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the NEWS

THE HVACR CONTRACTOR'S WEEKLY NEWSMAGAZINE SINCE 1926

November 21, 2011 | www.achrnews.com, Twitter, Facebook + LinkedIn

A bnp media PUBLICATION

The Adaptive Properties of Copper Piping

By Chris Mueller and Charles Stout, PE
For *The NEWS*

The HVACR industry has rightfully pursued and embraced HFC refrigerants with lower global warming potential (GWP). Transitions to R-410A and R-404A were accomplished over time, requiring significant coordination with and planning by OEMs. As illustrated in Figure 1, these refrigerants can operate at pressures that exceed R-22, for instance, by over 50 percent. The new darling of the industry, CO_2, only serves to raise the stakes in this high-pressure game. While the seals, compression ratios, efficiency ratings, and other considerations were painstakingly engineered, other system components were taken for granted.

So the refrigerants changed, but what about the standards governing products that transport and contain those refrigerants? UL 207 has provided a vehicle for the equipment manufacturers to deal with components that do not have individual pressure ratings sufficient to handle these new refrigerants. This involves certifying equipment as a system through various testing that essentially qualifies all components together.

The critical link that is missing in this chain is that of the piping used to interconnect the equipment. Copper tube and fittings are used for refrigeration and HVAC piping for many reasons, including the following:

- Proven durability, reliability, and corrosion resistance;
- Strong brazed joints;
- Superior heat transfer coefficient;
- Workability in the annealed state; and
- Ability to make field repairs and modifications

Copper tube and fittings are also field proven to be capable of handling the increased pressure of any commercially available (subcritical) refrigerant — whether natural or synthetic.[1] This is evident from more than 10 years of use in R-410A systems and, more recently, with CO_2. Nonetheless, the consensus standards governing copper tube and fittings do not provide design engineers with sufficient pressure ratings. Some have looked to utilize heavier wall tube, like Type K copper, while others continue to use standard refrigeration tubing given the material's proven track record.

Copper tubing can dependably function without issue in these higher-pressure systems, and one producer has pioneered the effort of qualifying their products accordingly. Efforts have been initiated at ASTM International and American Society of Mechanical Engineers (ASME) to modify the standards to incorporate higher performance metrics, providing all producers with a vehicle to qualify their products

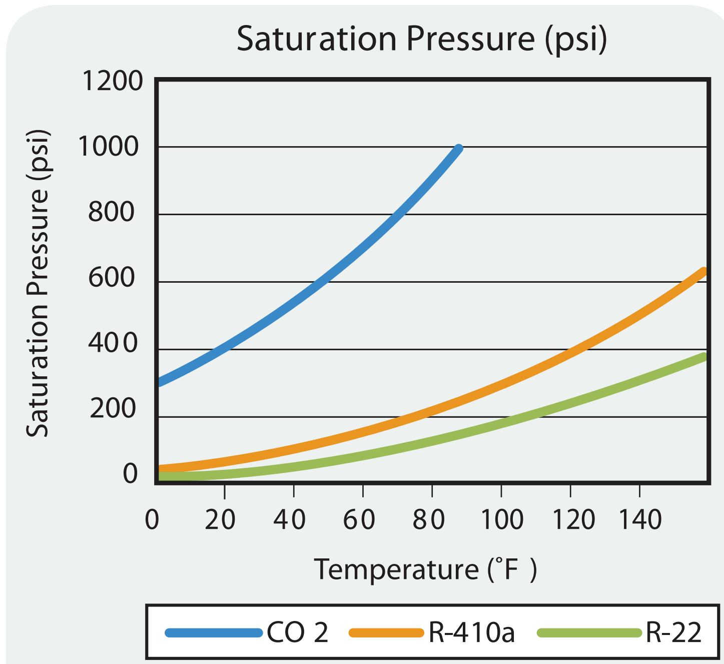

Figure 1. Refrigerant Saturation Pressure vs. Temperature

in concert. Unfortunately, the consensus standard bodies are not built for speed, even when the necessary end game is undeniable. Interdependencies and literal references between various standards only serve to further complicate the effort.

Qualification of Copper Tube + Fittings

What is not well understood in academic or industry circles is exactly how copper tubing responds to stress, specifically to high internal pressures. What is even further out of reach is a model for predicting the performance and, subsequently, predicting safe thresholds. One published formula for predicting failure points in cylindrical pressure vessels was applied to annealed copper tube and was found to miss the actual capabilities by over 1,000 percent.

Why? That formula is important and highly accurate for steel. But copper is a nonferrous metal with unique capabilities and properties — properties that shift in predictable and often favorable ways when subjected to heat and stress conditions. Many of these predictable property shifts are the same ones that ancient civilizations took advantage of in making tools for life-critical activities like personal combat, hunting,

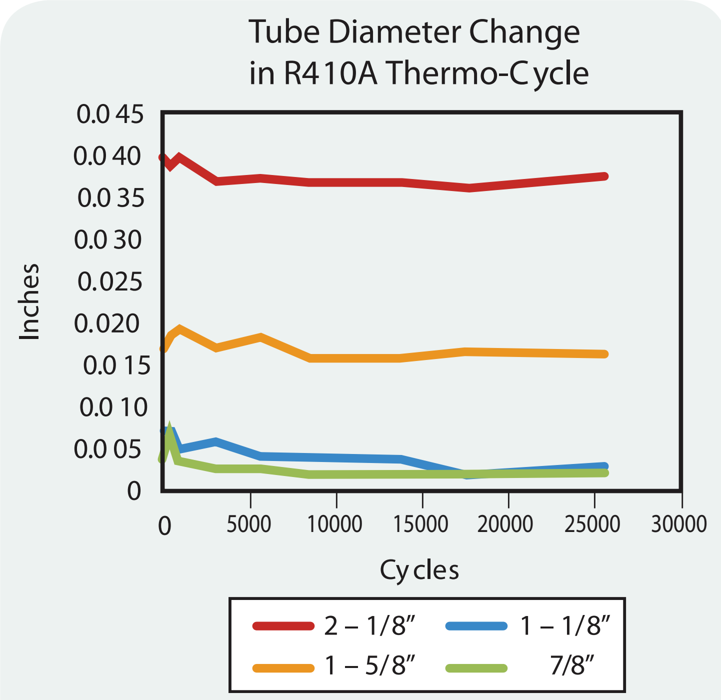

Figure 2. Plot of Change in Diameter (inches) vs. Number of Cycles

and cooking. Through extensive research and testing, those properties can be explained in new ways.

Materials Science 101

Stress and strain are some of the cornerstones of modern material design engineering. Perhaps the simplest depiction of these principles is a universal one that is generally misapplied in the HVACR industry — the tensile test. In this classic test of material strength, either a tube or a piece of flat metal (in the rough shape of a dog bone) is pulled from opposing ends with sufficient force to deform the material. That measureable force is known as stress. The material's response to this stress is a measurable deformation, known as strain.

The tensile strain of a material strip can generally be used to predict how the material might deform or strain when specific stresses are applied to the material. There are three key reasons that using a tensile test to qualify copper tubing does not work for the HVACR industry:

1. **Annealed Copper:** Copper tube and fittings are joined by brazing in HVACR applications at temperatures that will anneal a portion of the tube. Thus, the baseline properties start with a softened (and weakened) material, at least, when first installed.

2. **Work Hardening:** When copper stretches or strains (the deformation) due to a stress, the grain structure is reoriented and made stronger in a process known as work hardening. As more stress is applied, up to a point, copper simply continues to work harden and gets stronger and capable of handling even more stress.

3. **Hoop Strain:** Pulling on a dog bone effectively tests the strength of tube in the longitudinal direction (lengthwise). However, it does not mimic the force applied by pressurization within a pipe, which exerts its force to the entire circumference — known as a hoop stress. The response of copper tubing to this stress is known as hoop strain, a measure of the growth in diameter or circumference.

Adaptive Capabilities

Wernher von Braun, the preeminent rocket scientist of the 20th century, is credited with stating, "One test is worth a thousand expert opinions." If this is true, then what would a thousand tests be worth? A leading copper tube and fitting manufacturer has embarked on a testing mission to re-establish the fundamental design basis for copper in piping systems. The testing includes thermal cycling, strain hardening, cyclic fatigue testing, tensile testing, and ultimate burst.

While each test served a specific test, it is the collective result that provides the ultimate understanding. Thermal cycling of an amped up R-410A system served as both a real-world gut check and an accelerated life test. This effort was used to confirm a working life in excess of 30 years, well beyond that of residential or commercial HVAC equipment.

Strain hardening confirms that when annealed copper is subjected to a sufficient internal pressure, it will stretch (strain) ever so slightly. This stretch is always measurable as a change in diameter (hoop strain), never in length. A diameter change of only a few thousandths will have the effect of work hardening the material, which improves the grain structure and mechanical properties as noted above.

Of all the tests, perhaps cyclic fatigue testing presents the best opportunity to explain the critical adaptive phenomenon of copper. The test protocol, favored by UL 471 and 207 in many applications, involves subjecting an assembly to high-pressure pulses with a brief pause in between. The number of cycles required in fatigue testing can be as high as 250,000 to satisfy UL requirements.

Following the first pressure surge and subsequent work hardening (as established above) there are two potential outcomes with the subsequent pulse. Either the material is now strong enough to withstand the next pulse with no deformation, or the material stretches yet further and benefits from additional work hardening. Within a range, this process will continue until a balance is achieved between the internal pressure and the material capabilities. This phenomenon is shown in Figure 2, which depicts the results of an accelerated life test that equates to 33 years in operation.

The industry is working collectively to incorporate this knowledge and revise the consensus standards for the benefit of all design professionals. At least one copper tube and fittings manufacturer has already done sufficient testing to rate its core sizes as compliant with R-410A and CO_2. Ⓝ

End Note: 1. Ammonia is chemically incompatible with copper but would generally not otherwise exceed the pressure capabilities.

Chris Mueller is the head of product development at Mueller Industries' headquarters in Memphis, Tenn., and Charles Stout, PE, is director of R&D at Mueller Industries and serves on technical committees at ASME and ASHRAE.