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Proof-of-Concept Testing of Adhesive Joints for HVAC&R Applications

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Abstract

The formation of joints is a critical process in HVAC&R component manufacturing and system assembly. Brazed joints are the most commonly used, but there are several alternative methods including mechanical compression, press, and push joints. Adhesive joints have not been widely explored or evaluated for use in HAVC&R systems. In this study, a review of different joint types reveals that adhesive bonding is a promising joining method due to potential benefits in energy use, cost savings, and leakage reduction. In order to demonstrate an application procedure and explore the feasibility of adhesive joints, two proof-of-concept tests were performed. First, tube-to-tube joints were installed in a heat pump dryer system to confirm that adhesive can hold the system pressure without affecting performance. Second, adhesively bonded U-bend joint samples were tested using a shaker table following an ISO standard and benchmarked against brazed joint samples. There was no failure or wear observed for the adhesive or brazed joints. These proof-of-concept tests indicate that there is potential for use of adhesive joints to replace brazed joints in HVAC&R applications, which merits further investigation.

Keywords: ; HVAC&R system, Joints; Adhesive joints; Heat pump dryer; Vibration test

1. Introduction

In heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems, joints are commonly used to connect the refrigerant lines to other system components (such as compressors, condensers, evaporators, and filter dryers) and in the assembly of components such as tube-and-fin heat exchangers. The joints are critical to avoiding system leakage throughout the lifetime of operation. Refrigerant leakage is a direct greenhouse gas emission, but also results in additional indirect emissions by reducing the system energy efficiency and equipment lifetime. Leaks most typically occur at the locations of joints and connections in the system, and are usually caused by fatigue failures associated with temperature cycling, pressure cycling, vibration, or mechanical wear. According to a recent EPA report [1], HVAC&R equipment across many different application categories are facing leakage issues. Several of the common HVAC&R equipment categories shown in Table 1 have leakage rates of 10% per year or more due to faults in joining techniques, system design, and operations/ maintenance practices. Supermarket refrigeration systems can have up to 25% leakage per year due to the nature of field installing long line sets.

In order to address these issues, one of the critical tasks is to investigate, evaluate, and explore both existing and new joining technologies to reduce the leakage of refrigerant from HVAC&R equipment. Currently, brazed joints are the most commonly used, but there are several alternative methods including compression joints, press joints, push joints, and adhesive joints. Among these alternatives, adhesive joints have not been widely explored for use in HAVC&R systems and there has been a lack of evaluation and testing. This paper first reviews and compares different joint types and then reports two proof-of-concept tests performed using adhesive joints.

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Table 1. Estimated annual HFC leakage rates for common HVAC&R categories, according to the EPA [1].

Equipment Category	Estimated Annual HFC Leakage Rates (%)
Supermarkets and Other Retail	1-25
Mobile Air Conditioners	2-18
Cold Storage	15
Residential Unitary AC	12
Industrial Process Refrigerant	4-12
Centrifugal Chillers	2-11
Commercial Unitary AC	8-9
Packaged Terminal AC / Heat Pump	4
Refrigerated Appliances	< 1

2. Overview of Joining Technologies

A typical HVAC&R system consists of various individual components connected by tubes and joints to form a closed-loop piping system for cycling of the refrigerant. The components usually include compressors, heat exchangers, valves, and additional accessories such as filters, pumps, and sight glasses. In addition to the connections between these components, there are subassemblies consisting of numerous parts that must be joined together. For example, tube-and-fin heat exchangers are manufactured by joining individual tubes and metal sheets together with U-shape bends. In the majority of HVAC&R systems, copper tube-to-tube joints make up most of the connections. The review below focuses on joining technologies for copper, if not otherwise specified.

At each location where two components meet, joining technologies need to provide a mechanically adequate bond between the surfaces without any damage to the original part. These joints must meet structural requirements for load-bearing (if required) and to withstand the operating pressure of the system, allowing refrigerant to flow through unobstructed. Strong and reliable joints provide stable, efficient, and leak-free system operation; failures in joining cause refrigerant leakage having negative consequences including safety concerns, wasted energy due to system efficiency reductions, and pollution to the environment.

2.1. Brazed joints

Brazing is the most common joining technology in the HVAC&R industry. It is a well-established commercial process capable of producing strong joints between most metallic and ceramic materials, which has led to its widespread adoption in industry. Brazing can be performed both manually as well as in automated production processes. As defined by the American Welding Society [2], the term brazing encompasses a group of joining processes that bond materials by heating to a brazing temperature in the presence a filler metal having a melting point above 450 ℃ (840 °F); the brazing temperature does not cause melting of the base materials. The brazing filler metal becomes molten and is distributed by capillary action within the tight clearance between the two surfaces that are being joined. The assembly is then cooled, and the molten filler solidifies. The filler metal anchors the surfaces together owing to metallurgical reactions that lead to atomic bonding. For most tube-to-tube joints, a separate coupling tube, having a slightly larger diameter than the tube end being joined, is placed so that both tube ends have an overlapping area with the coupling where the bond is established. Alternatively, the two components can be connected directly without an overlapping coupling to form a butt joint.-Strong, uniform, leak-proof joints can be made rapidly and inexpensively with brazing, especially for joints that are inaccessible or for parts and components that may not be joined using other methods.

2.2. Mechanical joints

Mechanical joints can be categorized into several different types including compression joints, press-connect joints, and push-connect joints [3]. Mechanical joints are an alternative for brazed joints when using an open flame is either not desired or impractical. All mechanical joint types form a seal using mechanical pressure to physically close the leakage path. Mechanical joints are commercially available from several manufacturers.

Compression joints are usually composed of an outer compression nut and an inner compression ring or ferrule made of brass or copper. Ferrules most commonly have a shape of a ring with beveled edges. The longest sloping face of the ferrule usually faces the opposite direction of the nut. In the joining process, the nut is tightened and the ferrule is compressed between the nut and the tube. The ferrule will seal the gap between the tube and nut, producing a tight joint by clamping the end of the ferrule around the tube [3].

Press-connect joints rely on the excellent malleability of copper, forming a seal using a special gasket, usually of an O-ring shape, for joining. Using approved special pressing tools and jaws, the copper fittings are flattened into thin sheet on the tube that are being joined to form a leak-proof connection. [3].

A push-connect joint is another available type of mechanical joint that does not require heating or specialized tools, and can be made by hand. These joints are similar in principle to press-connect joints. On the inner diameter of the fitting, an integral elastomeric gasket or seal and stainless-steel gripping ring help to produce a leak-free joint. Once pushed on, the gripping ring and the gasket together provide a seal on the outer diameter of the insertion tube; the use of the gripping ring avoids the need for a pressing tool as in the press-connect joint.

2.3. Adhesive joints

Adhesive joining processes use an adhesive substance that holds materials together by surface attachment [4]. It is a widely used industrial joining method that has been adopted and proven reliable in several industry sectors, such as in automotive and electronics. While there are many types of adhesives, the ones used for structural bonding are typically cured in order to have adequate strength to transfer the loads through the joints. One-part adhesives need to be heated up before application and two-part adhesives need to be evenly mixed. Based on the application and assembly process requirements, there is freedom to design and develop adhesives with different characteristics such as the curing temperature/time, assembly time, or drying temperature/time.

A review of the scientific literature and survey of available products in the market reveals that adhesive joining (tube-to-tube or otherwise) is not a mature technology for application in HVAC&R systems. There is a lack of research and little information on product development and qualification standards specific to this industry. Most of the existing products focus on quick repair, instead of initial manufacture. Based on our product research, the few examples of adhesives used for HVAC&R joint repairs are two-part epoxies requiring heat curing. Epoxies are widely used as high-performance structural adhesives because of their ability to cure without producing volatile byproducts, high resistance to chemicals, and low shrinkage during curing [5,6]. When employed, the epoxy resin is mixed with hardener at a certain mass ratio to form a homogeneous mixture, which must be applied to a prepared/cleaned surface within a working time before it cures. The strength of the adhesive joint largely depends on the design of the joints, thickness of the adhesive, bonding area, and surface modifications the bonding area.

2.4. Summary comparison of different joint types

A qualitative comparison of brazed, compression, press-connect, push-connect, and adhesive joints are summarized in Table 2. In comparison with the other joining technologies, adhesive joints provide some unique features that are key to overcoming challenges facing the HVAC&R industry. Compared to brazed joints, using adhesive joints can potentially reduce the manufacturing energy and cost, and also avoids the risk of galvanic corrosion between dissimilar metals [7]. In addition, unlike the mechanical joints that are only available for very specialized geometries, the process of using an adhesive material to join between any surfaces is similar in nature to the use of a brazing material. This offers the potential to form adhesive joints in mass production with a similar assembly line as brazing. Being aware that the primary disadvantage of adhesive joints is the lack of established procedures for application and assembly, as well as their unknown reliability, this study aims to demonstrate a joining procedure to explore the feasibility of adhesive joints. A complete joining procedure is developed including surface preparation, adhesive preparation, adhesive application, and curing. Proof-of-concept tests are performed using adhesive joints in a heat pump dryer system and by placing joints on a vibration shaker.

Table 2. Summarized comparison among different types of joints considered for use in HVAC&R systems

Joint type	Various geometry	No open flame	Permeant fittings	No clamping tools	No extra components	Joining of dissimilar metals	Long-term reliability
Brazed	✓	×	✓	✓	✓	×	✓
Compression	×	✓	×	×	×	✓	×
Press-connect	×	✓	✓	✓	×	✓	✓
Push-connect	×	✓	×	✓	×	✓	×
Adhesive	✓	✓	✓	✓	✓	✓	?

3. Heat Pump Dryer System Demonstration

A proof-of-concept test is performed to demonstrate the use of adhesive joints in an HVAC&R system under normal working conditions. In addition to evaluating any potential effects on the system performance, the tests may expose any unexpected issues in the assembly process. The proof-of-concept test uses an adhesive to form tube-to-tube joints in a commercial heat pump dryer test stand, simulating an installation or repair in the field.

3.1. Experimental system

A heat pump system taken from a commercial clothes dryer is selected as the test system. The system components are summarized in Table 3. Fig.1 shows an image of the test stand alongside a schematic diagram of the flow loop with the primary components labelled. The system is a vapour compression cycle: the refrigerant vapour comes out of compressor and is condensed to liquid against ambient air through the subcooler and condenser. A separate fan is used to provide the airflow for the subcooler and to cool down the compressor. The liquid out of the condenser expands through a capillary tube and evaporates in the evaporator which then goes back to the compressor and closes the cycle. There is a blower that provides airflow for both the condenser and evaporator through the same air duct.

Table 3. Component specifications and materials in the heat pump dryer system

Component	Description
Compressor	HIGHLY (Shanghai Hitachi) BSD122DN-H3BDA
Condenser	Tube-and-fin type (Material: Aluminum)
Subcooler	Tube-and-fin type (Material: Aluminum)
Capillary Tube	Material: Copper
Evaporator	Tube-and-fin type (Material: Aluminum)
Filter Dryer	Material: Copper
Tubing	1/4-inch for discharge and 3/8-inch for suction (Material: Copper)

The commercial system introduces various factors that may influence the adhesive joint performance. The system has a relatively high pressure of up to 15 bar at 55 °C with R134a as the refrigerant. The tubing is exposed to sudden pressure changes and random vibrations when the compressor and blower are running. It is an oil-lubricated system with oil passing through the tubing along with the refrigerant. There is tension and torque on the joints caused by thermal expansion and contraction as the system heats and cools as it is cycled on and off. All of these factors simultaneously act on the adhesive joints in a manner that is hard to simulate through standardized testing.

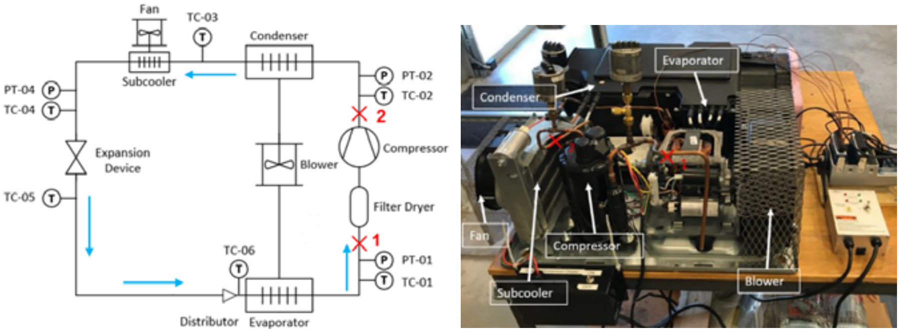

Fig. 1. Schematic drawing (left) and photograph (right) of the custom-instrumented heat pump dryer test stand with the locations of the pressure transducers (P) and thermocouple measurements (T) indicated. The adhesive joints are placed at the locations labelled "1" and "2".

The system was also selected due to its simplicity in system control. The system consists of a single speed compressor, blower and fan with a capillary tube. There is no active control, and hence, the system operating conditions are only determined by the refrigerant charge amount and environmental temperature. Within a lab-testing environment, the temperature stays relatively constant. The operating conditions can thereby be used as an indicator for the system refrigerant charge amount.

The system is custom-instrumented with sensors to monitor the operating conditions. Three pressure transducers and five thermocouples are installed to measure the pressure at several selected locations and the temperatures at the inlet/outlet of each component, as labelled in Fig.1. The pressure transducers measure from 0 – 500 psig with an accuracy of ± 0.65 psig. The thermocouples are copper-constantan (T) type with ± 1 ℃ uncertainty. Two different locations are selected for insertion of the adhesive joint based on the operating conditions of the system, as marked by red crosses in Fig. 1. Location "1" is at the compressor outlet where there is the highest temperature and pressure in the system; location "2" is at the compressor inlet, with the lowest temperature and pressure. At each location, the original tubing is cut with a chip-free tube cutter in the middle, leaving two open ends. A copper coupling is used to form a new tube-to-tube connection using the adhesive, as will be described in the subsequent section.

3.2. Adhesive joining procedure

A structural adhesive two-part epoxy was used as the bonding material for the application process. As suggested by the manufacturer, a manual applicator with a static mixing nozzle were used to evenly mix and apply the adhesive to the surface.

The outer tube surfaces were prepared by a traditional method of acetone cleaning, followed by sanding, and lastly a second acetone cleaning. The coupling is only acetone-cleaned because the inner surface of the small-diameter tube is inaccessible for sanding. Note that the coupling is a standard size for brazing purposes and is not specifically designed for adhesive joining. The gap size between the tube outer diameter and coupling inner diameter at both locations is measured to be 0.85 mm; this is within the recommended working range for the adhesive, which will guarantee a strong adhesive bond. Fig. 2 shows the location "1" tube cut, with the two open ends aligned after preparing the bonding surface; the coupling is shown slid onto the left-side tube end. The difference in color of the copper tube near the coupling indicates that the surface preparation removed the oxide layer and other contaminants. Before applying the adhesive, the two tube ends are aligned coaxially and pressed against each other to decrease the possibility of adhesive leaking into the inner surface of the copper tubing. The adhesive is circumferentially applied on the cleaned tube area to cover a region the same length as the coupling. The coupling is slowly slid along the tube until the cut is at the center of the coupling. It is ensured that the adhesive fills the gap between the tube and the coupling, with no visible openings; the assembled joint is shown in Fig. 2. Because the tube is in a horizontal orientation, the adhesive accumulates at the bottom of the tube due to the effect of gravity. The adhesive is left to cure at room temperature for 24 hours. After curing, an aluminum safety shield is placed around the joints in case of a catastrophic failure. The other adhesive joint in location "2" is manufactured following the same procedure.

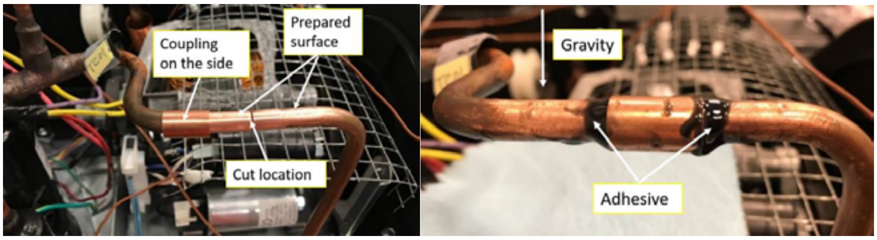

Fig. 2 Photographs of the cut location "1" for the tube-to-tube joint after preparing bonding surface (left) and within the coupling in place over the cut after application of the adhesive (right).

3.3. Testing procedure

Before cutting the tubes, a baseline test was performed to measure the system operating conditions. The system was charged with 428 g of refrigerant R134a, which is recommended by the manufacturer. All of the system components (e.g. the compressor, fan, and blower) were run at a fixed speed that was maintained constant for the duration of the test until steady-state operating conditions were achieved.

After recording the standard operating condition benchmark, the tubes were cut and re-assembled with adhesive joints as described in the previous section. Before recharging the system with refrigerant, a leakage check was performed by charging the lines with high-pressure nitrogen and pulling a vacuum on the system. The system high-side operating pressure is approximately 960 kPa and it was charged with nitrogen to 1900 kPa. After 72 hours, the pressure dropped by ~1% to 1880 kPa and then held steady. When a vacuum was pulled on the system, no pressure increase was observed after 6 hours. These tests confirm that the system was leak-free after the initial adhesive joining and ready for testing.

The system was charged with the same amount of refrigerant as during the baseline testing. After charging, a long-term test plan was followed for the adhesive joints: the system was run for several hours every one or two weeks, similar to the anticipated operation of the device, with the pressure and temperature recorded after reaching a steady operating point. The procedure evaluates whether the prototype adhesive joints can hold the pressure over a long time while being subjected to normal running cycles. The system pressures and temperatures are compared with baseline results, which would differ if there was a significant loss of charge.

3.4. Results and discussion

The operating conditions for the baseline and the case with adhesive joints case are compared in Fig. 3. The baseline condition is defined as the standard operating condition, achieved by the initial charge without any modification with adhesive joints. Several assumptions were made to calculate all state points where there is not a direct measurement, namely: no pressure drop in the condenser, constant enthalpy across the expansion devices, and two-phase operation the condenser and evaporator. Due to the long tubing and distributor before evaporator, there is an additional pressure drop between the capillary tube (point 5) and evaporator (point 6). This was treated as a second expansion device to accurately capture the pressure and temperature at the evaporator inlet.

The data presented in Fig 3. indicates that there is a consistent operation before and after installation of the adhesive joints. In both cases, between state points 5 and 6, there is additional pressure drop with the according temperature decrease. Also, note that the there is pressure drop across the evaporator, which explains the temperature decrease from state point 6 to 1. A small variation in the pressure and temperature, comparing the baseline and adhesive data, are attributed to slightly different charge amounts due to the refrigerant scale uncertainty and difference in the room temperature (21.9 ℃ for the baseline versus 22.4 ℃ in the adhesive case).

In order to further evaluate the feasibility of this concept, the system was operated periodically over the next 6 months per the testing procedure described in the previous section. The corresponding temperature-entropy (T-s) and pressure-enthalpy (P-h) diagrams are shown in Fig. 4, with the adhesive test operating points overlaid on a plot of the baseline condition. As shown in Fig. 4, the system performed consistently with each subsequent test after sealing the joints with adhesive. The consistent pressure level and system performance indicates that there was no leakage over the testing period and that the adhesive joints operate successfully under the temperature changes and vibrations associated with operation of the system using refrigerant R134a. Despite the limitations of testing only two adhesive joints over a moderate temperature/pressure range for a period shorter than the typical lifetime, as a proof-of-concept test, this suggests that adhesives may be feasible and practical to replace brazed joints in HVAC&R systems. Further testing is recommended to evaluate the performance of adhesive joints in HVAC&R systems to the point of failure or leakage.

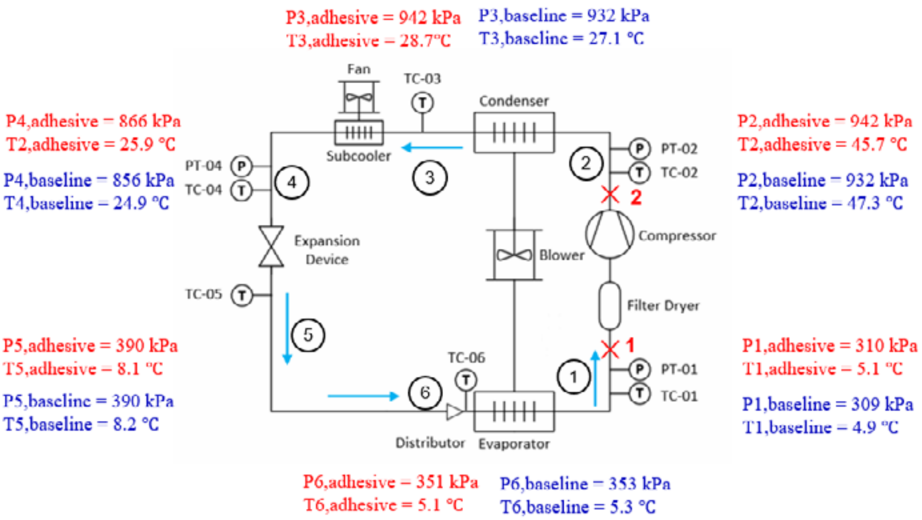

Fig. 3 Schematic diagram of the heat pump system showing the pressure and temperature values measured or calculated at each state point. The baseline data are shown in blue and the data for the tests with the adhesive joints are shown in red.

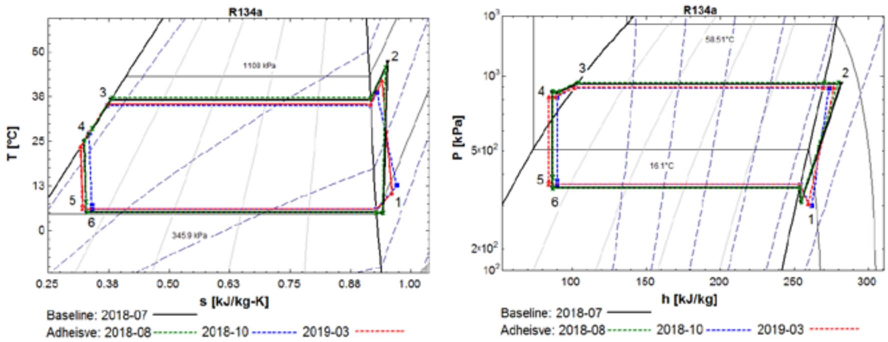

Fig. 4 T-s (left) and P-h (right) diagrams of heat pump system operation conditions at the baseline condition and for three selected tests over a 6-month period after installing the adhesive joints.

4. Vibration Testing

Failure in HVAC&R joints caused by vibration is one of the major concerns. Although the heat pump dryer testing showed that the joints can function in a real operating system under vibrations from the compressor and cooling loop flow, an accelerated test involving more intense and controlled vibrations is performed to evaluate whether a leakage may occur. Vibration testing is performed following the ISO standard 14903 [6], with the test parameters as given in Table 4. The vibration displacement and number of excitations are specified based on the tube size and require precise control.

Table 4 Vibration test parameters from ISO standard 14903 used to evaluate the survivability of the adhesive joints.

Pipe Diameter (mm)	Length (mm)	Displacement (mm)	Frequency (Hz)	Number of excitations
< 10	200	0.30	≤ 200	2 000 000
≥ 10 and < 20		0.25		
≥ 20 and < 30		0.20		
≥ 30 and ≤ 50		0.15		

4.1. Experimental setup

The separate vibration test is performed using a shaker test stand. The test system produces controlled vibrations to evaluate the reliability of components used in various applications.

Due to the large number of U-joints that are present in tube-and-fin heat exchangers, this joint geometry is selected for vibration testing. For this geometry, a U-bend tube is joined at both ends to straight tubes, as shown in Fig. 5. These two tube-to-tube joints are formed by flaring the straight tube for insertion of the U-bend with adhesive, rather than using a coupling. The outer tube diameters are 9.525 mm (3/8 inch) and the straight tube lengths are 152.4 mm (6 inches). A custom adhesive formulation from an industry collaborator (with characteristics similar to the previous one) is used for the joining process, which was performed by the industry partner. Two different sets of U-joints were tested: one set of 8 samples with adhesive joints and another set of 8 samples having brazed joints. Two types of joints are tested simultaneously for comparison.

The vibration exciter generates the vibrations of a specified frequency and displacement to drive the base plate. It is important to firmly clamp the U-joints to the base plate for both safety and accuracy of the testing. For this purpose, aluminum fixtures are custom-designed and fabricated to clamp the extended straight tubes while leaving the U-joints to hang freely at the end, similar to their configuration in tube-and-fin heat exchangers. The 3D drawings of the fixtures are shown in Fig 6. The bottom plate of the fixture is affixed to the shaker base plate using bolted connections through two large clearance holes. The bottom and top fixture plates are attached using bolted connections; eight bolts pass through clearance holes in the top plate and thread into the bottom plate. At the interfacing surfaces between these two plates, there are 16 half cylinder cavities designed to clamp the extended tubes of the samples. Black rubber sheets taped on the extended tubes between the plates and samples provide cushioning and fix the samples in place. The diameter of the cavity is sized to be slightly smaller than the outer tube diameter plus the thickness of the rubber sheet, such that the copper tubes are pushed firmly into place with compression of the black rubber sheets. Fig 5 shows a photograph of the two sets of U-joints with fixtures installed on the shaker test stand.

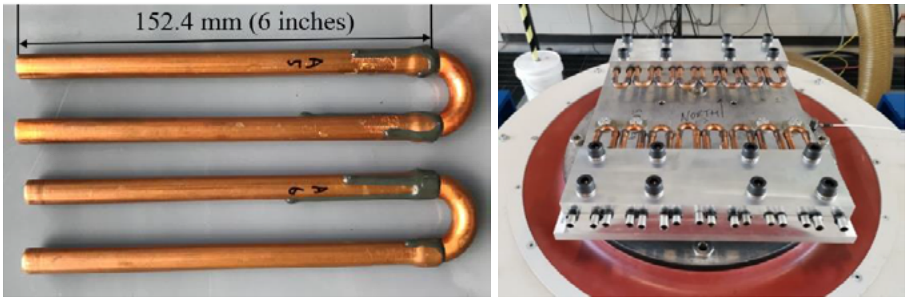

Fig. 5 Photographs of the U-shape joints with adhesive (left) and the fixtures containing a set of 8 samples each installed on the vibration shaker test stand.

4.2. Testing procedure

Following Table 4, the fixtured joints are subjected to vibrations with 0.3 mm displacement at a frequency of 125 Hz. The total number of the excitations is 2,000,000. The displacement and frequency of the test section are monitored and measured throughout the test. The joints are not pressurized with any fluid during the vibration testing in case of failure.

Before and after the vibration testing, the U-joint samples are each visually inspected and checked for leakage. Before vibration testing, fittings are soldered to the open end of the extended tubes to allow charge the samples with high-pressure nitrogen. During the soldering process, the U-joints were cooled using wet cloths to keep the temperature near room temperature. The samples with fittings are charged to 1700 kPa (approximately 250 psi) and immersed in water to observe if there are any air bubbles. The fittings are unsoldered and removed before placing the sample into the fixtures. The same process is repeated after the vibration testing.

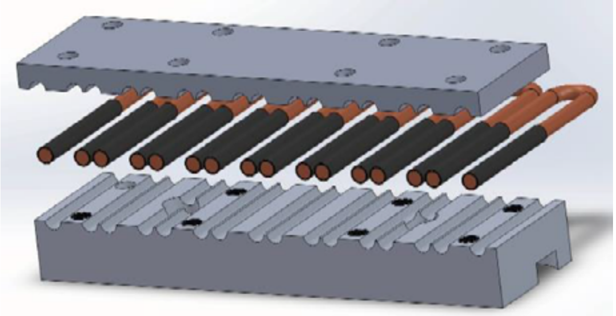

Fig. 6 3D Drawing of the fixture assembly with U-shaped joints wrapped with black rubber sheet.

4.3. Results and discussion

Before vibration testing, there were no cracks or imperfections in the adhesive or brazed joints, and all the samples were leak-free. The in-situ test stand measurements confirmed that the samples were subjected to 0.3 mm displacement vibrations at 125 Hz; the acceleration for the shaker was 21.2 g. The test stand ran continuously for 4.5 hours, which resulted in a total of 2,025,000 excitations. After testing, the rubber sheets used for fixing the samples into place were worn as expected, but the copper surface and the joints appeared the same as before testing for both brazed joints and adhesive joints as shown in Fig. 7. All the samples were confirmed to be leak free after testing. The results demonstrate that the adhesive joints are able to survive these extreme vibration conditions just as the brazed joints without any failures.

Fig. 7 Photographs of the U-shape joints after the vibration test for adhesive joints(left) and vibration joints compared with brazed joints (right).

5. Conclusions

Adhesive joints have the potential to replace brazed joints and improve system efficiencies in the HVAC&R industry. Compared to existing brazed and mechanical joints, the use of adhesives offers lowers cost, increase the ease of manufacturing without an open flame, and provides the flexibility to be applied to various materials and geometries. To demonstrate the application procedure and explore the feasibility of an adhesive joint, two separate proof-of-concept tests were performed using a heat pump dryer system and a vibration shaker test stand. An adhesive joining procedure is presented including surface preparation, adhesive preparation, adhesive application, and curing. For the heat pump dryer system, tube-to-tube adhesive joints were installed at the inlet and outlet of the compressor. The system was first pressurized to check for initial leaks and then charged with refrigerant for performance testing over a 6-month period. Results showed that the adhesive joints hold the refrigerant pressure without leaks and the system performs consistently before and after the installation of adhesive joints. For the vibration testing, copper U-bend samples were joined to straight tubes using either an adhesive or with a standard brazing method as a benchmark. These joints were fixed on an industrial shaker table and tested following an ISO standard for joints with 0.3 mm displacement at 125 Hz for 2,025,000 vibrations. The joints were leak checked before and after the vibration testing and no failures were observed for the adhesive or brazed joints. These proof-of-concept tests indicate that there is potential for use of adhesive joints to replace brazed joints in HVAC&R applications, which warrants further investigation.

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