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Durability and Performance Evaluations of SuperHydrophobic and Icephobic Coatings for Tube-Fin Heat Exchangers

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ABSTRACT

Mitigating frost on heat exchanger coils is key for developing high-efficiency heat pumps and enabling the widespread adoption of cold-climate heat pumps. Frost reduces heat exchanger (HX) performance by impeding airflow and adding thermal resistance, therefore taxing the system to consume more energy to satisfy temperature setpoints. Accordingly, heat pump systems have defrost cycles, which typically involve electrical heaters or hot-gas bypass systems, that consume extra energy to melt away the impeding frost/ice layer on coils. As presented in prior literature, enhanced HX surfaces (such as louvered fins or increased fin density) can accelerate frost development and thus have faster performance degradation through increased pressure drop across the coils. Thus, non-enhanced fin surfaces (such as wavy fins) with low fin densities, are typically employed in HVAC systems to minimize frosting impacts, however resulting in less compact units with lower performance under dry conditions. An alternative solution could be the use of durable superhydrophobic/icephobic coatings. This paper presents a systematic approach for testing various coatings for their viability to mitigate frost on Tube-Fin HXs. The tests shown in this paper were used as preliminary screening tests to identify coatings for a more comprehensive frost development assessment. Aluminum fin stock samples were coated by several coating vendors for understanding their hydrophobicity, icephobicity, and durability. This involved (a) an ice adhesion test to measure the maximum amount of shear force required to remove ice from the surface; (b) cyclic corrosion testing (CCT-4 standard) while qualitatively monitoring wear; (c) adhesion testing (ASTM D3359 standard) to further understand the coating-substrate bond strength; and (d) post-corrosion ice adhesion tests to characterize durability and potential performance of coatings over time in real-world environments. While most coatings maintained their wettability state after being placed in the corrosion chamber for over 1000 hours, qualitative wear and performance was shown to vary between different coatings of different chemical compositions. Variances in additives and base chemistries were shown to impact the long-term performance of the coatings. Selected coatings were then identified for a more comprehensive frost development assessment in a temperature and humidity-controlled wind-tunnel.

Keywords: superhydrophobic, icephobic, ice adhesion, corrosion testing, coating

1. INTRODUCTION

Heat pumps (HPs) development and deployment for harsher cold climate zones has become more prominent with the active drivers for decarbonization, electrification, and energy efficiency. As frost develops on HXs, whether for heat pump systems or refrigeration systems, airflow is impeded, adding thermal resistance and taxing the system to consume more energy to satisfy temperature setpoints. Accordingly, many heat pump systems include defrost cycles to mitigate the frost impact which introduces efficiency penalties, especially during heating seasons. Patil et al. (2017) published a review of heat transfer characteristics of HXs under frosting, defrosting, and dry/wet conditions and noted various methods of defrosting. The most common method of defrosting in HP systems was using a reverse cycle. However, this may also introduce degradation in thermal comfort due to heating interruption during defrosting (Minglu et al., 2010). Additionally, it necessitates resistance backup heating which has high electrical peak loads. Other methods of defrosting may include ultrasonic vibration (Tan et al., 2015) or recycling heat from the compressor systems (Long et al., 2014). These defrost penalties were seen to increase power consumption by 17.7% with automated defrost cycles (Bansal et al., 2010). Energy losses and environmental impacts due to frost formation are

applicable to the majority of outdoor coils for residential and commercial HPs (including rooftop, packaged terminal ACs/HPs, etc.) as well as commercial refrigeration systems such as supermarkets and cold storage warehouses. The study published by Li et al. (2021) presented the performance results for three different types of heat exchanger coils coated with a (super)hydrophobic or icephobic coating compared to uncoated coils to evaluate their effectiveness for reducing frost and ice adhesion. As part of that study, preliminary screening tests were conducted to evaluate and select which would be viable coatings for the coated coil frost performance testing. This paper describes the screening tests conducted and the results for various coating products. These mechanical and surface topological tests, although static measurement tests, allowed the selection or ranking of coating products to choose from for the frost performance test described in the Li et al. (2021) publication.

Various types of coatings have been studied previously to mitigate frost formation on surfaces. Nonetheless, there is a lack of a comprehensive cross-study involving environmental conditions, coating types, and surface geometries. This research explores the further understanding and viability of commercially available superhydrophobic and icephobic coatings for frost mitigation in HX applications. This paper evaluates the coatings' viability under corrosion testing using measurable performance metrics and showcases the performance differences to compare the effectiveness of various coating types.

2. MATERIALS & METHODS

2.1 Test Subjects and Setup

As a proxy for understanding the coatings' applicability and viability for frost prevention on heat exchanger coils and prior to evaluating their performance on HX coils, thin coupon samples of Aluminum 8006 (sourced from CSI Coils) and Aluminum 6061 (sourced from McMaster-Carr) were coated and tested. The 0.005-inch thick coupons were cut as 3 inches by 10 inches sheets. The Aluminum alloys were selected for their similar chemical composition to fin stock materials used in commercially available HX coils. Ice Adhesion testing was conducted, then the samples were exposed to a cyclic corrosion test in a salt-fog chamber. After the cyclic corrosion test, qualitative observations were made, and the corroded samples were tested again for Ice Adhesion. Samples C1 and C2 have the exact same ceramic/polymer hybrid base chemistry with C2 having an additional proprietary additive #1. C4 and C5 have a different proprietary ceramic hybrid base chemistry with additives #1 and #2 added, respectively. C3 is a polyurethane base chemistry with no additives.

Table 1 summarizes the different types of proprietary coating formulations tested. Samples C1 and C2 have the exact same ceramic/polymer hybrid base chemistry with C2 having an additional proprietary additive #1. C4 and C5 have a different proprietary ceramic hybrid base chemistry with additives #1 and #2 added, respectively. C3 is a polyurethane base chemistry with no additives.

Table 1: Coating Characteristics

Sample #	
Bare Surface	Uncoated aluminum coupon (either 6061 or 8006 alloy)
Sample A1	Covalently Bonded Hydrophobic Nano Coating
Sample A2	Covalently Bonded Hydrophobic Nano Coating
Sample B1	Polymeric resin
Sample C1	Ceramic/polymer hybrid base chemistry ^β (no additive)
Sample C2	Ceramic/polymer hybrid base chemistry ^β + proprietary additive #1
Sample C3	Polyurethane base chemistry (no additive)
Sample C4	Ceramic/polymer hybrid base chemistry ^γ + proprietary additive #1
Sample C5	Ceramic/polymer hybrid base chemistry ^γ + proprietary additive #2
Sample D1	Superhydrophobic Coating
Sample D2	Icephobic Coating

2.1.1 Ice Adhesion Testing

As a preliminary screening criterion for the research, the initial Ice Adhesion Test was performed on uncoated and coated aluminum coupons. This test measured the amount of shear force necessary to remove a block of ice frozen onto the surface sample. A force meter was used to gauge the amount of shear force required to dislodge the ice cylinder from the coated sample (see Figure 1 and Figure 2 for schematic and setup). While this is not a direct measure for frost formation rates, it serves as an indicator for the amount of energy required to remove ice from the surface of the heat exchangers fins. The lower the maximum shear force required, the more advantageous the coating could be for mitigating frost adhesion and removal from HX fin.

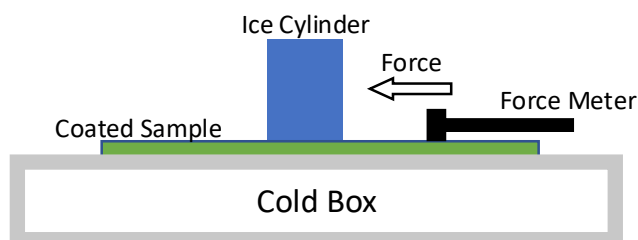


Figure 1: Schematic of Ice Adhesion Test Measurement

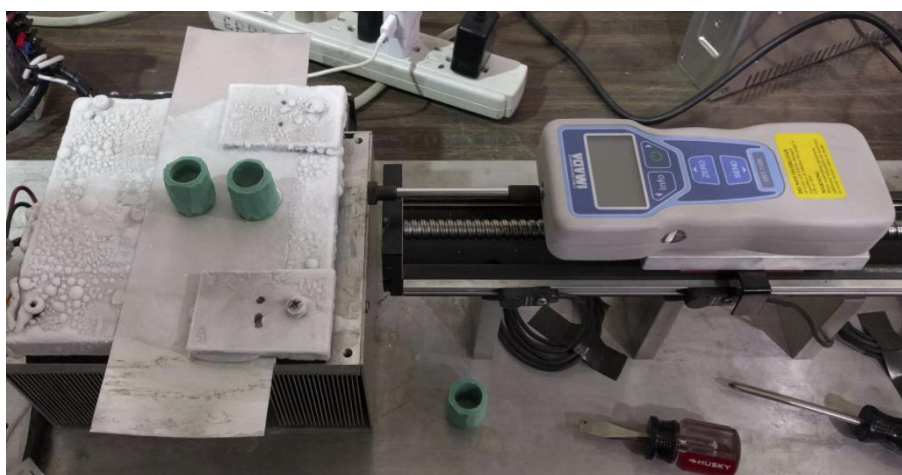


Figure 2: Ice Adhesion Laboratory Test Setup

Table 2 shows the results of the Ice Adhesion Test. Each set of tests were completed a minimum of two repetitions for reproducibility. The set of tests consisted of up to 6 points (i.e. ice cylinders) and the average maximum force was taken among all trials. The bare sample was an uncoated aluminum fin stock measuring 3" x 10" x 0.005". Coating vendors participating in the study were provided sample coupons of the same aluminum alloy to coat. The coated coupons were all tested in EPRI's Materials Lab Facility in Charlotte, NC. These preliminary results were used to screen coating types prior to coated coil frost performance testing.

Samples with a smaller Average Maximum Force less than the Bare uncoated sample were deemed better performing. From these preliminary results, samples A and samples B, were excluded from the remaining tests due to their increased maximum force compared to the bare samples. Coated coupon samples used in this Ice Adhesion test were not used in the following tests – new coated coupon samples were used for each set of tests.

2.2 Cyclic Corrosion Testing

A salt-fog corrosion chamber was used to simulate accelerated HX wear over time in harsh environments. Before being placed in the salt-fog chamber, the coupon samples were taped around the edges with electrical tape in order to avoid potential peeling due to the edge effects of the coated samples (see Figure 3). The salt-fog chamber exposed the coated samples to the CCT-4 Japanese Automotive Cyclic Corrosion Testing protocol. (Q-Lab, 2009) This protocol

was chosen because of its standard use in the automotive industry. The salt-fog chamber used a 5% sodium chloride solution and samples were exposed to the following steps for 1000 hours:

- 10 minutes Salt fog application at 35°C followed by
- 155 minutes Dry Off at 60°C followed by
- 75 minutes Humidity at 60°C, 95% RH followed by
- 160 minutes Dry Off at 60°C followed by
- 80 minutes Humidity at 60°C, 95% RH followed by
- 160 minutes Dry Off at 60°C followed by
- 80 minutes Humidity at 60°C, 95% RH followed by
- 160 minutes Dry Off at 60°C followed by
- 80 minutes Humidity at 60°C, 95% RH followed by
- 160 minutes Dry Off at 60°C followed by
- 80 minutes Humidity at 60°C, 95% RH followed by
- 160 minutes Dry Off at 60°C followed by
- 80 minutes Humidity at 60°C, 95% RH
- All steps repeated until target hours are reached.

Table 2: Ice Adhesion Test Results Summary

Sample #	Average Maximum Force (lbf)	Standard Deviation	Coefficient of Variance	% Difference to Bare Surface
Bare Surface	1.02	0.19	19%	0%
Sample A1	1.04	0.46	45%	2%
Sample A2	2.85	0.15	5%	179%
Sample B1	1.20	0.10	8%	18%
Sample C1	1.08	0.69	64%	6%
Sample C2	0.70	0.25	36%	-31%
Sample C3	0.74	0.29	39%	-27%
Sample C4	0.38	0.16	42%	-63%
Sample C5	0.35	0.05	14%	-66%
Sample D1	0.86	0.37	43%	-16%
Sample D2	0.54	0.31	57%	-47%



Figure 3: Coupon samples positioned for cyclic corrosion testing in salt-fog chamber.

Qualitative observations showed that some coatings performed better than others under the environmental stress. Some coatings experienced adhesive failure and/or coating fracture. This may be due to the difference in chemical composition and additives used in the coatings.

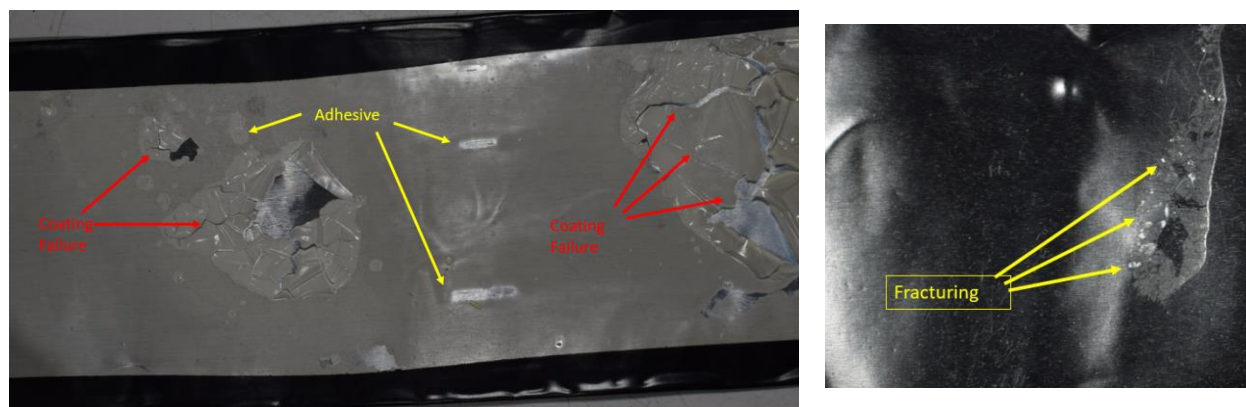


Figure 4: Qualitative assessment of coating degradation, such as adhesive failure or coating fracture, after cyclic corrosion testing in salt-fog chamber.

With samples enduring the salt-fog corrosion test, all coatings exhibited discoloration. Yellow, or brown smudging was common with grey or white spotting. White or grey spotting may be due to salt build-up from the saline solution when droplets condense on the sample surface. Yellow or brown coloring could be from chemical reaction or oxidation, with possible polymerization and crosslinking of molecules due to the cyclical high temperatures and humidity in the process. Due to the repetitive temperature fluctuations and the thin sample size, there was likely repeated thermal expansion and contraction to the samples throughout the salt-fog corrosion process. This was likely to cause tensile and shear stresses that could result in adhesive and/or coating fracture to the samples. Coating sample #C4 experienced both adhesive and coating fracture (Figure 4). The excess stresses to the coating may have caused the coating to fracture, leading to further adhesive failure as fog can penetrate the cracks, with further contraction and expansion throughout the process. The wettability of the samples was also observed before and after the corrosion testing with food colored distilled water (Figure 6). There was no noticeable difference in the wettability state for all samples, before and after the cyclic corrosion testing. A summary of observations is shown in Table 3 below.

Table 3: Summary of qualitative assessment of coating degradation after cyclic corrosion testing in salt-fog chamber

Sample Name	Discoloration	Adhesive Failure	Coating Fracture	Observations
C1	Yes	No	Yes	White smudges, coating fracture with blue discoloration
C2	Yes	No	No	White/gray spotting with brown/yellow smudges
C3	Yes	No	No	Slight white and gray discoloration in streaks
C4	Yes	Yes	Yes	Yellow discoloration, coating smudged off, coating cracked and falling off
C5	Yes	No	Yes	Yellow discoloration, spots & lines of coating missing from fracture
D1	Yes	No	No	Slight white and gray discoloration, slight yellow-brown smudging
D2	Yes	No	Yes	Slight brown/yellow discoloration, material missing from adhesive test, scratches/dimples in coating

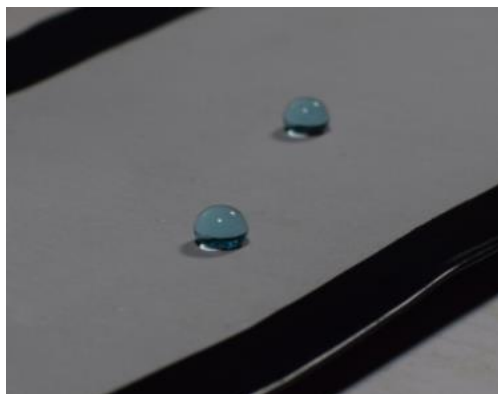


Figure 6: Surface wettability assessed with contact angle



Figure 7: Adhesive testing on coated coupon

2.2.1 Adhesive Testing

The ASTM D3359 protocol was used to test adhesion properties of the coating on the sample surface after corrosion testing. This involved first etching a 5cm x 5cm grid onto the surface of the sample and then applying an adhesive tape on the grid for 1 hour (see Figure 7). The tape is then ripped off and the samples are observed for the percent of area removed. Classifications were then given to the samples according to ASTM standards. Class 5B is the highest classification where edges are cut smooth with no squares detached. Class 4B is defined as when only a small amount of area is affected (<5%). (ASTM, 2011) All of the coatings were graded with the highest 5B ASTM classification, except for coating #C4 which received a 4B ASTM classification.

2.2.2 Post-Corrosion Ice Adhesion Testing

Another Ice Adhesion test was performed on the samples after the cyclic corrosion testing to identify any change in ice adhesion properties after being exposed to harsh environments. The same protocol was used as in the Ice Adhesion testing section above, except the exposed samples were rinsed with distilled water before testing to remove any salt remaining on the surface from the salt-fog chamber. The results are shown in Table 4 below.

Table 4: Ice Adhesion Test Results Summary after 100hrs of Cyclic Corrosion test in Salt-Fog Chamber

Sample #	Average Maximum Force (lbf)	Standard Deviation	Coefficient of Variance	% Difference to Bare (After Corrosion Testing)	% Difference to Bare (Before Corrosion Testing)
Bare	0.70	0.50	71%	0%	0%
Bare 2*	23.17	1.74	8%	0%	0%
C1	0.77	0.24	31%	10%	6%
C2*	13.63	2.79	20%	-41%	-31%
C3	1.15	0.05	4%	64%	-27%
C4	0.43	0.09	22%	-38%	-63%
C5	0.33	0.19	57%	-52%	-66%
D1	0.50	0.14	28%	-29%	-16%
D2	0.40	0.14	35%	-43%	-47%

*C2 sample was tested on a different 6061 aluminum alloy, so these results are compared to Bare 2 that used the same alloy.

In general, the samples maintained their performance under the ice adhesion test after their exposure to 1000 hours in the cyclic corrosion chamber. Compared to the uncoated samples, the coated samples maintained a comparable order of magnitude for the percent difference to the bare sample before corrosion testing (Table 4). This shows that there was minimal wear to the coatings and is an example of their durability under harsh environments. The overall absolute average maximum force was less compared to that before the corrosion testing, likely due to a change in the coated

surfaces' conditions. Since the salt-fog chamber uses a saline solution, it is possible that salt could have remained deposited on the samples even after rinsing with distilled water. Salt may have interfered with the ice freezing when testing the samples, resulting in less force required for removal.

3. CONCLUSIONS

This paper presented a series of mechanical and surface topological tests to assess the viability of various chemical coating formulations that may mitigate frost adhesion and removal from the fins of heat exchanger coils. Preliminary testing of ice adhesion properties on small aluminum substrates allowed for the initial screening of commercial coatings available. Coatings that had an ice adhesion force less than an uncoated sample showed potential in reducing frost development on HX. In order to understand the long-term durability of the coatings, a cyclic corrosion test was used to corrode the samples for 1000 hours. Most of the coatings performed well under the harsh environmental conditions, showing potential to be used in real-world environments. Qualitative observations showed no significant change in wettability, but some discoloration and/or fracturing was found in some samples. The ASTM D3359 protocol was used to test the corroded samples' adhesion to the aluminum substrate, with all except one coating rated with the highest classification. An additional ice adhesion test was then performed on corroded samples to understand any change to the preliminary tests. The results showed that most of the coatings had comparable ice adhesion test performance relative to uncoated samples. Some samples were seen to perform better, however this may be due to salt deposited on the surface after the salt-fog chamber. Although there was a noticeable fracture in the coating after corrosion testing, sample C5 was shown to have the best results after corrosion testing when looking at the Ice Adhesion force compared to an uncoated substrate. The sample was also able to withstand the ASTM D3359 test with the highest 5B classification.

It is important to note that the screening tests provide static measurements for assessing the coatings potential viability for use as frost mitigation on heat exchanger coils. Frost development and removal is a transient heat and mass transfer phenomenon. Thus, testing coated coils under a frost performance test setup and matrix would be necessary to effectively determine the advantage any of the coating products would provide for heat exchanger coil frost mitigation. The future work includes evaluating coated HX's at an HVAC system level, combined with alternate defrost cycling controls using other metrics beyond simple time or temperature-based algorithms to minimize system performance degradation and heat pumps carbon footprint in general.

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