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Design of Accelerated Fatigue Tests for Flame Free Refrigeration Fittings

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ABSTRACT

Refrigerant leakage from failed braze joints is a multi-billion dollar problem for the global HVAC&R industry. Leaks are typically caused due to mechanical fatigue from extreme pressure cycling, temperature cycling including exposure to freeze/thaw cycles, or vibrational wear induced from rotating electrical machinery. Three tests to accelerate mechanical fatigue were devised to simulate real world extreme conditions to determine possible failure modes of refrigerant components and joining technologies. The first test is a combined thermal/pressure shock test designed to simulate abrupt temperature and pressure changes due to start/stop cycles and frost/defrost mode changes. Field failures of brazed joints have been detected due to water being trapped in tight spaces and expanding during freezing, causing high stress on brazed joints. The second test is a vibration test, designed to simulate vibrational loads induced from rotating components in the system. The third and final series of testing is a freeze/thaw cycling profile which simulates ice buildup and defrost observed during heat pump operation. The test article is a flame-free tube fitting designed to work with refrigerants. Six different fitting sizes designed to connect tubes between 6.35 mm and 28.5 mm were subjected to the three tests described above.

1. INTRODUCTION

Open air flame brazing is the current state-of-the-art process for joining of refrigerant lines to system components (compressors, valves, heat exchangers, etc.) in the HVAC&R industry. Though brazing is well established, there are several potential pitfalls including the risks of using an open flame, skill level of the torch operator, formation of oxides inside the tube leading to contaminations, ability to join dissimilar metals especially aluminum and the costs associated with precious metals (silver) in the brazing material. Alternatives to brazing (often called cold or flame free) do exist, as many manufacturers offer system components with a flare fitting option. Though flare fittings can initially create a leak free seal, they are known to fatigue over time due to vibration and pressure cycling and are often required to be retightened. Other flame free technologies are available but are generally thought of to be too expensive for use in HVAC&R applications.

A growing way of joining in the plumbing industry is the press-connect fitting (CDA, 2010). This unique technology uses an elastic o-ring and specially designed crimp tool to create a leak free seal for potable water applications and has been found to be reliable in typical plumbing applications. Press-connect fittings do not require the use of a flame, thereby removing the issues with brazing described above. Recent innovations (Arment *et al.*, 2012) have presented press-connect fittings designed for use with refrigerants. This study will describe durability testing performed on this style of fitting.

2. FLAME-FREE TUBE FITTING

The test article for this study is a flame-free fitting designed to join tube carrying refrigerants. The fitting is designed be chemically compatible and structurally sound to work with refrigerants currently in widespread use in HVAC&R applications i.e. (R134a, R410A, R404A). Pictures of the fitting and the joining method appear in Figure 1 and

Figure 2. As shown in Figure 1 the fitting is made from a round piece of metallic tubing (in this case copper) and has two bulged sections near each end for placement of an o-ring. The o-ring material composition is selected to be both materially compatible with refrigerants and lubricants and elastic enough to make a leak free seal once compressed. To make a leak free connection, a metal tube is slid into each open end of the fitting, with the tube marked to ensure that the tube is inserted deep enough so that the o-ring can seal. Lastly a crimping tooling with a specially designed set of jaws is actuated to deform the fitting and create a leak tight joint. The fittings tested in this study are designed to join tube diameters with wall sizes listed in Table 1.

Figure 1: View of Flame Free Fitting

Figure 2: View of Fitting During and After Crimping

Table 1: Tube Sizes Tested

Tube O.D. metric	Tube O.D. (inches)	Nominal Wall metric	Nominal Wall (inches)
6.35 mm	¼”	0.76 mm	0.030”
7.94 mm	5/16”	0.81 mm	0.032”
9.53 mm	3/8”	0.81 mm	0.032”
19.1 mm	¾”	0.89 mm	0.035”
22.2 mm	7/8”	1.14 mm	0.045”
28.6 mm	1 1/8”	1.27 mm	0.050”

3. PRESSURE/TEMPERAURE SHOCK TEST

Components for use in vapor compression must be designed to continuously experience stop/start cycles as building air conditioning units are designed to cycle on and off several times a day. Systems that utilize R410A may experience particularly severe conditions as refrigerant containing components on the high side of the system can experience increases in pressures from 1000 kPa to 3200 kPa and increases in temperature from 20 °C to 90 °C in less than one (1) minute. In addition, when operating in heat pump mode, a thermal and pressure shock is experienced when the system switches from high pressure to the low pressure and vice versa to defrost the outdoor heat exchanger. Hourahan (1998) describes separate test methods for evaluating the thermal and pressure cycling fatigue seen in refrigerant lines and fittings. The testing method outlined for thermal fatigue analysis was to heat the pressurized sample to 132°C and then quench to 4°C using a water bath. A count of 62,000 cycles without failure was determined to be sufficient to determine that failure from thermal fatigue was not concern. The separate pressure fatigue cycling test performed involved rapid pressurization and depressurization of the test samples until failure, at multiple stress levels. The conclusion from fatigue testing was that, to ensure a reliable joint, the braze filler material needs to fully penetrate the joint and all imperfections on the material should be avoided. While both of these test methods independently verify the worthiness of a tube or joint, in refrigeration and air conditioning equipment, temperature and pressure are often closely coupled. For this reason, a method of testing the ability to withstand both pressure and temperature cycling fatigue simultaneously was developed. To provide a pressure and temperature cycling simulation, the test apparatus depicted schematically in Figure 3a and 3b was constructed. Installed, for evaluation, in this apparatus were a series of 16 fittings (four 1 1/8", two 7/8", two 3/4", four 3/8", and four 5/16").

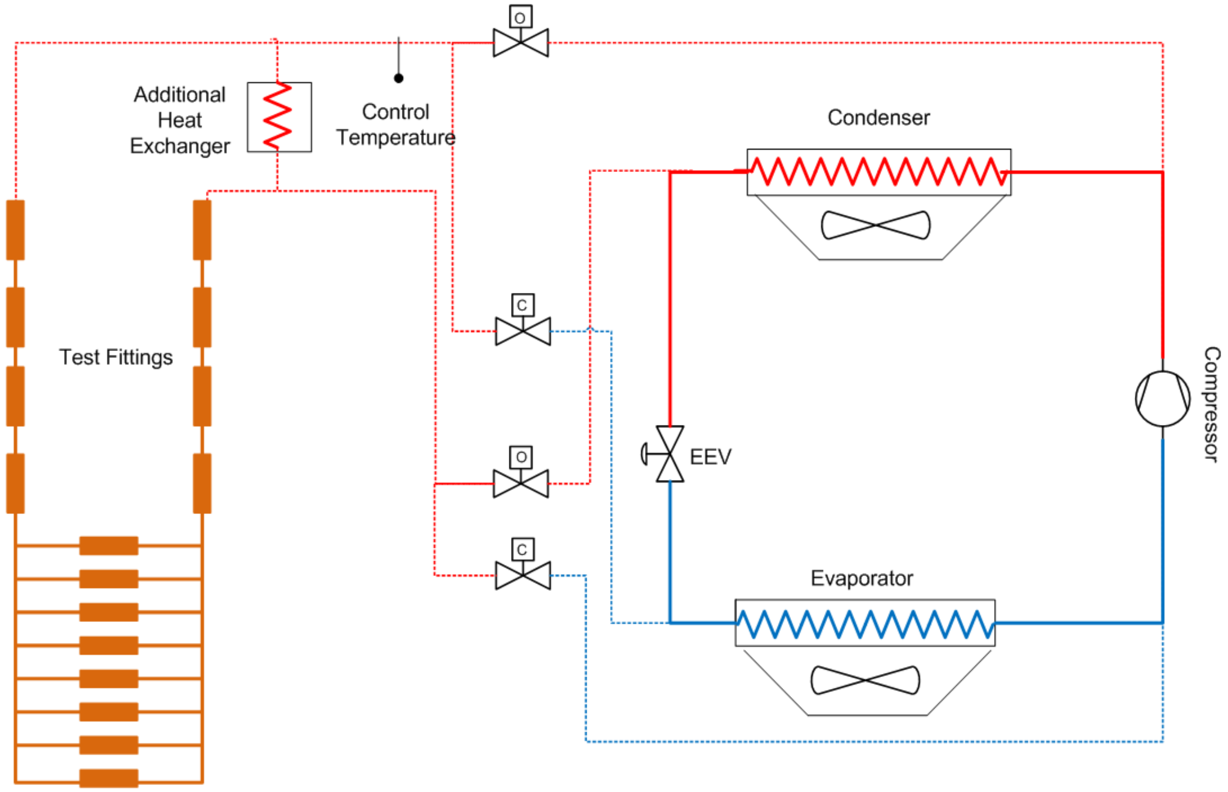


Figure 3a: Heating Mode Schematics for Thermal Shock Test

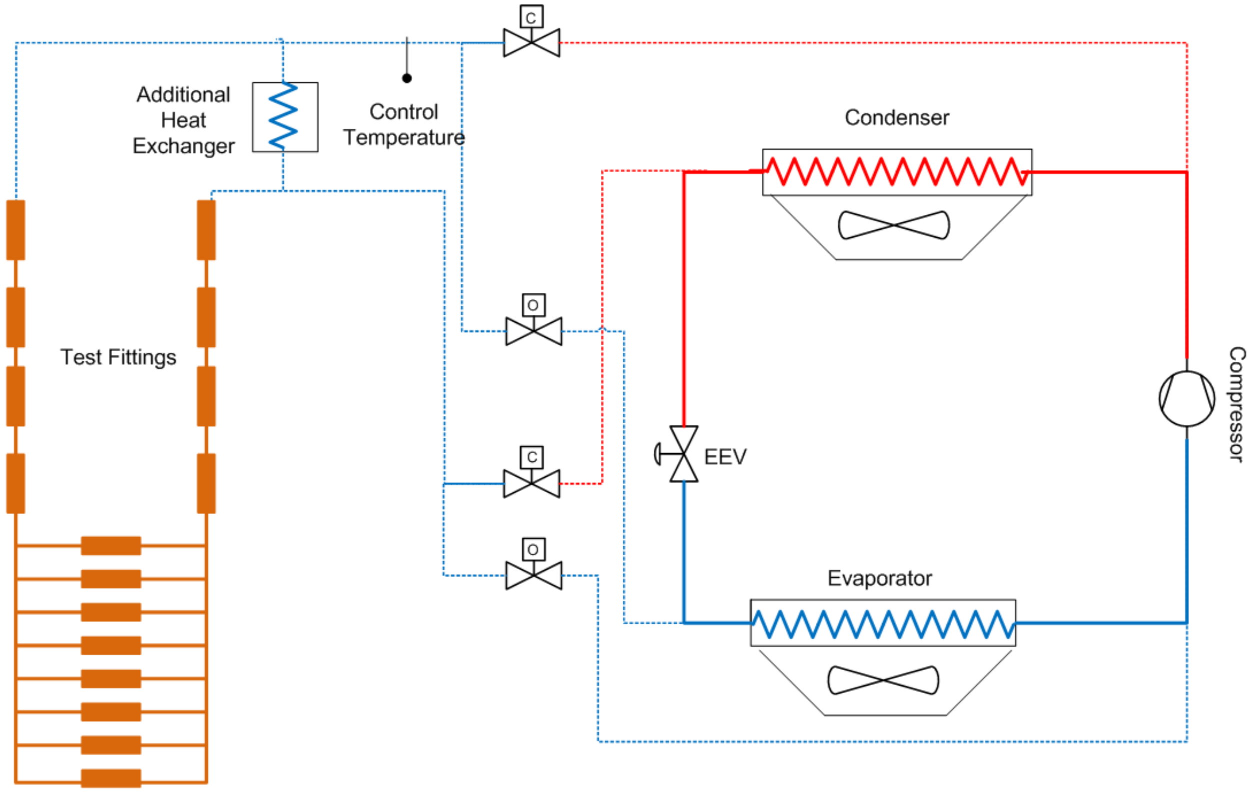


Figure 3b: Cooling Mode Schematics for Thermal Shock Test

The test apparatus uses an existing support vapor compression system with a set of solenoid valves used to direct either hot high pressure refrigerant or cold low pressure refrigerant to the test section. In heating mode, the hot discharge gas from the compressor is split between the condenser and the test section. Downstream of the test section is a small heat exchanger to fully condense the refrigerant before it is then recombined prior to entering an electronic expansion valve, where the fluid is expanded and fed to the support system evaporator. The system operates in heating mode until a temperature set point, 90°C, of the refrigerant leaving the solenoid valves and going to the test assembly is reached.

Upon reaching the high temperature set point, the system switches from heating to cooling mode through operation of the solenoid valves, as depicted in Figure 3b. In cooling mode, all discharge gas is sent to be condensed in the support system's condenser. The subcooled liquid is then sent through the electronic expansion valve, after which the low pressure two-phase fluid is split between the test units and the support system evaporator. This system configuration is maintained until a specified refrigerant temperature set point, ~12°C, at the inlet of the test unit is reached. At this point, the system is switched back into heating mode using the four solenoid valves. A chart showing the temperature and pressure profiles in the test fitting apparatus during several thermal cycles is shown in Figure 4. In this example, the first full heating cycle begins at approximately 10 seconds. The initialization of the heating cycle results in a sharp increase in both pressure and temperature for a few seconds. After this initial sharp rise in pressure and temperature, the rate of increase for both slows, but both still steadily climb until the set point is reached at approximately 45 seconds. Upon reaching the setpoint, the cycle switches to cooling mode which causes both the pressure and temperature to drop dramatically over the next 15 seconds. Over the course of nearly fifty days, all sixteen test fittings were subjected to continuous testing for a total of 80,000 pressure-temperature cycles, without failure. Weekly leakage testing was performed by spraying a soap solution on each joint and looking for forming bubbles to verify that no failures had occurred. At the end of the cycle testing, the test section was pressurized with nitrogen to 689 kPa (100 psi) and the test article were sprayed with soap solution to visually inspect for leaks. No leaks were identified at the end of the testing period.

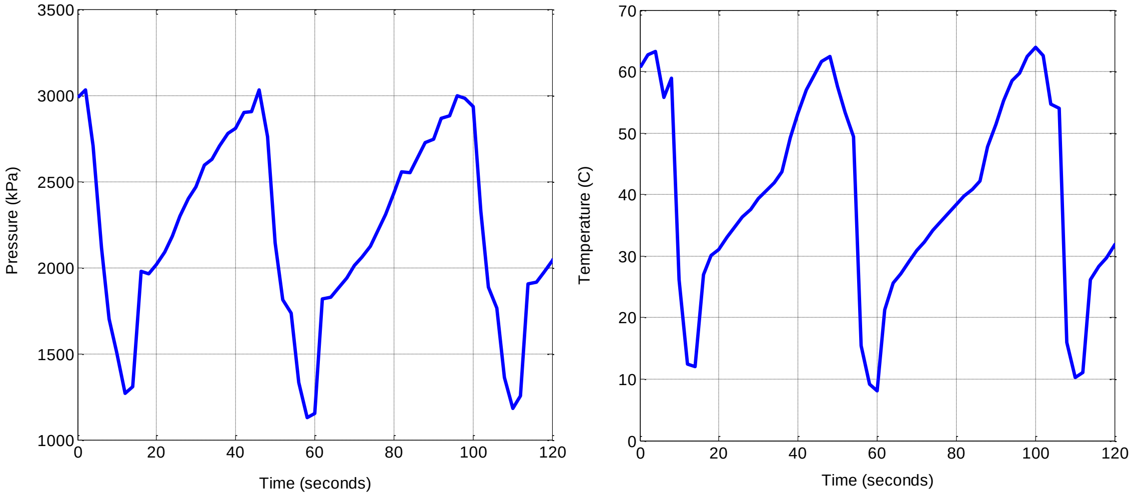


Figure 4: Example Pressure and Temperature Profiles during Shock Test

4. VIBRATION TESTING

Refrigerant leaks at braze joints caused by vibration induced failure are a major cause of concern when designing and fabricating HVAC systems. The1998 study by AHRI and CDA (Hourahan, 1998) suggested that the quality and depth of the braze joint is also important in reducing vibration related failures. To better study vibration induced fatigue, a test was conceived to simulate field vibration in refrigerant carrying tubes. The test set up, shown in Figure 5 has two tube supports with one support fixed and the other support oscillating vertically at an amplitude of +/- 3.0 mm. The oscillations are the result of a four bar mechanism coupled to a rotating motor with an eccentric shaft. The motor had a variable speed drive capable of producing oscillating vertical motion between 0 and 60 Hz on the fitting; however, all fatigue testing was performed at 28.5Hz (a 1725RPM motor running at 60Hz) The length between the supports is measured from the closest edge of each clamp to the other clamp. The values are a direct as a function of tube outer diameter size and are based off of the existing UL 109 standard for tube fittings. Table 2 presents the length between the fixed tube support and the oscillating tube support for the 6 tube diameters evaluated.

Table 2: Distance between Fixed Support and Oscillating Support for Vibration Testing

Tube O.D. (metric)	Tube O.D. (inches)	Tube Length
6.35 mm	¼”	304 mm
7.94 mm	5/16”	304 mm
9.53 mm	3/8”	304 mm
19.1 mm	¾”	457 mm
22.2 mm	7/8”	457 mm
28.6 mm	1 1/8”	608 mm

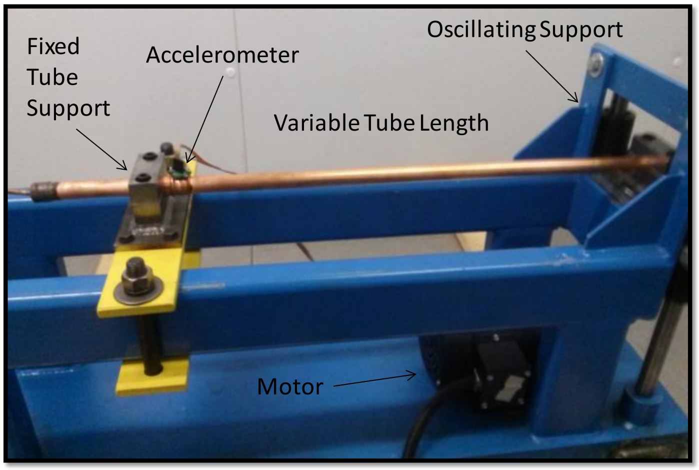


Figure 5: Vibration Fatigue Test Facility

An important feature of the test is the how the fitting is secured into the fixed support. The way tubing and components are supported in HVAC systems varies among manufactures and mechanical contractors, thus it was decided to choose what would be a worst case scenario and secure the back half of the fitting into the fixed support. This is detailed in Figure 7. A specially machined clamp is bolted around the back half of the fitting and then firmly affixed to the facility. This causes the "pivot point" to be located in the center of the braze free fitting itself. To evaluate the severity of the vibrational load, a 1-D accelerometer was attached across the fitting and tube, as shown in Figure 6.The acceleration at this joint was monitored using a datalogger sampling at 300Hz. Exemplar data in both the time and frequency domain from testing of a 22.2mm (7/8”) sample is shown in Figure 7. The up and down motion from the oscillating support causes a very consistent acceleration of approximately +/- 1g. The primary frequency occurs at the 28.5Hz provided by the motor, with a very small amount of power occurring in the second harmonic. All of the fittings listed in Table 2 were pressurized to 2750kPa and cycled at least 1 million times as described above. After vibration cycling, all of the fittings were subjected to a leak test at a pressure of 2750kPa.

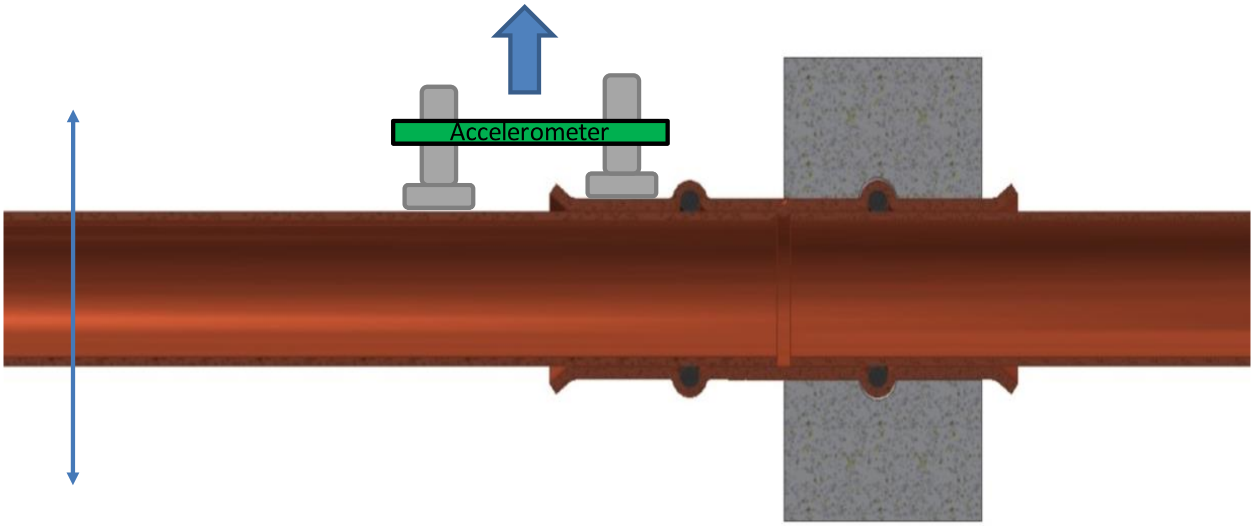


Figure 6: Diagram of Fixed Support and Fitting during Vibration Test

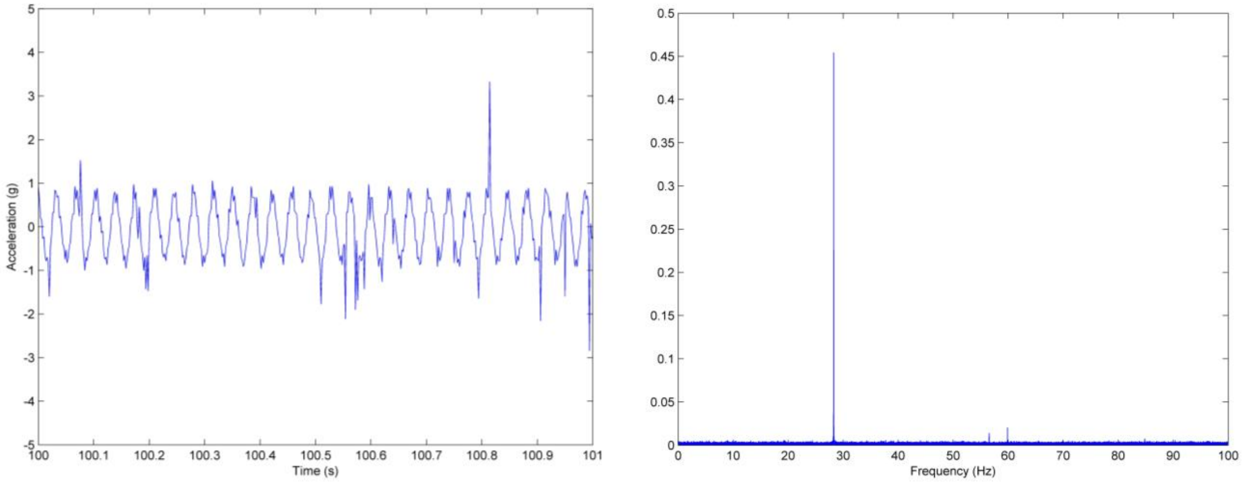
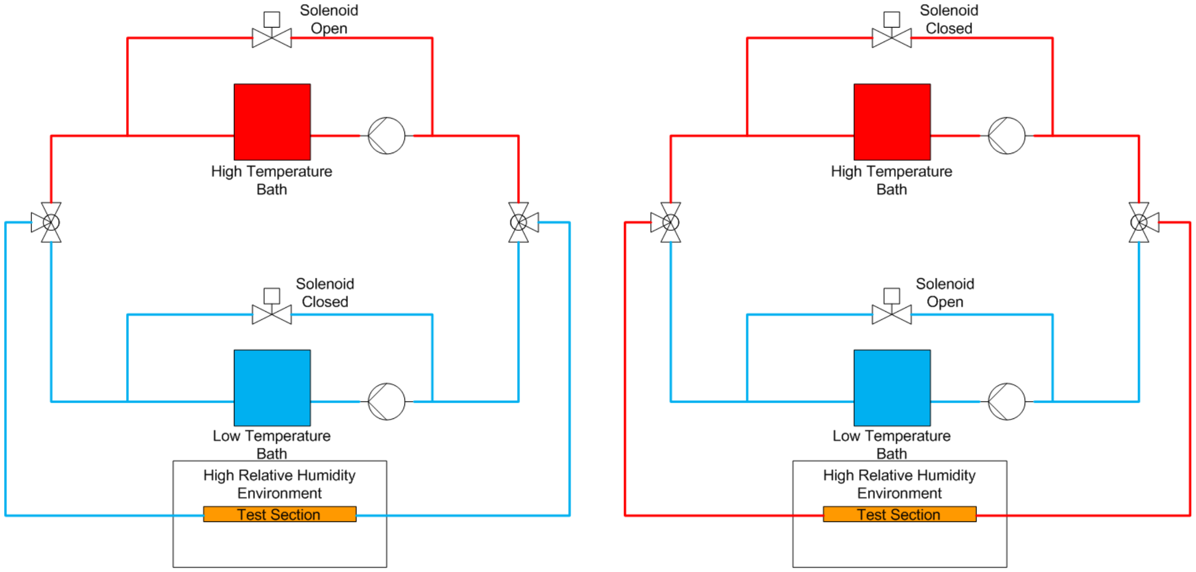


Figure 7: Example Time and Frequency Domain Data for 22 mm (7/8") Fitting

5. FREEZE/THAW TEST

Another reliability and performance concern for reversible heat pump systems is the numerous frosting and defrosting cycles that any component in an outdoor environment must endure. One concern specific to fittings and joints is the infiltration of water into small crevices, going through expansion and contraction during freeze/thaw cycles eventually leading to the failure of the fitting or joint. To simulate this potential failure mode a lab scale freeze/thaw cycling test was devised in which a test section comprised of sixteen (16) fittings were contained in a high relative humidity environment. A diagram of the test setup is shown in Figure 9. An alcohol solution near -40 °C is first pumped through the test section for a fixed amount of time which causes condensation on the fittings eventually leading to ice formation. Once the set amount of time has elapsed, solenoids valves are switched and a warm alcohol solution near 20 °C flows through the test section for a fixed amount of time. This higher temperature fluid causes the ice formation to melt completing the freeze thaw/cycle.



a) Freeze Cycle

b) Thaw Cycle

Figure 9: Operational Schematic for Freeze Thaw Cyclic Facility in Heating and Cooling Modes

An example of images and the wall temperature profile from a single 22.2mm fitting through two freeze/thaw cycles is shown in Figure 10.The temporal plot of the wall temperature profile begins near the end of a thaw cycle. At 80 seconds, the wall temperature peaks at approximately 6°C. The corresponding image shows that there are liquid droplets left on the fitting from the previous thaw cycle. When the solenoid valves are switched, the temperature begins to decrease quickly until, at about 175 seconds, ice/frost is clearly forming on the walls of both the fitting and the tube. The ice formation is also apparent in the gap between the fitting and the tube as shown by the photograph of the top of the tube. At the end of the freezing cycle, approximately 280 seconds, the wall temperature reaches a minimum of -22°C and the tube and fitting are clearly covered in a layer of frost/ice with the frozen droplets hanging in the position that they melted at during the previous thaw cycle. At this point, the solenoid valves are switched and the warm fluid begins to circulate through the test section. About halfway through the thaw cycle, the frost/ice is mostly melted from the surface of the fitting, but ice still exists in the droplets. As the freezing cycle is re-initialized ice/frost begin to form again.

Control of the cycling was achieved using a timer, the cycle time was consistently 8 minutes long with nearly repeatable temperature profiles over all tests. The freeze/thaw test loop was allowed to run for over 5000 cycles (nearly 28 days), simulating approximately 10 years of field conditions. In general, the frosting conditions exhibited over the entire course of testing was very similar to that described above. Occasionally, droplets would fall off the samples during thaw cycles to be replaced during the subsequent freezing cycle. During the testing the facility was shut down after 1250 cycles (weekly) to leak check the fittings to determine if there were any failures. This test was performed by pressurizing the test section with nitrogen at 689 kPa (100 psi), spraying a soap solution on the fittings and looking for leaks. A similar leak check was performed at the end of testing as well, to confirm that no failures were caused by the testing.

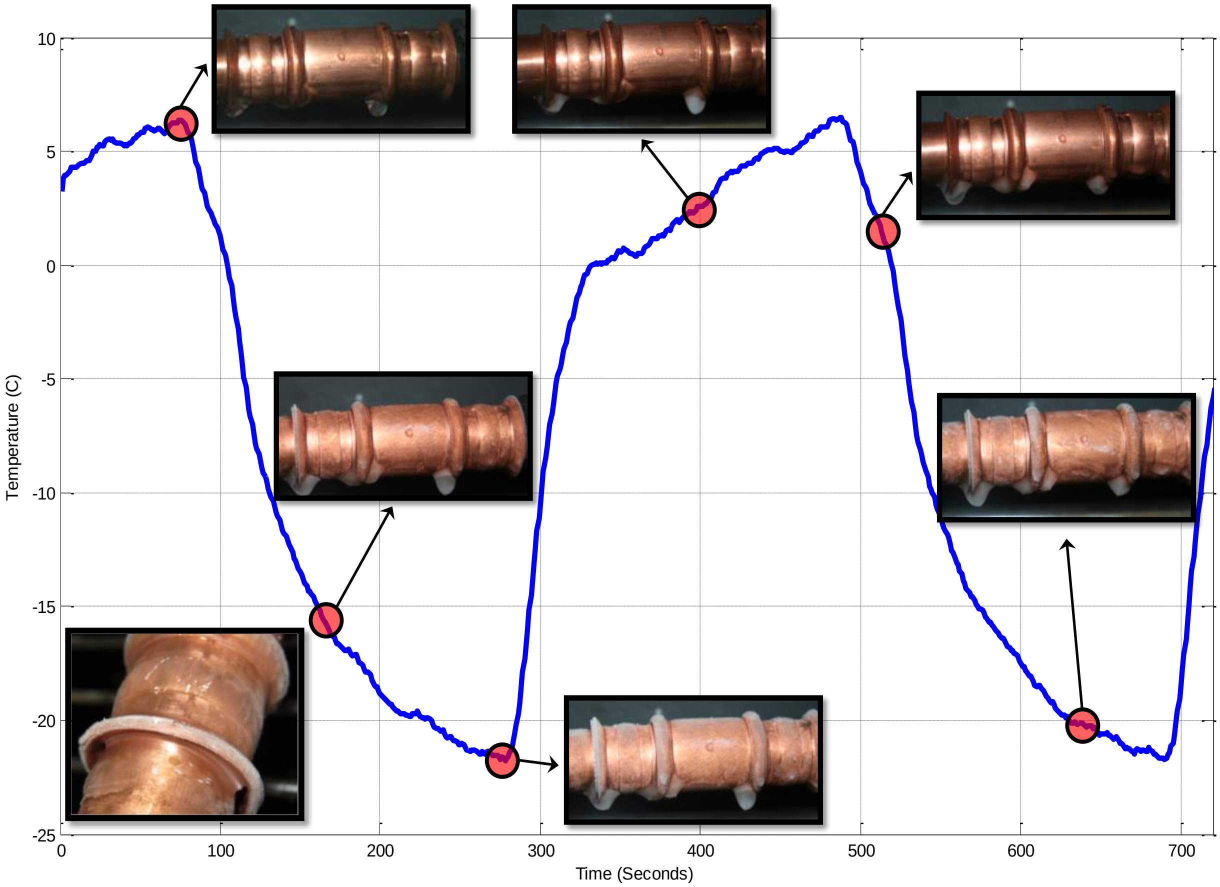


Figure 10: Formation and Melting of Ice and Associated Wall Temperatures

6. CONCLUSIONS

Recent advances in copper press-connection technology have led to the development of a new flame-free fitting suitable for use with many typical refrigerants in HVAC&R applications. In order to verify the durability of this new kind of press-connection type fitting, three test protocols were developed and employed in six different tube sizes to investigate the effects of pressure and temperature cycling, vibration, and freezing and thawing of water on the fitting. The first test cycled the fluid pressure and temperature within the samples from approximately 1100kPa to 3000kPa and 12°C to 90°C, respectively, over 80,000 times on series of 16 sample fittings spanning the range of 6.35mm to 28.6mm. Resilience to vibration was tested by fixing a tube and fitting assembly at one end and oscillating it at the other at a frequency of 28.5Hz. This test was performed on test fittings for all 6 fitting sizes and cycled for over a million cycles. The third and final series of test simulated frosting and defrosting by alternating the flow of cold and warm fluid through a series of fittings in order to form ice/frost on the joints between tube and fitting and then melt it. Over 5,000 of these freezing and thawing cycles were performed on a total of 16 test fittings spanning all 6 sizes. At the end of all tests, leak tests were successfully performed to ensure that the durability of the test fittings was maintained over the test period.

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