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Evaluation of Stainless Steel Press Fittings for Use in Transcritical R744 Refrigeration Systems

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ABSTRACT

Successful implementation of R744 (CO₂) as a refrigerant on a large scale and its introduction to new applications has motivated the development of new system components tailored specifically for use in high-pressure R744 systems, including reliable, low-cost refrigeration fittings. One option for fittings to be used in R744 systems are quick and reliable press fittings. Previous research has shown that this type of fitting can undergo extended vibration and thermal (pressure and temperature) cycling without compromising the fitting. This paper investigates the durability of stainless steel press fittings designed specifically for R744 systems, with particular focus on the effects of rapid decompression and carbonic acid exposure on the fittings. Rapid decompression is of concern due to the tendency of O-ring material to absorb CO₂ molecules at high pressure and temperature, resulting in possible expansion and bursting of the O-rings when pressure drops and the CO₂ absorbed by the O-rings attempts to escape very rapidly. Additionally, the presence of moisture in an R744 system can result in the reaction of CO₂ and H₂O, resulting in the formation of carbonic acid; the exposure of the refrigeration system components to this weak acid over time can compromise parts different of the refrigeration system, possibly including joints. The effects of decompression and acidity on stainless steel press fittings and their O-rings have been tested and are reported in this paper. The results show that the tested press fittings and O-rings were able to withstand the CO₂-specific durability tests without compromising the sealing ability and strength of the fitting.

1. INTRODUCTION

Mechanical (flame-free) joints and tube fittings for refrigeration and air-conditioning applications have been receiving increased attention during the past several years. It appears that technology relying on crimping or pressing is especially attractive due to the much shortened time it takes to make a fitting connection and the ease of assembly for less-experienced technicians. Compared to flare or compression fittings, which are of course also flame-free, the press/crimp style fittings potentially offer some economic advantages as well. Previous studies carried out by Elbel *et al.* (2016) and Wilson and Bowers (2014) investigated the durability of aluminum and copper press fittings after being exposed to different realistic harshness tests, including freezing-thawing cycling, pressure-temperature cycling, and vibration testing. The results showed that both material selections are suitable for this type of fitting, and no failures that would compromise the integrity of the connection occurred. This study is a continuation of the previous investigations on the durability of press fittings. The focus of the presented work is on the investigation of press fittings made from stainless steel, with a specific focus on the design and execution of CO₂-specific harshness tests, including explosive decompression testing and carbonic acid testing of the stainless steel press fittings and their O-rings.

2. STAINLESS STEEL PRESS FITTINGS BACKGROUND

Press or crimp fittings function by using a radial O-ring pressed between the body of the fitting and the tube to hold internal pressure on each end of the fitting. Figure 1(a) shows the inside of a press fitting; a tube is inserted on each end of the fitting past the O-ring on each end. The tube is held in place and the O-ring seal is made using a crimping tool, as shown in Figure 1(b).

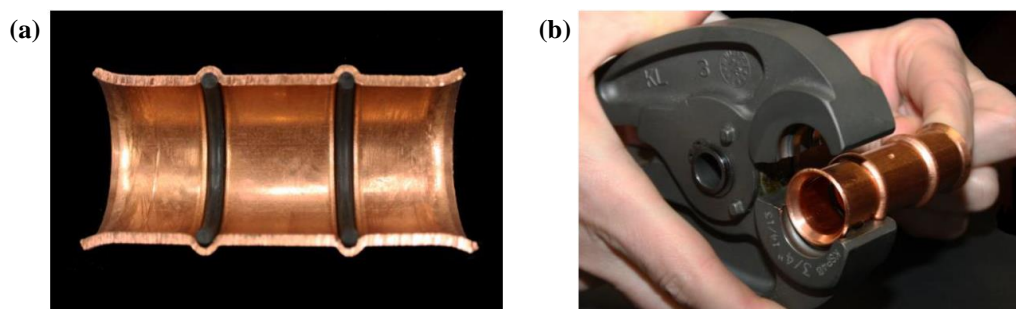


Figure 1: (a) Cut-away image of press fitting, and (b) press fitting crimping tool (Wilson and Bowers, 2014).

The need for stainless steel fittings arises with the increased use of carbon dioxide (CO_2 , R744) in air-conditioning and refrigeration. Especially when used in transcritical mode, the R744 refrigerant pressures on the heat rejection side of the system can exceed pressures that are beyond the material strength limits of copper and aluminum, especially in parts of the system that operate at high temperature as well (such as the discharge line). The required wall thickness grows quickly for lower yield strength materials, particularly for large diameter piping systems, which makes stainless steel a logical choice for R744 systems. The challenge is therefore not seen so much in material strength, as stainless steel readily provides the mechanical properties that allow for operating pressures of 140 bar even at elevated compressor discharge temperatures while still allowing for an adequate safety factor. What needs to be addressed in more detail is the suitability of the O-ring seal on which the crimp/press fitting type relies on. These stainless steel press fittings would also be of interest for ammonia (R717) systems, though a different O-ring material, such as PTFE, would be needed for R717 compared to R744.

Figure 2(a) shows an example of a stainless steel press fitting for a 1/2" (12.7 mm) tube (already crimped to the tube), while Figure 2(b) shows the associated O-ring for the 1/2" size fitting. The material used for the O-rings in the press fittings is a hydrogenated nitrile butadiene rubber (HNBR) with 90 durometer. The O-rings are approved by the manufacturer for a temperature range of -40°C to 149°C . The O-rings are recommended for use with oils, grease, water/steam, glycol, and HFC's. The O-rings are not recommended for use with strong acids among other fluids (Parker, 2000).



Figure 2: (a) 1/2" stainless steel press/crimp fitting and (b) 1/2" HNBR O-ring.

The fittings used in the previously mentioned studies carried out by Elbel *et al.* (2016) and by Wilson and Bowers (2014) also used O-rings for sealing purposes, but the working fluid used in these previous studies was R410A, which operates at much lower pressure than what is found in transcritical CO_2 systems. In addition to the higher pressure, the much smaller molecule size of CO_2 , in comparison to those of synthetic HFC or HFO refrigerants, makes it even more demanding for the O-ring to provide adequate sealing capabilities resulting in acceptable refrigerant leak rates.

Rather than simply repeating the test sequences presented in the two previous studies on the stainless steel fittings with CO₂ instead of R410A, the aim of this work was to explore the challenges specific to the combination of using CO₂ refrigerant in conjunction with O-ring seals. One area of interest is the explosive decompression effect that can occur when high pressure CO₂ is released too quickly and the small refrigerant molecules, which can be readily absorbed into the polymer O-ring material, are not given sufficient time to diffuse out of the O-ring. During the final step of decompression, the specific volume of CO₂ increases very rapidly causing the O-ring to be torn apart by CO₂ molecules expanding while still being trapped inside the polymer material. Examples of O-ring failures caused by explosive decompression can be seen in Figure 3.



Figure 3: Images of O-ring failures due to explosive decompression (left image from Seal & Design, right image from Marco Rubber & Plastics).

In addition to explosive decompression, the use of CO₂ as a refrigerant also presents a unique challenge in terms of the possible formation of carbonic acid if moisture is present in the system. Moisture can enter refrigeration systems due to contact with ambient air during system assembly, incomplete evacuation during system vacuuming, permeation through seals, and impure refrigerant charge. Once water has entered the system through one of the possible routes mentioned above, the situation is quite different when comparing CO₂ to more conventional HFC refrigerants. Water present in the system gets absorbed by the oil (and depending on the oil type can cause a non-reversible, chemical reaction), and by both the liquid and vapor phases of the refrigerant. For HFC refrigerants, the amount of water that can be absorbed in the vapor phase is of the same order of magnitude as the amount of water that can be held by the liquid phase. In other words, if water gets absorbed by the refrigerant it will remain absorbed by the refrigerant as the fluid passes throughout all components of the vapor compression cycle. For CO₂, however, the amount of water that can be dissolved is much smaller for the vapor phase than for the liquid refrigerant phase, as demonstrated in Figure 4. As a consequence, water that was held by the liquid phase will be released as ‘free water’ into the system as the liquid CO₂ evaporates in the evaporator because the vapor CO₂ phase is not capable of retaining the same amount of water as the liquid phase. Consequently, the largest quantities of ‘free water’ are observed in the suction line of the system, right before the fluid enters the compressor. Therefore, the use of driers is particularly important for CO₂ refrigeration systems to prevent excessive amounts of water to precipitate as ‘free water’.

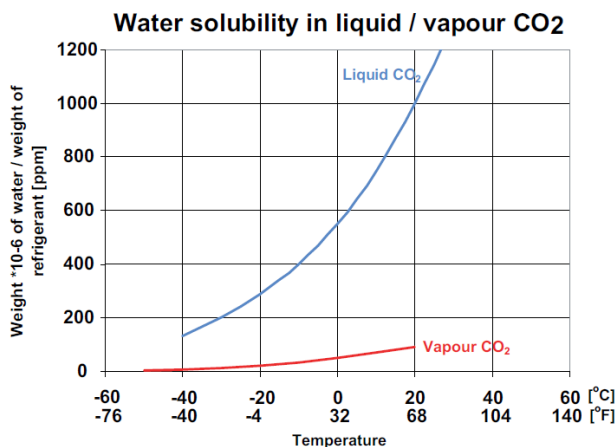
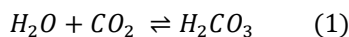


Figure 4: Comparison of solubility of H₂O in liquid vs. vapor CO₂ (Danfoss, 2009).

The refrigerant CO_2 can react with the moisture or water to form weak carbonic acid (H_2CO_3), as shown in Equation (1). Additionally, carbonic acid can further react with water to form bicarbonate (HCO_3^-) and hydronium ion (H_3O^+), as shown in Equation (2). These acids (H_2CO_3 and H_3O^+) are of concern because they can degrade polymer materials, such as that used in common O-rings.



3. EXPLOSIVE DECOMPRESSION TESTING

As discussed above, the use of CO_2 as a refrigerant poses a unique challenge in terms of the durability of O-ring material to withstand explosive decompression. As the sealing ability of press fittings relies on O-rings, any splitting or bursting of the O-ring in press fittings caused by explosive decompression will likely compromise the sealing ability of the fittings. In order to study the effect of explosive decompression on the stainless steel press fittings as well as the O-rings material, a series of rapid de-pressurize tests were performed on the stainless steel fittings as well as bare O-rings. A schematic of the facility used for the rapid de-pressurization tests is shown in Figure 5. The tested fittings and bare O-rings were connected to a CO_2 supply tank. For each test, the system was charged with a set amount of CO_2 and heated to increase pressure and temperature to their target values. The fittings and O-rings were contained within a lab oven (internal dimensions of approximately 0.5 m square, 1.6 kW heating capacity) during the testing in order to control the temperature that they experienced. A solenoid valve was used to allow for rapid release of CO_2 in order to simulate the explosive decompression effect.

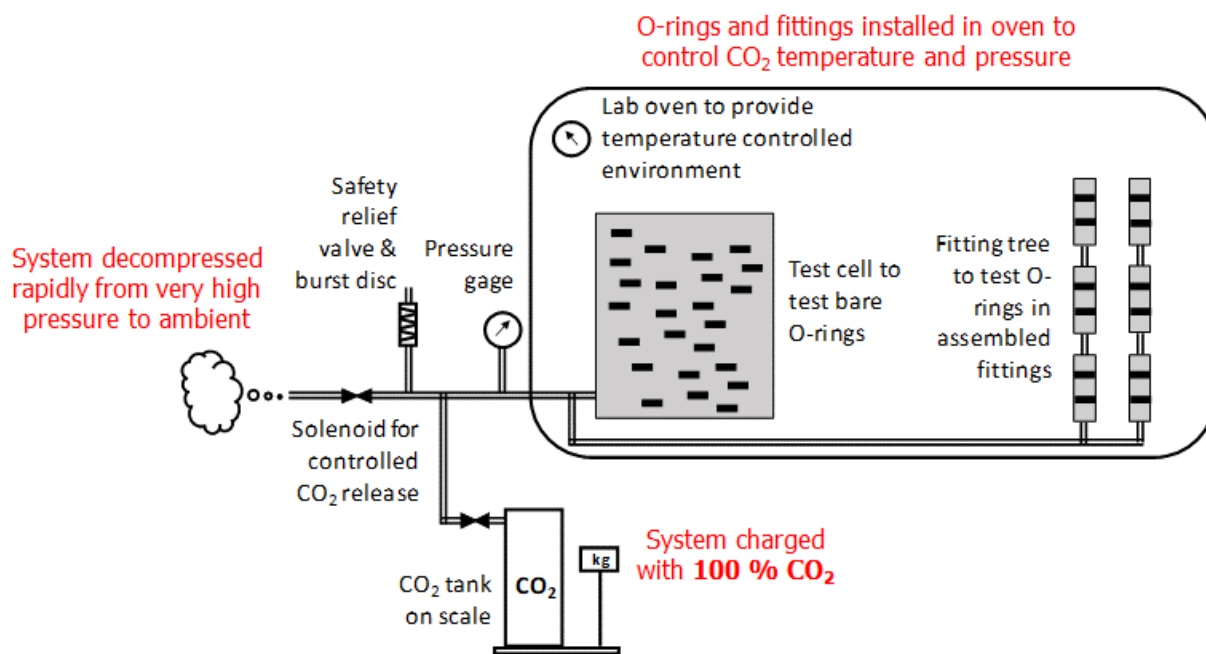


Figure 5: Schematic of CO_2 explosive decompression facility.

Two different fitting and O-ring sizes were tested: 1/2" fittings and O-rings and 5/8" fittings and O-rings (dimension corresponds to tube outer diameter, fitting and O-ring inner diameter). For each size of fittings and O-rings, three different applications of oil were investigated: Dry O-rings and fittings with no oil, O-rings and fittings with factory oil, and O-rings and fittings with factory oil and compressor oil. The factory oil is a type of silicone oil that the O-rings are coated in by the fitting manufacturer in order to allow the O-ring to be installed in the fitting more easily during production. The compressor oil used in the tests was a POE oil. Oil is known to absorb CO_2 in refrigeration systems, and it is possible that a layer of oil on the outside of the O-rings could affect the absorption and the release

of CO₂ by the O-rings during the tests, which is the motivation for testing different oil applications during while performing the explosive decompression tests. Using both factory oil and compressor oil would likely be the most realistic environment for the fittings for most applications. Table 1 shows the total number of fittings and O-rings tested for each combination of fitting size and oil application. A total of 10 decompression tests were performed on each fitting and O-ring, which is most likely many more rapid decompressions than a fitting would generally experience during its operational lifetime.

Table 1: Number of O-rings and fittings tested for each size and oil application combination.

	1/2" size		5/8" size	
	Fittings	O-rings	Fittings	O-rings
Dry fittings and O-rings	5	25	5	25
With factory (silicone) oil	3	25	3	25
With factory (silicone) and compressor (POE) oils	3	25	3	25

For each decompression test, the following procedure was followed:

1. The system was first vacuumed and then charged with a specific amount of pure CO₂ to allow the target temperature and pressure to be met.
2. The lab oven was used to heat CO₂ inside the fittings and the O-ring test section to 150°C, during which time the pressure of the CO₂ in the fittings and O-ring test section increased to approximately 130 to 150 bar. This test temperature and pressure represent the maximum temperature and pressure at which any fitting in a CO₂ refrigeration system would generally operate (compressor discharge).
3. The CO₂ was held at this condition for approximately 3 hrs. duration once these temperature and pressure targets were reached in order to allow the O-ring material time to absorb CO₂.
4. After holding at high temperature and pressure for 3 hrs., the CO₂ release valve was opened, allowing the system to rapidly depressurize.
5. This decompression test procedure was repeated 10 times on each O-ring and fitting.

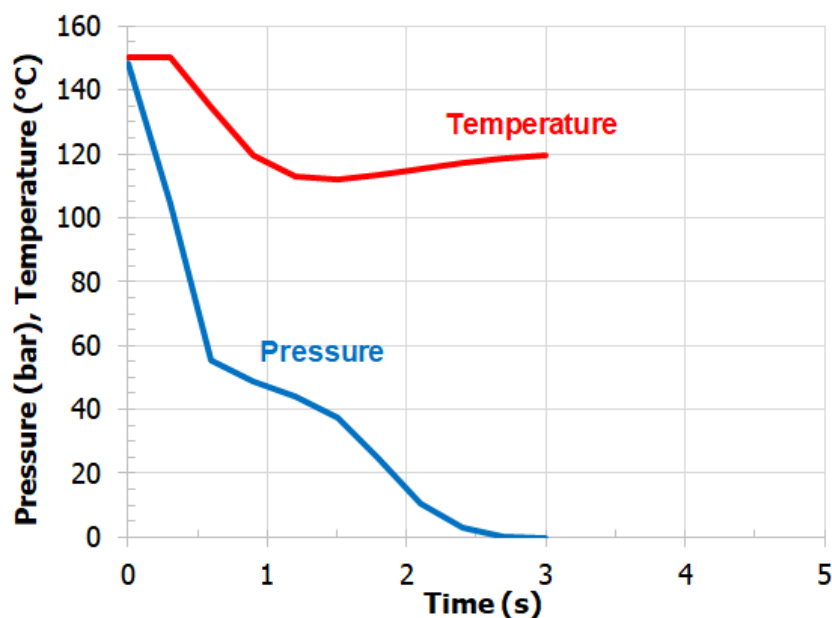


Figure 6: CO₂ pressure and temperature profiles recording during an example decompression test.

The CO₂ pressure and temperature profiles recorded during an example decompression test are shown in Figure 6. It can be seen that the decompression process takes place over approximately 3 seconds, which essentially represents a worst case explosive decompression scenario for the fitting and O-rings. Temperature also drops initially as well, due to the depressurization, but eventually levels off due to the large thermal mass of the fittings and connection tubing compared to that of the CO₂ in the system. This rapid decompression would likely only occur in the case of a relief valve or burst disk release or a catastrophic failure (tube or component rupture). All decompression tests had very similar pressure and temperature profiles, each lasting between about 3.0 and 3.5 seconds.

For the case shown in the figure, decompression from 150 to 1 bar in 3.0 seconds, the average decompression rate is approximately 50 bar s⁻¹ or 3,000 bar min⁻¹. In comparison to common standards for O-ring decompression testing (e.g. ISO 23936:2, 2011 or NORSOK M710, 2001), which generally specify a decompression rate on the order of 20 bar min⁻¹, the decompression rate used during the testing reported in this paper is significantly harsher for the fittings and O-rings being tested here. Even during the last several bar of decompression (last 0.5 seconds), for which the volume of CO₂ expands most rapidly and the O-ring is most susceptible to failure due to rapid expansion, the decompression rate is still well above 100 bar min⁻¹.

After each set of O-rings and fittings underwent 10 decompression tests, the O-rings were visually inspected for any compromising of the material surface (bursting or splitting) or any expansion of the O-ring. Figure 7 shows a visual comparison of a new or untested O-ring with one of the tested O-rings (dry). No splitting, bursting, or expansion was observed on any of the O-rings that underwent explosive decompression testing. This indicates that even the repeated, extreme explosive decompression testing performed on the O-rings does not seem to have any effect on this O-ring material and would not be expected to compromise the sealing ability of the stainless steel press fittings. It also seems that whether or not factory and compressor oil are applied to the O-rings and fittings before testing does not have an effect on the results, as no failures were observed regardless of whether or not the oils were applied. Each set of fittings was also leak tested with nitrogen after the 10 explosive decompression tests. The fittings were leak tested at 150 bar for 15 minutes. No visible leaks were observed during the leak test, verifying that the explosive decompression testing did not compromise the sealing ability of the stainless steel press fittings.



Figure 7: Visual comparison of decompression tested (dry) and new/untested O-rings shows no detectable damage to the O-ring that underwent 10 rapid decompression tests.

Interestingly, while none of the test O-rings showed any signs of failure during or after decompression testing, several non-test O-rings that were being used in auxiliary components of the system, such as the solenoid valve and the burst disc, did experience failures and began leaking after several decompression cycles. These failures generally occurred after 6 – 8 decompression tests (fewer tests than the actual test O-rings underwent). Figure 8(a) shows a Viton O-ring that was used in the CO₂ release (solenoid) valve, which showed signs of bursting after several decompression tests, as shown in the figure. Figure 8(b) shows a nitrile rubber (Buna-N) O-ring that was used to seal a burst disk, which experienced splitting after several decompression tests, as shown in the figure. These observed failures indicate that the decompression test procedure described here was sufficiently harsh as to cause splitting in standard O-rings used in common refrigeration system components. The fact that no splitting was observed in the test O-rings (material compound KB163-90) indicates that these O-rings are able to withstand decompression processes that would otherwise cause splitting or bursting (and thus leaking) in standard O-rings.

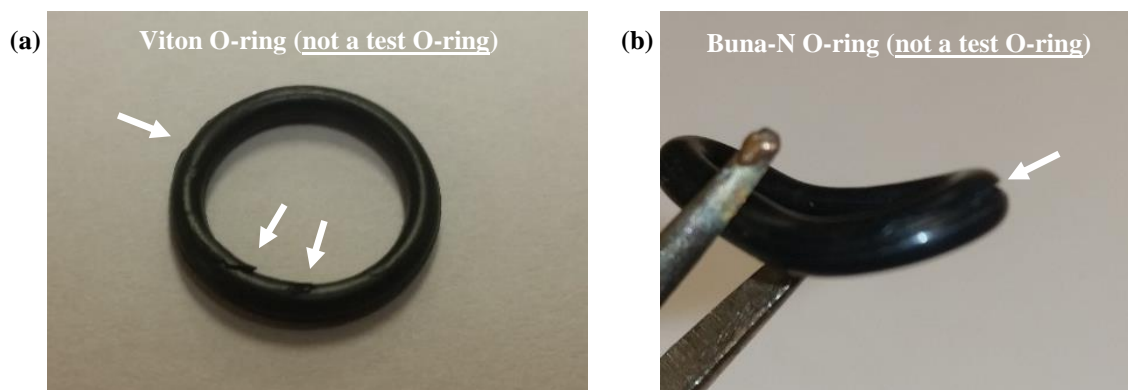


Figure 8: Non-test O-ring failures: (a) Bursting observed in Viton O-ring and (b) splitting observed in Buna-N O-ring.

4. ACIDIC COMPATIBILITY TESTING

As described above, CO₂ refrigeration systems are also at potential risk of having the material of components degraded by acid (H₂CO₃ and H₃O⁺) that forms as a result of moisture in the system reacting with the refrigerant CO₂. In order to evaluate the effect of moisture on the sealing ability of stainless steel press fittings, several 1/2" and 5/8" (5 each) fittings were exposed to carbonic acid at elevated temperature and pressure. A small layer of carbonated water was added to the assembly of fittings, and the fitting assembly was pressurized with CO₂ and held at 40°C temperature and 58 to 59 bar pressure for a duration of 4 weeks. Thus, the CO₂ and water would react naturally under these conditions in a manner very similar to how they would react in an actual CO₂ refrigeration system. At this condition, it is estimated that the carbonic acid had a concentration on the order of 25 ppm and a pH near 3.5.

After 4 weeks of acid exposure, the CO₂ and water were removed from the fitting assembly, and the fittings were leak tested with nitrogen, similar as to the above procedure checking whether the explosive decompression fittings had passed or failed the harshness test. No visible leaks were observed on the fittings when the post-acid exposure leak test was performed, indicating that the acid exposure has no noticeable effect the sealing ability of the stainless steel press fittings and that the fittings had passed the harshness test.

In addition to the fittings, several O-rings were sealed in separate containers filled with either distilled water (pure H₂O) or carbonated water (H₂O + CO₂) to see the effect that liquid water may have on the O-rings; 5 O-rings of each size (1/2" and 5/8") were placed in distilled water, while an additional 5 O-rings of each size were placed in carbonated water, for a total of 20 O-rings tested in either distilled or carbonated water. The O-rings were held in the two different types of water for a duration of 1 week. Figure 9 compares samples of the 1/2" O-rings that were stored in water for 1 week with an original 1/2" O-ring. It can be seen that very little difference in size exists between different O-rings, with the O-ring placed in carbonated water being measured slightly larger in diameter, though even this very small expansion would not be expected to affect the press fittings. Furthermore, no changes in or material degradation of the surface any of the O-rings that were stored in the distilled or carbonated water were observed. These results indicate that acidic effects caused by the presence of moisture in CO₂ refrigeration systems would be expected to have no effect on the O-rings and by extension the sealing ability of the stainless steel press fittings.

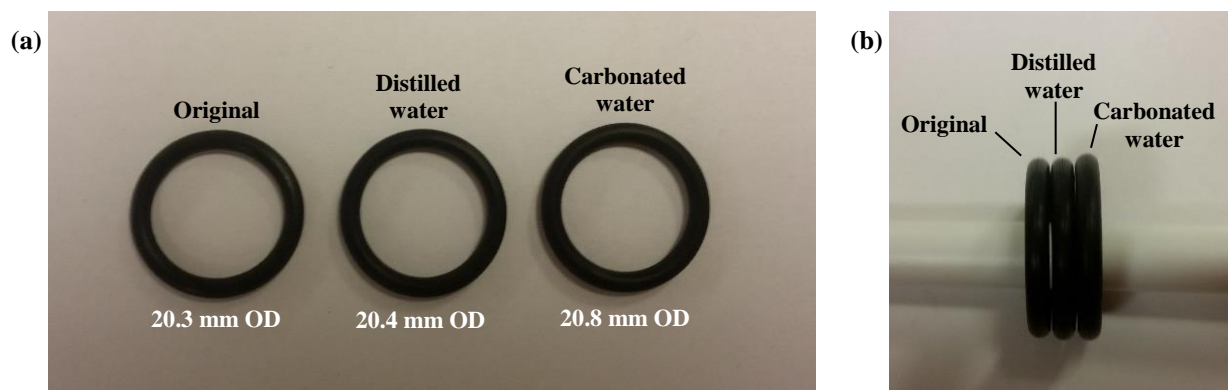


Figure 9: Comparison of size of original 1/2" O-ring, O-ring stored in distilled water for 1 week, and O-ring stored in carbonated water for 1 week.

5. CONCLUSIONS

This paper has presented the results of a study investigating the suitability of stainless steel press fittings for use in CO₂ refrigeration systems. Previous studies had shown that this type of press fitting is durable enough to withstand harshness tests involving freezing-thawing cycling, pressure/temperature cycling, and vibration testing without compromising the fitting. This study has focused on testing the stainless steel press fittings and their O-rings for resistance to the effects of explosive decompression and carbonic acid, two effects of specific concern for CO₂ refrigeration systems.

Explosive decompression is a concern because the small molecule size allows O-rings to readily absorb CO₂, but a rapid de-pressurization of a CO₂ system, and thus rapid volume expansion of CO₂, is sometimes observed to cause bursting or splitting of some O-ring materials. In order to test the HBNR O-ring compound used in the stainless steel press fittings for effects of explosive decompression, a set fittings was pressurized with pure CO₂ up to high temperature and pressure (150 bar and 150°C), held for several hours, and then de-pressurized at an extremely high rate (on the order of 3,000 bar min⁻¹). The holding condition, the decompression process, and the number of repetitions (total of 10 for each fitting and O-ring) all represent worst-case scenarios that would ever practically be experienced in a CO₂ system. Even under these extreme, worst-case test conditions, no compromising of the sealing (leak-tightness) of the fittings was observed, indicating that explosive decompression is not a concern for the stainless steel press fittings investigated in this study.

Additionally, the fittings were also tested for their resistance to the acidic effects that develop due to the presence of moisture in a CO₂ system (formation of H₂CO₃ and H₃O⁺ acids). A set of fittings was held at elevated temperature and pressure while being exposed to the combination of CO₂ and water, creating an environment similar to what would be experienced in a CO₂ system with moisture infiltration. After 4 weeks of acidic-environment exposure, no compromising of the sealing (leak-tightness) of the fittings was observed. These results from decompression and acidity testing indicate that the stainless steel press fittings tested in this study are not affected by either of these CO₂-specific challenges and thus are suitable for use in CO₂ refrigeration systems.

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