Copper Development Association Inc.
Copper Alliance

Dispelling Misinformation about Corrosion of HVACR Coils

Round Copper Tubes Prove Superior to Round Aluminum Tubes in Nearly All Applications

Round copper tubes are the preferred material for heat exchanger coils in nearly all applications. They are the tried-and-true, *de facto* industry standard. Round copper tubes have a proven record of performance, durability, and corrosion resistance in nearly all environments. They are superior also with respect to manufacturing as well as repair costs if needed.

Copper tubes, including condensers and evaporators, remain the first choice for air-conditioning, refrigeration, and heat-pumping applications. Tube diameters for round tube plate fin (RTPF) heat exchangers range from conventional three-eighth inch (9.52 mm) tubes down to the current 5 mm technology and smaller, including smooth and inner-grooved tubes.

Round copper tubes are highly competitive against brazed aluminum microchannel coils. Microchannel coils showed promise as an alternative to RTPF coil but failed to live up to expectations in the field. The small "microchannels" in the ribbon-like extruded tubes increase the local (inside the tube) heat transfer coefficients (HTCs), allowing for compact heat exchangers; however, microchannel coils have been plagued by maldistribution of refrigerant, large header volumes, difficulty with defrosting and poor drainage. Cleaning serpentine-style fins squeezed between the ribbon-like multichannel tubes is difficult; hence, fouling and clogging are problematic. Fouling also aggravates issues with corrosion.

A better way to increase the heat transfer coefficient of HVACR tubes is to use smaller-diameter copper tubes. Smaller diameter copper tubes debuted in the high-volume production of room air conditioners and are now well-accepted in a wide range of applications.

Small-diameter copper tubes benefit from inside-the-tube enhancements. These inner grooves, also known as "microfins," improve the local heat transfer coefficients. The result is more efficient condensers and evaporators and more efficient HVACR systems. Smaller diameter tubes with internal enhancements deliver efficiency, materials savings, and refrigerant reduction without the disadvantages of brazed aluminum microchannel.

The Truth about Corrosion

As the HVACR industry transitioned to smaller diameter copper tubes, a few industry stakeholders raised concerns that the smaller copper tubes might be more susceptible to pitting and formicary corrosion. They argued that the thinner walls of the 5 mm tubes made the tubes more susceptible. As tube diameter decreases, the burst pressure of tubes increases, allowing reduced thicknesses of tube walls and hence savings on material costs.

These claims of susceptibility to corrosion were baseless. "Class action" lawsuits were eventually dismissed. Courts ruled that corrosion affected only a small percentage of heat exchangers regardless of tube diameter. Any corrosion of copper tubes is quite rare, and formicary corrosion is even rarer. False claims were roundly dismissed upon closer examination of the evidence [1].

The truth is that pitting and formicary corrosion occurs in response to a narrow class of chemical contaminants in the environment. Pitting and general corrosion are more common in aluminum heat exchangers, including brazed microchannel and round aluminum tubes.

Furthermore, corrosion has little or nothing to do with the diameters of round tubes. It occurs because of chemical contaminants, mainly in the environment, and is relatively rare compared to the total number of RTPF heat exchangers.

Formicary corrosion has been known about for decades. While tens of millions of copper round tube heat exchangers have never experienced formicary corrosion, a few thousand may be subject to this corrosion when exposed to certain chemicals. Less than one heat exchangers per hundred may be affected by formicary corrosion. Where this type of corrosion occurs, the remedy is to replace the heat exchanger with one that has a suitable coating to protect it from corrosive chemicals in the environment.

Service failures and leaks typically occur rapidly if pitting and formicary corrosion are initiated in aggressive environments. It is difficult to imagine how tube diameter or tube wall thickness are factors. While anecdotal evidence exists, such corrosion affects only a minute percentage of the total number of units produced using the new technology. In other words, such corrosion mechanisms do not offer a valid case against using smaller-diameter copper tubes, and such cases have been rightfully dismissed [1].

An honest discussion of corrosion must consider that the service lifetimes of heat exchangers in real-world environments are typically limited to about 10 to 15 years, as suggested by the warranties offered by OEMs and for coils in the aftermarket.

The Case Against Aluminum

Well-maintained copper tube coils could last considerably longer, but 15 years is considered an acceptable service life. Coatings and maintenance can extend the service life for both aluminum and copper coils. Coatings are typically mandatory for aluminum coils since they are affected by humidity and temperature. That adds costs to the manufacture of aluminum coils.

For copper coils, coatings are typically applied only when it is anticipated that the coils will be used in chemically aggressive environments. Any good coil maker or service technician is well-versed in the gamut of coatings available for copper and aluminum evaporators and condensers. The Copper Development Association provides extensive information about various types of coatings for copper [2].

Aluminum heat exchangers have finite service lives and eventually corrode. Copper's durability and corrosion resistance is superior to aluminum. The thermal conductivity metals is typically higher for purer alloys. Just as nature abhors a vacuum, it is not fond of pure metals. When metals are exposed to atmospheric conditions, they react with moisture and chemicals in the environment to form undesirable compounds. This process is called "corrosion." It can be slowed, but corrosion is in one direction only, that is, towards further deterioration of the metals. At best, it can only be slowed down.

Copper and aluminum naturally form a protective passivation layer that slows corrosion. A green patina forms naturally on copper and bronze. Also called "verdigris," the patina on copper usually consists of a mixture of copper chlorides, sulfides, sulfates, and carbonates.

Similarly, a very thin layer of aluminum oxides quickly forms on aluminum upon exposure to oxygen. Aluminum metal is highly reactive. Without this protective layer, it would quickly "burn away" upon exposure to oxygen. The thickness of this "aluminum passivation" is self-limiting since it blocks further diffusion of oxygen to the aluminum metal beneath it. Certain chemicals can attack these ultra-thin layers in the environment. Their protection is far from absolute, and corrosion of aluminum fins and tubes is quite common.

The aluminum industry has attempted to introduce aluminum heat exchangers into the HVACR industry for decades, going back at least fifty years to the 1980s. These attempts typically fail because aluminum deteriorates rapidly in humid environments, especially in salt air and salt water. A chalky, white coating of aluminum oxide and unpleasant pitting is very common with aluminum in heat exchanger applications. Brazed aluminum microchannel enjoyed success in the auto industry, where it is used for car radiators with glycol antifreeze as a coolant; however, the brazed aluminum has met mixed success in the HVACR industry, where higher pressures and stress corrosion cracking are factors.

Microchannel heat exchangers also proved incompatible with India's hot, humid climates and other tropical and subtropical regions. These heat exchangers enjoyed a few years of popularity in India until it was learned that they are incompatible with hot, humid climates [3].

Corrosion of Copper Tubes

In the case of round copper tubes, coatings are the exception rather than the rule. One reason is that bare copper is a better heat conductor than coated copper tubes. Another reason is cost. Coatings can add costs to manufacturing. In the lion's share of cases, copper round tubes with aluminum fins do not need coatings. They provide extended service lives and are unaffected by pitting or formicary corrosion.

The causes of formicary corrosion nowadays are almost always due to environmental factors. Most distributors and HVACR contractors will never encounter formicary corrosion. Nevertheless, they should know the basics of formicary corrosion and recognize it when and if it occurs in the field.

Pitting, Pinholes, and ANC

Formicary corrosion is well-studied academically. A fascinating technical literature has developed around this topic because it is easy to reproduce formicary corrosion in a laboratory. The first step is exposing the copper surface with a 1000 ppm acetic acid solution. Under certain conditions of acidity, temperature, and exposure to carboxyl acids, pits can form on the surface of the copper and subsequently generate the networks of tunnels characteristic of ant nest corrosion (ANC).

The pitted area of contaminated copper and copper compounds behaves like a local anode (positive electrode), while the nearly pure copper acts as a cathode (negative electrode). Consequently, the pits can spread and grow, resulting in formicary corrosion, pinholes, and, ultimately, leaks in the copper tubing.

Pitting also occurs in aluminum tubes, so round aluminum tubes are almost always coated in HVACR applications, especially in indoor evaporator coils, where aluminum round tubes are occasionally used in AC systems today. Coatings always add to the total cost of coil manufacturing, reducing the tubes' thermal conductivity. Coatings on aluminum round tubes are much thicker than the thin aluminum oxide layer that naturally forms when aluminum is exposed to the atmosphere.

Formic Acid and Formicary Corrosion

The name "formic" comes from *formica*, the Latin word for "ant," and the name of the genus many ants belong to. Believe it or not, formic acid was first obtained from the distillation of ants, hence its name. Although ants and other insects produce significant amounts of formic acid, the chemical is now made industrially. The word "formicary" is also related to ants, but in a different way. The use of the word "formicary" to mean "ant nest" is attested in the English language since at least 1816. It is derived from Medieval Latin *formicarium* and ultimately from Latin formica "ant." So, the phrase "formicary corrosion" is synonymous with ant nest corrosion (ANC), although the derivation of "formicary" is distinct from the derivation of the "formic" acid. Perhaps to avoid this confusion, the technical literature refers to this type of corrosion as "ANC."

ANC begins in the presence of carboxyl acids. Chemistry students may recognize these acids by the COOH group attached to an R-group. The carboxyl (COOH) group is so named because it is composed of a carbonyl group (C=O) and a hydroxyl (OH) group.

The simplest carboxyl acid is commonly known as formic acid and is officially known as methanoic acid. Formic acid has a hydrogen atom for the R-Group attached to the COOH group. Next up is acetic acid, officially known as ethanoic acid. It has a CH3 group attached to the COOH group. In short, acetic acid has two carbon atoms, and formic acid has only one carbon atom.

Acetic acid is the most common acid involved in the initiation of ANC. Vinegar is about 4-6 percent acetic acid in water. The Latin word for vinegar is *acetum*, from which "acid" is also derived. Ethanol fermentation occurs in the absence of oxygen, whereby sugars (such as glucose, fructose, and sucrose) in the presence of yeast are converted into ethanol and carbon dioxide. Further fermentation in the presence of oxygen and yeast results in acetic acid that is, vinegar, a fact known by winemakers for many thousands of years.

Precursors to ANC

Organic acids such as acetic acid, citric acid, and oxalic acid are useful for cleaning metals by creating a lift-off effect between particles and surfaces. They also have carboxylic functional groups and so could initiate ANC. Also, alcohols can be converted into carboxyl acids under certain conditions, such as when ethanol undergoes a second fermentation phase in the presence of oxygen and changes to acetic acid.

Coil manufacturers may use various solvents, lubricants, and cleaners to produce tubes and coils. If carboxyl acids or their precursors are left inside the tubes, then ANC could begin inside the tube under certain conditions. These phenomena are well understood today by manufacturers at every step of the supply chain. Most, if not all, formicary corrosion today will occur from contaminants introduced from outside the tube. Manufacturing processes include thorough cleaning and rinsing steps that safeguard against corrosion events.

That said, what environments are unsuitable for copper tubes? What applications require coatings on copper tubes? One extreme example includes fruit processing plants, which use ethylene gas generators to ripen fruits like bananas. Alan H. Brothers writes about fruit processing plants in an informative article titled "Detecting and Eliminating Causes of Coil Corrosion" [4]. Brothers and Sole also review the main types of coatings available to protect against corrosion in aggressive environments [5].

Brothers states that the combustion byproducts combined with the moisture prevalent in humid, equatorial regions form a weak acid that eats pinhole leaks into the coil tubing in a year or less. The mixture of ethylene gas, high humidity, and a myriad of cleaning chemicals used to ensure sanitation at the facility inevitably results in ANC on uncoated copper tubes. According to Brothers, most problems with ANC occur when environmental acids corrode coils from the outside in. That is even more true today, as copper tube suppliers and coil makers are extremely vigilant about eliminating sources of ANC from their manufacturing processes.

Other harsh environments that could trigger ANC from the "outside-in" are as follows [4]:

- Fermenting yeast (lactic acid from milk) in a bakery walk-in cooler
- Chlorine from an indoor swimming pool or aquatic process.
- Urine (ammonia) from dead animals in meat processing plant coolers
- Sulfur from well water used in cleaning coils or rooms with coils.
- Fertilizer (ammonia) in agricultural building evaporative coolers

Bastidas et al. 2006 estimated that ten percent of all premature failures of copper tubes used in the heating, ventilation, and air-conditioning (HVAC) industry result from ant-nest corrosion. They review the various pathways and environmental chemicals that could initiate ANC and provide an extensive list of earlier references [6].

Pits and Tunnels

Corrosion resembles a mining operation with its pits and tunnels. In both cases, copper metal atoms corrode and are carried away, but there is a difference between pitting and ANC. In the case of pitting, negative ions such as fluorine or chlorine attack the thin film that normally protects the underlying metal, and local corrosion ensues around a tiny electrochemical battery. This pitting progresses linearly through the thickness of the tube, forming a pinhole. On the other hand, ANC might begin with pitting, but it soon branches out to create a network of microscopically corroded tunnels within the tubing wall. These tunnel networks are substantially more extensive than the surface pitting above them. The result is the same in any case. Papadopoulou et al. call this tunneling "tortuous" pit propagation [7]—Eventually, the pits or tunnels break through on the other side.

A Deeper Dive into ANC

Electrochemistry and surface science are fascinating topics. Through laboratory research, much progress has been made in understanding the basic mechanisms underlying pitting and formicary corrosion. Though relatively rare, formicary corrosion has been known to affect heat exchanger coils since the 1970s. Today, OEMs and coil manufacturers are keenly aware of this type of corrosion and do everything possible to eliminate the causes from the manufacturing processes.

The tunnels resemble ant nest-type structures, and hence, this is called Ant Nest Corrosion [ANC]. This type of corrosion is readily produced in the laboratory and has been the subject of many academic and scientific studies in peer-reviewed literature. The interested reader could explore this topic deeply by following the references in some recent papers.

Baba and Kodama reproduced ANC in copper tube samples exposed to a wet atmosphere containing formic and acetic acid vapor. They proposed a mechanism for generating this type of corrosion in 1995 [8]. More recently, Lachowicz conducted a metallographic study and observed that the orientation of the formed tunnels can be related to their movement along the grain boundaries [9].

Such research is invaluable as it helps to identify the factors affecting the development of ANC. Research could also help OEMs, coil makers, and end-users take precautions to reduce the occurrence of ANC.

Examining samples in the field can also be useful in minimizing occurrences of ANC. From a practical point of view, Brothers and Sole identify the usual suspects as acetic acids and acetates (formed by combining acetic acid with a base) [5]. These chemicals are found in adhesives, paneling, particle board, silicone caulking, cleaning solvents, vinegar, foam insulation, and other products. Formic acid can be found in cosmetics, disinfectants, tobacco and wood smoke, latex paints, plywood, and other materials.

When these chemicals are deposited on an HVACR coil along with moisture and oxygen, they could be a primary cause of ANC. Either remove the chemicals from the environment or replace the coil with a suitably coated coil. When a contractor finds a coil with ANC or pitting, the first step is determining what in the environment contributes to the corrosion. Swapping out the coil for an identical coil would be unwise unless the environmental conditions are identified and remedied. It will be better to replace the coil with an OEM coil or an aftermarket coil with a corrosion-resistant coating.

Coatings to the Rescue

Hundreds of useful, clear coating products are on the market, formulated from numerous polymers, solvents, and additives. The user selects a coating based on economics, intended life, desired transparency, and expected service conditions from these.

Many coating manufacturers prefer to custom blend coatings and work closely with users to solve their specific problems. There are numerous standard compositions, which can be ordered by trade names and will satisfy many needs.

For heat exchangers, coatings can generally be divided into *polymer coatings* and *silanes* [5].

Polymer coatings are typically thick epoxy or phenolic coatings, which are generally inexpensive and easy to apply. They are thicker than silanes, so they decrease heat transfer more. Many polymer coatings are also sensitive to ultraviolet (UV) degradation and can crack off the coil surfaces over time.

Silanes are organofunctional silicones. They are hybrid compounds of silica and resin-like organic materials. They improve the bonding between metals to organic resins. Silane-based coatings are composed of alcohol and water and are applied in a thinner coat compared to polymer coatings. They are usually applied only by a licensed applicator. They are typically harder and more abrasion-resistant than polymers.

Coil makers and HVACR OEMs have extensive experience with coatings for residential, commercial, and industrial applications. There are excellent coatings available specifically in the supply chain for HVACR applications. In designing coils for HVACR applications, selecting an appropriate coating is an essential part of the design process.

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The Bottom Line

In nearly all cases with copper tubes, coatings are not necessary. Nonetheless, a suitable coating is appropriate when the heat exchanger coil will be used in a chemically aggressive, corrosive environment.

Most, if not all, OEMs and aftermarket suppliers offer off-the-shelf coating options. Some OEMs provide coatings on all their coils as a precautionary measure, as with aluminum tubes. Typically, however, a coating is not required, and the coating will needlessly reduce the heat transfer efficiency of the coil. Coatings add to the initial cost as well as the operating cost.

In the final analysis, copper tubes are the superior choice for heat exchanger coils and will remain for the foreseeable future. Compared to copper, the aluminum round tubes and aluminum microchannel tubes are much more susceptible to corrosion. Aluminum can corrode in environments that are quite benign to copper.

Copper has the ideal combination of physical properties for HVACR equipment. Round copper tubes offer long service life and high efficiency with few disadvantages in nearly all HVACR applications.

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