

USING SURFACE COATINGS TO EXTEND LIFE AND IMPROVE PERFORMANCE IN INDUSTRIAL AIR CONDITIONERS

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1. INTRODUCTION

Air conditioners are commonly used to keep electronics cool in various areas, such as industrial automation, telecommunication equipment, security and defense systems as well as other indoor and outdoor electronics applications. The electronics may be housed in protective enclosures, where air conditioners deliver cooled air to keep the entire enclosure at desired temperatures for optimum electronics operation.

The operating environment of these air conditioners can be aggressive and may present harsh elements, such as chloride and sulfur compounds in coastal areas, sulfur oxides and nitrogen oxides in industrial polluted areas, as well as airborne particles, cutting oils and solvents on factory floors. Air conditioners are typically packaged units, with air-to-refrigerant condensers and evaporators. These heat exchangers are often constructed with copper coils and aluminum fins, allowing refrigerant to flow within the tubes while air flows through the fins. Heat exchangers are susceptible to hostile environments and, over time, contaminants can corrode the heat exchangers or particles can accumulate within them. This causes the heat exchanger performance to degrade, leading to capacity loss, high head pressure and, eventually, compressor failure.

To minimize heat exchanger corrosion and dust accumulation, coatings can be used

to protect metal parts from harsh industrial environments. This white paper will discuss the different types of corrosions present, common coils used in air conditioners and salt spray and dust loading testing results, which indicate the effect of coatings on air conditioner performance and efficiency.

2. TYPE OF CORROSIONS

Corrosion, by definition, is the destruction of material, usually metal or alloy, by chemical reaction with its environment. Air conditioners can be exposed to various corrosive environments, leading to decay of the condensers and evaporators, causing premature system performance loss and eventual system failure.

There are many types of corrosions, however, the most common types of corrosion within air conditioners are galvanic corrosion and general corrosion. Formicary corrosion also affects copper.

2.1 Galvanic Corrosion

Galvanic corrosion occurs naturally when dissimilar metals are in contact in the presence of an electrolyte, e.g., moisture. In galvanic corrosion, the more active metal corrodes at a higher rate due to ion migration. In copper tube-aluminum fin heat exchangers (condensers and evaporators), galvanic corrosion starts at fin collars where the aluminum fins and copper tubes are in contact. As the aluminum fins corrode, the thermal resistance of the heat exchanger

increases, resulting in capacity loss and high head pressure.

One way of preventing galvanic corrosion of coils is to eliminate the galvanic couple, for example, all-aluminum or all-copper coils. Another more common way of preventing galvanic corrosion is to isolate the two dissimilar metals from the electrolyte through the use of protective coatings, creating a barrier between the galvanic couple and the electrolyte. Without electrolyte at the interface of the dissimilar metallic couple, galvanic corrosion cannot occur. Yet another way of preventing galvanic corrosion is to insulate the electrical connection of the dissimilar metallic couple through a non-metallic coating. An example of this is pre-coated fin stock, which creates an insulation layer and removes the electrical contact between the dissimilar metallic couple.

2.2 General Corrosion

General corrosion is the degradation of metal by reacting with its surrounding environment, such as oxidation. Environmental contaminants, such as sulfur and nitrogen-based electrolytes combined with chloride often accelerate corrosion of copper coils, causing leaks and failure of refrigeration systems. General corrosion also requires the presence of moisture to maintain the corrosion process.

2.3 Formicary Corrosion

Formicary corrosion commonly occurs within copper tubes, through condensation attracting airborne contaminants. Tiny pinholes on the surface form networks of interconnecting tunnels through the coil wall, resulting in refrigerant leaks. The contaminants that cause formicary corrosion are organic acids, most commonly formic and acetic acids. There are three conditions required for formicary corrosion to occur: the presence of oxygen, the presence of organic acid and the presence of moisture. Due to these requirements, formicary corrosion mostly occurs to evaporators, which are wet due to condensate generated from air dehumidification.

3. TYPE OF COILS

In addition to understanding the various forms of corrosion that can occur in air conditioners, it is also important to know the different types of coils on which corrosion forms. Discussing commonly

used coils that are seen in air conditioners, in addition to their pros and cons, this section serves as a guideline for designers, marketing and sales to select the most appropriate products for different applications.

3.1 Uncoated Coils

The most common condensers and evaporators coils have uncoated copper tubes mechanically bonded to aluminum fins. Because the coils and fins are in direct contact, the coils can achieve high thermal efficiency provided there is no corrosion. When galvanic corrosion occurs, the tube and fin mechanical bonding deteriorates, resulting in increased thermal resistance and decreased coil thermal efficiency.

3.2 All-Aluminum Coils

All-aluminum coils share a common metallic couple, which eliminates the potential for galvanic corrosion. Since the piping in air conditioners is mostly copper, caution should be taken to protect the joints where all-aluminum coils join the rest of the system. These coils also prevent formicary corrosion when used as an evaporator.

3.3 Pre-Coated Aluminum Fin Coils

Pre-coated coils have pre-coated fins and uncoated tubes. The fin stock is coated with baked-on coatings prior to fin stamping process. When assembled into coils, the thin layer of non-metallic coating provides insulation between the two dissimilar metals of the coil (copper and aluminum) to disrupt the electrical connection between them, minimizing galvanic corrosion. Pre-coated coils offer improved corrosion protection compared to uncoated copper tube aluminum fin coils, and they can be an economical alternative to e-coated coil for mildly corrosive environments.

3.4 E-Coated Coil

E-coat, also known as electrocoat, is an effective surface coating that provides superior corrosion resistance to the metal surface of industrial parts. It is a painting process that, instead of dipping, deposits the paint or lacquer coating onto the parts using electrical current. This process is also known as electrodeposition, and can be divided into 4 distinct zones:

1. Pretreatment
2. Electrocoat (e-coat) bath
3. Post rinse
4. Bake oven

Pretreatment

Prior to the e-coat bath, the coils are cleaned with alkaline cleaners, removing dirt and oils from parts' manufacturing processes. Then, iron or zinc phosphate pretreatments are used to provide durable adhesion between the e-coat and the substrate (copper tube and aluminum fin), to prevent the coating from peeling off. Pretreatments also add another layer of corrosion protection should there be any pinholes in the e-coat. The part is then rinsed with deionized water before going into the e-coat tank. Pretreatment is a critical step in the e-coating process, as it ensures reliable bonding of the metal and coating later in the process.

E-coat bath

The e-coat bath is a mixture of 80-90 percent deionized water and 10-20 percent paint solids. The deionized water acts as the carrier for paint solids, which consist of resins, pigment and small amounts of solvents. The resin is the main material for the final paint film, which provides the corrosion protection. Pigments provide color, gloss and corrosion protection as well, while solvents help ensure the deposited film has a smooth appearance.

Because the resin is an electrical insulator, the paint deposition process is self-limiting and slows down as the part becomes electrically insulated by the applied coating. By regulating the applied voltage, paint can be applied to a part at a controlled film thickness. During the e-coat process, paint solids deposit initially in the areas closest to the counter electrode and, as these areas become insulated to current, solids are forced into more recessed, bare metal areas to provide complete coverage. This unique phenomenon is particularly important for tiny cavities where fin and tube joints, high fin densities and enhanced fins such as lanced fins are present, as it allows the coating to penetrate into all coil cavities and cover the entire coil assembly, including the fin edges and fin lances without bridging.

Post rinse

To improve part aesthetics and maintain e-coat process efficiency, the part must be rinsed upon exiting the e-coat bath to remove excess paint solids not deposited electrically but cling to the part. The rinsed off excess paint solids are returned to the bath for high-coating application efficiency.

Bake oven

After the post rinse, the coated parts enter the bake oven. The bake oven crosslinks and cures paint resin film, resulting in a high quality finish without runs, drips and sags. For most e-coat, the bake temperature is 375 degrees Fahrenheit, however, there are low temperature cure e-coat materials, which allow parts to be coated containing seals, bushings and bearings, etc.

Compared to other surface coating methods, the benefits of E-coated coil include:

1. Total coverage of complex parts with smooth, consistent and flexible coating that penetrate deep into all coil cavities, including fin-tube joints, fin edges and other internal recessed areas.
2. Can be applied to enhanced fins, such as lanced fins or high-fin density coils, without bridging the lances and fins.
3. Thin and uniform film thicknesses allow bent fins to be straightened without cracking or delaminating the coating.
4. Minimal increase in thermal resistance compared to uncoated coil because of the thin film thickness and uniformity.

The e-coating process completely isolates the coil from the contaminated environment by creating a thin, extremely durable and flexible film that covers the entire copper tube aluminum fin coil surface, including cavities and recesses areas. For example, in areas where the fin collar and the expanded copper tubes are in contact, the coil is isolated against any contaminants, providing superior corrosion protection against the most severe environments.

3.5 Salt Spray Test Results

The above coatings provide various effects on heat exchanger corrosion in harsh environments. This section will discuss and illustrate these results through scientific testing procedures.

A 30 day accelerated corrosion test (ASTM-B117-09 salt spray test) was completed on coil samples with different types of coatings: 8 FPI uncoated, 12 FPI blue hydrophilic pre-coated and 12 FPI e-coated samples. The samples were cut from full coils and the first exposed fin layer on the samples were removed to avoid any scratches on the fins due to cutting. All coils came from the same supplier. Figure 1 shows a picture of test

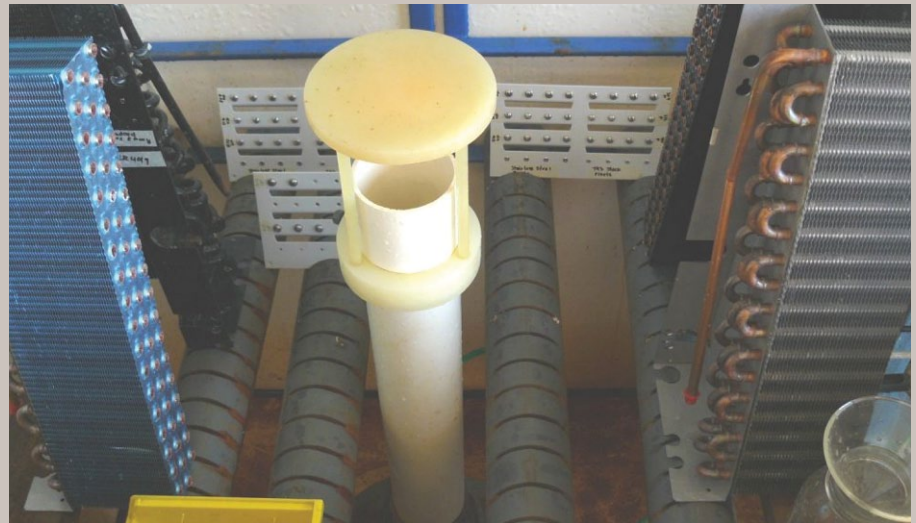
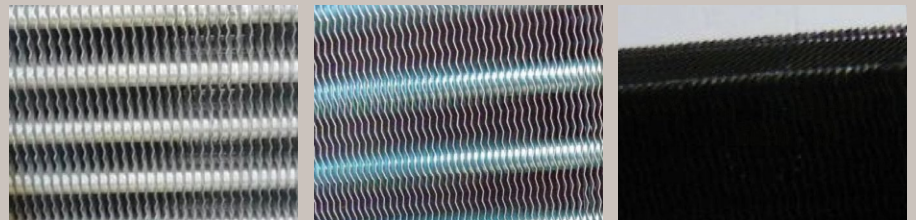


Figure 1. Test Setup

Day 0



Day 14

Day 30

Uncoated

Blue Hydrophilic Coating

E-Coating

Figure 2. Salt Spray Test Samples and Results

setup. All samples were placed in the same salt fog chamber so they were subject to the same conditions. Figure 2 shows the pictures of samples at 0, 14 and 30 days into the test.

Test results indicated e-coated coil performed significantly better than other coatings. At 14 days into the test, pitting corrosion was found on both the uncoated

and the blue hydrophilic-coated coils. At the end of test (30 days), no pitting was found on the e-coated sample. However, the other samples were completely corroded through in various places. The e-coated sample had some red rust on its sheet metal brackets, while the uncoated and blue hydrophilic-coated coils had the most.

TABLE 1. DUST ACCUMULATION TEST MATRIX

Test #	FPI		Coating			Screen		Wash Options			Fin Pattern
	8	12	Un-Coated	E-coatings	Hydrophobic Coatings	Yes	No	Factory washed	Un-washed	Hose washed	
1	•		•			•					New Ripple
2	•			•		•					New Ripple
3	•		•	•			•				New Ripple
4	•		•				•				New Ripple
5		•				•					New Ripple
6		•		•		•					New Ripple
7		•	•	•			•				New Ripple
8		•	•				•				New Ripple
9	•					•					HiF
10	•				•		•	•			New Ripple
11	•				•		•		•		New Ripple
12		•			•		•	•			New Ripple
13		•			•		•		•		New Ripple
14	•				•		•			•	New Ripple
15		•			•		•			•	New Ripple

4. DUST ACCUMULATION

In addition to corroded fins, a clogged condenser can also cause capacity loss and high head pressure. In an air conditioner, the function of a condenser is to reject the heat absorbed from the evaporator and the energy used by the compressor (here, the compressor heat dissipation is ignored). For common tube and fin condensers, extended fins are necessary for a condenser to reject the heat. Unfortunately, the fins also provide more surfaces for dust, particles and fibers to accumulate. For a condenser, the amount of heat it can reject can be found by the following equation:

$$Q = \frac{A \cdot \Delta T_{lm}}{R}$$

Q is the amount of heat rejected; R is the overall thermal resistance between air and refrigerant. R is a function of refrigerant flow rate as well as air flow rate. In general, increasing the flow rates would reduce the thermal resistance. A is the total surface area to transfer the heat from the refrigerant to the air. A is the total fin and tube surface areas exposed to the air. ΔT_{lm} is a logarithmic average temperature difference between air and refrigerant.

A clogged condenser can significantly reduce air flow, which increases the overall thermal resistance. From equation (1), to reject the same amount of heat, ΔT_{lm} must increase, resulting in higher condensing temperature/pressure. In reality, the system would balance at lower Q and higher ΔT_{lm}. Therefore, the compressor must work at higher head pressure, leading to higher power consumption, lower system efficiency and lower cooling capacity.

4.1 Dust Loading Test Results

A dust loading test was performed on various coils to determine the effect of coil fin density, fin pattern, coating and surface cleanliness on dust accumulation. Table 1 shows the test matrix. During the test, the coil was installed in a duct transition and sealed in place with a top gasket. Figure 3 shows pictures of the test setup. ASHRAE standard 52.2 test dust was used, which consists of 72 percent SAE Standard J726 test dust (fine), 23 percent powdered carbon and 5 percent milled cotton

linters. Airflow was set at 650cfm for all tests. The coil was grounded for all tests to eliminate static electricity. Dust was loaded in 20g increments, up to 100g. After each incremental dust loading, the coil (and filter as necessary) was removed and weighed. The results are shown in Figure 4. It should be noted that all results shown in Figure 4 are without the use of insect screen.

4.2 Effect of Fin Density

Here, fin density is defined as the number of fins per inch. Figure 4 shows that, as expected, higher fin density collects more dust. As fin density increased from 8 FPI (fin spacing ~ 3mm) to 12 FPI (fin spacing ~ 2mm), dust accumulation also increases. However, to reduce dust accumulation, one cannot solely rely on reducing fin density because the amount of heat the condenser can reject is proportional to its surface area (equation 1). The loss of surface area cannot be fully compensated by reducing overall thermal resistance. For example, from 12 FPI to 8 FPI, the heat transfer surface area reduces by more than 30 percent. It is very difficult to compensate this loss through reduction in the overall thermal resistance, which includes refrigerant side thermal resistance, air side thermal resistance and tube thermal resistance. Depending on the coil design, air side thermal resistance is typically 60-70 percent of the total thermal resistance. If the condenser air flow is increased by 50 percent, the reductions in air side thermal resistance and overall thermal resistance may be estimated to be of the order of 20 percent and 14 percent, respectively. Therefore, compared to a system using a 12 FPI condenser, a system using an 8 FPI condenser would run at a higher discharge pressure and lower capacity. Or, a larger 8 FPI condenser must be used to obtain equivalent system performance. Additionally, increased air flow also increases fan power consumption. As a general rule of thumb, power consumption increases as a cubic power of flow rate increase.

Higher fin density coil with appropriate surface coating can achieve low dust accumulation while maintaining high system performance.

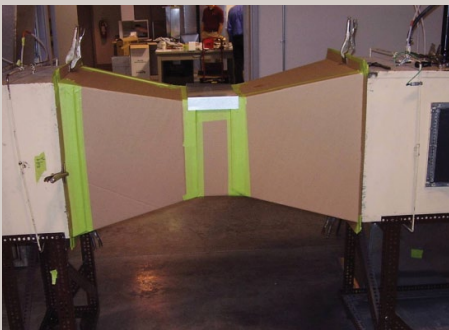


Figure 3. Dust Accumulation Test Setup

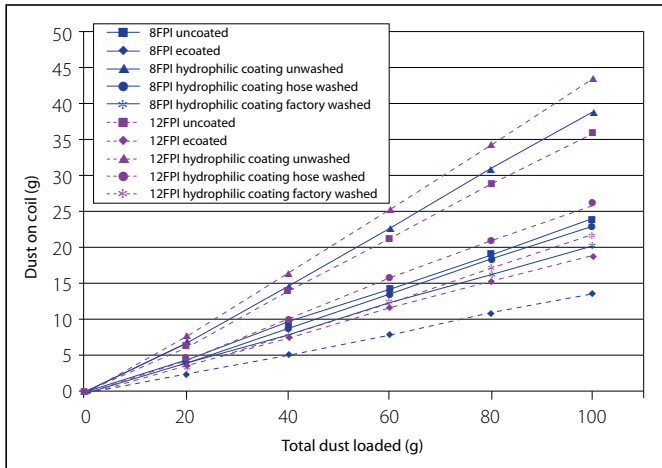


Figure 4. Effect of Fin Density, Coatings and Coil Cleanliness on Dust Accumulation

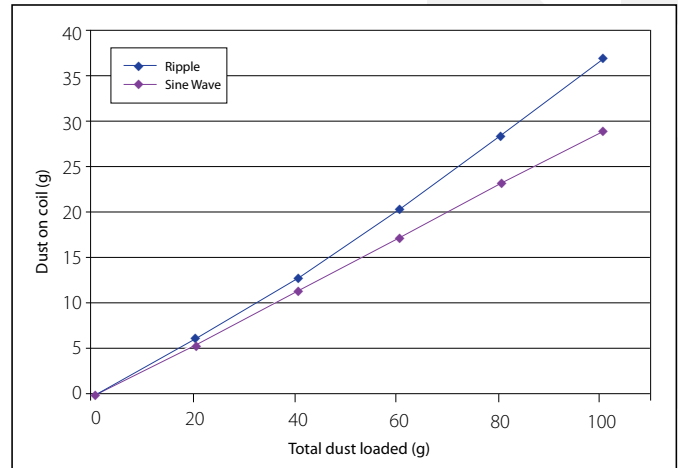


Figure 5. Effect of Fin Pattern on Dust Accumulation

4.3 Effect of Coating

Surface coating has a significant effect on dust accumulation, as it is shown in Figure 4 that e-coated coils have substantially less dust accumulation compared to uncoated coils. Furthermore, 12 FPI e-coated coil accumulated less dust than 8 FPI uncoated coil due to the E-coated coils' smoother fin surface, including sharp corners and edges. Additionally, e-coated coils are oil free after the e-coating process, which means dust and fibers are less likely to stick onto it. Therefore, e-coated coils are suitable for condenser applications where airborne contaminants are present, while allowing higher fin density to achieve increased system performance.

Caution must be taken when considering e-coated coils for evaporator applications due to condensate blow-off. During the AC operation, it is important to drain the condensate from the evaporator. Poor condensate drainage may cause condensate blow-off, which may lead to possible failure of electric and electronic components inside the cabinets. Condensate blow-off is a function of air stream velocity across the coil, fin spacing, fin pattern and surface wettability. E-coating reduces the surface wettability due to its hydrophobic nature, therefore potentially causing condensate blow-off at a much lower velocity.

The hydrophilic coated coil was constructed with pre-coated fins and it collected more

dust compared to the uncoated coil. This may be because the surface of hydrophilic coating is not as smooth in order to increase the surface wettability (hydrophilic), making the dust likely to cling to the surface. Also, the fins are pre-coated with manufacturing oil/lubricant residual on the surface, which also helps collect dust. Both hydrophilic coated coil and uncoated coil are suitable for applications with clean air. When used in evaporator applications, the condensate aids in washing off the manufacturing oil/lubricant residual, making the surface fully wet.

4.4 Effect of Oil/Lubricant Residual

Dusts (particles, fibers) in the surrounding environment tend to cling to uncoated and pre-coated coils. Uncoated coils and pre-coated coils may have oils/lubricant residual on fin surface from manufacturing process, e.g., stamping and tube expansion. Using hot water to hose wash the coil reduces dust accumulation substantially. Further reduction in dust accumulation may be obtained by factory wash with appropriate solvent. Figure 4 shows the 12 FPI factory washed hydrophilic coil collected less dust than the 8 FPI uncoated coil, but more dust than the e-coated coil.

4.5 Effect of Fin Pattern

Fin pattern also affects the dust accumulation. As shown in Figure 5, with the same fin density, wavy fins accumulate less dust compared to ripple (corrugated) fins.

5. CONCLUSIONS AND RECOMMENDATIONS

For the same fin and tube construction, uncoated copper tube aluminum fin coils provide high performance for non-corrosive environments. Application of this coil in harsh, corrosive environments is likely to deteriorate its performance due to corrosion.

Pre-coated copper tube aluminum fin coils provide moderate corrosion protection and may be used in mildly corrosive environments.

Uncoated and pre-coated coils are likely to accumulate more dust due to manufacturing oils and lubricants used in fabricating processes. With appropriate washing procedures to remove the oils and lubricants, dust accumulation reduced substantially. However, these coils still collect more dust compared to e-coated coil.

E-coated coils provide superior corrosion protection of the coils. E-coating also substantially reduces the coil dust accumulation. These characteristics make e-coated coils the ideal choice for condensers working under harsh industrial environments.