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DEVELOPMENT OF A DURABLE VAPOR PHASE DEPOSITED SUPERHYDROPHOBIC COATING FOR STEAM CYCLE POWER GENERATION CONDENSER TUBES

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ABSTRACT

The condenser performance benefits afforded by dropwise condensation have long been unattainable in steam cycle power plant condensers due to the unavailability of durable and long lasting wetting inhibiting surface treatments. However, recent work in superhydrophobic coating technology shows promise that durable coatings appropriate for use on condenser tubes in steam cycle power generation systems may soon become a reality. This work presents a nano-scale, vapor phase deposited superhydrophobic coating with improved durability comprised of several layers of rough alumina nano-particles and catalyzed silica with a finishing layer of perfluorinated silane. This coating was applied to solid, hemi-cylindrical test surfaces fabricated from several common condenser tube materials used in power generation system condensers: Titanium, Admiralty brass, Cupronickel, and Sea Cure stainless steel condenser tube materials as well as 304 stainless steel stock. The development evolution of the coating and its effect on condensation behavior on the above materials are presented. Results show that the performance enhancement, measured in rate of heat transfer spikes corresponding to condensate roll-off events, was best for the titanium surface which produced 64% more events than the next most active material when coated using the most durable surface treatment tested in this work.

INTRODUCTION

As electrical power production costs continually rise due to governmental regulations and increasing fuel costs, power producers must diligently seek capacity and efficiency increases in all generation system components and subsystems in order to keep up with ever increasing power consumption. Current condenser design procedures for steam power generation systems assume filmwise condensation instead of the preferable and more efficient dropwise mode of condensation because traditionally there has been no method of maintaining dropwise condensation in the harsh environment produced inside a power generation condenser [1]. The major hurdle to the widespread implementation of hydrophobic coatings on power generation condenser tubes to allow dropwise condensation is the poor durability of these coatings. Low durability coatings do not provide the longevity of coating

effectiveness to make their use economically viable, and the difficulty in installing coated condenser tubes without damaging the coating further discourages their use. In order to realize the performance increases potentially afforded by dropwise over filmwise condensation sufficiently durable superhydrophobic coatings and improved installation procedures must be developed.

The condensate mobility and heat transfer advantages offered by dropwise over filmwise condensation are well documented [2-5]. During dropwise condensation, droplet mobility greatly increases the rates of heat and mass transfer because as droplets move they expose portions of "fresh" condensing surface that are free of a liquid thermal barrier. Because of this, dropwise condensation can produce heat transfer coefficients up to ten times those produced during filmwise condensation [3]. This has motivated many efforts to study and produce superhydrophobic surfaces that excel at achieving dropwise condensation. Several methods have been explored but the one that has emerged as the most promising is microscopic surface texturing. This technique usually consists of microscale surface features covered with a nanoscale texturing. The nanoscale texture produces the superhydrophobic characteristics and the microscale features serve to protect the nano-texture from being completely removed by mechanical abrasion or filled with foreign material during handling or coming in contact with other objects [1].

One of the earlier works studying hierarchical micro/nano textured surfaces found that when new, these types of surface exhibited superhydrophobic characteristics that would quickly diminish during condensation but when a hydrophobic coating was applied over the two-tier surface texture the superhydrophobic properties were more stable and lasted longer, and a higher degree of droplet mobility was achieved [6].

Droplet mobility on superhydrophobic surfaces can be quite dramatic. Several studies have reported observing droplets remove themselves from the surface via a spontaneous jumping phenomenon that occurs as the result of a coalescence event [3,7-10]. The first such report was made by Boreyko et. al. [3] in which, jumping droplets were observed moving away from the condenser surface at speeds as high as 1 m/s. Subsequent studies have found methods of giving the jumping droplets a horizontal component of velocity [8] which can allow the jumping droplet to clear multiple other droplets from the condenser surface instead of only removing itself [9]. This is done by forcing the coalescence event to occur around a vertical obstacle, such as micromachined pillars, which gives the resulting jumping droplet a horizontal component of velocity which causes the moving droplet to collide with others on the surface taking them with it as it moves off of the surface [9].

While micro-machined pillars may not be a realistic surface treatment for condenser tubes in a power generation system without prerequisite advances in manufacturing and handling techniques and systems, the droplet mobility offered by these surfaces is impressive and shows the enormous potential improvements that may be made to condenser performance in the future. Currently there are several other methods of achieving dropwise condensation and even superhydrophobicity on tubular metallic substrates being studied. Manvel used several treatments to promote dropwise condensation on horizontal copper-nickel condenser tubes in [4]. He reported a 53% improvement in outer heat transfer coefficient when dropwise condensation was promoted by applying a fluorocarbon coating called Nedox, and a 45% improvement in outer heat transfer coefficient on similar dropwise condensing tubes sputtered with TFE compared to bare copper-nickel tubes [4]. Another study recorded a heat transfer coefficient improvement of an impressive 250% on gold plated aluminum tubes with a dropwise condensation promoting organic self-assembled monolayer (SAM) compared to a similar tube without the SAM [5]. Miljkvoic et. al. reported developing a promising technique for forming a superhydrophobic layer on copper tubes [10]. In this study a layer of nano-scale, sharp, knife like copper oxide structures was grown on the surface of copper tubes and then sealed with a vapor phase deposited silane coating. Dropwise condensation on these tubes produced heat transfer coefficients up 85% higher than on filmwise condensing bare copper tubes and under certain conditions small droplets were observed jumping from the tubes [10].

Although there are large heat transfer performance benefits to be gained by utilizing superhydrophobic coatings on condenser tubes in power generation plants and on many other phase change heat exchangers, this technology has yet to be widely implemented because all current methods of promoting dropwise condensation are relatively fragile [5]. The objective of this paper is to report the development and testing of an alumina nano-particle vapor phase deposited superhydrophobic coating for metal substrates adapted from a similar coating currently used to protect consumer electronics from water damage. This surface treatment shows promising durability performance potential while maintaining sufficient non-wetting characteristics and can be applied to condenser tubes in-situ through vapor deposition processes.

TEST SURFACE FABRICATION

Test surfaces were prepared using Southern Company-provided one-inch-diameter condenser tube samples in the following materials: Titanium, Admiralty brass, SEA-CURE and Cupronickel. To produce solid test surfaces, capable of conducting heat, the following fabrication sequence was followed. Aluminum support mandrels were fabricated to match the inner diameter for each tube sample. These were pressed into the tube samples to support them radially and axially to allow the tubes to be clamped and machined like solid round rods. The tube and mandrel assemblies were then machined into one-inch long half cylinders, resulting in a

25mm x 25mm base area matching the cooled surface footprint in the experimental facility (described below). The remaining mandrel material was then removed. Lead was cast directly into each half tube section. After cooling, the lead casting and tube section were separated and then permanently joined using silver based thermal interface material and epoxy. Additional flat and half round control surfaces were produced using 304 stainless steel stock machined to the desired dimensions.

After fabrication was completed, surface treatments were applied in an RPX-540 Vapor Deposition System. The system deposits customized nano-composite structures using a hybrid VPD/ALD (vapor phase deposition/atomic layer deposition) process. Up to five precursors can be sequentially applied to create a variety of specialty films for each specific application. All the precursors are heated to create a reservoir of chemical vapor and their introductory timing, dose, and order is controlled by a LabVIEW-based software system with automatic process operation.

A typical coating process is as follows. Incremental layers of Al_2O_3 nanoparticles are accumulated by repeating VPD cycles, followed by a 600-cycle pyridine-catalyzed silica protection film and a final perfluoronated silane finish layer for superhydrophobicity.

SURFACE TREATMENT DEVELOPMENT

Several coating methods have been studied in recent years. Technologies like CVD (Chemical Vapor Deposition) and ALD (Atomic Layer Deposition) enable nanoparticle film deposition with good uniformity and precise control. Primary scientific merits include the improvement of the process efficiency while maintaining the coating quality. A recent improvement on the CVD process includes introducing varying functional end-group terminated silanes to increase the reactivity of the CVD precursors. A modified VPD (Vapor Phase Deposition) apparatus has the ability to produce aluminum oxide nanoparticles from a gas phase reaction which can then be anchored and coated by the SiO_2 and hydrophobic layers. Superhydrophobic coatings have the potential to revolutionize the condensation process. Since different application environments emphasize corresponding film properties, VPD coated substrates are designed for durability, water-resistance performance, electrical properties, thermal properties and other properties based on process requirements.

Two different coatings were produced for condensation and durability evaluation, both were based on a superhydrophobic coating, called Repellix, developed for silicon substrates and currently used to inhibit wetting on microprocessors in portable electronic devices. Repellix is a nanoparticle coating based on a VPD process which uses sub-atmospheric pressure gas phase flow-through the reactor. This coating scheme is highly suited for large batch processes and can be easily scaled. The unique nanostructure of the film is created using a cross between ALD-based surface limited reactions and CVD-based condensation process conditions in which super-saturated vapor conditions are created directly over the targeted coating surface. During the process, a metal organic precursor is oxidized in such a way that the required film roughness and aerial coverage for superhydrophobicity is obtained. Subsequently, the nanoparticles are immobilized into a silica-based matrix to improve the film's durability. It was observed that the use of alternating between deposition/immobilization and adhesion steps similar to conventional ALD resulted in films with better uniformity and durability compared with non-layered deposited films. The final step in the process sequence employed is a surface modification treatment with a perfluoronated agent to create a surface with low energy state over entire film.

The base nanostructure of alumina is formed by the following oxidation reactions (asterisk indicates surface-bound species):

$$2Al(CH_3)_3 + 3H_2O \rightarrow Al_2O_3 + 6CH_4 \text{ or by}$$

$$2AlOH^* + 2Al(CH_3)_3 \rightarrow 2[Al\text{-}O\text{-}Al(CH_3)_2]^* + 2CH_4$$

$$2[Al\text{-}O\text{-}Al(CH_3)_2]^* + 3H_2O \rightarrow Al_2O_3 + 2AlOH^* + 4CH_4 \quad (1)$$

Since the mechanical durability of this nanoscale topography is a major challenge, a pyridine catalyzed process is introduced to strengthen the film and increase its durability:

$$\text{Overall Reaction: } SiCl_4 + 2H_2O \rightarrow SiO_2^* + 4HCl$$

$$Si\text{-}OH^* + SiCl_4 + C_5H_5N \rightarrow SiO\text{-}Si\text{-}Cl_3^* + HCl + C_5H_5N$$

$$Si\text{-}Cl^* + H_2O + C_5H_5N \rightarrow Si\text{-}OH^* + HCl + C_5H_5N \quad (2)$$

Finally a perfluoronated agent, Phobix, is applied to increase the surface superhydrophobicity:

$$CF_3(CF_2)7(CH_2)_2SiCl_3 + 3H_2O \rightarrow CF_3(CF_2)_7(CH_2)_2Si(OH)_3 + 3HCl$$

$$Si\text{-}OH^* + CF_3(CF_2)_7(CH_2)_2Si(OH)_3 \rightarrow CF_3(CF_2)_7(CH_2)_2Si\text{-}O\text{-}Si + 3H_2O \quad (3)$$

While Repellix displays adequate durability on the silicon substrates for which it was developed, when applied to metallic substrates it is very fragile and can be removed from the surface with a very light wipe with a fingertip. The two coatings developed from Repellix for condensation and durability evaluation are modifications to the original Repellix

formulation (detailed in Table 1) targeting two potential weaknesses of the Repellix coating on metallic substrates.

The first modification targeted the potentially weak initial bonding between metal and alumina nanoparticles possibly due to low density of hydroxyl group on metal surface. To correct this, a thin layer of silica was added before the alumina layer, which increases the hydroxyl group density and results in stronger surface bonding between nanoparticles. This formulation is called modified Repellix and formulation details can be found in Table 2.

The second modification to Repellix is called Repellix 2.0 and was developed to increase the durability of the coating nanostructure by enhancing the robustness of the silica layers. This formulation replaces the Linkerrix+Pyridine reaction with an HMDSO (hexamethyldisiloxane)+O_2 plasma to deposit a thin oxide, which results in much thicker deposited silica layers making the nanostructure more durable. Details for this formulation can be found in Table 3.

TABLE 1: REPELLIX PROCESS PARAMETERS

Deposited Film (Each Cycle)	Chemical partial pressure used for reactions (mTorr)					Typical Reaction Time (secs)	Number of Cycles
	TMA	Zorrix	Linkerrix	Pyridine	Phobix		
Rough Al_2O_3	300-400	200-300				30	4
Catalyzed Silica		200	200	100		10	600
Hydrophobic SAM		1000			250	300	2

TABLE 2: MODIFIED REPELLIX PROCESS PARAMETERS

Deposited Film (Each Cycle)	Chemical partial pressure used for reactions (mTorr)					Typical Reaction Time (secs)	Number of Cycles
	TMA	Zorrix	Linkerrix	Pyridine	Phobix		
Catalyzed Silica		200	200	100		10	50
Rough Al_2O_3	300-400	200-300				30	4
Catalyzed Silica		200	200	100		10	600
Hydrophobic SAM		1000			250	300	2

TABLE 3: REPELLIX 2.0 PROCESS PARAMETERS

Deposited Film (Each Cycle)	Chemical partial pressure used for reactions (mTorr)				
	TMA	Zorrix	O_2	HMDSO	Phobix
Rough Al_2O_3	300-400	200-300			
Plasma Enhanced Silica			40	160	
Hydrophobic SAM		1000			250

Durability Testing

Water erosion durability tests were performed on modified Repellix and Repellix 2.0 coated flat 304 stainless steel test surfaces. In these tests tap water flowing at six liters per minute through a 3 mm nozzle impinged the surface which was secured by a jig 30 cm below the nozzle and tilted 45 degrees from the flow direction. Images of droplets deposited on the surfaces were taken before the tests and periodically during testing to measure contact angle degradation. The surfaces were dried with compressed air before droplets were deposited and contact angle measurements were taken using National Instruments Vision Assistant software. Testing was stopped when the contact angle dropped to 90° or below. Both modified Repellix and Repellix 2.0 displayed dramatic durability improvements over the original Repellix formulation on metallic substrates which was not included in the water erosion tests because the coating was so fragile it did not withstand handling on most test surfaces. Modified Repellix coated surfaces initially display a contact angle of approximately 120° which degraded to about 93° after 2.5 hours of water erosion and then further degraded to 70° after another half hour of erosion (3 hours total). Repellix 2.0 coated surfaces start with a contact angle of 151° which classifies this coating, in new condition, as superhydrophobic [5]. Additionally Repellix 2.0 was able to withstand water erosion for approximately three times as long compared to modified Repellix before the contact angle degraded to 90° (8 hours versus 2.5 for modified Repellix). For comparison, the original Repellix coating applied to a silicon substrate creates an initial contact angle for water of 148° and degrades to 90° after 7.5 hours of similar water erosion testing. Figure 1 shows a plot of contact angle degradation for the two coatings tested.

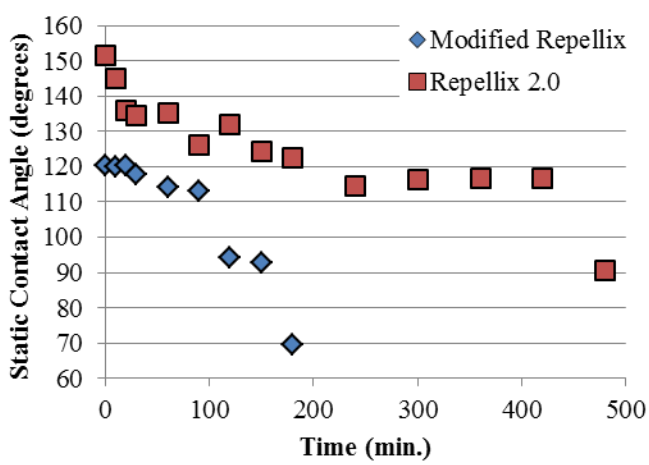


FIGURE 1: STATIC CONTACT ANGLE VERSUS TIME FOR WATER ERROSION TESTS ON MODIFIED REPELLIX AND REPELLIX 2.0 COATED FLAT 304 STAINLESS STEEL SURFACES

EXPERIMENTAL FACILITY AND METHODS

Experimental Equipment

All condensation experiments were performed in a custom designed and fabricated condensation chamber to provide a controlled atmosphere for observing condensation phase change. This chamber is mounted on four pneumatic vibration isolating feet (Newport SLM-1A) to minimize the effect of equipment and building vibrations on the condensation process. It features three orthogonally oriented indium tin oxide film heated windows (Seaclear Ind. 150 x 150 x 9.5 mm electrically heated windows) to allow visualization of condensate behavior. Internal chamber temperature and pressure is measured using a k-type thermocouple and pressure transducer (Omegadyne model no. PX319-050A5V). A custom measurement head (described in greater detail below) gathers temperature data to calculate temperature profiles and heat fluxes through the test surfaces. A surface-mount thermistor (Omega OL-729) measures the surface temperature of the test surfaces. A schematic of the experimental facility is provided in Figure 2.

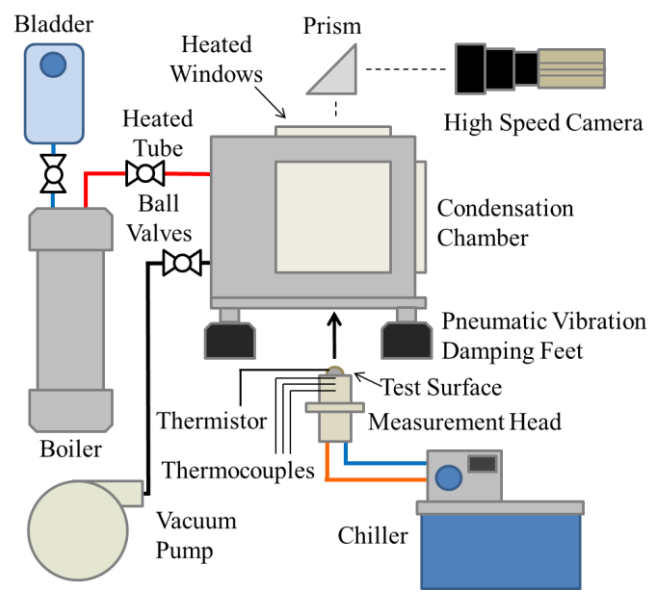


FIGURE 2: EXPERIMENTAL FACILITY SCHEMATIC

A boiler constructed of stainless steel pipe and fittings with two cartridge heaters produces the vapor that is supplied to the condensation chamber through braided stainless steel tubing wrapped in a rope heater (Briskheat model HSTAT101006) to prevent vapor from condensing in the tube.

Non-condensable gasses are removed from the condensation chamber and boiler before each experiment using a vacuum pump (Welch-Ilmvac Dryfast Ultra 2042). The deionized water to be used in each experiment is held in a soft silicone bladder connected to the boiler while the non-condensable gasses are evacuated.

Cold water is supplied and circulated through a channel plate affixed to the bottom of the measurement head by a lab chiller (Neslab Endocal refrigerated circulating bath RTE-4) to extract heat from the condensation chamber through the test surface attached to the top of the measurement head and thereby promoting condensation on the test surface.

A high speed camera (Kodak Motioncorder model 1000) is used to capture imagery of the condensation process.

Measurement Head and Data Reduction

The measurement head is an aluminum conductor insulated with hard PTFE to insure 1-D conduction through the aluminum. A series of three k-type thermocouples embedded into the center of the aluminum conductor in a portion with a constant cross section (25 mm square) allows the measurement of a temperature gradient that can be used to calculate heat flux and surface temperature. The end of the aluminum conductor that extends outside of the condensation chamber is attached to a channel plate and is cooled by chilled water flowing through the channels. This extracts heat from the opposite end of the conductor, inside the condensation chamber upon which the test surfaces are adhered with Dow Corning TC-5622 thermal grease, lowering the surface temperature and promoting condensation. The data collected from the series of thermocouples is used to deduce the heat flux, extrapolate test surface temperatures and calculate heat transfer coefficients. Figure 3 shows a cut away image of the measurement head containing thermocouple placement detail.

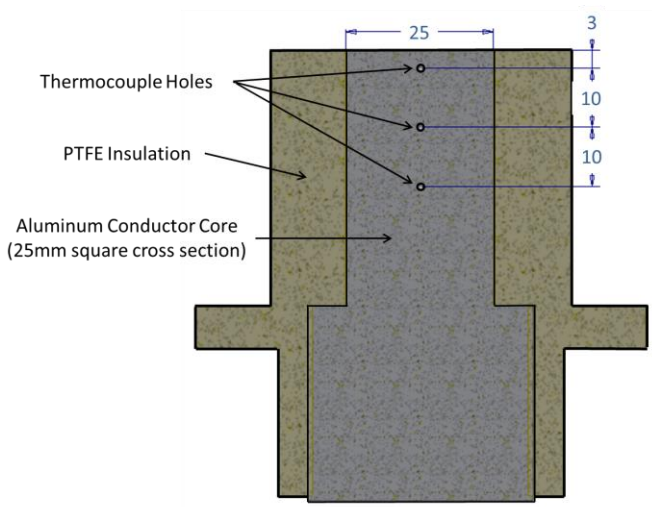


FIGURE 3: CAD HALF SECTION VIEW OF MEASUREMENT HEAD. DIMENSIONS IN MM.

The temperature distribution in the aluminum conductor is calculated by inputting the temperature measured by the thermocouples and their distances from the top surface of the measurement head into a built-in-function of LabVIEW that applies a least squares fit to generate a second order polynomial temperature distribution equation for each data collection iteration during an experiment. The temperature distribution equations can then be used to calculate the heat flux (and temperature) at the top of the aluminum block (x=0) by taking the derivative of the equation and applying Fourier's Law.

To calculate the heat transfer coefficient, the surface temperature must first be calculated. This is done by assuming 1-D steady state conduction through the thermal grease and test surface and calculating the thermal resistance. Thermal resistance values are impossible to calculate without knowing the thickness of the material imposing the resistance. Because there are no reliable method of measuring the thickness of the thermal grease between the test surface and the measurement head, a surface mount thermistor was used to measure the surface temperature under controlled conditions to determine the average thermal resistance of the thermal grease and test surfaces. The calculations are performed as follows:

$$\Delta T = (T_{Test} - T_{AL}) = q \times R$$

$$T_{Test} = q \times R + T_{AL} \tag{4}$$

Where T_{Test} is the temperature of the test surface, T_{AL} is the temperature of the aluminum block at x=0, q is the heat flux and R is the thermal resistance.

For the half-cylinder test sections the surface temperature actually varies with the distance from the surface to the top of the measurement head. An average resistance value was calculated by using a quasi-average surface temperature. This temperature was measured by placing the thermistor on a specific height on the curved surface that was determined to be where the local surface temperature would equal the quasi-average surface temperature. This height chosen was the average thickness of the half-round test surfaces or 0.39 in. A jig was made to hold the thermistor at this height on the half round test surfaces during experimental runs. Figure 4 shows how this value was determined.

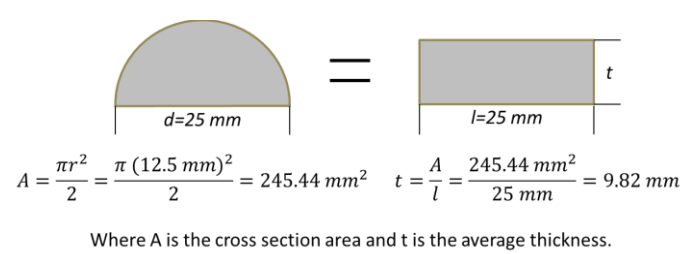


FIGURE 4: HALF-CYLINDER AVERAGE THICKNESS DETERMINATION

The reason the thermistor values aren't used to calculate heat transfer coefficients is that during an experiment when

the condensation chamber is filled with hot vapor the thermistor outputs a temperature somewhere between the test surface temperature and the vapor temperature.

Once the heat flux and the surface temperature are calculated, the heat transfer coefficient is calculated using Newton's Law of cooling.

Experimental Procedure

The surface to be tested is adhered to the exposed top surface of the measurement head's aluminum core using Dow Corning TC-5622 thermal grease. The condensation chamber and boiler are then closed with the ball valve between them left open. The ball valve between the boiler and the silicone bladder is closed and 1000 mL. of deionized water is poured into the silicone bladder and excess air in the tube connecting the bladder to the boiler and the bladder itself is removed before sealing the bladder.

Non-condensable gasses are evacuated from the boiler and condensation chamber and the ball valve between them is closed. The valve between the boiler and silicone bladder is then opened drawing the deionized water into the boiler, once all the water has entered the boiler the valve between it and the bladder is again closed and the heaters are turned on.

Chilled water is allowed to flow to the measurement head and after the proper temperature is reached the valve between the boiler and condensation chamber is opened allowing vapor into the condensation chamber, data acquisition and video recording is started. After 20 minutes all systems are stopped. Each test surface was used for three experimental runs for an assessment of performance repeatability.

RESULTS AND DISCUSSION

As expected, the modified Repellix and Repellix 2.0 coatings greatly decreased the wettability of the test surfaces to which they were applied. As shown in Figure 5, the bare surfaces exhibited condensate films or large irregularly shaped droplets, while the Repellix coated surfaces were covered with smaller, more spherical droplets.

The spherical shape indicates that they have relatively low contact angle hysteresis and are in a Cassie-Baxter state. Repellix 2.0 coated surfaces tended to have a smaller droplet size and more regular spherical droplet perimeters than the surfaces coated with modified Repellix. As seen in Figure 5, the bare flat 304 stainless steel surfaces also produced discrete round droplets meaning that the surface had a lower wettability than bare surfaces of different materials. This is because of the fine surface finish on the material used to fabricate these surfaces. The application of modified Repellix and Repellix 2.0 coatings did still reduce wettability on the flat 304 stainless surfaces. For the same conditions, high droplet densities (number of droplets per unit area) indicate a more hydrophobic or less wettable surface. Since all flat 304 stainless steel test surfaces have the same surface area, the number of droplets present after 5, 10 and 15 minutes of condensation activity were compared. The comparison chart in Figure 6 clearly shows that the Repellix 2.0 coated surface produced the largest number of droplets and is therefore the most hydrophobic of the three surface treatments.

It stands to reason to expect that the surfaces coated with the most hydrophobic coating (Repellix 2.0) would exhibit better heat transfer performance than the bare or even modified Repellix coated surfaces because hydrophobic condensing surfaces promote dropwise condensation which can be a 10 times more effective heat transfer mechanism than filmwise condensation. However, for every half cylinder test specimen material except titanium, the Repellix 2.0 coated specimens produced the lowest heat transfer coefficients and the bare surfaces produced the highest heat transfer coefficients for a given material. Table 4 contains maximum heat transfer coefficient values (average of three runs) for all tube material test surfaces.

TABLE 4: MAXIMUM HEAT TRANSFER COEFFICIENT VALUES FOR TUBE MATERIAL TEST SURFACES

Material	Heat Transfer Coefficient (W/m^2K)		
	Bare	Modified Repellix	Repellix 2.0
Admiralty Brass	808.2	399.1	323.4
Cupronickel	675.4	550.6	306.5
Titanium	218.1	1646.8	2046.9
SEA CURE	2423.4	1893.0	464.1

To make sense of this somewhat surprising result, it must be understood that in order to realize the heat transfer performance improvements that are possible for dropwise condensing systems, the drops must move and sweep other drops off of the surface creating freshly cleared areas on the condensing surface. If the droplets are stationary, they create a local thermal resistance that can be larger than that of a film because drops on a hydrophobic surface tend to have heights greater than the thickness of a film on a corresponding hydrophilic surface under the same conditions. Figure 7 shows a comparison of the average number of roll-off events for modified Repellix and Repellix 2.0 coated tube material. A roll-off event was defined as an instance when a droplet was removed from the surface by gravity.

Often these droplets will remove other droplets in their path on their way off of the surface. The information shown reveals that the titanium was the only material to have a heat transfer improvement with the Repellix 2.0 coating since it had a large number of roll-off events. SEA-CURE had the next highest number of events and also has the second highest heat transfer coefficient values for the Repellix 2.0 coated surfaces. The trend also holds for the Repellix 2.0 coated Admiralty brass and Cupronickel surfaces.

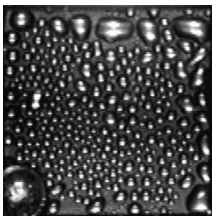
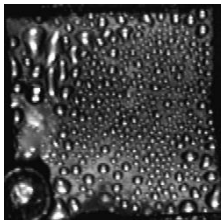
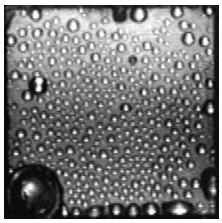
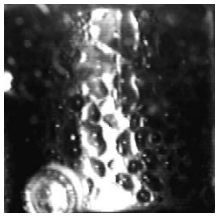
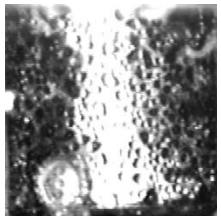
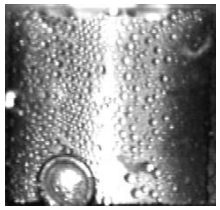
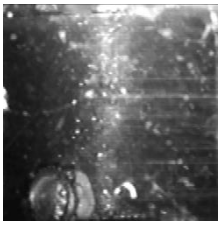
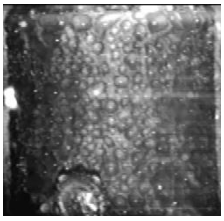
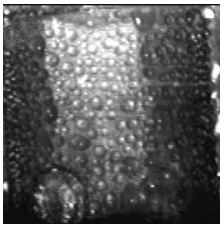
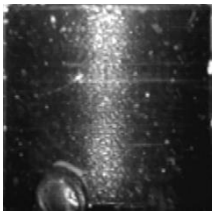
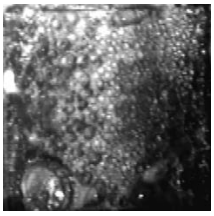
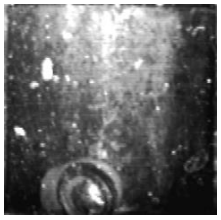
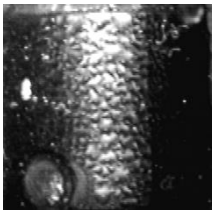
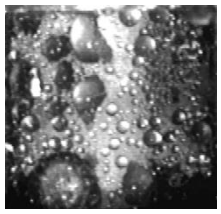
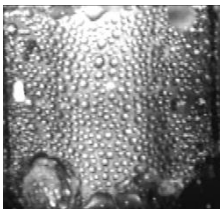
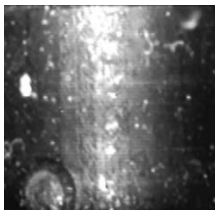
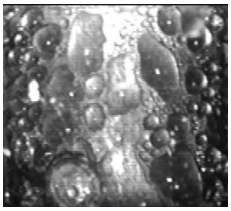
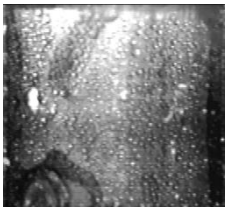
Material	Bare	Modified Repellix	Repellix 2.0
Flat 304			
Round 304			
Admiralty brass			
Cupronickel			
Titanium			
SEA-CURE			

FIGURE 5: COMPARISON IMAGES OF BARE SURFACES, MODIFIED REPELLIX COATED SURFACES AND REPELLIX 2.0 COATED SURFACES TAKEN AFTER 10 MINUTES OF CONDENSATION ACTIVITY.

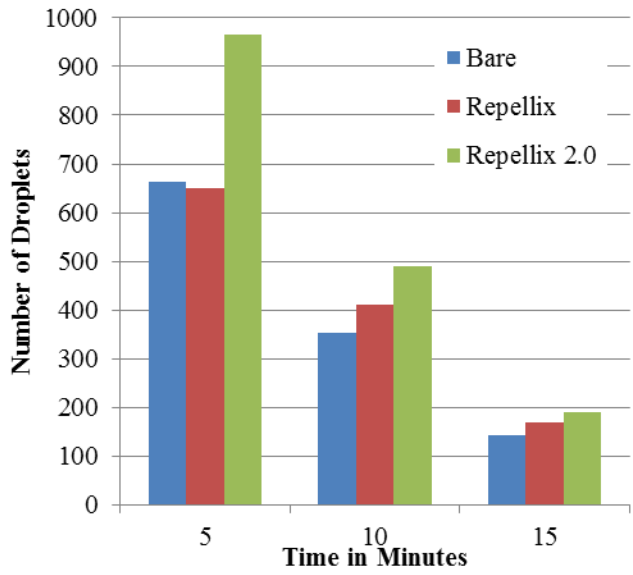


FIGURE 6: COMPARISON OF DROPLETS PRESENT ON FLAT 304 STAINLESS STEEL SURFACES AFTER 5, 10, AND 15 MINUTES OF CONDENSATION ACTIVITY

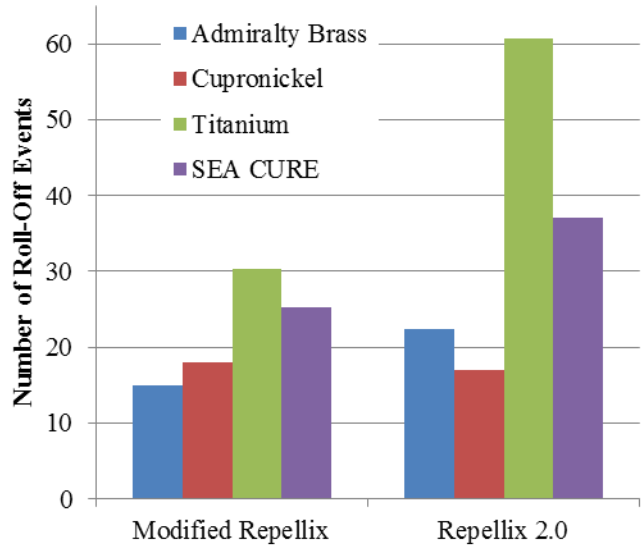


FIGURE 7: AVERAGE NUMBER OF ROLL-OFF EVENTS FOR EACH MODIFIED REPELLIX AND REPELLIX 2.0 COATED TUBE MATERIAL

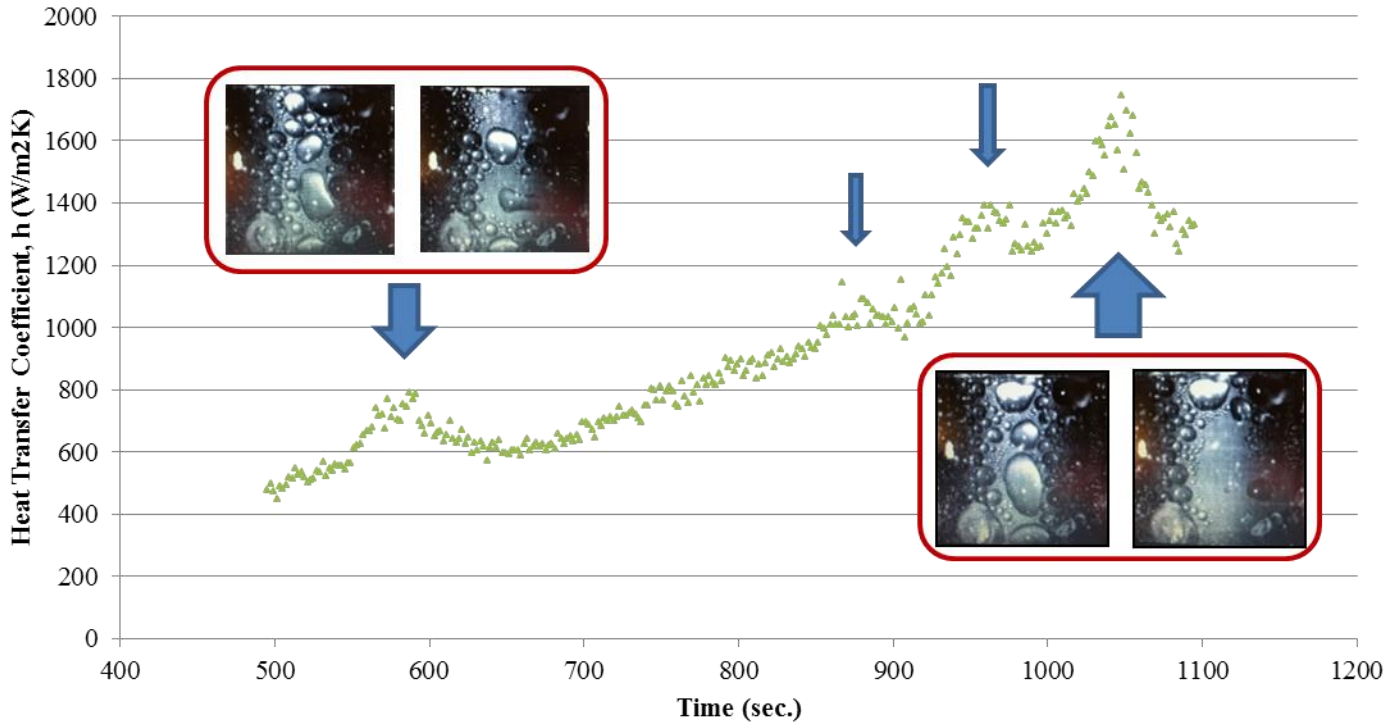


FIGURE 8: HEAT TRANSFER COEFFICIENT SPIKES ON REPELLIX 2.0 COATED TITANIUM TEST SURFACE. ARROWS INDICATE HEAT TRANSFER COEFFICIENT SPIKE AFTER ROLL-OFF EVENT. TWO INSETS SHOW THE SURFACE BEFORE AND AFTER ROLL-OFF EVENT.

As stated earlier, these roll-off events drive the increased heat transfer coefficient values that can be achieved in dropwise condensation. The heat transfer on the cleared surface left behind by an event is uninhibited by any additional thermal resistance imposed by condensate films or stationary drops. Without roll-off events, superhydrophobic dropwise condensing surfaces do not offer improved heat transfer performance. Figure 8 illustrates the heat transfer performance gains achieved by the Repellix 2.0 coated Titanium surfaces which produced a high number of roll-off events.

It is anticipated the normal operating environment of a power-plant condenser with flowing condensing steam and machinery vibrations will inherently provide plenty of impetus for droplet mobility. Testing in an actual situation incorporating flowing vapor would is an obvious next step.

CONCLUSION

Customized nano-composite superhydrophobic coatings were successfully developed and applied to test surfaces. Their effect on the heat transfer performance of test surfaces constructed of various materials was recorded and identified. Surfaces tested included two stainless steel 304 surfaces used for benchmarking, and four tube samples provided by Southern Company; admiralty brass, cupronickel, SEA-CURE and titanium. While the surfaces tested did meet goals related to robustness and retention of hydrophobic properties, additional effort is clearly needed to promote droplet mobility. Although the mobility issue would appear to be largely addressable by actual process conditions wherein the flow of condensing vapor and machinery vibration would provide enough of a driver to cause droplet motion.

Progress in using surface modifications to enhance thermal performance needs to include methods to increase the robustness of coatings, methods to provide scaled-up rapid re-application of the coatings during planned plant outages, and improvements in the mobility of condensing droplets. Surfaces studied in the literature that promote droplet mobility require complex fabrication sequences that are not feasible for scale-up to mass production. Further studies need to address the need for fabrication simplicity while promoting mobility and coating robustness. A good next step would be to test the performance of these coatings applied in-situ on actual working condenser tubes in an environment that more closely mimics that of a condenser in a power plant.

ACKNOWLEDGMENT

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