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VERTICAL SURFACE DROPWISE CONDENSATION HEAT TRANSFER USING SELF-HEALING COATINGS

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ABSTRACT

In a traditional Rankine cycle, the condenser system for coal-fired power plants uses a pumped cooling water system to reject heat to a wet or dry cooling tower. Heat rejection occurs in a shell and tube heat exchanger by filmwise condensation of low-pressure steam on steel, copper, or titanium. The use of steam surface condensers typically results in low thermal performance on the steam-side due to the filmwise mode of condensation present on common material options. The low thermal performance results in a substantial operation and maintenance cost. To improve the thermal performance and durability of steam surface condensers, a self-healing, replenishable film-forming amine (FFA) coating deposited on the condenser tubing is proposed. The FFA coating not only promotes efficient dropwise condensation on the condenser tubing but also protects the surface from oxidative corrosion. To measure the thermal performance enhancement of these coatings, a custom test apparatus was used for flat plate condenser surfaces. The initial results suggest improved thermal performance for several condenser materials. Additional findings primarily suggest the affinity of the coating for the condenser material will affect the overall thermal performance enhancement, as well as secondary reasons, including constriction resistance and the coating concentration. Further testing will confirm the self-healing benefits of these coatings.

Keywords: dropwise condensation; self-healing coatings; film-forming amines; power plant cooling

1 INTRODUCTION

Film-Forming Substances (FFS) are a family of coatings that are used primarily for corrosion protection of metal surfaces. Film-forming amines (FFA) are a subset of this group of coatings that spontaneously form a molecular layer of short polymer chains with a distinct functional group [1]. This functional group, called the “head”, is an amine that is capable of forming a covalent chemical bond with the substrate surface material. The other end, called the “tail”, is a long-chain hydrocarbon, engineered to have a desirable surface property such as ultra-low surface energy. This is demonstrated in Figure 1. The application of these coatings has been primarily used for oxidative corrosion resistance of metal surfaces, such as those used in steam evaporators and surface condensers for power plants [2,3,4]. Most blends of FFA coatings are non-wetting (i.e. hydrophobic) and promote efficient dropwise condensation. This phenomenon occurs when the critical surface energy is appreciably lower than that of the surrounding fluid, which generates a finite wetting angle and low contact angle hysteresis. With this mode of condensation, high thermal performance condenser surfaces can be realized with heat transfer coefficients as much as 5-20x higher than traditional filmwise condensation [5]. However, the application of FFA coatings for improved heat transfer is underdeveloped.

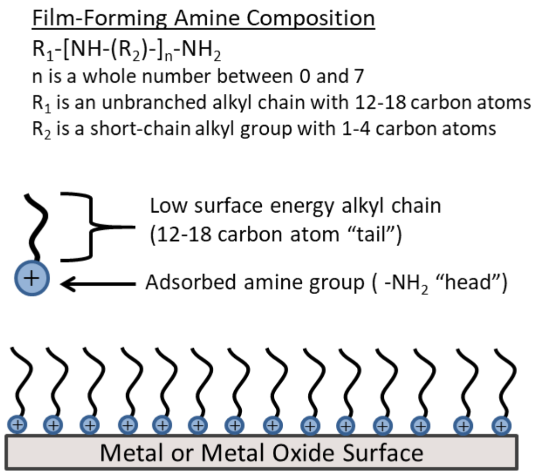

Figure 1: Film-forming amine coatings deposited on a metal or metal oxide surface.

Dropwise condensation on non-wetting surfaces has many applications in two-phase thermal managements technologies, including power plant steam condensers [6], vapor chambers [7], and heat pipes. High heat transfer enhancement using dropwise condensation (DWC) has been of interest since the earliest published work in 1930, which reported an order of magnitude higher heat transfer coefficients compared to filmwise condensation for comparable conditions [8]. Although there are a multitude of different coating mechanisms to generate ultra-low surface energy, many issues remain to create a consistent, practical surface for industrial use. One key issue includes poor coating lifetime [9]. To alleviate this problem, FFA coatings have been proposed as a self-healing, regenerative coating solution for steam surface condensers. The hydrophobicity of the surface can be sustained over time due to oxidative corrosion protection with direct injection of additional FFA coating solution into a steam evaporator [10]. This concept is illustrated in Figure 2, with a more detailed configuration shown in Figure 3.

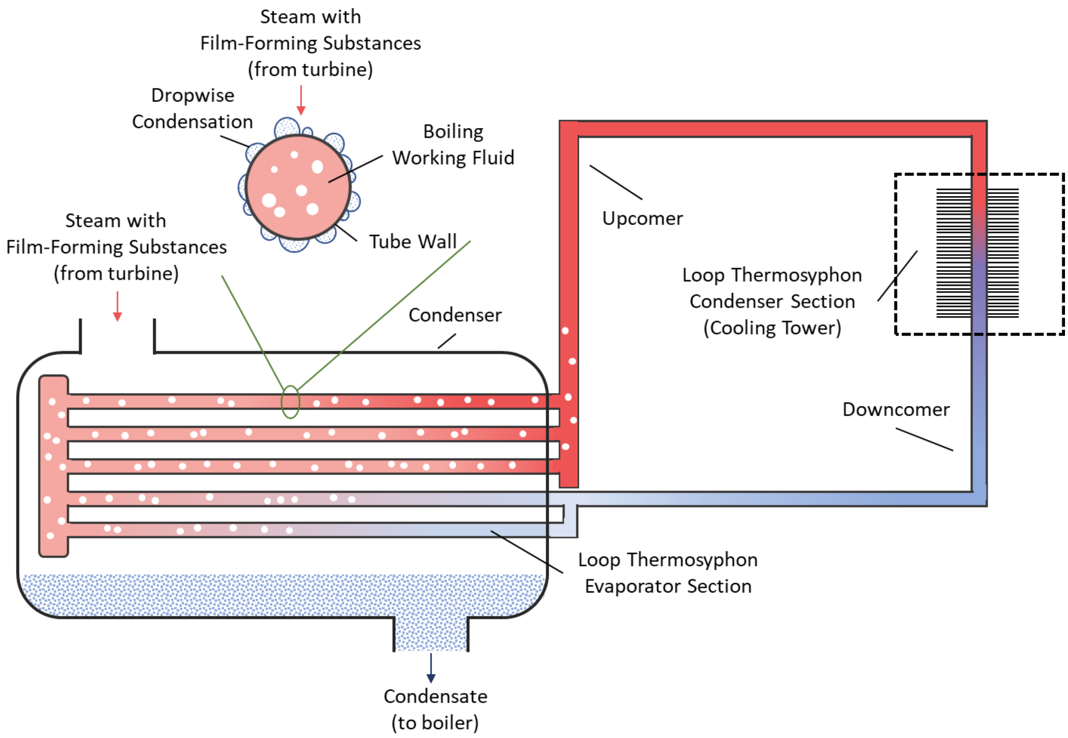

Figure 2: Application of FFA coatings to a steam surface condenser with a loop thermosyphon replacing a traditional pumped cooling water system to reject heat to a cooling tower.

This study specifically investigates the thermal performance benefits of using FFA coatings on smooth condenser surfaces for common engineering materials. The condensation heat transfer coefficient is evaluated on copper, carbon steel, and stainless steel flat condenser surfaces using FFA and non-FFA, or neutralizing amine, coating solutions of PAS 6074. The initial results indicate a consistent improvement in thermal performance using these coating solutions to generate dropwise condensation. Corrosion protection of these surfaces have been realized with correct coating procedures. Additional work is focused on sustaining long-term dropwise condensation on these surfaces using continuous coating injection and replenishment.

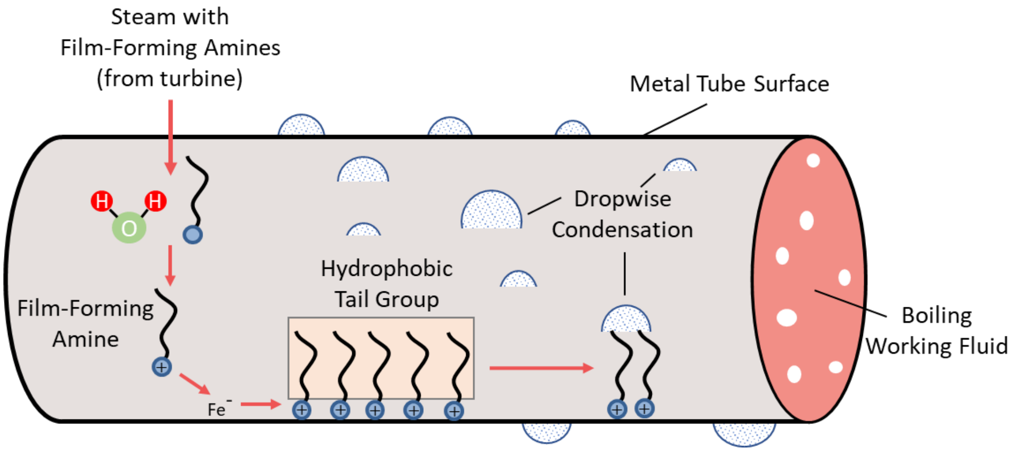

Figure 3: Detailed configuration of FFA coating applied to a steam surface condenser tube.

2 EXPERIMENTAL

Test samples were machined out of commercially available copper alloy 101, mild carbon steel 1018, and stainless steel 304. These materials are most commonly used in steam surface condensers. Figure 4 and Figure 5 provide an in-depth look at the details of the experimental apparatus. The active condensing surface is a 5.59 cm by 2.03 cm area centered in the test block. The material surfaces were first prepared using 1200 grit sandpaper to create a smooth, mirror finish. The surfaces were then cleaned with acetone, deionized water, and finally dried with dry nitrogen gas. The FFA coating was applied using an aqueous 6ppm solution of PAS 6074, where the active ingredient is octadecylamine with a blend of neutralizing amines. The test blocks were submerged in a sealed bath of the solution for a 24-hour period and subsequently dried with dry nitrogen gas. Each sample was tested for thermal performance in the experimental apparatus using the coating solution, which was injected following the use of a vacuum pump to evacuate the system. Vapor was produced in the evaporator and driven by vapor pressure to the condensation chamber. Following condensation of generated saturated vapor, liquid condensate drained from the condensation chamber to prevent buildup of a liquid pool. The absolute pressure for each experimental test was held constant during data collection to achieve steady state, at approximately 120 kPa. The non-condensable gas (NCG) chamber was pumped to vacuum pressure conditions to collect NCG and then used to purge the condensation chamber of any internal NCG buildup before data collection. A thermocouple array was used to evaluate the surface temperature of the substrate for heat transfer calculations. Thermal paste (DOW CORNING 340) was used to ensure precise thermal coupling of the thermocouples to the thermocouple wells. Results were collected over a range of heat flux data by varying the cartridge heater input and water chiller output. A transparent sight glass was incorporated to observe the dropwise condensation phenomenon. Contact angle goniometry was completed before testing as a measure of promoter effectiveness.

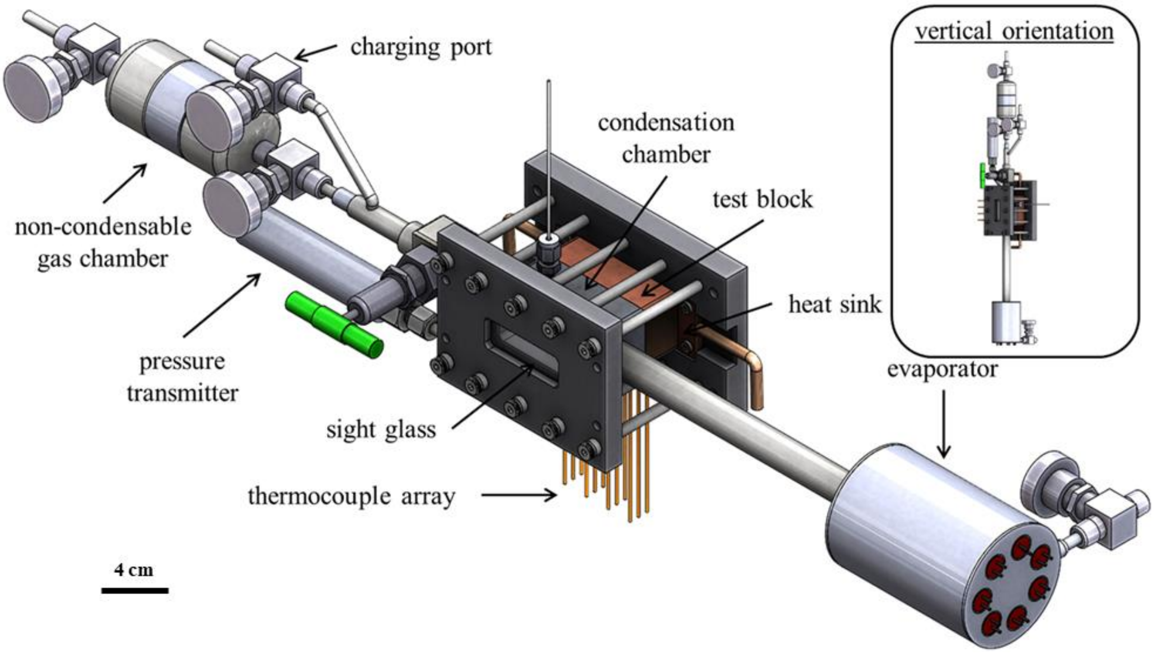

Figure 4: The test setup, where the actual orientation is vertical (shown in inset) with the evaporator below the condensation chamber, showing its various components.

Conduction calorimetry was used to calculate heat flux and extrapolate the surface temperature during dropwise condensation. Temperature measurements were acquired at several known locations within the test samples. Linear regression was then used to determine the thermal gradients across the block and extrapolate the surface temperature during dropwise condensation. The consistent linearity of this data confirms the use of this technique. Heat flux through the block was calculated using Fourier's law,

$$\boldsymbol{q = k_s \frac{dT}{dz}}. \tag{1}$$

The experimental dropwise condensation heat transfer coefficient was calculated using the measured saturated vapor temperature of the condensing steam and the surface temperature,

$$\boldsymbol{q = h(T_g - < T_s'' >)}. \tag{2}$$

The combination of these equations using an energy balance at the surface gives a simplified expression for calculating the dropwise condensation heat transfer coefficient from experimental measurements,

$$\boldsymbol{h = \frac{k_s \frac{dT}{dz}}{T_g - < T_s'' >}}. \tag{3}$$

Figure 5: Actual test setup used in the lab to measure the thermal performance of condenser surfaces.

3 RESULTS & DISCUSSION

3.1 Thermal Performance Evaluation

Contact angle measurements were completed prior to thermal performance testing using a custom in-house goniometer. This was done to ensure the coating affinity and density was similar for each coated condenser material. The results of this effort are seen in Figure 6 for the advancing contact angle and Table 1 with the advancing and receding contact angle measurements. The measurements were consistent and close to 90º for the advancing contact angle, which was sufficient to move forward to thermal performance testing.

Figure 6: Advancing contact angle (θ_a) for FFA coating on each condenser material.

Table 1: Advancing and receding contact angle measurements for each surface material.

	Copper		Stainless Steel		Carbon Steel	
	θ_a	θ_r	θ_a	θ_r	θ_a	θ_r
Average	88.9º	77.0º	82.7º	76.3º	87.9º	80.1º
Standard Error	0.8º	2.3º	1.3º	3.7º	0.6º	1.1º

The data in Figure 7 represents the local vapor-to-surface temperature difference as a function of the local condensation heat flux for several condenser materials using both coating solutions. The "non-FFA" coating solution contains only neutralizing amines, while the "FFA" coating solution contains both neutralizing amines and film-forming amines. The "non-FFA" coating solution is used as a control to compare against using film-forming amines. Power plants typically use blends of neutralizing amines for pH control, while film-forming amines are only used if corrosion protection of heat transfer surfaces is required [11]. Each data point represents a time-averaged value for specific experimental setpoints of heat input and heat removal. The data in Figure 8 takes the previous data to examine as the local heat transfer coefficient as a function of condenser material thermal conductivity. This is done to more easily compare the thermal performance results for each condenser material.

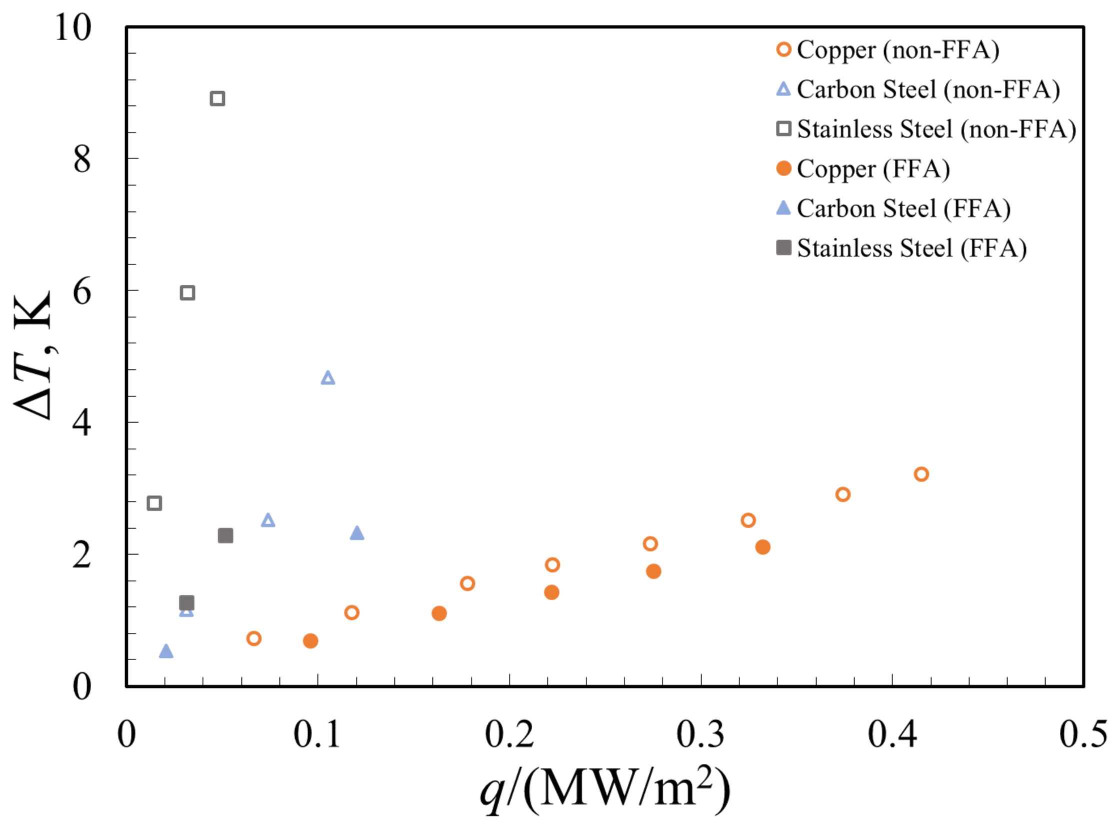

Figure 7: The local vapor-to-surface temperature difference as a function of the local condensation heat flux for each condenser material and coating solution.

Each condenser material will be examined to further understand the preliminary results. For copper, high thermal performance was observed (h = 151 kW/m^2-K) for the "FFA" coating, which is consistent with previously acquired results using standard thiol-based self-assembled monolayer coatings [12,13]. It is evident that the FFA coating does not add additional thermal resistance on the condenser surface, which some research has indicated with dense cross-linking. The similarly high thermal performance of the "non-FFA" coating solution is due to the neutralizing amines deposited on the condenser surface, contributing to a short-lived, low surface energy. The results for carbon steel and stainless steel are similar and demonstrate reduced thermal performance. This is understood to happen due to constriction resistance, which is a phenomenon during dropwise condensation that constricts heat flow at the surface due to the low thermal conductivity of the condenser material [14, 15]. The presence of larger departing droplets, especially at low heat flux, leads to relative adiabatic regions on the surface leading reduced thermal performance. In this case, there will be an upper limit to improved thermal performance on carbon steel and stainless steel surfaces. The initial results obtained fit into this model, as evidenced by Figure 8. Results were only able to be obtained for a short period of time, typically less than 10-20 minutes due to the low concentration and volatility of FFA in solution. Following a vent of NCG, it was theorized the concentration of FFA drastically reduced leading to these short-term results. While these thermal performance results for carbon steel are promising (h = 45 kW/m^2-K), the appropriate test conditions need to be determined in order to maintain the concentration of FFA in solution. Stainless steel exhibited the same issue. The "non-FFA" coating solution for both carbon steel and stainless steel exhibited mixed dropwise and filmwise condensation results, due to the reduced affinity of the amine groups on the surface.

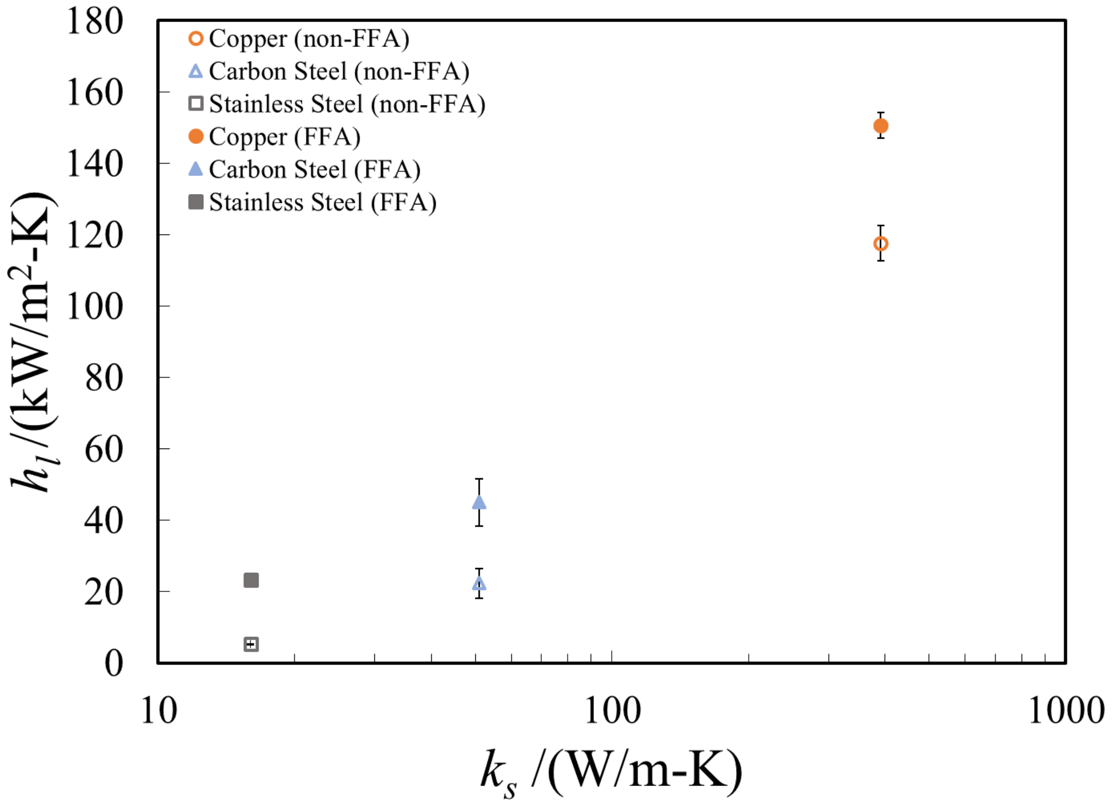

Figure 8: The local heat transfer coefficient as a function of the condenser thermal conductivity.

3.2 Coating Reliability

To gain additional insight into the thermal performance results, images of the condenser surface were taken during dropwise condensation experiments and following testing. These images are seen in Figure 9 and Figure 10, respectively. The first observation realized from the images in Figure 9 reveal the need for a consistent concentration of FFA in solution. Due to the volatility of the FFA coating, the coating density is not maintained on the condenser surface, which leads to mixed modes of dropwise and filmwise condensation. The second observation relates to the aforementioned constriction resistance, due to the presence of larger departing droplets on the steel surfaces compared to copper. This visual evidence is key in understanding the reduced thermal performance on the steel condenser surfaces compared to copper, in relation to the observed constriction resistance.

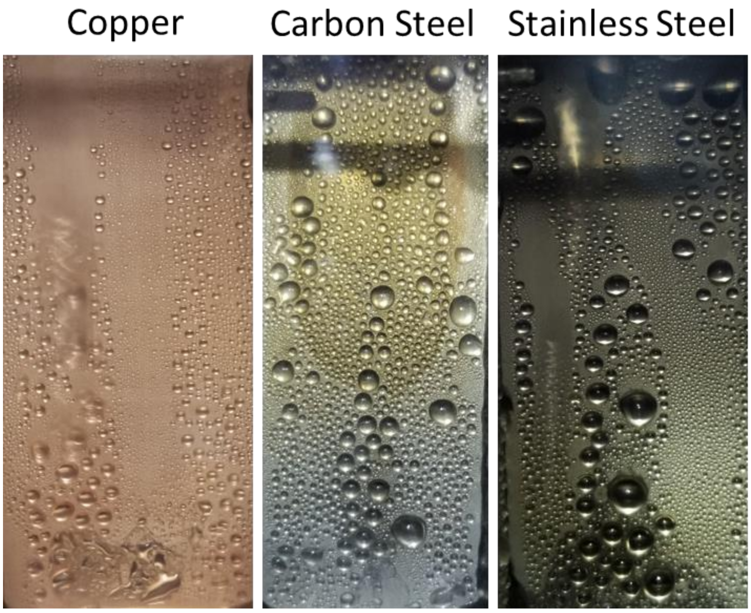

Figure 9: Dropwise condensation on each condenser surface.

The images in Figure 10 reveal the effects of the FFA coating following its use. The most interesting result is demonstrated for copper, where the FFA coating prevented oxidation of the condenser surface, leaving it in its original condition. The non-FFA coating did not prevent oxidation, as expected. This was a key finding in the application of FFA coatings in order to demonstrate their reliable, long-term use for corrosion protection. Both the carbon steel and stainless steel surfaces demonstrated different findings. The non-FFA coatings led to expected oxidation of the surfaces, forming a magnetite layer. The FFA coating did not prevent corrosion, as expected from the aforementioned thermal performance results. With the inconsistent coating density, certain portions of the surface were protected leading to mixed modes of condensation. The following work will use an injection system to maintain the coating concentration on the surface during testing. Irregularities in coating concentration may also be a result of condenser surface preparation, where dissolved oxygen should not be introduced during the coating process. Solving these two issues will lead to a more robust coating application for long-term use.

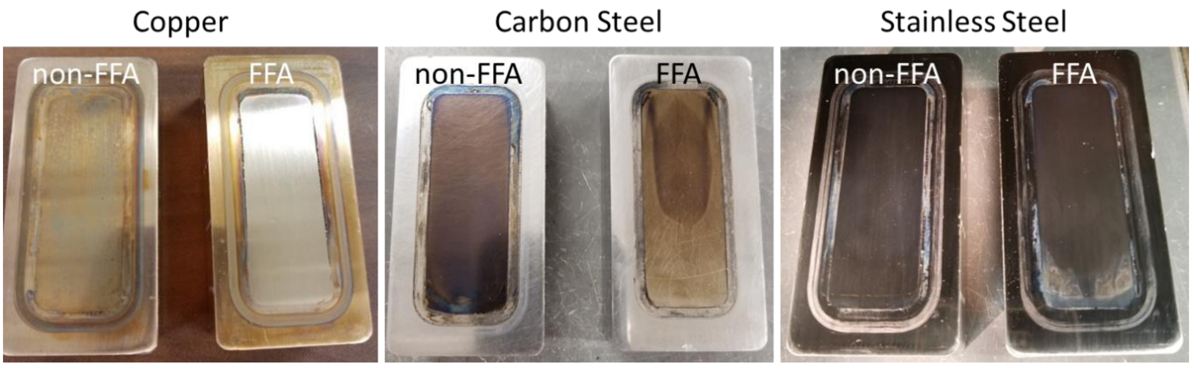

Figure 10: Condenser surfaces following initial dropwise condensation testing for both "non-FFA" and "FFA" coating solutions.

4 CONCLUSIONS

To improve the thermal performance and durability of steam surface condensers, film-forming amine coatings were deposited on flat condenser surfaces to promote dropwise condensation. To measure the thermal performance enhancement of these polymer coatings, a custom test apparatus was used to measure the local heat transfer coefficient. The initial results suggest that improved thermal performance for copper, carbon steel, and stainless steel can be achieved. These results are consistent with previously acquired data for similar coating/material systems and observations concerning reduced thermal performance for low thermal conductivity surfaces. Further observations suggest the coating concentration requires control to maintain a dense coating application on the condenser surface. Further testing will include this capability to provide more consistent thermal performance results and evaluate the repeated self-healing capabilities of these coatings.

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