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D Colbourne
P Solomon
R Wilson
L de Swardt
R Nosbers
M Schuster

Development of R290 Transport Refrigeration System

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Why this topic?

- Find out about the development process for a prototype system for use in refrigerated transport applications using a flammable refrigerant
- Gain a better understanding of how refrigerant flammability hazards can be overcome
- A practical example of compliance with ATEX and other safety requirements
- How lifecycle emissions from transport applications could be reduced

1 Abstract

Transport refrigeration systems for small and large trucks have been developed using R290. They are electrically driven via a diesel engine and alternator and include a variable speed drive for capacity control. For the design of the systems the main aspects addressed were circuit optimisation and integration of safety measures. Circuit optimisation comprised system simulations in order to select compressors and redesign of heat exchangers in order to achieve the same cooling capacities as R404A, whilst maximising improvement in COP and reducing refrigerant charge as much as possible. Subsequent to this, measurements were carried out to validate the performance with R290. In order to mitigate the flammability risk of using R290, several aspects were addressed. In terms of the equipment redesign, other than charge size reduction, the main changes were to remove potential sources of ignition or apply pre-ventilation to remove any build-up of potentially flammable mixtures. Additionally, a leak identification feature was integrated into the system controls whereby a suspected substantial leak would result in a shut-down of the system and a warning signal to ensure the amount of refrigerant that can leak into the refrigerated space is limited. Extensive leak simulation tests were carried out to characterise the development of potentially flammable concentrations around the condensing unit and surrounding area, within the refrigerated and adjacent spaces. Conformity to the relevant parts of EN 378, SANS 10147 and the essential health and safety requirements of the Atex (equipment) directive were confirmed.

2 Introduction

Transport refrigeration includes intermodal containers, refrigerated ships, refrigerated train carriages, air cargo containers and refrigerated road vehicles, including vans, trucks and trailers. The emissions of refrigerant from this sector accounts for about 5% of the total (as tCO2-eq) although it varies by country. Due to their widespread use, refrigerated road vehicles (RRVs) represent the largest portion of direct emissions. Typically annual leakage is high compared to other sub-sectors, with values ranging around 15% to 50% of the system charge per year depending upon region, system manufacturer and local conditions. Currently the majority of RRVs use R404A and R22, with a smaller percentage on R134a and R410A, although recently some RRV system manufacturers announced adoption of other alternative refrigerants including R452A as well as R744. In parallel to conventional vapour compression systems, several manufacturers are supplying open cryogenic systems with R728, where the refrigerant is vented to atmosphere. To-date, there have been limited trials with using hydrocarbons, particularly R290 in Australia, Germany (where an indirect system was used) and the UK, however, they have not become commercialised on a wider scale.

This article describes the development of a prototype R290 system for use in a medium size RRV. The starting point for the development was a baseline R404A system followed by a number of stages, as illustrated in Figure 1. Since the primary concern is overcoming the flammability hazard of R290, the majority of the steps address risk minimisation. This involved reduction of refrigerant charge, development of an active leak limiting response safety system (ALLRSS), improving leak tightness, identification of potentially flammable zones and subsequently addressing potential sources of ignition within those zones. If the failure modes and effects analysis (FMEA) and quantitative risk assessment (QRA) yield any concerns, prior steps are re-evaluated in order to help minimise the risk further; these steps are consistent with the approach given in EN 1127-1. When the risk is believed to be sufficiently low, final compliance against a safety standard is carried out followed by drafting of guidance for users and finally applying the prototypes for field trials. In addition to safety matters, performance (capacity and efficiency) is also important. Since these parameters are closely linked to the charge reduction process, they were carried out simultaneously.

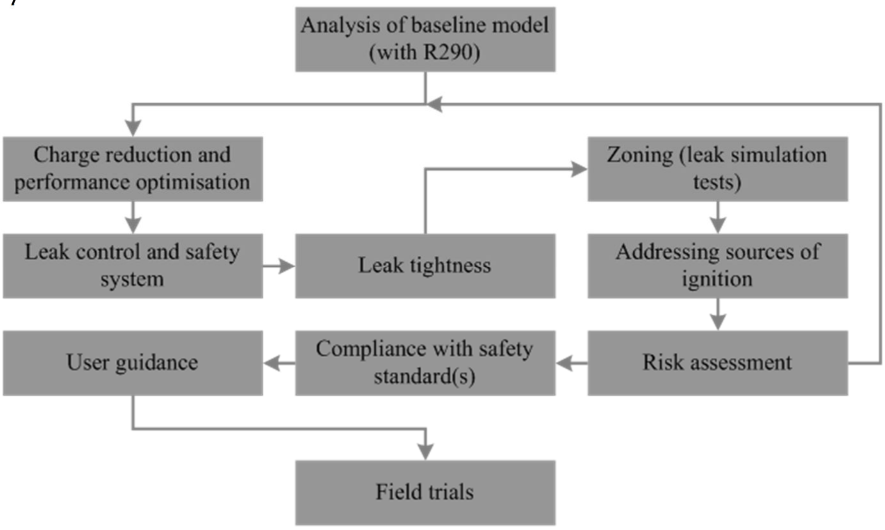

Figure 1: Summary of the main stages in the development of an R290 transport refrigeration system

3 Description of Baseline Model

The baseline model from which the prototype was developed is a factory sealed pre-charged monoblock system (Figure 2) that is installed into RRVs at the factory. The system of the "MT460" model comprises an evaporator, condenser, electronic expansion valve, compressor, receiver, accumulator and interconnecting piping and valves. Compressor is electric driven so the condensing unit housing also comprises a diesel engine and alternator. Nominal cooling capacity is approximately 8 kW for medium temperature (MT) and 4.5 kW for low temperature (LT) operation, which typically correspond to truck bodies of around 7 – 9 m in length. Originally, the refrigerant charge was 3.5 kg of R404A and about 1.5 kg when charged with R290. Critical to consideration of safety measures, the numerous conditions that the system will experience must be accounted for. These include: the RRV being in-use or not; the RRV being stationary (closed or un/loading) or in transit; it may be empty, loaded or partially loaded; the refrigeration system may be on, off or in (hot gas) defrost.

Figure 2: Picture of the MT450 unit

4 Charge Reduction and Performance Optimisation

The first step in risk reduction is minimisation of the mass of flammable material, which may be partly achieved through charge reduction. The strategies for reducing refrigerant charge are well reported (e.g., IIR, 2014), although the optimal approach can vary depending upon the particular system architecture, operating conditions and so on. As a first step, the strategy was as follows:

- Select R290 compressor to provide at least the same nominal cooling capacity at rating conditions as the baseline R404A model.
- Reduce charge in the condenser, evaporator, interconnecting piping, receiver and accumulator as much as possible, whilst maintaining nominal cooling capacity and COP at rating conditions no lower than baseline R404A model and without negatively impacting upon system functionality.

- Further optimise condenser and evaporator design to maximise COP without reduction in capacity.

The simulation tool IMST-ART (www.imst-art.com) was used to facilitate the charge minimisation and optimisation process. Performance testing the baseline model with R404A and R290 yielded data-points against which the IMST-ART tool was calibrated and from thereon, the iterative charge minimisation and system component optimisation process was carried out with the IMST-ART tool.

The key changes to the component design were: reduction of condenser and evaporator tube size (from 10 mm to 5 mm and 10 mm to 7 mm, respectively) and in particular adjustment of their circuitry, smaller liquid line diameter and approximately halving the volume of the liquid receiver and accumulator. Redesign of heat exchangers was within the physical constraints of the existing coil block sizes. A practical hindrance to the use of the optimum circuitry was the limited availability of heat exchanger production with small diameter tubes, so a compromise option was used. The finalised design yielded an actual working charge of 0.62 kg R290, which is about 20% of the original R404A charge size and 40% of the R290 charge when applied to the baseline model.

Following confirmation of the model output with the R290 prototype, its performance over a range of ambient conditions is compared against that of the baseline R404A model in Figure 3 and Figure 4 for MT and LT, respectively. For both MT and LT conditions, the R290 model has consistently better COP (about 15 – 25% at MT and 10 – 30% at LT) and in fact at the lowest and highest ambient temperatures it tends to exhibit a greater improvement over R404A than at the rating conditions. Cooling capacity of the R290 model shows a “flatter” performance curve, i.e., the variation across a wide range of temperature is less than with R404A. At higher ambient temperatures the cooling capacity is greater than R404A (15 – 20%), whereas at lower ambient temperatures R290 tends to be about 5% lower than R404A; this behaviour is contributed to by the small diameter tubes in the R290 model leading to greater condenser pressure drop at higher capacity conditions. A broader parametric assessment indicated that greater improvement in COP could be achieved with the R290 model with alternate heat exchanger designs, but these required greater refrigerant charge and thus at the expense of increase in flammability risk.

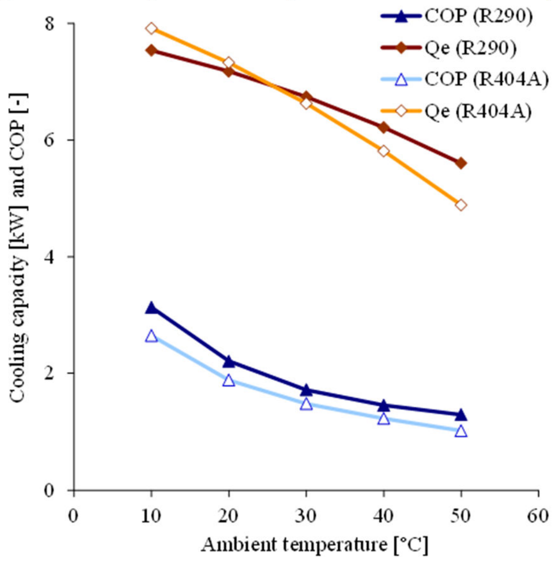

Figure 3: Performance for MT (T = 0°C)

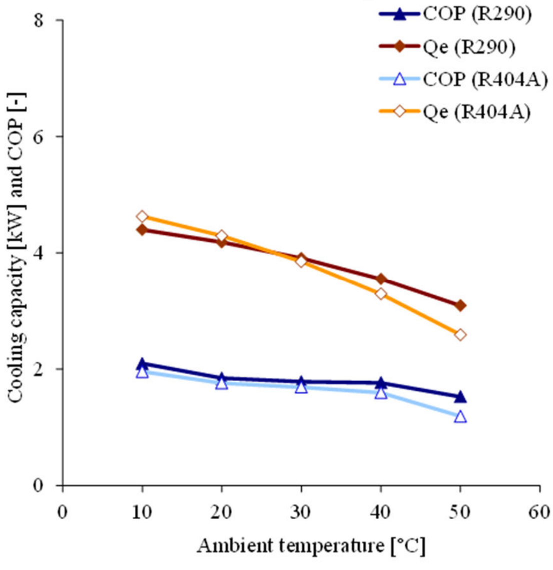

Figure 4: Performance for LT (T = -20°C)

5 Safety Measures

5.1 Active leak limiting response safety system (ALLRSS)

In the event of a leak occurring within the refrigerated space, it is desirable to minimise the quantity of refrigerant released and further to activate additional measures to mitigate the possibility of ignition. This approach can be separated into sensing and mitigation; the application of such measures for R290 systems is addressed in detail elsewhere (e.g., Colbourne et al, 2013; Colbourne et al, 2012). Usual sensing method of gas detection is not considered a suitable option for RRVs because the requirement for regular calibration of the detector is awkward, especially in the present case since the RRVs may be widely distributed across Southern Africa. Additionally, there are concerns over the possibility for contamination leading to regular false positive responses. Instead, the preferred sensing method is selected system working parameters; although this approach typically has lower sensitivity to leakage than a gas detector, reliability should be considerably better (since it relies on standard temperature and pressure measurements and controller response signals and it is not necessary to re-calibrate sensors). Once a leak has been identified, the mitigation actions primarily involve a system shut-down so that only a limited quantity of refrigerant remains within the evaporator, with the remainder being trapped in the condenser/receiver (in the event of a low-side leak), initiation of the evaporator airflow (if it is not already on) and an alarm for the RRV driver to take the appropriate actions. Alternatively, if the leak occurs from within the condensing unit, then the refrigerant would disperse comparatively safely in the open air (see section 5.3).

With regards to the selection of initiation set-points, it is important to determine the appropriate balance between working parameter response due to a release of a given mass and the possibility of a "false" signal arising from an unforeseen combination of conditions that mimic a loss of charge (and which could thus unnecessarily compromise the refrigerated product).

Assessment of the system response to a loss of refrigerant addressed leaks during the three operating modes: off, on and defrost. A leak during off-mode is of minor concern since tests showed that if the system is already off then a maximum of 110 g is released or less than 40 g if the system has terminated with pump-down. For the on and defrost modes, the effectiveness of the leak control system was evaluated by initiating an instantaneous leak from the evaporator, either during normal operation or one minute into defrost. Two leak holes were tested (1 mm and 3 mm diameter) and at MT and LT box temperatures. Results of the released mass measurements, determined once the internal pressure reached 0.1 bar(g) are shown in Figure 5; the charged mass was 650 g ± 15 g. Under normal operation, the response of the system seemed to be more sensitive to larger leaks, where the 3 mm diameter hole tended to result in about 30 g less charge being released. However, the response seemed to be more receptive to the box temperature, in that about 80 g more was released when the system was operating at LT. This is explained by the working charge at LT being less than at MT so more refrigerant is backed-up into the receiver, where the system parameters only effectively react to the leak once that excess charge is depleted. This was also seen in the IMST-ART simulation results.

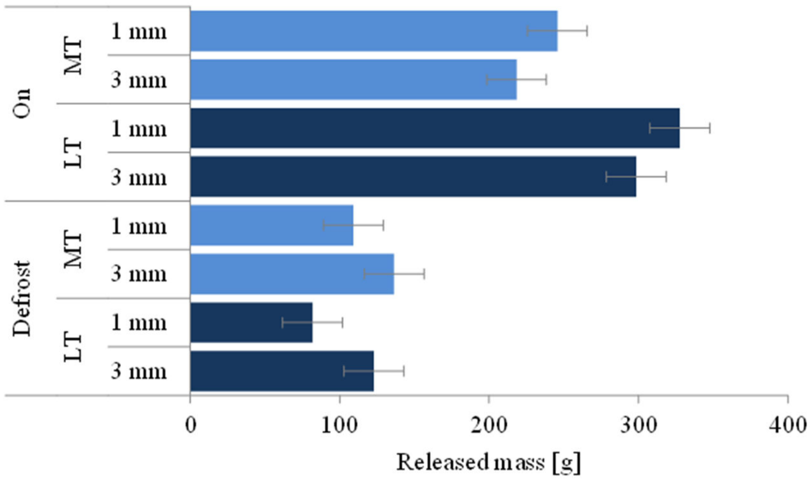

Figure 5: Released mass under different conditions

Several combinations of selected working parameters were tested for valid responses to a leak during defrost and those which provided the most repeatable (albeit less sensitive) response was chosen for the control system, as included in Figure 5. Nevertheless, the released mass during defrost is substantially less than during normal operation (about half) and whilst there seems to be little distinction between the results at different box temperatures, larger leak holes seemed to lead to a greater released mass. By comparison to the released mass observed with the safety control system, when the leak was allowed to exhaust the system without intervention, the released mass was approximately 600 g. Thus the leak control system can reduce the leakable mass (into the refrigerated space) by at least half, which significantly reduces the possibility of a flammable mixture developing therein. Although under most conditions, there is little chance of a flammable mixture being created in the event of the entire charge being released into the refrigerated box, the ALLRSS offers a major benefit in terms of avoiding a flammable mixture when it is overloaded with product and the free volume of the space is greatly displaced.

5.2 Leak tightness

Improved leak tightness is essential for risk reduction as it helps reduce the likelihood of a give leak size occurring. Consideration of existing production procedures and analysis of source/location and causes of all reported leaks across the entire fleet within warrantee yielded useful targets for interventions necessary for leak reduction. The following were adopted:

Almost entirely eliminate "detachable" joints (e.g., flares), especially within the refrigerated space
Following tightness testing according to EN 378
Where possible, select components complying with ISO 14903
Ensuring the system is technically durably tight according to EN 1127-1
Eliminate of use alternative components and joint locations vulnerable to frequent leakage
Additional training on jointing and brazing for factory assemblers

It is too early to have quantitative evidence of improvements in leak reduction arising from these measures, but previous experience suggests significant benefits should be expected.

5.3 Zoning

"Zoning" refers to the identification of zones of potentially flammable concentrations arising from a release of refrigerant and is the approach used to assess for compliance with the Atex directive (2013). This is necessary to determine the locations where active sources of ignition (SOI) must be avoided. The concept and principle methodology for identification of potentially flammable zones is provided in EN 60079-10-1 (2010) and an option developed specifically for refrigeration applications is described within EN 378-2: 2016. In short, this involves simulating a leak of refrigerant at a rate of ≥60 g/min and measuring the concentration at relevant locations. For the analysis, two general leak locations are applicable: condensing unit and evaporator unit, and therein several leak positions are chosen. Further, four control volumes (CV) were selected, as well as all possible positions of SOIs; see Figure 6. For condensing unit leaks, selected leak positions included coil return bends, compressor discharge, filter-drier/sight glass and were tested both when the condenser fans are on and off. With evaporator leaks, in addition to the different leak positions and the evaporator fans being on or off, consideration is also given to the loading, the use of strip-curtains and whether or not the doors are open, closed or in the process of being opened following a leak.

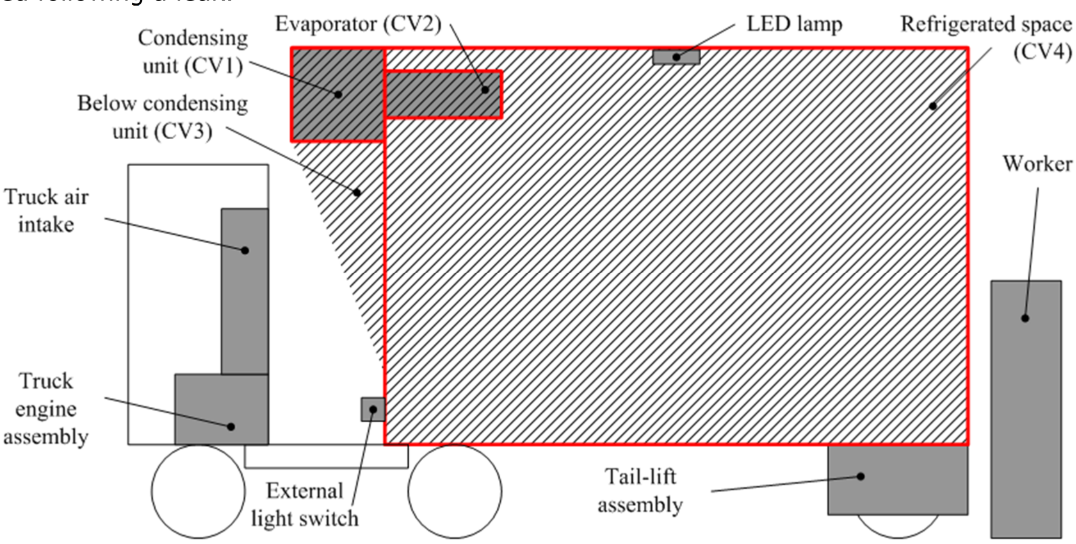

Figure 6: Schematic diagram of RRV and refrigeration unit with typical locations of SOIs (greyed) and identified potentially flammable zones (hatched)

A summary of the maximum concentrations following a 650 g release into an 8 m long, 42 m^3 RRV box are provided in Table 1.

General observations are:

- Within the condensing unit and fans are off (and the RRV is indoors and stationary) flammable concentrations were measured throughout the majority of the space. When condenser fans are on, all positions have very low concentrations.
- Concentrations at positions below the condensing unit (such as the truck air intake or external switch) are very low with or without fans running.
- For leaks within the evaporator unit, concentrations at the fan motors can exceed the LFL but are typically less than LFL when operating.
- At the ceiling/LED lamp, concentrations never exceed the LFL.
- At floor level (especially directly below the evaporator) the concentration can exceed the LFL when the space is empty and can reach up to three times the LFL when the space is loaded with product.
- However, when the fans are on the concentration both at the floor and ceiling is always close to the average (homogenous) concentration on account of the high airspeed causing rapid mixing.
- At positions beyond the rear door (tail lift or smoking worker), whilst the doors are closed almost no values were recorded, although the highest values occurred once the doors are opened but still never approached the LFL.
- If the doors were opened and the worker placed hands on the sill, on the occasion that the evaporator fans were off and the space was loaded with product, one test yielded a concentration just above the LFL

Figure 7 and Figure 8 present some examples of concentration behaviour arising from a leak under different conditions. The red arrow indicates the time at which the doors of the refrigerated space are opened. According to these tests, the identification of potentially flammable zones can be applied to the RRV and refrigeration unit, as indicated as the CVs in Figure 6.

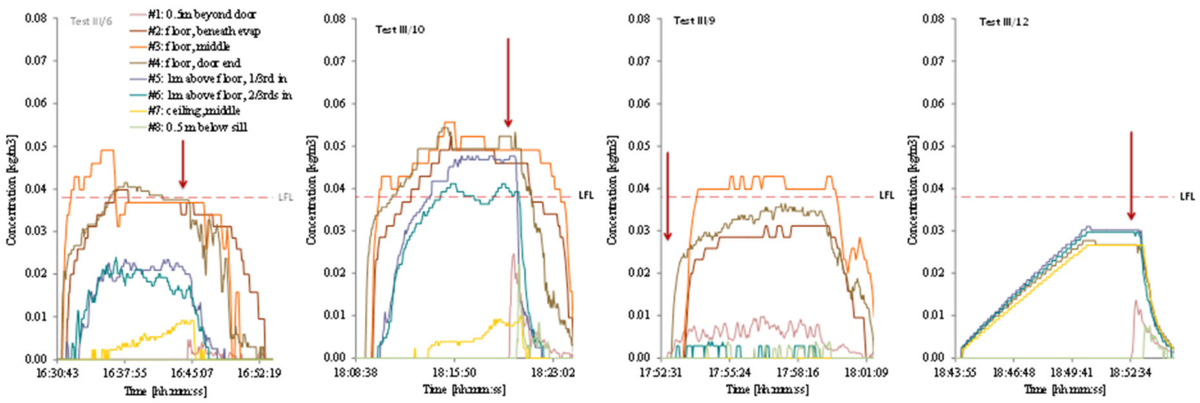

Figure 7: Examples of measured R290 concentrations: (a) empty, doors closed (b), loaded, doors closed, (c) loaded, doors open, (d) loaded, doors closed and evaporator fans on (note legend for 7(a) applies to all)

Figure 7 (a) shows measured concentrations in the case of a refrigerant release when RRV space is empty and doors are closed. Concentrations beneath the evaporator exceed LFL momentarily for the final part of the release and gradually decay to below LFL. However, in the case that yeh space is loaded with mock product (empty, sealed boxes), the concentration across the entire RRV space floor and up to a high of about 1 m exceeds LFL even following cessation of the release, and is especially high close to the release source location. Where the release occurs in a loaded space but the doors are open (c) – such as when the RRV is being loaded or unloaded – only the location immediately below the evaporator exceeds LFL; the other locations throughout the RRV space remain below LFL. Lastly, in the event of a release whilst the evaporator fan is operating and the RRV space is loaded and the doors closed, almost "perfect" homogenous mixing is observed, indicating that no localised flammable mixtures will arise. For the examples in Figure 7 an arrow indicates the time at which the RRV space doors were opened. Here there is a consistent observation that the flow concentration within the RRV space remains "high" (above or near the LFL) for less than three minutes, irrespective of the internal conditions.

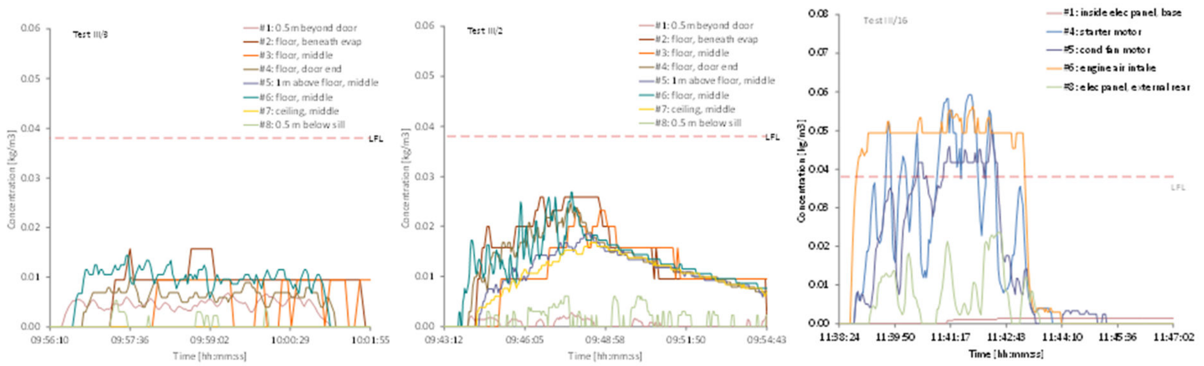

Figure 8: Examples of measured R290 concentrations: (a) empty, doors open (b), empty, doors open but with strip curtains, (c) condensing unit with no airflow then condenser fan pre-purge

In Figure 8 (a) and (b) a comparison is made between the releases being made whilst the rear doors are open with and without strip-curtains, respectively. With the doors open only, the refrigerant is seen to migrate directly out of the RRV space, whereas with strip-curtains there is a gradual build-up of refrigerant concentration followed by decay over 12 – 15 minutes until the floor concentration approaches 0%. Not only does this demonstrate the effectiveness of the strip-curtains but it also indicates that in the event of a suspected release a longer wait or active opening of the strip-curtains is required to ensure draining of the released refrigerant from the RRV space. Figure 8 (c) shows an example of the effectiveness of the pre-purge action, which is initiated prior to initiation of the engine. In this example, after about 5 minutes the condenser fan is seen to effectively reduce refrigerant concentrations from above LFL to a fraction of the LFL within a matter of seconds, despite continued release of refrigerant. The same result was observed irrespective of the release position.

5.4 Addressing sources of ignition

EN 378: 2016 states that within the potentially flammable zones, there should be no items that arc or spark or create high temperatures (>350°C for R290) under normal operation. (EN 1127-1 provides further guidance in terms of identification of possible SOIs.) The following assessment therefore applies to each CV.

Control volume 1: There are several potential SOIs. The electrical panel is in a sectioned off area and as a result the concentration even on the external surface of the panel is very low and the condenser fan motor is a non-sparking type. Two items that present a concern are the starter motor and the diesel engine air intake (which is not a SOI in itself but combustion of a flammable mixture could result in exhaust flames). A conceivable scenario is a sudden catastrophic leak just prior to a demand for cooling and thus the starter motor arcs and/or the engine draws in a refrigerant/air mixture – both potentially leading to ignition. Since these two elements are fundamental to the operation of the refrigeration system they cannot be eliminated. Therefore pre-purge ventilation is used whereby 20 s prior to initiation of the diesel engine, the condenser fans operate to purge the condensing unit of a flammable mixture. Testing demonstrated this strategy is highly effective.

Table 1: Maximum concentrations (kg/m^3) during leak simulation tests (650 g, ~80 g/min)

SOI sampling position	Leak location					
	Condensing unit		Evaporator unit			
	Fans off	Fans on	Fans off		Fans on	
			Empty	Loaded	Empty	Loaded
Engine air intake	0.059	0.004	0	0	0	0
Starter motor	0.058	0.004	0	0	0	0
Cond fan motor	0.046	0.004	0	0	0	0
Cond elec panel	0.031	0.004	0	0	0	0
Truck air intake	0.003	0	0	0	0	0
Ext light switch	0.002	0.001	0	0	0	0
Evap fan motor	0	0	0.065	0.022	0.016	0.033
LED lamp	0	0	**0.009	**0.006	0.012	0.027
Ref space floor	0	0	0.049	0.099	0.015	0.030
Tail lift assbly	0	0	*0.007	-	*0.005	-
Worker (fag)	0	0	*0.008	-	*0.003	-
Worker (hand)	0	0	*0.024	*0.040	*0.011	*0.014

* when doors were opened after release ended; ** Certain tests when the leak jet was directed horizontally the concentration here reached 22 g/m^3; NB: LFL is 0.038 kg/m^3

Control volume 2: It is always possible to develop a flammable concentration within the evaporator unit. Therefore the evaporator fan/motor assembly must comply with the requirements of the applicable Atex (2013) harmonised standards. No other electrical items (except for thermocouples with negligible current) are present.

Control volume 3: In all RRVs surveyed, there are no potential SOIs within this location.

Control volume 4: Ordinarily there are no potential SOIs here. The only electrical item is an LED lamp which is both non-sparking and operates at low voltage and current, insufficient to create a spark that could ignite R290 even in the event of a fault. The one conceivable condition of concern is when a worker opens the door, evaporator fans are not operating subsequent to a leak and the RRV is fully loaded. If the worker places hands on the sill or floor of the RRV and a static charge is present, ignition could potentially occur. However, this is deemed highly unlikely since any potential difference would be discharged as the worker makes contact with the metallic door levers.

6 Assessing Safety

6.1 Risk assessment

With a functional prototype unit, a quantitative risk assessment QRA) is necessary to estimate the probability of ignition and the severity of consequences. It essentially identifies the likelihood of a leak, the chance of a SOI being active and within the subsequent flammable mixture arising from the leak. This should be conducted in consideration of all the possible operating modes, load conditions, RRV states and so on. The likelihood of leakage is considered for the various normal operating conditions (on, off, during defrost), but also when other typical faults may have occurred, for instance during failures of the engine/alternator/battery, condenser/evaporator airflow, compressor, EEV, hot gas bypass valve. In addition, the equipment also relies upon the ALLRSS to minimise the quantity of refrigerant entering the refrigerated space so a failure mode and effects analysis (FMEA) is necessary to appraise its reliability and how it could impact on the overall risk. The elements of the control system are indicated in Figure 9. Using the service database it is possible to assign fault probabilities to the various elements, which provides overall probabilities of failure for the leak control system.

For the QRA, each of the possible operating conditions and failure scenarios therein are evaluated for the various situations: RRV in use or not in use; RRV being stationary (closed or un/loading) or in transit; empty, loaded or partially loaded. Considering selected leak hole sizes, the subsequent volume and duration of the flammable mixture and the type and characteristics of possible SOIs within that mixture are estimated for each relevant CV. SOIs were accounted for in terms of faults of electrical components and where relevant their external protection, but also possibility of introduced SOIs from workers, such as lighting cigarettes, use of power tools, etc. Using standard techniques (e.g., Colbourne and Suen, 2008) and leak frequencies from a previous study on R290 in transport refrigeration systems (Jansen and van Gerwen, 1996), ignition frequencies were determined.

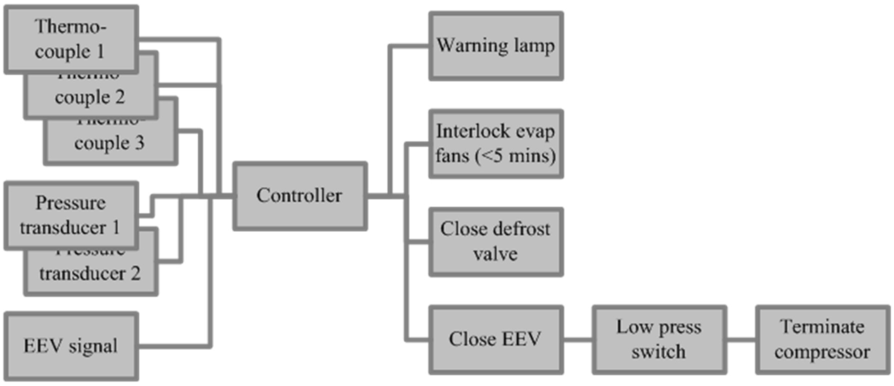

Figure 9: Elements of leak control system

An example of the results using more pessimistic assumptions is provided in Table 2, which also includes values for maximum consequences, overpressure (OP) and thermal intensity (TI). The ignition frequency is low, i.e., less than 1 ignition event per 1 million RRV-years. The most vulnerable locations are the condensing unit and the refrigerated space. For the condensing unit, even though the likelihood of a formation of a flammable mixture is extremely low (due to high air speeds), it contains many electrical parts and if there is a fault with any of them, or if the pre-purge ventilation fails, it is assumed that the resulting spark, arc or high temperatures could ignite a release. With the refrigerated space, the possibility of a flammable mixture is far more likely due to the confinement, although the possible presence of an active SOI is relatively slim. Surrounding the condensing unit, apart from there almost always being high airspeeds, it is extremely unlikely that any SOIs would be introduced and therefore the ignition frequency is substantially lower than elsewhere. For ignition of a mixture in the condensing unit and surrounding area or in the evaporating unit, the TI imposed on a person 1 – 2 m away is very low and would be insufficient to cause pain. Conversely, the TI for a person theoretically standing at the door of the refrigerated space is substantially higher and implies a small (<10%) possibility of mortality. However, as was shown in the zoning tests such a flammable mixture would not occur if the doors were open (the exception being if a person were trapped inside the space). Similar to the TI, the OP from ignition within the condensing unit and the surrounding area and evaporator unit is very low, but fairly high for ignition within the refrigerated space (when the doors are closed). The resulting OP is dictated by the values at which the doors will be forced open.

Table 2: Summary of ignition frequencies

Ignition location	Ignition frequency (y^{-1})	Max consequences	
		TI ($s(kW/m^2)^{4/3}$)	OP (kPa)
Condensing unit (CV1)	1.9E-07	~20	~1
Surrounding condensing unit (CV3)	4.9E-10	~10	0
Evaporator unit (CV2)	1.4E-08	~20	~4
Refrigerated space (CV4)	1.5E-07	~1000	~20
Total	3.6E-07	-	-

To put these values into context, they can be considered against comparable risks, such as the frequency of fires of refrigeration appliances or frequency of truck accidents. Comparing against the fire risk of comparable equipment for which data is available, the background fire risk (that is, typically due to electrical faults and not associated with the use of flammable refrigerants) for air conditioners in USA about 2×10^{-5} y^{-1} (Hall, 2012) and about 1×10^{-5} y^{-1} for domestic refrigerators in the UK (DCLG, 2014). These fire frequencies are about 100 times higher than the estimated ignition frequency. In terms of vehicle accidents, OGP (2010) states 22 injuries and fatalities associated with goods vehicles per 10^9 vehicle-km travelled; this gives an injury/fatality frequency of 2×10^{-8} km^{-1}. Assuming that RRVs travel somewhere in the range of 10,000 – 50,000 km per year, the frequency of injuries/fatalities is no less than 1×10^{-4} y^{-1} per vehicle. Even on the pessimistic supposition that every single ignition event led to an injury or fatality, the additional risk from using R290 is 1,000 times lower than the background injury/fatality risk from road accidents. Another way to gauge the calculated risk is to compare against targets from health and safety authorities. For example, the UK Health and Safety Executive considers the risk of fatality of one in a million (workers or members of the public) per annum to be extremely low and thus is deemed "negligible" (HSE, 2001). Since the incidence of fatalities from ignition of gas releases is around 1 in 100 to 1,000, the additional risk posed by the use of R290 is easily considered as "negligible".

6.2 Compliance with safety standards and regulations

The applicable safety standards include EN 378: 2016 and SANS 10147: 2009 and in addition, the essential health and safety requirements (EHSRs) of the Atex (workplace) directive.

Within the context of the application of a flammable refrigerant, the RRV system and application was assessed against all applicable clauses within EN 378: 2016. Whilst the same exercise was carried out for SANS 10147:2009, the requirements relating to A3 refrigerants are substantially less mature than those within EN 378 and accordingly less satisfactory for covering the wider considerations relating to flammability safety. Notwithstanding, it is also noted that whilst transport refrigeration systems are within the scope of EN 378, a number of the requirements are not consistent to such systems.[1] Accordingly a number of clauses require additional consideration and risk assessment to ensure the intention of the requirement is met.

An additional issue is definition of access category, location class and corresponding charge size limits. For the condensing unit part of the system, the access category may be considered as 'a' since it will be passing through public spaces. Since this part of the system is in an open space, the maximum charge would be 5 kg. For the evaporator part of the system, the access category is considered under two separate modes. In one mode, the refrigerated space doors are closed and it is unoccupied, i.e., it is not an access category 'a', 'b' or 'c' and thus determination in this of the maximum charge is subject to discussion. In the other mode, the RRV doors are open and workers are present within the space loading and unloading produce. Under this condition, the access category is 'b' and so the maximum charge is 2.5 kg; the allowable charge (being space volume × 20% of LFL) is difficult to define since the room volume is greater than the RRV space only due to the doors being open. However, taking the volume of the RRV space for which the RRV system is intended, the allowable charge would be about 0.32 kg. Whilst this is about half of the RRV system charge, it is considered acceptable since the ALLRSS will limit the releasable charge to less than 0.32 kg and – even in the event that this maximum quantity is released within the period between door openings, the initiation of the airflow will guarantee that the refrigerant is homogenously mixed within the space thereby ensuring no localised high concentrations.

6.3 Guidance

Awareness of those involved with the RRV refrigeration system – primarily service technicians and the driver – is important for risk reduction. Guidance on how to service the refrigeration system safely must be provided to technicians in the form of literature and training. Additionally, truck drivers must be briefed on the topic and made aware of the ALLRSS so that they can take appropriate precautions if there is an indication that a major leak has occurred within the refrigerated space. User/operation and service and maintenance manuals are also revised and updated to include the relevant information, especially applicable to the flammability issues and associated system functionality.

7 Initial Field Trials

Field trials were initiated at the end of November 2016. The purpose of the field trials is primarily to check the good operation and functionality of the R290 RRV system under the variety of real-life conditions, i.e., beyond laboratory conditions, and also to observe the effectiveness of the ALLRSS, should a substantial leak occur. In order to support the field trial, the RRV system was comprehensively instrumented according to the table below:

[1] Discussions within the working group 6 under CEN TC 182 responsible for development and revision of EN 378 seldom includes the topic of transport refrigeration within its deliberations.

Table 3: Instrumented parameters during field trials

Monitored parameters	Remarks
RRV space temperature set-point	Used for LT (-24 deg C) to date
RRV space air temperature at – evaporator inlet, evaporator discharge, space right/front, space right/back, space left/front, space left/back	Typically within +/- 2 K of the set-point once steady conditions achieved
Coil surface temperature	
Ambient temperature	Ranged from 15 to 42 deg C
Suction line temperature	
Liquid line temperature	
Compressor discharge pressure and suction pressure	
AC voltage and DC voltage	Depending upon whether using mains or alternator
Compressor current and frequency	
Engine rotational speed	
Relative humidity of ambient and within RRV space	Ambient ranges from 13% to 88%, RRV space from 35% to 100%
R290 concentration within RRV space	Zero at both locations
R290 concentration within condensing unit	
Door position (open/closed)	Typically opens at least once every two hour during use
Cooling/defrost mode	

An example of some important parameters is provided in Figure 10, which is typical of the entire field trial period to date. Here there are several door openings, variation in ambient temperature, degrees of loaded, etc. Importantly, evaporator coil and air inlet temperature recover rapidly following door openings or changes in external conditions and remain close to constant thereafter. So far field trials indicate positive results.

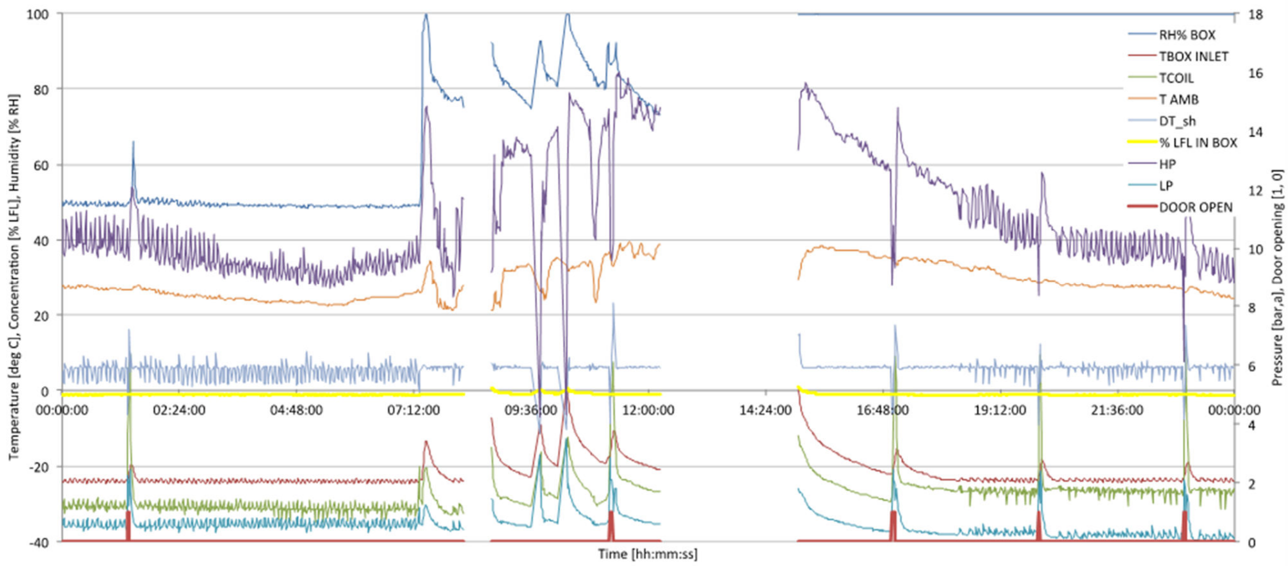

Figure 10: Selected data from one day of field trial (note: no logging when unit is powered off)

8 Final Remarks

A prototype refrigeration system for RRVs has been developed, allocated model reference "MT480". Major aspects of the development were significantly reducing the refrigerant charge and adopting the ALLRSS. A risk assessment indicates that the level of flammability safety of the prototype should not present any concerns, within the context of residual risk associated with trucks (e.g., being involved with accidents) and other comparable situations. Now that the prototype has been developed and tested, it is undergoing field trials, so far with favourable results.

The motivation behind the project is to reduce the emissions of greenhouse gases. An initial assessment of lifecycle emissions suggests about 16% lower diesel consumption – which translates explicitly into reduction in "indirect" emissions – and on account of the negligible GWP of R290 an elimination of "direct" global warming emissions. Overall, the R290 model is expected to generate only 34% of the global warming emissions (in terms of tCO2-eq) compared to the R404A baseline model.

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About the author

Dr Daniel Colbourne specialises in environmental, performance and safety aspects of alternative refrigerants and systems. He works on behalf of various organisations and companies, including GIZ Proklima. He is a member to the UNEP refrigeration Technical Options Committee and various BSI, CEN, ISO and IEC working groups on refrigeration safety and a member of the Institute of Refrigeration Technical Committee.

References

1. Atex Directive. 2013. Directive 94/9/EC of 23 March 1994 on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially Explosive Atmospheres, fourth edition, September2012, Update December 2013.
2. Colbourne D., Hühren R., Rajadhyaksha D. (2013) Refrigerant leakage control for R-290 in split type refrigeration and air conditioning systems. Proc. IIF-IIR. Compressors 2013: 8th International Conference on Compressors and Coolants, Častá - Papiernička.
3. 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
4. Colbourne, D., Suen, K. O., 2008. Risk analysis of flammable refrigerants, Part 2: Methodology for calculation of risk frequencies and flammable quantities, Proc. 8th IIR Gustav Lorentzen Conf., Copenhagen, Denmark
5. DCLG, 2014. Fire Statistics: Great Britain April 2012 to March 2013. Department for Communities and Local Government. Office for National Statistics, London, UK.
6. EN 1127-1: 2011 Explosive atmospheres. Explosion prevention and protection. Basic concepts and methodology
7. EN 378: 2008. Refrigeration Systems and Heat Pumps –Environmental Requirements
8. EN 60079-10-1: 2009. Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres.
9. Hall, J.R., 2012. Home Fires Involving Air Conditioning, Fans or Related Equipment. NFPA, USA.
10. HSE, 2001. Reducing risks, protecting people. Health and Safety Executive, HMSO, Norwich, UK.
11. International Institute of Refrigeration (IIR) (2014). 25th IIR Informatory Note on Refrigerant Charge Reduction in Refrigerating Systems. International Institute of Refrigeration, Paris, France.
12. ISO 14903:2012, Refrigerating systems and heat pumps -- Qualification of tightness of components and joints
13. Jansen, C. M. A., van Gerwen, R. J. M. Risk assessment of the use of flammable refrigerants. (In transport refrigeration.) R95-189. Final Report of TNO, Apeldoorn, Netherlands. 1996.

14. OGP, 2010. International Association of Oil & Gas Producers. Risk Assessment Data Directory. Land transport accident statistics. Report No. 434 – 9. March 2010
15. SANS 10147: 2009 Edition 4.1, Refrigerating systems including plants associated with air-conditioning systems

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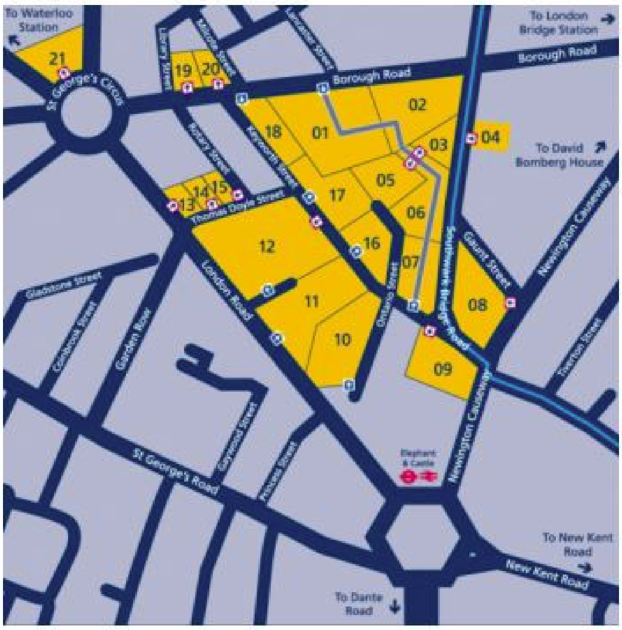

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