mm^2 for R32 (that it was originally determined for) it means that other A2L refrigerants having a lower pressure have to rely upon an "artificially" elevated assumed leak rate. This is not logical (i.e., it suffers from the list of errors given above) and is disproportionately advantageous to higher pressure refrigerants such as R32 and more prohibitive to lower pressure refrigerants such as R1234yf and R1234ze. In principle, the same fixed hole size approach should be used equally for all flammable refrigerants.

[10] In cases of corrosion, the entire charge would have been released well before the hole had grown to these larger sizes (growth occurs over a period of weeks or months, not minutes or even hours or days). Leaks due to human intervention cannot be considered or accounted for, otherwise no safety measures would ever be regarded as effective. Only additional measure intended to minimise effects of human intervention can be accounted for.

Presently for any A2 or A3 refrigerant, a single value of mass flow rate is used regardless of operating conditions. However, for some types of system different parts of the cycle will only operating at lower or higher temperatures/pressures and the corresponding section of the unit could adopt leak rates to better reflect the local operating condition[11].

For systems with the compressor also within the occupied space, the concept does not apply, but in the event that all the other enhanced tightness criteria are met, some sort of adjustment to the leak size should be adopted, rather than having to revert to the old charge limit formula.

Additional work

Considering the data from the three (Japanese and European) studies, the combined dataset of approximately 2,000 leak samples is very small compared to the number and variety of leaky systems throughout the world. Given this relatively small sample, it is difficult to discern trends within the leak data associated with system design, selection of components, location of parts, age of system and so on. A wider, more comprehensive set of leakage data, perhaps in the order of tens of thousands, would enable more precise assumptions of leak hole size to be identified. As a result, systems designed and constructed according to certain criteria (such as level of leak tightness testing, types of compressors, site- or factory-sealed, selection/types of components used, etc.) could benefit from the advantages (cost, flexibility, etc.) of smaller leak size assumptions. Moreover, it would enable different types of equipment to be better designed to achieve a more similar level of risk ("1/safety").

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3.2.2 Sub-topic: Dispersion in quiescent rooms

Issues

A refrigerant leak into a closed space, such as a room, forms a flammable mixture as it transitions from 100% refrigerant to 100% air. Where there is not imposed air movement within the space, i.e., conditions are quiescent, dispersion of the refrigerant is reliant only upon the relative movement caused by its own momentum, generated by the force of the leak (jet) and due to the negative (or positive) buoyancy of the mixture in air. Refrigerant emerging from a leak hole is 100%, pure refrigerant, but exchange across the

[11] For example, cooling-only systems with external expansion devices will not experience indoor pressures exceeding that which corresponds to the indoor temperature, whereas the pressures experienced in the outdoor part of the system will at times be much higher. Thus, it is appropriate to define assumed leak mass flow rates accordingly so that mitigation measures are defined accordingly. However, this should also be done in tandem with scaling down assumed hole sizes to more realistic values.

interface of the jet or plume results in entrainment of the surrounding air and subsequent dilution of the jet/plume. The rate of dilution of the refrigerant dictates the developing concentration of the refrigerant. The rate of dilution is dictated by several factors, including the jet or plume velocity, distance travelled, width or perimeter of the plume, impingement against surfaces, confinement of volumes, diffusion coefficient (a function of the fluid properties), and so on. This rate of dilution affects the concentration of the settled or stratified mixture, which for denser-then-air refrigerants such as HCs, is on the floor. Since the dilution process involves entrainment of the mixtures surroundings, if the surroundings already contain refrigerant, the rate of change of concentration slows. Thus, as more and more refrigerant leaks out, the concentration of the settled mixture becomes higher and can eventually exceed the LFL, thereby forming a flammable layer.

Essentially, an allowable charge limit (ACL) is defined as the point at which so much refrigerant has been released (under the defined conditions) that a flammable layer/mixture is not (quite) formed, i.e., there is no flammable stratified layer.

Development of a previous edition of IEC 60335-2-40 (2003) employed certain assumptions about the source conditions of the refrigerant leak (in addition to leak rate), including that the release occurring at very low momentum (thereby greatly minimising entrainment), from an axisymmetric outlet and that the state of the release into the room was as pure refrigerant. This led to minimal dilution of the release. Rational analysis and subsequent experimental work proved that these onerous assumptions were erroneous and fundamentally unsound.

Handling

Experiments found that in reality, all leaks (from piping) occur at very high velocity and – partly enhanced by impingement on internal surfaces – there is significant dilution of the jet within the enclosures housing the AC&HP piping, heat exchangers, components, etc. As such, an already dilute mixture emerges from the AC&HP housing and in a distribution influenced by the housing geometry and openings. In addition to the pre-dilution, high aspect ratios of AC indoor units enable substantially more dilution than that of an axisymmetric plume and floor concentrations – for a fixed release mass – are substantially lower than those based on the prior assumptions. Accordingly, considerably more refrigerant can be released before reaching LFL at the floor, thus greater charge quantities can be tolerated[12].

Outcomes

Combined with the improved assumptions of leak rate, numerous tests were carried out with actual AC&HP units to determine how much refrigerant could be released under these realistic conditions before LFL was exceeded. This provided the basis for the formula for allowable charge limit. Whilst different AC&HP enclosures were tested, limiting parameters (i.e., “concentration factor”) were chosen based on the enclosures that led to highest concentrations.

Extensions

Given that alternate equipment housings led to different concentrations (interpreted as allowable charge amounts), the inference is that (a) different factors can be applied for different equipment, (b) specific models could be tested to provided dedicated factors and (c) the design of housings can be adjusted to enable greater dilution of releases and thus larger allowable charge limits. See section 3.2.5. Proposals were offered to address such options but consensus was not achieved.

Additional work

Further testing of different AC&HP units, in different sized rooms, etc., is always beneficial to support improvements in the approach. Further improvements or increases to ACLs are foreseeable where the CF

[12] Once diluted with air, refrigerant vapour cannot “re-concentrate” over time.

can be increased upon the condition of unit enclosures that better facilitate dilution of a leak (or where smaller leak sizes are assumed, as discussed in section 3.2.1).

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Tang, W., G. He, W. Sun, S. Zhou, D. Cai, Y. Zhu, Assessment of leakage and risk reduction of R290 in a split type household air conditioner, Int. J. Refrig. 89 (2018) 70–82.

Wu, X., Z. Yang, Y. Shi, Assessment on refrigerant charge limitation basing on a comprehensive consideration of combustion characteristics [J], J. Eng. Thermophys. 34 (11) (2013) 2011–2014.

Zhang W., Yang Z., Li J., et al. 2013. Research on the flammability hazards of an air conditioner using refrigerant R-290. International Journal of Refrigeration, vol. 36, no. 5

Zhang, W., Z. Yang, J. Wang, D. Lv, Z. Zhong, Leakage research of split-type air- conditioner using R290 as refrigerant, J. Refrig. 34 (6) (2013) 42–47.

Zhang, Y., C. Liu, T. Wang, L. Pan, W. Li, J. Shi, et al., Leakage analysis and concentration distribution of flammable refrigerant R290 in the automobile air conditioner system[J], Int. J. Refrig. 110 (2020) 286–294.

Zhong, Z., W. Tang, X. Zhou, K. Li, C. Guo, G. He, Experimental study and optimization of indoor leakage safety of R290 household air-conditioner [J], Cryogenics 2 (2017) 59–65.

Colbourne D., Vonsild A. L. 2022. Refrigerant egression to connected spaces in relation to hydrocarbon charge limits. Proc. 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2022). Trondheim, Norway

3.2.3 Sub-topic: Dispersion under airflow

Issues

The mechanisms influencing the dilution of leaked refrigerant were summarised in section 3.2.2. If the surrounding air has a velocity in a direction tangential to that of the jet or plume, then the rate of entrainment will be increased proportionally to the relative velocity. Accordingly, rate of dilution is similarly increased and resulting concentrations will be correspondingly lower. Incrementally higher air velocities similarly increase the rate of mixing until the space becomes almost homogeneously mixed and most local pockets of refrigerant/air mixture are at or are close to the average space concentration (i.e., release refrigerant mass divided by space volume). Such an effect can be exploited, where a minimum airflow rate is specified for a fan associated with the AC&HP equipment (or indeed for an independent fan), so that formation of flammable concentrations can be almost avoided.

Handling

A series of experiments were carried out with a variety of AC&HP equipment (as well as commercial refrigeration units) in order to validate theoretical aspects of the dispersion process and develop a simple model for determination of a minimum airflow rate necessary for achieving near-homogenous mixing in the event of a refrigerant leak. This was then translated into an expression for use in the standard, so as to account for the basic characteristics of AC&HP equipment as well as specified leak rates.

Outcomes

Provided that airflow is “guaranteed” – either through permanent operation or by means of leak detection – then an allowable refrigerant charge calculation, based on a fraction of the LFL throughout the entire room, may be adopted. The standard includes a basic allowable charge formula, applicable to both “normal tightness” and ETRS; the only difference being different assumptions for leak rate which leads to different minimum airflow rates.

Extensions

Further refinements to the calculation for minimum airflow can be made to better match to particular AC&HP equipment characteristics, but it is unlikely that there are many gains to be made.

The allowable charge formula uses a “concentration factor” of 0.5 for A3 refrigerants; with the highly effective mixing it is in principle feasible to increase it to 0.6, 0.7 or even 0.8, thereby increasing allowable charge for a given space. On the other hand, it would minimise the built-in safety margin reserved to account for uncertainties, such as room congestion, unexpectedly large leaks, airflow blockages and so on.

Work was also carried out to validate the approach for A2Ls, but within the WG21, stakeholders with interests focussed on A2L opted to defer the option. Holding such a position is a rather odd stance since this approach potentially enables greater refrigerant charge than the so-called “reaching height” concept adopted for A2Ls and moreover is substantially less complicated and thus less vulnerable to practitioner error.

Additional work

One remaining area of improvement relates to the "maximum safe leak rate" (MSLR), within Annex PP, which is the leak size above which the integral airflow must be initiated. Currently, there is single value fixed at 6×LFL g/s, being 9 g/min for R290; the presumption is that leak rates below this will not form a flammable layer within the room even once the entire charge has been released since there is ample time for the mixture to diffuse. However, experiments found that when units are above floor level, the MSLR can exceed 9 g/min by a significant amount. With an MSLR of 9 g/min, leak detection equipment needs to be rather sensitive and, in some cases, more than one gas or ultrasonic sensor may be needed, inferring high cost and material requirements. Having a higher MSLR reduces the burden for most systems, which are not floor-mounted. Experimental work was conducted and a suitable correlation has since been developed to determine MSLR as a function of unit height and room size.

Literature

Colbourne D., Suen K. O. 2003. Equipment design and installation features to disperse refrigerant releases in rooms. Part II: determination of procedures. Int. J. Refrig.

Colbourne D., Suen K. O. 2003. Equipment design and installation features to disperse refrigerant releases in rooms. Part I: experiments and analysis. Int. J. Refrig.

Colbourne D., Suen K. O. 2018. Minimum airflow rates to dilute A2L refrigerant leaks from refrigeration systems. Proc. 1st IIR international conference on the application of HFO refrigerants, Birmingham.

Colbourne D., Suen K. O. 2018. Minimum airflow rates to dilute R290 concentrations arising from leaks in room air conditioners. Proc. 13th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2018). Valencia, Spain

Colbourne D., Suen K. O. 2022. Airflow to disperse refrigerant leaks from hydrocarbon refrigeration systems. Int. J. Refrig., vol. 137, pp. 220–229

Hu, M., Li, J., Liu, Z., Li, T., 2018. Experimental and numerical simulation analysis of R-290 air conditioner leak. Int. J. Refrig. 90, 163–173.

Jia, L., Jin, W., Zhang, Y., 2015. Analysis of indoor environment safety with R32 leaking from a running air conditioner. Procedia Eng. 121, 1605–1612, 2015.

Jin, W., Gao, P., Zheng, Y., 2017. Experimental study on ventilation effect on concentration distribution of R32 leaking from floor type air conditioner. Energy Procedia 105, 4627–4634, 2017.

Quanyi Liua,Hui Zhanga, Yi Liua, Hong Huanga, Xiaole Zhanga, Zhipeng Lib, Wei Yao. 2013. Influencing factors of flammable refrigerants leaking in building air conditioning system. Procedia Engineering vol. 62 pp. 648 – 654.

3.2.4 Sub-topic: Releasable charge

Issues

Hitherto, RACHP safety standards were based on the presumption that whatever refrigerant charge was filled into the system would leak out. However, in practice, not the entire refrigerant charge will (or indeed can) leak out. Further, shut-off valves and similar components can be used to trap refrigerant within parts of the system so that the releasable amount can be substantially less. Therefore, if the amount that is released is less than the charged amount, then it is reasonable to consider that amount with regards to allowable charge quantities.

Handling

The main consideration is how to quantify what the releasable charge is, taking into account operating conditions, cycle type, function of components and so on. A test method was developed based on the reasonably most pessimistic arrangement, set of conditions and operating modes. The initial proposal was based on physically collecting refrigerant that leaked from an orifice and then weighed. However, some stakeholders preferred an alternative method, where the leaked refrigerant is released to the atmosphere and the quantity retained in the system is recovered and measured, which is then used to deduce the released mass. The determined releasable charge may then be regarded as the refrigerant charge when it comes to determining the charge limit or minimum room size.

Outcomes

The method was integrated into the standard, along with additional requirements related to response of detection systems, reliability of valves used to retain charge and repeatability of the test.

Extensions

The current test method differs from the originally proposed method, which may be preferable under some situations. Subsequently, alternative test methods have emerged in the literature and test institutes, which may offer better convenience, accuracy or other advantages; these methods should be made available within the standard.

An extension of the releasable charge method was developed further for A2L refrigerants, aimed at multisplit systems with a variety of different indoor unit combinations (since it would be impractical for test all possible combinations) – this may be termed the “discretised releasable charge” method. In principle, this extension could also be applied to A3s and the opportunity should be offered.

The most significant limitation, though, is that for A3 refrigerants it is still restricted to systems containing no more than 26×LFL (about 1 kg) due to the upper charge limit of direct systems for occupied spaces (see section 3.2.7).

Additional work

A more detailed assessment of the alternative methods, including the A2L discretised releasable charge for A3s, should be evaluated and integrated into the standard.

Due to the overall complexity and resource-heavy needs for carrying out the testing, numerical/calculation methods should be developed and cross-checked against test results in order to offer an easier route for equipment producers to implement the concept. Extensive work, covering a range of conditions and system architectures would likely be required before accepting a numerical releasable charge methodology.

Literature

Colbourne, D., Hühren, R., Rajadhyaksha, D. D., Et Al. 2013. Refrigerant leakage control for R-290 in split type refrigeration and air conditioning systems. Compressors 2013: 8th International Conference on Compressors and Coolants, Castá Papiernicka, Slovak (Republic)

Colbourne, D., Hühren, R., Vonsild, A. 2012. Safety concept for hydrocarbon refrigerants in split air conditioner. Proc. 10th IIR-Gustav Lorentzen Conference on Natural Working Fluids (GL2012). Delft, The Netherlands.

He G., Sun W., Tang W., et al. 2019. The application and risk assessment of R290 in split type household air conditioners. Proc. 25th IIR International Congress of Refrigeration: Montréal, Canada

Tang W., He G., Cai D., et al. 2017. Investigation of the practical method for enhancing the safety of R290 split type household air conditioner. Proc. 5th IIR Conference on Thermophysical Properties and Transfer Processes of Refrigerants, Seoul, South Korea

Tang W., He G., Cai D., et al. 2017. The experimental investigation of refrigerant distribution and leaking characteristics of R290 in split type household air conditioner. J. Applied Thermal Engineering, vol. 115

Tang W., He G., Sun W. 2018. Assessment of leakage and risk reduction of R290 in a split type household air conditioner. International Journal of Refrigeration, vol. 89

3.2.5 Sub-topic: Enclosure geometry

Issues

As mentioned in section 3.2.2, it was found that the design and construction of a unit can have a significant effect on developed floor concentrations and thus ACLs. Whilst it is difficult to characterise the effect directly based on these construction characteristics, a correlation was found between the concentration of the refrigerant-air mixture emerging from the enclosure openings and the "concentration factor" (CF) in the ACL formula.

Handling

Based on the experimental observations, it was thus proposed to measure the exiting concentration from a unit and determine the appropriate CF from the correlation. The CF could then be used in the ACL formula (instead of the default value) to determine allowable charge appropriate for the equipment under consideration. This would represent a method for determining ACL that is somewhere between the conventional calculation method and the surrounding room test (see section 3.2.8). Moreover, it could encourage designs of units and enclosures that lead to high vales of CF to be used if higher charge amounts were needed or simply designs that helps disperse leaks better (if using the default CF).

Outcomes

There was no consensus for adopting the proposal.

Extensions

The proposal will again be discussed in the next revision round.

Additional work

Further measurements should be carried out to further validate the approach, particularly demonstrating that the correlation between existing concentration and CF match the allowable charge determined with full room tests. Improvements to the measurement method of existing concentration, especially across a wider range of different types of units would be appropriate.

Literature

Colbourne D., Suen K. O. 2018. Assessment of factors affecting R290 concentrations arising from leaks in room air conditioners. Proc. 13th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2018). Valencia, Spain

Colbourne D., Suen K. O. 2021. Hydrocarbon refrigerant charge limits for quiescent rooms. Int. J. Refrig. Vol. 125, pp 75–83

Colbourne D., Suen K. O. 2022. Concentrations of hydrocarbon refrigerant exiting from RACHP equipment enclosures. Proc. 15th IIR-Gustav Lorentzen conference on Natural Refrigerants, Trondheim, Norway

3.2.6 Sub-topic: Room obstacle effects

Issues

To achieve consistency across concentration measurements, release tests to simulate leaked refrigerant into rooms are usually carried out in absence of any furniture, obstacles or other obstructions within the test room. However, this raises the question of whether findings remain valid when there is not an empty room. There are technical arguments stating that having objects in the room assists with dilution and conversely that the inhibit dilution, thus leading to lower or higher concentrations.

Handling

Considering the two main ACL/AQL determination methods (quiescent and with airflow), analyses were carried out to address both. Under quiescent conditions, experiments were carried out, where a test room was filled with a collection of random furniture and similar objects, "solid" (e.g., boxes, cupboards), non-closed (E.G., bookshelf) and frame structures (e.g., chairs). For airflow conditions, a CFD study was carried out, evaluating a variety of different room furniture arrangements. In both cases, there were only small changes in maximum floor concentrations.

Outcomes

With the currently applied concentration factors (CF), any increases in floor concentration were regarded as sufficiently small to be accounted for by the various built-in safety margins. As such there is no need to add additional margins to the determination of ACL/AQL for either quiescent or airflow cases.

Extensions

Not applicable.

Additional work

As with any situation that involves infinite variables, furniture arrangements can arise that lead to higher concentrations. An example may include where solid furniture forms a barrier across an entire room. However, such arrangements are probably very rare and the need to account for them is eliminated when considering the probability of a large leak and the probability of such an arrangement. It is not deemed necessary to carry out additional work in this regard.

Literature

Colbourne D., Suen K. O. 2018. Assessment of factors affecting R290 concentrations arising from leaks in room air conditioners. Proc. 13th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2018). Valencia, Spain

Prakash, C Ram, MR Gautham, D Mohan Lal, S Devotta, D Colbourne. 2021. CFD simulation of HC-290 leakage from a split type room air conditioner. Proc IMechE Part E: J Process Mechanical Engineering, 0(0) 1–11

3.2.7 Sub-topic: Upper charge limits

Issues

The upper charge limit (UCL) or cap limit is a value above which the charge is not permitted to exceed, regardless of the room size, system location, etc. UCL essentially acts as a constraint to the maximum size or capacity of a system. Currently the UCL for A3 (and A2) refrigerants is 26 m^3 × LFL for systems in an unoccupied space. for systems in a ventilated enclosure, unoccupied space or outdoors it is 130 m^3 × LFL. These correspond to about 1 kg and 5 kg, respectively, for R290. Conversely, for A2Ls, the UCLs are 52 m^3 × LFL (around 15 kg) or 260 m^3 × LFL (about 80 kg) and in fact the 260 m^3 × LFL is also applicable to direct ETRS equipment.

Particularly for manufacturers where ranges of room ACs which extend up to about 12 kW, this constraint can mean that it is not possible to shift all models to an HC refrigerant, thus discouraging any shift to an A3 refrigerant. By comparison, the UCL for A2Ls is very liberal and does not impose any such restriction for almost any type of equipment.

Arguably, the purpose of the UCL is a sort of “comfort factor”; it may be regarded as providing a boundary against practitioners applying excessive quantities of flammable substances, where the existing prescribed safety measures may apparently be insufficient to achieve a tolerable level of risk. The basis for selection of these values is, however, unknown or justified arbitrarily. The 1 kg UCL was a reduction from 1.5 kg that was already within (at the time) national standards, such as DIN 7003, NPR 7600 and BS4434. The 5 kg matched the 5 kg limit in these standards for outdoor public access areas. Still, the technical basis (if any) for the choice of these values remains uncertain.

For equipment within the scope of the standard, a UCL of 5 kg is not a hindrance, 1 kg limit causes potential problems for some larger reversible split ACs (in the range of 10 to 15 kW nominal cooling capacity), especially multi-split, when longer interconnecting piping is involved. Proposals (requests) were made to increase the UCL to 1.5 kg (about 40 m^3 × LFL), but consensus was not reached.

Handling

Work has been carried out (mainly under other standards) to identify the implications on flammability risk of increasing the UCL. This found that – provided that the allowable charge limit was adhered to – a higher UCL did not increase flammability risk, indeed it resulted in a lower ignition frequency. (This can be interpreted as, two smaller systems in smaller rooms complying with the allowable charge limit led to a greater risk than one larger system with double the charge in a room twice the size. It is actually safer to use one larger system then two smaller ones.)

Outcomes

No change to the standard.

Extensions

Particularly for systems located in occupied spaces, there is a need for an increase in UCL to enable entire ranges to shift to HC refrigerants.

Additional work

More detailed risk assessments may be needed to better characterise the implications of such an increase and identify whether additional mitigation measures need to be considered. Within the current revision process (under IEC SC 61D MT28), a new proposal has been submitted and supported by a detailed risk assessment[13]. This risk assessment shows no increase in risk or a significant reduction in risk with larger charge amounts (whilst adhering to the ACLs). Use of two or more smaller systems instead of one larger system increases the risk by at least an order of magnitude; it is irrational for a safety standard to encourage installations with higher risk.

Literature

CEN TR 17608: 2021 State of the art on the use of flammable refrigerant alternatives, in particular from class A3, in refrigeration, air conditioning and heat pump equipment

Colbourne D., Suen K. O., Li T. X., Vonsild A, Vince, I. 2020. General framework for revising class A3 refrigerant charge limits – a discussion. Int. J. Refrig. vol. 117, 2020/09

IEC SC61D MT28-052 Assessment higher UCLs

WG11 and WG6 documents

3.2.8 Sub-topic: Surrounding concentration test

Issues

As was identified in section 3.2.2, the developed concentration within a room arising from a given leak size can be strongly affected by the design and construction of the indoor unit housing. Similarly, in section 3.2.3 the benefit of integral airflow was highlighted. In experiments it was found that the ACL could differ by a factor of two, depending upon the enclosure or more if integral airflow was employed. Since it is not easy to relate detailed characteristics of the enclosure or, and in combination with certain airflow patterns, to the ACL, an easier approach to facilitating this behaviour is to carry out individual tests on specific AC&HP designs. Furthermore, testing also provides manufacturers with improved certainty that their particular product(s) would not form a dangerous concentration in real installations.

Handling

A surrounding concentration test, similar in set-up to that in Annex CC test in IEC 60335–2–89, comprising a unit installed according to the instructions and with simulated leaks being made from selected points. Concentrations are then measured at vulnerable locations within room beyond the housing of the unit.

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[13] Document 61DMT28-0XX

Resulting data is used to determine whether LFL is exceeded or not and provide indications as to design (or charge) changes to otherwise ensure against external flammable concentrations.

Outcomes

A proposal was made for inclusion in IEC 60335-2-40, but consensus was not reached[14].

Extensions

Such a test could easily be integrated into the standard and it could lead to improved designs of equipment and innovation of integrated mitigation features to help achieve lower concentrations/greater charge quantities.

Additional work

Further testing of different types of equipment, refrigerant quantities, room sizes is desirable, so that the concept can be demonstrated more clearly to stakeholders. Questions related to test room set-up, sensor positioning and so forth are still under discussion.

Literature

http://lifefront.eu/

IEC SC 61C/735/INF Background to document on development of safety requirements under IEC SC 61C WG4 for commercial refrigeration appliances using more than 150 g of flammable refrigerants

Meljac, L., Forsen, M., Colbourne, M. 2021. Increasing flammable refrigerant charge size without compromising safety. Proc. 13th IEA Heat Pump Conf., Jeju, Korea

3.3 Ducted systems

3.3.1 Sub-topic: Ducted system charge limits

Issues

So-called ducted systems comprise refrigerant-containing parts located in an “air handling” enclosure, from where the conditioned air is blown along one or more ducts to rooms. Usually there are return air ducts which draw the room air back to the air handler for further treatment.

Conventional determination of ACL is based on the size of a single room, but in the case of a ducted system the air may be distributed to more than one room and in most such systems the refrigerant charge would exceed the ACL if it were based on a single room. To resolve this for A2Ls, it is permitted to consider the size of all rooms supplied by the ducting system to determine the ACL (provided integral airflow is incorporated in the appliance—either activated by a leak detection system or continuous); however, this is not permitted for A2 and A3 refrigerants, those posing a major barrier to their application in such systems.

Handling

During a project to develop R290 ducted AC equipment, numerous tests and CFD calculations were carried out to investigate behaviour in general and validity of charge limits. Aspects such as dilution and mixing along ducting, at duct discharge, migration out of equipment housings and effectiveness of initiating airflow following an internal release were evaluated. It was concluded that with typical design and construction characteristics, the use of R290 could be easily and safely applied, avoiding formation of flammable mixtures in virtually all situations. Moreover, the existing measures within the standard were broadly sufficient to be applied to class A3 (and A2) refrigerants.

[14] A test is already included in IEC 60335-2-89 for commercial refrigerating appliances and is within the draft prEN 378-1 and draft ISO 5149.

Outcomes

The proposal was not accepted, on the basis that the draft standard already contained many changes supporting A3 refrigerants. It was remarked that national committees would object if there were too many positive changes. The proposal has been resubmitted to MT28.

Extensions

Not applicable.

Additional work

Further concepts have been proposed, where a damper system is used at the air handler, so that if a leak were to occur, the air could be redirected and ventilated to the outside. This may be regarded as a sort of variation of the releasable charge concept. However, to date, no trials on the effectiveness of the method have been carried out.

Literature

Colbourne D., Arango A., Dickson E., Et Al. 2018. Safe design of R290 ducted air-conditioning equipment. Proc. 13th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2018). Valencia, Spain

Colbourne, D., Hühren, R., Vonsild, A. 2012. Safety concept for hydrocarbon refrigerants in split air conditioner. Proc. 10th IIR-Gustav Lorentzen Conference on Natural Working Fluids (GL2012). Delft, The Netherlands.

Elatar A., Abu-Heiba A., Patel V., Et Al. 2018. Evaluation of flammable volume in the case of a catastrophic leak of R-32 from a rooftop unit. Int. J., Refrig., vol. 91

Elatar A., Abu-Heiba A., Patel V., Et Al. 2018. Risk assessment of catastrophic leak of R452B from packaged unit into a residential space. Proc. 1st IIR international conference on the application of HFO refrigerants, Birmingham.

Wang H., Cao T., Hwang Y., Chang S. D. 2020. Performance comparison of three refrigerants in a novel unitary air conditioning system. Proc. 14th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2020). Kyoto, Japan.

Wang H., Cao T., Hwang Y. 2019. A novel unitary air conditioning system design for flammable refrigerants and building ventilation. Proc. 25th IIR International Congress of Refrigeration: Montréal, Canada.

3.4 Sub-topic: Potential and critical leak points

Issues

It is important to have assumptions about where refrigerant may leak from. Of the potential leak points, those which would result in highest concentrations are regarded as critical leak points.

Potential and critical leak points are necessary for leak simulation tests (for measuring concentrations at ignition sources), for determining releasable charge and for evaluating effectiveness of leak detection methods and/or sensor positioning.

A potential leak point is defined as:

> *any point in the refrigerating system that can be a weak point due to manufacturing processes, exposure to damage, sharpness of a bend, or similar stresses*

The definition can lead to subjective interpretations.

Within Annex FF, it is stated that potential leak points are not those which:

> *– are protected from potential damage during normal operation, service and maintenance;*
> *– have no connecting joints;*
> *– have no bends with centreline bend radius less than 2,5 times the external pipe diameter*

However, the suitability of such criteria is contentious, as for example, some connecting joints (such as brazed or welded joints) are known to be stronger/tighter than the pipe itself and leaks are not so uncommon in wider bends (e.g., as found in the leak size study discussed in section 3.2.1).

There are various implications associated with the definitions and guidance for identifying potential leak points.

From a practical perspective, a literal interpretation could lead to (unnecessarily) testing a vast number of potential leak points.
Also testing points that are highly unlikely to leak or to the contrary missing points that are more likely to leak.

Another paradoxical implication – that was attempted to be addressed by including the “no connecting joints” condition – is that if a system has been designed to eliminate all those potential leak points, the inference is that there is no possibility of leakage. And if this is the case, then the concept of refrigerant charge limits should not apply.

Handling

The topic was handled through numerous iterative discussions, anecdotal reports of system leaks and “what if” analyses.

Outcomes

The text mentioned above was (reluctantly) agreed, in absence of better proposals.

Extensions

Not applicable.

Additional work

Not applicable.

Literature

ASHRAE. ASHRAE-1808: Servicing and installing equipment using flammable refrigerants: assessment of field-made mechanical joints

EN 1127-1:2019 Explosive atmospheres. Explosion prevention and protection - Basic concepts and methodology

IEC 60079-10-1:2020 Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres

ISO 14903:2017 Refrigerating systems and heat pumps. Qualification of tightness of components and joints

3.5 Sub-topic: Ventilated enclosure

3.5.1 Sub-topic: Airflow rate and safety system

Issues

A “ventilated enclosure” arrangement is where a system or part of system is contained within relatively well sealed housing. This housing is either continuously ventilated to the outside or employs ventilation that is initiated by leak detection. The fan, ducting and associated energy use can impose not-insignificant costs so optimisation of the concept is important.

Handling

Since this concept can be used with split systems (such as split air-to-water heat pumps), it was therefore important to revise the requirements to account for ETRS designs, whereby the smaller assumed leak rate leads to lower incremental costs.

Outcomes

Leak rates for ETRS systems was added to the requirements.

Extensions

None.

Additional work

Further work on ventilated enclosures has identified additional aspects that could benefit from. Examples include enclosure tightness, the 10 enclosure volumes limitation and others.

Literature

CEN-TC 182-WG 6_N1739

3.6 Sub-topic: Leak detection

3.6.1 Sub-topic: Gas sensor requirements

Issues

Various mitigation measures require some form of leak detection, of which gas sensing is one option. If gas sensors are to be used, they must provide a minimum level of sensitivity, reliability and functionality. Different sensors will potentially provide a wide range of such performance, so it is necessary to specify performance criteria that provide confidence that these minimum levels will be achieved (throughout the AC/HP lifetime).

Handling

An ad hoc group (AHG) was convened, comprising gas sensor experts, representatives of manufacturers, etc. in order to develop material. This involved some testing and review of results within the AHG.

Outcomes

A new annex was drafted, comprising a series of requirements relating to sensitivity, reliability and functionality, including contamination, poisoning, response time and so forth.

Extensions

Since these requirements are equally needed by various other RACHP standards, it has been proposed to extract the annex and form a new technical specification (TS), eventually leading to a new standard (rather than the requirements being located in the AC/HP standard and others having to refer to it.

Additional work

The annex was drafted in a short period and it is now recognised that substantial improvements are necessary, which is being carried out within a new MT under IEC SC 61D.

As discussed below (sections 3.6.2 and 3.6.3), similar issues arise with the use of other detection methods and it may be appropriate to also include requirements within the same document as for gas sensors.

Literature

AHRI. 2017 AHRTI-9009: Leak detection of A2L refrigerants in HVACR equipment.

AHRI. 2021. AHRTI-9014: Assess refrigerant detector characteristics for use in HVACR equipment.

Elbel S., Zheng J. 2021. Evaluation of various refrigerant leak detector technologies for use with low-GWP A2L refrigerants (AHRTI #9014). Proc. 2nd IIR Conference on HFO Refrigerants and Low GWP Blends

3.6.2 Sub-topic: Detection using ultrasonics

Issues

Various mitigation measures require some form of leak detection, of which sensing local ultrasonic noise is one option. If ultrasonic transducers are to be used, they must provide a minimum level of sensitivity, reliability and functionality. Different sensors will potentially provide a wide range of such performance, so it is necessary to specify performance criteria that provide confidence that these minimum levels will be achieved (throughout the AC/HP lifetime).

Handling

The concept is relatively embryonic (for this application) and initial discussions questioned the general feasibility of the technology. Preliminary evaluations and testing showed it to be potentially effective.

Outcomes

The technology is permitted and basic requirements are included, although nothing addresses transducer sensitivity, reliability or functionality in detail. (Subsequent work has shown that these transducers are considerably more robust than most gas sensors.)

Extensions

Not applicable.

Additional work

As discussed below (section 3.6.3), similar issues arise with the use of other detection methods and it may be appropriate to also include requirements within the same document as for gas sensors.

Literature

Colbourne, D., Vonsild, A. 2003. Detection of R290 leaks in RACHP equipment using ultrasonic sensors. Int. J. Refrig. Vol. 151, pp 342-353

3.6.3 Sub-topic: Detection with system parameters

Issues

Various mitigation measures require some form of leak detection, of which sensing changes in system operating parameters is one option. If system parameters are to be used, detecting values such as temperature, pressure and flow rate rely on various sensors and these must provide a minimum level of sensitivity, reliability and functionality. Different sensors will potentially provide a wide range of such performance, so it is necessary to specify performance criteria that provide confidence that these minimum levels will be achieved (throughout the AC/HP lifetime).

Handling

The concept is relatively well known, although more within the scope of general fault-finding than specifically for leak detection for safety purposes. The general feasibility of the technology is acknowledged and previous evaluations and testing showed it to be potentially effective.

Outcomes

The technology is permitted and basic requirements are included, although nothing specifically addresses sensitivity, reliability or functionality in detail. However, there is ample experience with pressure transducers and thermocouples and they are already designed with high levels of reliability because they are otherwise often used for (pressure) safety.

Extensions

Not applicable.

Additional work

As discussed below (sections 3.6.2 and 3.6.3), similar issues arise with the use of other detection methods and it may be appropriate to also include requirements within the same document as for gas sensors.

Literature

Chen, Guangming, Fang, Jiahao, Li, Zetian, Zhang, Shaozhi. 2023. Theoretical analysis of the impacts of refrigerant leakage on the performance of a flash tank vapor injection heat pump. Int. J. Refrig. Volume 147, Pages 10-19

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Li Z., Shi S., Chen H., et al. 2020. Machine learning based diagnosis strategy for refrigerant charge amount malfunction of variable refrigerant flow system. International Journal of Refrigeration, vol. 110

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Llopis-Mengual B., Navarro-Peris E. 2023. Coupling effects in fault detection and diagnosis for variable speed air-to-water propane heat pump with subcooling control. Proc. 26th IIR International Congress of Refrigeration: Paris, France

Llopis-Mengual B., Navarro-Peris E., Barceló Ruescas F., Corberán J. M. 2022. Modeling and simulation of the impact of soft faults in a reversible air-to-water propane heat pump. Proc. 19th International Refrigeration and Air-Conditioning Conference at Purdue.

Yoo J. W., Hong S. B., Kim M. S. 2015. Numerical study for detection of refrigerant leakage in vapor compression refrigeration cycle. Proc. 24th IIR International Congress of Refrigeration: Yokohama, Japan

Yoo J. W., Hong S. B., Kim M. S. 2017. Refrigerant leakage detection in an EEV installed residential air conditioner with limited sensor installations. International Journal of Refrigeration, vol. 78

3.7 Sub-topic: Miscellaneous and peripheral studies

As interest in low GWP flammable refrigerants grows, there has similarly been an increase in the number of studies related to the subject in general, which are to some extent of relevance to the work under IEC SC 61D. Subject areas include the following:

- Charge reduction – whilst not a safety measure directly, nor handled by safety standards, it is nevertheless an important element of safe system design.
- Other RACHP equipment – various flammability safety aspects applicable to other RACHP equipment, but out of the scope of IEC 60335-2-40. Indeed, the considerations are much the same as those under this standard, but subject to slightly different considerations according to the type of equipment.
- Consequences of ignition – most activities are focussed more on reducing likelihood of ignition rather than minimising the severity of ignition events. The topic is nevertheless important when considering overall reduction of flammability risk.
- Quantified risk assessment – numerical calculation of the probability of ignition of the flammable refrigerant and severity of subsequent consequences (such as overpressure, thermal dose and

secondary fire). This is a useful approach to help gauge the significance of the perceived hazards against the likelihood of comparable events for established equipment and products.

Some example literature sources related to these subject areas are provided below. In addition, a list of projects under the AHRI is provided in Table 2. (Several of these are mentioned above in relation to several of the discussed sub-topics.)

Table 2: List of flammable refrigerant projects[15]

Projects	Project Description	Status
NFPA study on professional refrigeration equipment	NFPA study on group A3 refrigerants in refrigeration equipment for commercial kitchens and retail stores: https://www.nfpa.org/education-and-research/research/fire-protection-research-foundation/projects-and-reports/evaluation-of-the-fire-hazrd-of-ashrae-cass-a3-refigerants-in-commercial-refrigeration-applications	Complete
AHRTI-9007-01: Benchmarking risk by whole room scale leaks and ignitions testing of A2L refrigerants	A2L refrigerants leak and ignition testing under whole room scale conditions was conducted to develop data and insight into the risks associated with the use of A2L refrigerants versus A1 refrigerants while considering ambient conditions (temperature and humidity) and refrigerant lubricants. View Report	Complete
AHRTI-9007-02: Benchmarking risk by whole room scale leaks and ignitions testing of A3 refrigerant	This project is to conduct A3 refrigerant leaks and ignitions testing under whole room scale conditions, understand the risk associated with the use of A3 refrigerants, and provide test data to support future revisions of relevant safety standards associated with using A3 refrigerants. View Report	Complete
AHRTI-9015: Assessment of refrigerant leakage mitigation effectiveness for air-conditioning and refrigeration equipment	The objective of this project is to demonstrate the efficacy of refrigerant leakage mitigation strategies contained within residential split-systems, packaged air-conditioning equipment and commercial refrigeration products. View Report	Complete
ASHRAE-1806: Flammable refrigerants post-ignition risk assessment	The objective of this project is to understand the Severity of events where flammable refrigerants are ignited under different scenarios for various HVAC&R products.	Ongoing
ASHRAE-1807: Guidelines for flammable refrigerant handling, transporting, storing and equipment servicing and installation	This project accessed flammable refrigerant safety guidelines and/or requirements that exist domestically and internationally. The assessment will be used to propose requirements/guidelines for the safe handling, storing and transporting of flammable refrigerants.	Complete
ASHRAE-1855: Determination of the impact of combustion by-products on the safe use of flammable fluorinated refrigerants	The overall objective of the project is to understand the HF and COF2 exposure risk if ignitions of flammable halogenated refrigerants occur and how to clean up following a variety of ignition events, as well as to identify knowledge gaps.	Ongoing
ORNL: Determination of setting charge limits for various types of equipment employing flammable refrigerants	The primary objective of the project is to examine the currently imposed limits for flammable refrigerant alternatives (A2L, A2, and A3) and identify reasonable adjustments to these limits as appropriate. ORNL Report Part 1, ORBL Report Part 2	Complete
ORNL: Experimental evaluation of refrigerant leak characteristics for different HVAC&R equipment types	The objective of the project was to quantify actual leak rates and duration for various pieces of equipment by conducting refrigerant leak tests under operating conditions representative of actual applications. ORNL Report	Complete

[15] From https://www.ahrinet.org/analytics/research/ahri-flammable-refrigerants-research-initiative, accessed 26th January 2024

Projects	Project Description	Status
NIST: Modelling tools for flammability ranking of low-GWP refrigerant blends	The project is to develop modelling tools that can predict the burning velocity of arbitrary mixtures of R32, R125, R134a, R152a, 1234yf, and 1234ze(E), so that flammability of a blend can be minimized, while simultaneously maximizing performance related to other parameters.	Ongoing

Literature (limited selection)

Anderson K., Lundahl G., Granryd E. 2022. Air-air split AC with minimum charge of propane. Proc. 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2022). Trondheim, Norway

Colbourne D. 2014. Comparative risk assessment of hydrocarbon refrigerant in a refrigerator and split air conditioner. Proc. 11th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2014). Proceedings. Hangzhou, China

Colbourne D., Suen K. O. 2015. Comparative evaluation of risk of a split air conditioner and refrigerator using hydrocarbon refrigerants. International Journal of Refrigeration, vol. 59

Dankwerth C., Methler T., Braungardt S., Sonner C., Oltersdorf T., Miara M., Schossig P., Schnabel L. 2021. Evaluation of a low charge heat pump circuit using propane. Proc. 13th IEA Heat Pump Conference 2021: Heat Pumps – Mission for the Green World.

Dankwerth C., Methler T., Oltersdorf T., Schossig P., Schnabel L. 2020. Experimental evaluation of a charge reduced heat pump module using 150g of propane. Proc. 14th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2020). Kyoto, Japan

Ghoubali R., Byrne P., Bazantay F. 2017. Refrigerant charge optimisation for propane heat pump water heaters. International Journal of Refrigeration, vol. 76

Hansen B., Kujak S. 2018. Review of methodology to set safety factors for A2L flammable refrigerant being adopted by product safety standards. Proc. 1st IIR international conference on the application of HFO refrigerants, Birmingham

Hrnjak P. 2019. Rational approach to refrigerant charge reduction. Proc. 25th IIR International Congress of Refrigeration: Montréal, Canada

Kujak S., Hansen B., Schultz K. 2016. Considerations and methodologies for the safe use of flammable refrigerants for air conditioning. Proc. 12th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2016). Edinburgh, United Kingdom

Methler T., Dankwerth C., Joos L., Fugmann H., Morawietz K., Schnabel L. 2022. Experimental analysis of various refrigerant circuit component combinations for low charge propane heat pumps. Proc. 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2022). Trondheim, Norway

Winthereik F. P., Pedersen P. H., Lauridsen T. 2022. Hot water heat pump with low-charge propane refrigerant. Proc. 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2022). Trondheim, Norway

Zhang W., Yang Z., Zhang X., et al. 2016. Experimental research on the explosion characteristics in the indoor and outdoor units of a split air conditioner using the R290 refrigerant. International Journal of Refrigeration, vol. 67

4 Final remarks

Previously, IEC 60335-2-40 was extremely restrictive to the application of HC refrigerants, to the point that it effectively precluded their use in most AC units for about two decades.

From 2015, over a period of 7 or 8 years, working groups under IEC SC61D, WG16 and then WG21, developed requirements and underlying assumptions to enable wider potential use of HC refrigerants in various product groups that fall under the scope of the standard.

The main subject for revision is the allowable refrigerant charge amount, which was the primary restriction for application of HCs. Whereas the previous version restricted the quantity of HC (e.g., for wall units) to about 10 – 20 g/m^2 of room area, the revised requirements increase this to between 25 g to over 100 g/m^2, depending upon which mitigation measures are applied. The incremental costs of these additional measures are generally negligible or relatively modest if applied intelligently[16].

Contributing to this was the improved understanding and characterisation of release conditions and how they affect room concentrations. Overall, there are several related sub-topics that are pivotal to the wider application of A3 refrigerants that were the subject of thorough investigation.

First is the assumption of leak rate. Previous requirements were often based on the so-called 4-minute leak fallacy. Whilst the use of this assumption has become popularised, it is known to be fundamentally flawed and does not stand up to even basic technical analysis. Instead, new requirements use a substantially more robust approach, based on assumed leak hole size, originating from extensive field studies and mass flow derived from choked flow of the applicable refrigerant. Whilst not perfect, this approach is technically defensible and is consistent with other approaches within industries that employ hazardous substances.

Second is an improved understanding of the condition that a leak emerges from equipment housing. Previously, an imposed assumption was that "pure", 100% refrigerant vapour exited the unit housing. Extensive measurements found that in all cases, the exiting mixture concentration was weak in HC, due to internal turbulence and mixing with air due to impingement of a leak jet onto immediate internal surfaces. The resulting low concentration emerging from indoor units leads to much lower concentrations within the room and across the floor. Accordingly, significantly more refrigerant can be released below room concentrations approach LFL. The behaviour was found to be broadly proportional to room size (and release amount).

Related to this is the third aspect, being how the refrigerant disperses throughout a space. Understanding of this behaviour under quiescent conditions is fairly well understood, although extended experimentation was also carried out to better characterise how the release distributes throughout a room under the pre-mixed conditions (as discussed above). However, the dispersion behaviour when the release occurs simultaneously with fan operation of an RACHP unit had been largely unexplored. The existing edition of the standard employed a method (limited for use with A2Ls only) that relied on the so-called "reaching height" concept, where a mixture is blown up into the room and then assumed to dilute during its decent. Apart from the methodology being rather complex, the underlying assumptions and mixing phenomenon associated with this approach were found to be lacking, so an alternative approach was developed, based on whole room mixing. Following extensive experimental work, a discrete formula was developed and implemented, that enables minimum airflow to be identified, based on basic ACHP unit and leak characteristics, ensuring that the released refrigerant would be homogenously mixed in the room and localised flammable concentrations avoided.

Fourth, is related to the prior assumption that all the refrigerant charged into the system will be released in the event of a leak. This is never the case, since some refrigerant will always reside inside the system at atmospheric pressure and also within the compressor lubricant. Typically, this corresponds to around 10% of the system charge amount, but depends upon system design, function and components. Moreover, additional features can be applied to a system, such as shut-off solenoid valves, which enable greater quantities of refrigerant to be retained within other parts of the circuit, prevented from being released. Depending upon the system design, leak detection method applied and control strategy, such a concept can retain between 15% up to 95% of the system charge. However, due to the upper charge limit (see section 3.2.7), this approach cannot be extended to systems containing beyond about 1 kg of HC refrigerant. If the charge can be reliable retained in the system, this should not be a constraint.

Despite a satisfactory outcome to the process and substantial accumulation of improved understanding associated with the application of A3 refrigerants in RACHP equipment, there are numerous areas where

[16] https://www.green-cooling-initiative.org/fileadmin/user_upload/Report_Can_HCs_be_used_for_HPs_in_Europe_2022.pdf; https://www.green-cooling-initiative.org/fileadmin/user_upload/2022_Proklima_Split_AC_Assessment.pdf

further understanding is sought and improvements in requirements should be implemented into IEC 60335-2-40 and corresponding national/regional standards. In summary, these include:

- Further empirical data on leaks, to enable better characterisation of size in relation to system design and manufacturing, choice of components and operating conditions (section 3.2.1).
- Development of a test method, where the concentration factor (CF) is determined for a specific product or particular design, so that the ACL can benefit from any special design (if applied) that helps improve dilution of a refrigerant leak (section 3.2.5 and 3.2.8).
- Develop an alternative approach for maximum safe leak rate (MSLR) that is less stringent than the present requirement, for when installations can tolerate higher leaks without the need for integral airflow (section 3.2.3).
- Revision of the releasable charge method to enable new and alternative methods (section 3.2.4).
- Extend the “discretised” releasable charge method to A3 refrigerants (instead of only A2Ls) (section 3.2.4).
- Eliminate the limitation of 26×LFL for releasable charge for A3 refrigerants (section 3.2.4).
- Extend the upper charge limit (UCL) for A3 refrigerants to beyond 26×LFL or ideally, eliminate the UCL entirely (section 3.2.7), which could be done through a combination of numerical, computational and experimental approaches.
- Enable the total room size approach for ducted systems to be used with A3 refrigerants, not only A2Ls (section 3.3.1).
- Apply improvements to “ventilated enclosure” concept to take account of enclosure tightness and handling of other aspects (section 3.5).

The process of harmonising national and regional safety standards will benefit greatly from utilisation of the background research, discussion, and conclusions reached in the IEC working groups as described in this report. Additional work as outlined above would also contribute substantially to the further development of requirements in the IEC 60335-2-40 standard and corresponding national and regional safety standards, to overcome the remaining constraints on the design and adoption of equipment using HC refrigerants.