CHARACTERIZATION OF LEAKAGE VERIFICATION PROCEDURES IN REFRIGERATION CIRCUITS APPLIED TO MARITIME CONTAINERS

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Abstract

The evolution of portable refrigeration units and the refrigerants used with them has facilitated enormous advances in autonomous refrigerated maritime shipping containers and temperature control. This has permitted the shipping of products with very strict temperature requirements. It is very important to have a correctly designed system in which the amount of fluid is calculated for a specific construction. A mass above design requirements increases the cost of the finished product. If the mass of refrigerant is below design requirements, more energy is required to maintain the target temperature and, therefore, maintenance costs increase. This paper describes a process to test for leaks in refrigeration equipment. This process can assure the tightness of refrigeration circuits against small leaks over their working lives.

Keywords: *reefer container, production process, limits, permeability, leak.*

Introduction

When a small leak of this fluid occurs in a refrigeration system, and this leak continues over time, the performance of equipment, most importantly its capacity to control the temperature, progressively diminishes [3]. On the other hand, if the mass of refrigerant gas is increased, performance does not increase beyond design specifications [10]. Corberán [4] demonstrated experimentally and empirically the existence of an optimal mass of refrigerant. Due to the reduced volume of mobile systems, which require a minimal mass of refrigerant, it is especially important to maintain a sufficient quantity of refrigerant fluid inside the refrigerant circuits over their working lifetimes. As such, for a refrigeration system working with its optimal refrigerant mass, it is vital to avoid performance loss caused by refrigerant fluid leaks

All refrigeration systems have a natural tendency to lose refrigerants, as their working pressure is higher than atmospheric pressure. The most common leaks are found between the compressor and the expansion value [12], which coincides with the greatest differences in pressure between the interior and exterior of the circuits [6]. Leaks contribute to a reduction in performance, increased consumption by the ship´s auxiliary systems and an increase in maintenance costs, including accelerated depreciation of equipment. Further, depending on the refrigerant used, a leak can have an important economic impact [12].

At present, the environmental impact of refrigerants is rapidly diminishing [14, 17, 19]. With respect to the refrigerants most commonly used with mobile systems, the GWP (Global Warming Potential) of HFC134a is 1430, for HFO134a: 1430, for HFO1244yf: 4 and for R744: 1.

The limit established in the Kyoto Protocol was 150 [9]. HFO1234yf performs slightly below HFC134a, but its environmental impact rating is much lower and it has the great advantage of requiring no modifications to existing circuits when used as a substitute [12, 20]. However, the use of more environmentally sustainable refrigerants has its economic dimension. Although moderated through the application of taxes on refrigerant gases with a high greenhouse effect, substitutes end up costing 13 times more than conventional gases.

Due to both the obligation to comply with current legislation and the environmental and economic impacts, it has become necessary to guarantee the complete tightness of refrigeration systems, assuring the absence of leaks and porosities from the moment of fabrication and throughout their working lives. An occasional leak might be relatively easy to detect, but a small structural leak can be very difficult to find. Because of this, it has become necessary to develop a useful method of leak detection.

Leaks in refrigeration circuits can be located directly through halogen detectors [15], acoustic wave sensors [1] immersion or UV (ultraviolet) amongst other techniques. Nevertheless, these methods are not viable for or capable of locating the very small leaks that can affect the operation of refrigeration systems over their lifespans. Leaks can be located through indirect methods in which other variables in the system, such as, for example, pressure and temperature are observed. The results of these observations are analysed from a statistical point of view [1, 21, 25, 26], or in comparison with other reference models [7, 19, 26].

The most classic leak test is detection through immersion, through which leaks down to a size of 7g/y can be detected, which can be considered a significant leak. This is an economical test, but one difficult to apply and relatively ineffective [13]. Other methods based on leak detectors are limited by their incapacity to detect small leaks, and these must be very close to the sensor used. The limitations of the existing leak detection systems described above has created the need to develop new leak detection methods.

Although some studies have been made about leaks detection in pipes using mathematical models, is difficult to yield accurate mathematical results, especially in the detection of so small leaks in refrigeration circuits that ensure the equipment tightness over their whole lifetime. Elaoud et al [5] presented a technique for detection and location of leaks in a single pipe, by means of transient analysis of pressure waves governed by two coupled non-linear, hyperbolic partial differential equations with pressure dependent coefficients. It was tested with hydrogen-natural gas mixtures, and may be useful for pipelines with flow but not when flow rate is null. Tian et al [18] proposed a locating algorithm based on pressure difference profiles; the minimum detectable leak ratio was 1% for R22 and 4% for ammonia. Some small leakages were undetectable and neglected by this method, and then it does not allow ensuring the tightness over its useful life.

The best results in looking for leaks in mobile refrigeration equipment are obtained by combining direct and indirect methods. The change in pressure inside circuits over a period of time is measured, while variables such as the pressure applied, the temperature of the test, environmental humidity and the fluid used are controlled. Statistical analysis is applied to test results.

To analyse the tightness at manufacture of circuit components, control methods such as pressure or vacuum chambers are used, through the analysis of a tracer gas in a controlled atmosphere. In the laboratory, there are many different means to search for leaks and the quality of the tests is superior, primarily because there are no severe time limitations.

The most effective quality control technique that can be used once different components are already assembled is the test of fall in pressure over time in a pressurized circuit. In this test, the circuit is filled with inert gas, which helps eliminate humidity. It also facilitates the following test, that of measuring the increase in pressure over time in a circuit containing a vacuum.

When a low density inert gas is used, such as helium, as well as locating leaks of a small diameter equivalent due to the very small diameter of the helium molecule, comparison methods such as a gas tracer can be employed. However, it must be taken into account that helium is capable of permeating though flexible tubes and rubber joins (permeability). Helium molecules can become stored in porous materials (memory effect), as well as having a “corrosive effect” on components containing aluminium.

In Table 1, you can see the methods employed as well as important variables.

Table 1. Method to look for leakage [8, 21]

Method	**Standard gas**	**Detectable Leakage**		**Pressure**	**Measurable**
		mbar·l·s^{-1}	**g·y^{-1} HFO1234yf**		
Pressure	Air, Ni, He	10^{-4}	$7 \cdot 10^{-1}$	Positive	Yes
Vacuum	Air	10^{-4}	$7 \cdot 10^{-1}$	Vacuum	Yes
Water pressure	Water	10^{-2}	70	Positive	No
Immersion	Air	10^{-3}	7	Positive	No
Helium sniffer	Helium	10^{-12}	$7 \cdot 10^{-9}$	Positive	Yes
Refrigerant Sniffer	Refrigerants	10^{-5}	$7 \cdot 10^{-3}$	Positive	Yes
Halogen	Halogens	10^{-6}	$7 \cdot 10^{-3}$	Positive	With limits
Thermic conductivity	Specifics gases	10^{-3}	10^{-1}	Positive	No
Ultrasonic microphone	Air and additives	10^{-2}	70	Positive	No
Foaming additives	Air and additives	10^{-4}	$7 \cdot 10^{-1}$	Positive	No

The objective of this investigation has been to design a control procedure based on non-invasive methods that would grantee the tightness of refrigeration circuits used in maritime transport containers during their working lifetimes. Different trials have taken into account the refrigerant gas used and a testing process has been implemented that prioritizes a minimum use of time: the test process must be completed quickly. Because of this, the test parameters have been set according to prevailing pressure and the time taken to conduct the test.

Materials and methods

No circuit is completely sealed, and this is not really necessary. The goal is that any leak must be sufficiently small so as not to influence operating conditions such as pressure or temperature. As such, the requirements for the test have been greater where the interior pressure of the circuit has been higher and the density of the fluid has been lower.

To quantitatively register leaks, it is necessary to define a leak (Q_L) as the loss of pressure over time, and according to the volume of the circuit. In this way, a leak with a value of 1(Q_L=1), corresponds to a pressure loss of 1 mbar in 1s in a circuit with a volume of one litre. The unit of measurement for leaks is therefore mbar·l·s^{-1}

$$Q_L = \frac{d(pV)}{dt} \tag{1}$$

Taking into account that p·V = m·R·T/M, then:

$$Q_L = \frac{R\,T}{M}\,\frac{dm}{dt} \tag{2}$$

R: constant (R= 83.14 mbar·l·mol^{-1}·ºK^{-1})
T: temperature in ºK
M: molecular mass of the standard gas g·mol $^{-1}$
dm: decrease of mass during the test (g)
dt: test time (s)

Based on equations (1) and (2) and for a gas of known molecular mass, the leak can be determined. It is possible to determine the existence of a gas leak, measuring times and pressures in the circuit during the test, but it is necessary to weigh the circuit before and after the test, which can be difficult during the production process. A simpler method is necessary; however, this formula is useful to establish the groundwork. Like example of a detectable leak, it can be supposed that we have a circuit with an optimal mass of 1000g, with a tolerance of +/- 10g, which has a lifespan of 10 years. The maximum allowable leak is approximately 77·10^{-7} mb·l·s^{-1}. If we assume that the time interval available to carry out the test is four minutes, the detectable leak would be approximately 18·10^{-4} mbar·l·s^{-1}. To summarize, to locate a leak in a refrigeration circuit in a controlled environment (laboratory) without time restrictions, is possible. As part of the production process, it is more difficult.

The objective of this research has been to establish a test model for tightness testing that will assure the seal of refrigeration circuits over their working lifetimes. To do this, the system must have calibrated leaks at different points in the circuit to establish the control parameters (pressure and time) required to achieve a quality test with a high degree of reliability.

Some of the advantages of using an indirect method based on equations (1) and (2) are that the test pressure is close to the operational pressure of the circuit in which a leak could occur, and that the refrigerant gas itself can be used as a tracer gas.

To achieve this objective, it is necessary to construct physical models of both the standard circuits and the test bench. However, beforehand, the processes for different stages of testing must be established.

Design of a leak test model

There is an obvious necessity to test for leaks inside circuits in both directions, that is to say, from the inside out (a pressurized circuit) and from the outside in (circuit containing a vacuum). Figure 1 illustrates the test model established to test the tightness or seal of low volume circuits, which contain a resultantly low mass of refrigerants. The following stages have been designed:

P1: To avoid damaging the measuring equipment, the prevailing pressure in the circuit is measured so that, if the circuit was previously filled, the system will not allow the test to continue.

P1 - P2: A constant pressure is applied to the interior of the circuit with an inert gas (N), and the change in pressure is observed. The objective is that the interior of the circuit reaches the pressure applied in a time to be determined. This stage is called the Pressure Test.

P2 - P3: Once the target pressure (P2), is achieved, the circuit is isolated and there is a waiting period for the pressure to equalize at all points in the circuit. No measurements or decisions are taken. This stage is called stabilization.

P3 - P4: Once the inert gas is inside the isolated, pressurized and stable circuit, we observe the fall in pressure over time and make a decision according to the results. This stage is called the Pressure Drop Test. Once this test is complete, possible positive leaks have been tested for, that is to say, leaks that occur with the circuit under pressure. It should not be forgotten that positive pressure is normally the case with refrigeration circuits. However, it is considered it essential to look for negative leaks (with the circuit containing a vacuum). In this way, leaks of a structural character that cannot be found under pressure (the position of the 0-rings, joins with insufficient torque) can be detected. For this reason, pressure is released inside the circuit and the creation of a vacuum is begun.

P5 - P6: To achieve a vacuum rapidly, an unstable first stage vacuum is created, which is called the pre-vacuum, through a Venturi tube. With this device, two objectives are achieved: An acceptable vacuum in as little time as possible, and the protection of the vacuum pump.

P6 - P7: When the system is under 150mb, the vacuum pump it turned on. This stage is called the Vacuum Test and it has the objective of reaching a target pressure in a determined time.

P7 - P8: Once this objective of establishing a vacuum inside the circuit is achieved, the circuit is isolated and the changes in pressure over time are observed. This stage is called the Test of Decreasing Vacuum.

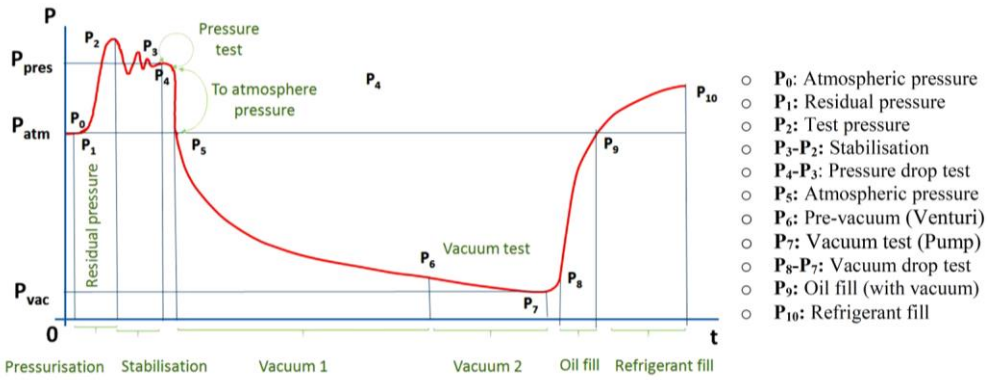


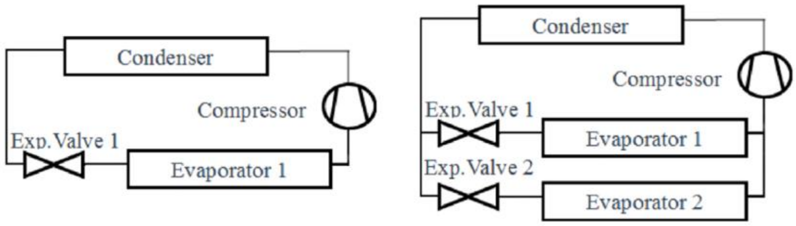
Figure 1. The Pressure-Time curve: Model leak test design process.

If the circuit passes the test stages described above, it will be filled first with polyalkylene glycol (PAG) and then with refrigerant. To achieve the fastest possible time in each one of the test stages, the key moment is the one in which the pressure stabilizes. The Figure 2 shows that applying constant pressure through two points, one in the high pressure circuit (HP) and the other in the low pressure circuit (LP), a stable pressure was only achieved above 10 bar, from the 8th second. Following this principle of stabilization, the time required for each stage can be determined. The times can be seen in the table of Figure 2.

A value of 10.5 bar was established as the test pressure value, and the objective in the vacuum stage was the highest grade of vacuum that could be achieved. Limits were established experimentally through statistical analysis.

Once the different phases of the test were defined, a physical model of the refrigeration circuits and the test bench was constructed. To be able to simulate the different architectures of different shipping containers used in maritime transport, which have different circuits with different capacities and components, two circuits were constructed. One simulates a system with a single evaporator and the other a system with a double evaporator. Both models are illustrated in Figure 3.

To be able to carry out the necessary measurements as has been described; a test bench was constructed, as illustrated in Figure 4. This consists of a pressure module, one supply module and one vacuum module. To carry out this study and to be able to statistically analyse the results obtained, the complete test has been carried out on each one of the model circuits. After each cycle, the circuit has been completely dismounted and remounted, renewing each of sealed units and couplings, so that the setup is the only factor affecting the test. The process of tightness testing is shown in figure 1, with times shown in Figure 2. The experiment has been repeated 1000 times, 500 with each variant of the circuit. The results obtained were recorded (Table 2).



	Compressor	Condenser	Exp. Valve	Evaporator	Refrigerant Mass (Kg)
Short circuit	1	1	1	1	0,6
Long circuit	1	1	2	2	1,0

Figure 3. Refrigeration system diagrams.

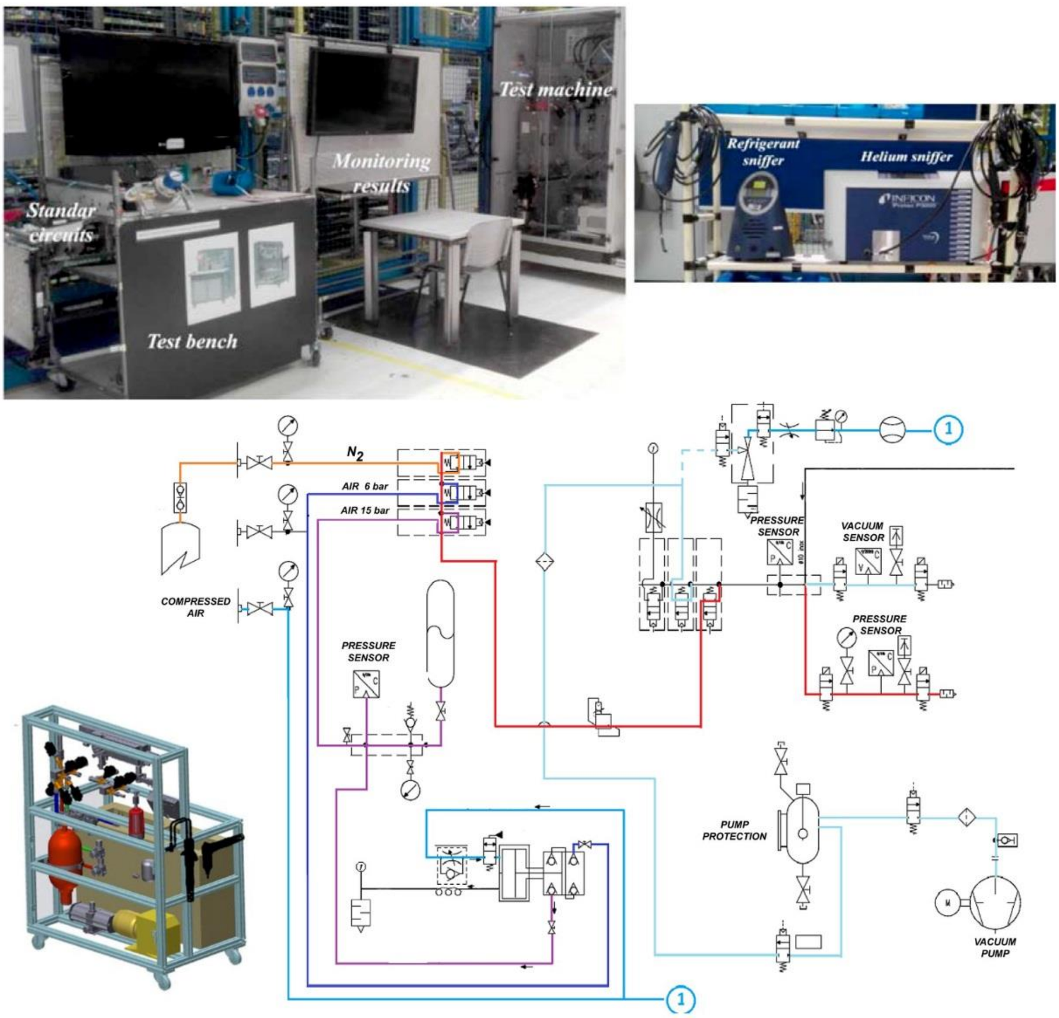


Figure 4. Laboratory layout and diagrams

Results and discussion

This research discussion can be divided in two main stages, a pressure drop test and a vacuum test.

Pressure drop test

The pressurisation stage consists of increasing the pressure inside the circuit with an inert gas (Nitrogen), and then we test to see if we achieve the target pressure within a certain time limit.

If we look at the curve of the Figure 5 "Events - Pressure" it can be seen that with a constant pressure input of 10.5 bar during 10s, in a majority of tests, in the short circuit a higher pressure was reached at the end of the stage as compared with the tests performed in the larger circuit.

Thus, in the short circuit, the highest number of repetitions (101 of 500) occurred at 10.25 bar of pressure and, in 98% of the tests performed, at a pressure higher than 10.17 bar. If we establish the same criteria for the higher capacity circuit, we see that the greatest number of repetitions (106 of 500) occurred at a slightly lower pressure than in the short circuit: 10.16 bar and the clustering of 98 % of tests was above 10.13 bar.

If the right hand side of the curve (high pressure), it can be seen that while in the short circuit more than 20% of the tests performed had a result higher than 10.25 bar, in the larger circuit, the value was only reached in 0.2% of the tests (1 event).

Table 2. Monitored results (example)

Type	Pres. (bar)	Stab. (bar)	Δ. Pres. (bar)	Vac.1 (mbar)	Δ Vac. (mbar)	Vac.2 (mbar)	Δ Vac. (mbar)	Time (s)
Short	10.2	10.09	0.01	2	9.8	0.2	0.3	162
	10.28	10.22	0.01	2.1	9.1	0.1	0.1	163
	10.28	10.2	0.01	1.8	7.5	0.3	0.4	162
Long	10.27	10.25	0.02	5	20	0.2	0.3	198
	10.17	10.15	0.02	2.8	14.6	0.1	0.1	197
	10.27	10.24	0.03	3.2	14.8	0.3	0.5	198

Last of all, leakage was simulated in both the short circuit and the long circuit, resulting in all the simulated leakage in the short circuit being detected by this pressure test, but not in the long circuit. If the O-ring is removed from the junction between the expansion valve and the second evaporator (the furthest point from the measuring points), this leakage is not detected by this test. However, the leak is detected by a tracer gas test. This test was performed with Helium sniffer and with a refrigerant sniffer. The leak was detected in both cases.

With the circuit under pressure, stabilized and isolated from the outside after the stages of pressurizing and stabilization, the drop-in pressure was observed over time. For a fixed time (5s.), the limit values beyond which a circuit is considered to be non-leak-proof are assessed.

In Figure 6 (diagram events / pressure: Pressure drop test results), two completely different curves can be seen, with well differentiated groupings. In the short circuit, 90% of the tests are grouped below 20 mbar, and the remaining 10% tests are dispersed between 20 and 150 mbar. The highest number of events occurs at 10 mbar (370 of 500). In the long circuit, the largest number of events (229 of 500) occurs at 30 mbar. However, 90% of results can only be encompassed from a value below 80 mbar. The remaining 10% of results are dispersed between 80 and 140 mbar.

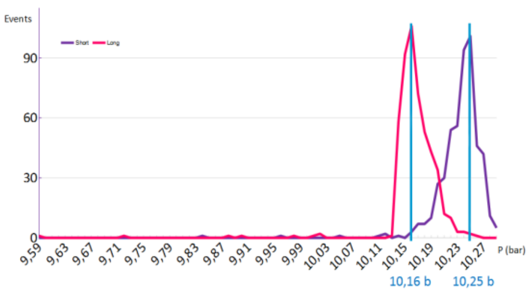


Figure 5. Pressure test results

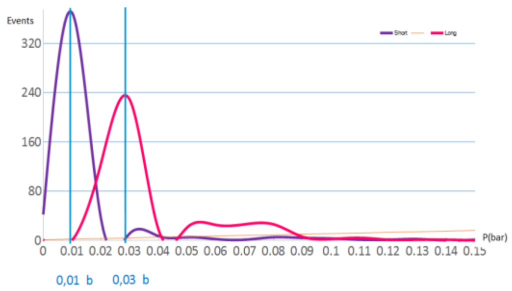


Figure 6. Pressure drop test results

At this stage, leakage was simulated, loosening different junctions and observing the evolution of the pressure drop. Leaks caused in the short circuit were detected quickly, however in the long circuit, leakages were not detected until the pipe was almost completely loose. These leaks were detected quickly with helium and refrigerant sniffers.

The stages of the pressurization, stabilization and pressure drop tests are the only steps proposed with positive pressure

Vacuum tests

After the pressure test was completed, the nitrogen pressure was released to the atmosphere. A vacuum process was started with a Venturi tube. The objective was to achieve an acceptable vacuum level in the shortest possible time. This stage is not a control stage, but a stage in which, by means of a Venturi tube, a vacuum can be established quickly. The result was a low-quality vacuum (very unstable) as it can be seen in Figure 7.

In this initial vacuum stage, the circuits reached a vacuum below 5 mbar, but this vacuum has very low stability. If the circuit is isolated, the vacuum is lost very quickly and the quality of the test is greatly reduced. It was necessary to achieve a much more stable vacuum to perform a vacuum increase test.

In Figure 8 (Diagram events /pressure: Increase vacuum after the initial vacuum stage) the spread of the results obtained after isolating the circuits can be seen for a 3 seconds time interval.

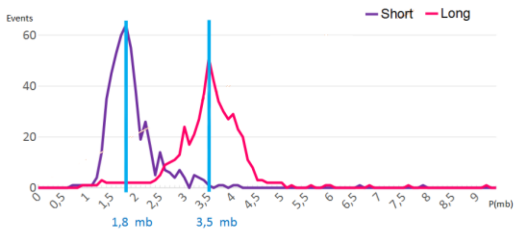


Figure 7. Vacuum with venturi tube

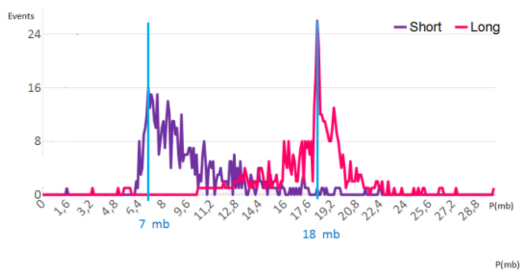


Figure 8. Increase vacuum after the initial vacuum stage

After the calculated time had elapsed, with the vacuum pump in motion, a second vacuum test stage was performed in which a higher quality vacuum was achieved than that reached with venturi tube. The result was a high quality vacuum and consequently, tightly grouped test results.

Once again, it can be seen that the curve of short circuit is grouped below 0.2 mbar, with a higher number of events. In both variants, the cluster is at 0.2 mbar, but the number of events below 0.3 mbar in the short circuit is higher than in long circuit.

In Figure 9 (Vacuum results) you can see the result curves of the two circuit variants. The curve's slope is greater for the lower the capacity circuit. While 99% of the results for the short circuit are below 1 mbar, the same number of events in the long circuit occur below 2.5 mbar. So it seems, at first glance, that the test parameters cannot be the same for both circuits.

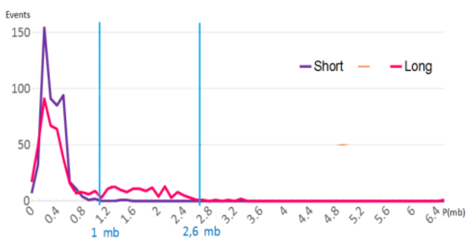


Figure 9. Vacuum results

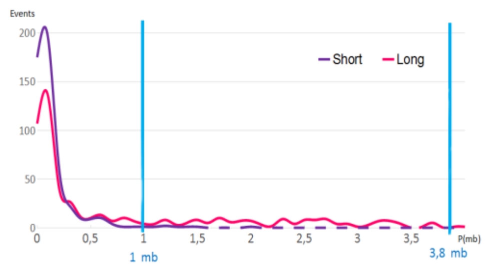


Figure 10. Δ Pressure during vacuum test

All detected leaks were confirmed as real leaks, but not all simulated leaks were detected at this stage. Micro-leaks caused by lack of tightness in the joints were not detected. However, they were detected with the refrigerant and / or helium sniffer.

The last stage of the vacuum test was carried out by creating a vacuum inside the circuit, isolating the circuit containing the vacuum created in the previous stage and observing the vacuum decline over time.

Once again, in the curve it can be observed that results for the short circuit are much more stable than the results obtained from tests carried out on the circuit of greater volume. While in the short circuit only two events were obtained above 1 mbar (all with confirmed leakage), in the long circuit 131 events were measured above 1 mbar. Most importantly, only a small proportion of these events were confirmed as real leaks.

To summarise, for the short circuit all detected leaks were confirmed as real leaks, and for the long circuit not all detected leaks were confirmed as real leaks, but these were so small leaks that can be extremely difficult to be confirmed by conventional methods as helium sniffers. Some of the simulated real leaks were not detected in the vacuum test, but these leaks could be confirmed by conventional methods.

Conclusions

The evolution of refrigerants used in refrigerated shipping containers has made it necessary to use more demanding quality control techniques during the manufacturing process. This need is due to environmental motives in the case of HFC refrigerants and for economic reasons in the case of HFO refrigerants. Physicochemical motives are important in the case of refrigerants synthesized from CO_2, as these require an increase in operating pressure or the critical point temperature.

It is not enough to ensure statistically the tightness of circuits in the quiet of the laboratory. To guarantee quality, leak tests must be carried out on 100% of the fabricated circuits off the production line. It is necessary to take into account the demands of the manufacturing process, especially production time, so that the finished product does not become more expensive. Therefore, there is a clear need for a leakage control process that does not leave residues in circuits, ensures their tightness during their useful working lives and which can be executed within an economically viable timeframe.

In this work, a leakage verification process in refrigeration equipment has been presented, this process ensures the circuit tightness against small magnitude leakages of refrigerant fluid over its entire lifetime. In the experimental process a very low proportion of leaks were not confirmed as real leaks, but these were so small leaks that was very difficult to be confirmed by conventional methods as helium sniffers. Some simulated real leaks were not detected in the vacuum test, but these leaks was confirmed by conventional methods. This process has proved being an effective tool to be applied to the refrigeration circuits sealing verification, due to their capacity to detect leakages of small magnitude.

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