Technoeconomic Benefits of Film-Forming Amine Products Applied to Steam Surface Condensers

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ABSTRACT

In a conventional Rankine cycle, the majority of power plants employ surface condensers that use pumped cooling water to reject heat from the cycle. In such cases, heat rejection occurs in a shell and tube heat exchanger by filmwise condensation of low-pressure steam on stainless steel, titanium, brass, or copper-nickel tubing. To improve the thermal performance of steam surface condensers, a replenishable film-forming substance (FFS) can be applied to the condenser tubing to promote efficient dropwise condensation. Conventionally, film-forming amine product (FFAP) coatings protect boiler surfaces from oxidative corrosion, which substantially reduces the operation and maintenance costs. To quantify the technical and economic benefits of FFAP coatings applied to condenser tubing due to the promotion of dropwise condensation, a thermal resistance network model was established. Using a representative steam surface condenser, the improvements in thermal performance (overall heat transfer coefficient) and process parameters (net plant efficiency, cooling water flowrate, and turbine backpressure) were determined due to the enhancement in the condensation heat transfer coefficient. Experimentally measured condensation heat transfer coefficients for common condenser materials were compared with the modeling results and were found to be within attainable bounds. Finally, the trend in total heat exchanger cost reduction is generalized to understand the trade-off between reduced surface area for heat rejection and increase in coating application costs for a replenishable coating system.

NOMENCLATURE

A	area [m^2]
a	amortization factor
C	cost
D	diameter [m]
$E()$	enhancement ratio
h	local heat transfer coefficient [W·(m^2·K)$^{-1}$]
ΔP	pressure drop [mbar]
s	fouling factor
n	number of
Q	heat transfer rate [W]
TTD	terminal temperature difference
U	overall heat transfer coefficient [W·(m^2·K)$^{-1}$]
V	volumetric flowrate [L·s^{-1}]

Greek Symbols

δ	thickness [m]

Subscripts

cap	capital
c	condensation
cw	cooling water
e	energy
g	gas
hx	heat exchanger
i	inner
m	maintenance
o	outer, outlet
p	passes
t	tubes, tubing
w	wall

INTRODUCTION

The power engineering industry utilizes protective water chemistry in steam-water cycle and boiler systems to mitigate corrosion [1,2]. With proper implementation, the reduction in iron transport results in less frequent plant shutdowns and lower maintenance costs to replace process equipment [3]. Polyamine chemistry or film-forming amines (FFA) are the family of coatings used, which spontaneously form a molecular layer thick polymer chain with a low surface energy end group [4]. One functional group, called the "head," is an amine 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 ultra-low surface energy. An example of a generic FFA coating applied to a metallic substrate is shown in Figure 1. Research in this field has investigated the phase distribution of polyamines in the vapor and liquid phases [5], corrosion inhibition life testing on different metallurgies [6], unique polyamine chemistries to enhance corrosion inhibition properties [7], and the kinetics of mass loss at different temperatures, FFA chemistries, and metallurgies [8,9]. While this application is entrenched in the power engineering industry, corrosion research continues to investigate "green" and long-life chemistries to further reduce plant capital and operating costs.

Traditionally, polyamines have been applied to the steam-water cycle and boiler sections of power plant systems to mitigate corrosion of alloys [10]. The corrosion protection benefits of film-forming amine product (FFAP) coatings is demonstrated in Figure 2. Untreated low carbon steel (C1010) exhibits minimal resistance to corrosion over time when exposed to an aerobic sodium chloride solution near room temperature. The corrosion rate on untreated carbon steel steadily increases over time, leading to irreparable damage to the metal tubing. For the same conditions, a low carbon steel coupon treated with a FFAP limits the corrosion rate and protects the metal surface. The FFAP forms a hydrophobic film (i.e. monolayer), which acts as a protective barrier between the bare metal surface and corrosive medium [11].

Several case studies have shown that the use of a FFAP is effective as a corrosion inhibitor in both industrial and utility steam generators. Robinson et al. [12] report the polyamine/FFAP field trail case study conducted at an 850MW gas turbine combined-cycle plant. Prior to feeding polyamine, the plant was on ammonia (NH_3)/ethanolamine (ETA) treatment and was struggling to reduce corrosion and iron transport during both cycling and continuous operation. With a polyamine treatment program, the plant observed a 10- to 100-fold reduction in iron transport across all units during both continuous operation and in start-up conditions. This reduction in iron transport is credited to the corrosion inhibition effect of the polyamine treatment. Plant start-up results of this study are shown in Figure 3. In addition, the use of polyamine treatment, within an all-volatile treatment (AVT) program, has been reported to protect air-cooled condensers (ACC) with carbon steel tubing against corrosion at coal-fired power plants [13]. Typical concerns with ACCs at power plants using traditional AVT

Film-Forming Amine Composition

$R1\text{-}[NH\text{-}(R2)\text{-}]_n\text{-}NH_2$

n is a whole number between 0 and 7

R1 is an unbranched alkyl chain with 12–18 carbon atoms

R2 is a short-chain alkyl group with 1–4 carbon atoms

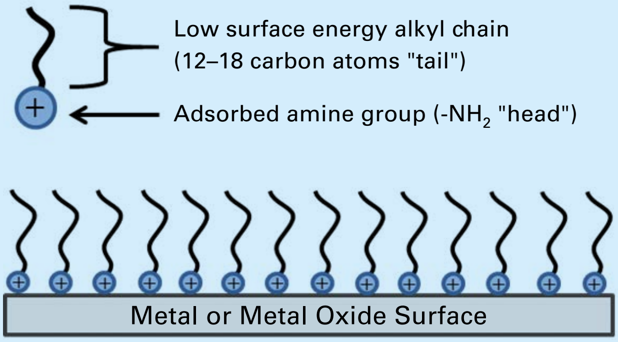

Figure 1:
Film-forming amine coatings deposited on a metal or metal oxide surface.

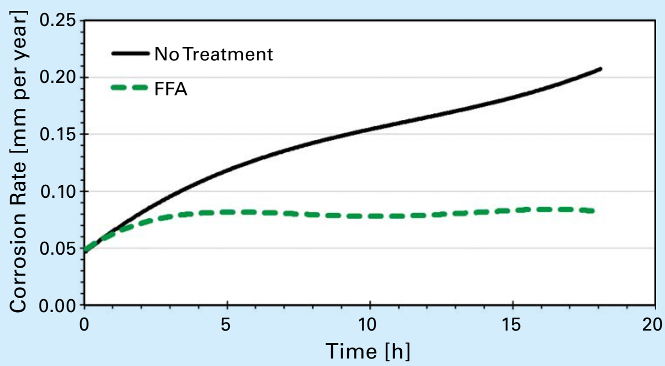

Figure 2:
Corrosion protection behavior of a FFAP treatment on mild carbon steel. The corrosive medium is an oxygen saturated (7–10 $mg \cdot L^{-1}$ O_2) and 200 $mg \cdot L^{-1}$ NaCl solution with a pH = 9.5 (adjusted with NaOH) at temperature = 22 °C ± 1. The FFAP treatment used is a common blend produced by Suez (3 $mg \cdot L^{-1}$ active FFAP). Results were obtained by employing the non-destructive electrochemical measurement technique, Rp/Ec trend.

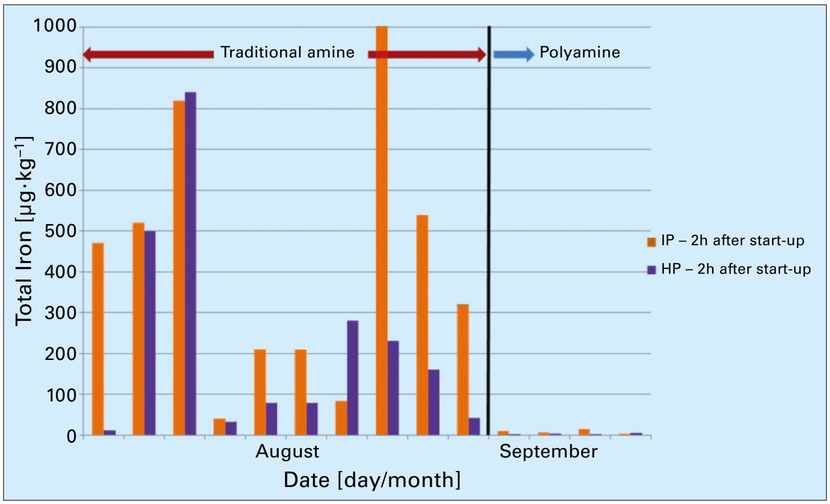

Figure 3:
Reduction in iron concentration in the intermediate-pressure (IP) and high-pressure (HP) sections of the HRSG unit of an 850MW combined-cycle plant due to polyamine treatment. There was a 10- to 100-fold reduction in iron transport during continuous steady-state operation and start-ups, respectively (data not shown) [12].

(e.g. NH_3) include flow-accelerated corrosion (FAC) during continuous operation along with minimal wet and dry lay-up corrosion protection, which results in an increased iron transport during start-ups. With a polyamine program, these issues are reported to be mitigated as the cumulative iron corrosion product transport is reduced in boiler feedwater and condensate systems during cold start [13]. Hydrophobic surfaces are also observed in the boiler/steam system, including on the air-cooled condenser. These case studies, among others [14,15], are evidence that FFAP treatments not only provide protection during continuous operation but also can improve downtime protection, providing a practical means to enable thermal energy storage for flexible operation. With polyamine treatment, plants can extend equipment inspections and replacement, increase the intervals between chemical cleanings, and may avoid unexpected failures and shutdowns, thereby making power plants more reliable and cost-effective to operate.

An additional benefit of FFAPs is that blends can be tailored to be non-wetting (i.e. hydrophobic), which can promote efficient dropwise condensation (DWC) on condenser surfaces. New studies have emerged to determine the thermal performance benefits of FFSs applied to power plant steam surface condensers [16,17]. The DWC phenomenon occurs when the critical surface energy is appreciably lower than the surface tension of the surrounding fluid, generating a finite wetting angle and low contact angle hysteresis. This mode of condensation can result in local heat transfer coefficients as much as 5 to 20 times higher than traditional filmwise condensation (FWC) [18]. Since the earliest published work in 1930, DWC heat transfer coefficients that are an order of magnitude higher than FWC have been reported when tested at comparable conditions [19]. Although there are a multitude of different coating mechanisms to generate DWC, many issues remain in creating a long-life coating for industrial use [20]. FFAPs maintain the hydrophobicity of a condenser surface for long life due to oxidative corrosion protection and "self-heal" due to direct injection of additional coating on the protected metal surfaces. A detailed configuration of this mechanism is shown in Figure 4. Besides additional experimental work to validate the thermal performance results observed using FFAPs applied to condenser tubing, the technoeconomic benefits have yet to be fully realized within the context of the entire condenser thermal resistance network. While the cooling water-side thermal resistance dominates compared to the steam-side and wall thermal resistances, appreciable improvement in the condensation heat transfer coefficient leads to considerable improvement to the overall thermal performance and plant process parameters. The extent of this improvement dictates the economic value of using FFAPs to promote DWC in a representative steam surface condenser.

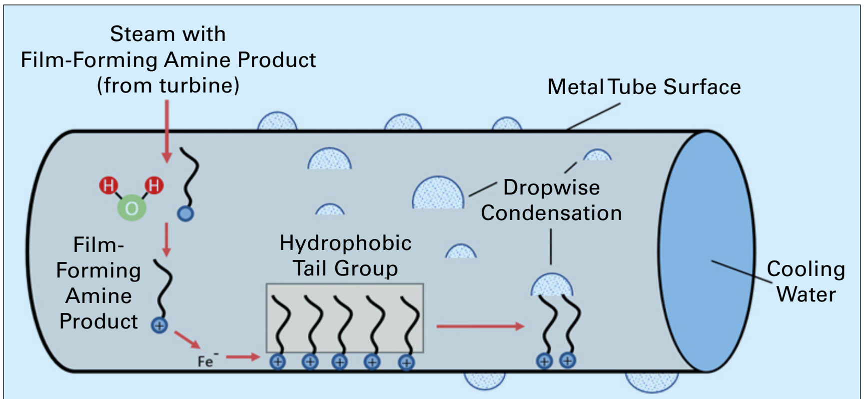

Figure 4:
Detailed configuration of FFAP coating applied to a steam surface condenser tube.

This study specifically investigates the technoeconomic benefits of FFAPs applied to water-cooled steam surface condensers. A thermal resistance network model is established using representative steam surface condenser operational and physical parameters. Using the enhancement in the condensation heat transfer coefficient, the improvement in the thermal performance (overall heat transfer coefficient) and process parameters, such as net plant efficiency, cooling water flowrate, and turbine backpressure, is determined. Experimentally measured DWC heat transfer coefficients for common condenser materials are included with the modeling results to demonstrate the potential improvements in these parameters and are found to be within attainable bounds. Finally, as a potential cost improvement to the design and operation of surface condensers, the reduction in capital cost by reducing the tubing surface area required must not be exceeded by the cost of materials and application of the coating system [21]. To understand this trade-off, the trend in total heat exchanger cost reduction is generalized based on the reduced surface area for heat rejection and increase in coating application costs.

THERMAL RESISTANCE NETWORK MODEL

To determine the thermal performance improvement of a steam surface condenser due to the transition from filmwise to dropwise condensation, a thermal resistance network model is established. This improvement is explicitly due to the enhancement in the condensation heat transfer coefficient, h_c. This model specifically simulates the change in the heat exchanger thermal performance within the context of the entire thermal resistance network. This analytical model begins with the temperature of saturated steam, transitions to an outer and inner tube wall temperature, and ends with the average cooling water temperature through the tube. The proposed thermal resistance network model is visualized in Figure 5, which is in a serial configuration. The three thermal resistance values to account for are: R_c (condensation), R_w (wall), and R_i (internal). Although the condensation resistance is not the most dominant thermal resistance term, its relative decrease in value due to the dropwise mode of condensation is examined to reveal the overall thermal performance benefits of using self-healing and non-wetting coatings. To determine these resistance terms, first the heat transfer rate, Q, is defined as shown in Eq.(1):

$$Q = UA_o \Delta T_{LM} \quad (1)$$

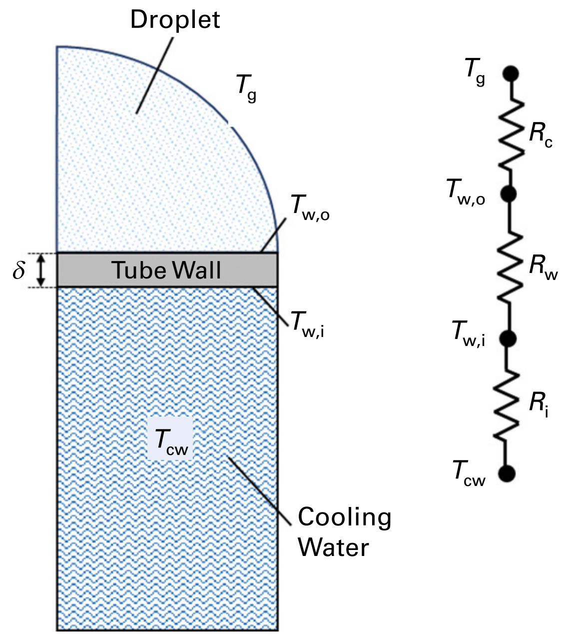

Figure 5:
1-dimensional representation of the demonstrated thermal resistance network model for saturated steam, T_g, condensing on a portion of the tube wall on the shell-side, with heat removal due to cooling water, T_{cw}, on the tube-side.

where U is the overall heat transfer coefficient, A_o is the outer surface area of the condenser tubing, and ΔT_{LM}, is the logarithmic mean of the temperature difference between the vapor and cooling water inlet and outlet streams.

The heat transfer rate, Q, is equivalent to the heat removal rate that the steam surface condenser is designed for based on geometrical and operational parameters. Using conventional analysis, the overall heat transfer coefficient, U, can be determined using the aforementioned resistance network and is defined as:

$$U = \left(\frac{1}{h_c} + \frac{A_o \ln\left(\frac{D_o}{D_i}\right)}{2\pi k_t L_t n_t n_p} + \frac{A_o}{A_i h_i}\right)^{-1} \quad (2)$$

R_i is determined using the Gnielinski correlation [22], R_w is determined using geometrically defined values, and Rc changes experimentally depending on the mode of condensation.

Table 1 defines the numerical values used for several constants in Eq. (2). These choices are based on conventional steam surface condenser tube sizes, materials, and geometrical dimensions [23]. U is an indicator of the overall thermal performance of the steam surface condenser and its relative improvement is critical to understanding the value of non-wetting coatings.

Parameter	Value
T_g	38.3°C
V_{cw}	14.124 L·s^{-1}
Approach temperature	11.1°C
Tube material	Stainless Steel 304L or titanium
D_o	2.857 cm
δ	0.0794 cm
L_t	4.572 m
n_t	7000
n_p	2
A_o	5746 m^2
A_i	5427 m^2
k_t	17 W·(m·K)$^{-1}$
D_i	2.699 cm

Table 1:
Assumed constants for thermal resistance network model [23].

The algorithm used to determine the change in thermal performance of the steam surface condenser due to the change in the mode of condensation is defined as follows. First, each thermal resistance in the network and consequently, U, is calculated using Eq. (2) along with the parameters defined in Table 1. Then, the heat transfer rate, Q, is determined using Eq. (1). Assuming an equivalent heat transfer rate for each mode of condensation, an enhanced value of h_c is used to recalculate U for the dropwise mode of condensation. Finally, a new logarithmic mean temperature difference, ΔT_{LM}, is found using this new value for U with the original heat transfer rate, Q, and outer surface area, A_o. This recalculated logarithmic mean temperature difference relates to a smaller degree of subcooling during the dropwise mode of condensation. To delineate the improvement in the thermal performance of the steam surface condenser, an enhancement ratio, $E(h_c)$, is used. This enhancement ratio is the ratio of the value of the condensation heat transfer coefficient during DWC to its value during FWC and is defined as:

$$E(h_c) = \left(\frac{h_{c,DWC}}{h_{c,FWC}}\right) \tag{3}$$

U can be compared against the improvement in h_c to provide context to the improvement in the entire thermal resistance network due to the enhanced dropwise mode of condensation.

To then relate this improvement to relevant plant parameters, NETL's case study on steam surface condenser metrics is used [23], along with the change in the saturated pressure of steam (or turbine backpressure). This case study uses the terminal temperature difference (TTD), which is the difference in the vapor temperature, T_g, and the outlet cooling water temperature, $T_{cw,o}$, to infer changes in the net plant efficiency and cooling water consumption rate. The TTD is defined in Eq. (4) as:

$$TTD = T_g - T_{cw,o} \tag{4}$$

In the transition from filmwise to dropwise condensation, the TTD improves due to the reduction in condenser subcooling. In the proposed thermal resistance network model, the calculation of the improved ΔT_{LM} also necessitates a calculation of an increased outlet cooling water temperature with the improved h_c. With the improved TTD determined, a higher net system plant efficiency and reduced water consumption rate is found using NETL's model. This same reduction in subcooling leads to an appreciable reduction in backpressure on the turbine. This decrease in pressure drop is found using the change in the saturated pressure of steam at the condenser tube wall. Specifically, this can be used by the power plant user to gauge how their own system would improve in power produced based on turbine backpressure reduction, leading to real energy cost savings.

PLANT PERFORMANCE RESULTS

The thermal performance results are interpreted in two distinct ways to relate to comparable steam surface condenser systems. In Figure 6, the enhancement in U is determined as a function of the enhancement in h_c due to the promotion of DWC by the FFAP coating. The curves represent the modeling results, while the data points are the experimental enhancements in h_c for each condenser material found at 101 °C [16] and the expected enhancement in U based on the model. In other words, the discrete data is the experimental results for $E(h_c)$ and the potential for $E(U)$ using the thermal resistance network model. The materials used experimentally are copper 101, low carbon steel, and stainless steel 304L. Copper is commonly used as a baseline performance for various self-assembled monolayers, carbon steel is of interest as a low-cost tubing alternative to stainless steel, and stainless steel is commonly used as a surface condenser tubing option. The reduction in h_c for low thermal conductivity materials is due to constriction resistance, where high coverage of large departing droplets dominates for low thermal conductivity materials [24]. Each curve is represented by a different initial value of the FWC heat transfer coefficient ($h_{c,FWC}$) to demonstrate how the enhancement in U varies depending on the relative value of R_c. With the same enhancement in h_c, a smaller value for $h_{c,FWC}$ represents a greater enhancement in U since R_c is initially a more dominant term. This implies that a precise value for $h_{c,FWC}$ is required in order to fully interpret the thermal performance benefits of replenishable DWC. The superimposed experimental data reveals the realizable bounds of enhancement in U (15–120%) with experimentally achievable enhancement in h_c. Although the experimental values of h_c are not definitive for all condenser process conditions, they do represent the empirical maximum enhancement in h_c for each condenser material using FFAP coatings.

Conversely, in Figure 7, the enhancement in U as a function of the initial FWC heat transfer coefficient ($h_{c,FWC}$) is shown. The data is represented as such to quickly interpret the potential gain in U if the enhancement in h_c is known from experimental findings. Interpretation using this plot further reveals the influence of the initial value for R_c, as all the curves converge to a similar value in $E(U)$ with increasing $h_{c,FWC}$. A greater initial R_c value for FWC is less valuable for transition to replenishable DWC, which can be determined by the power plant engineer using Eqs. (1) and (2) rearranged to solve for $h_{c,FWC}$.

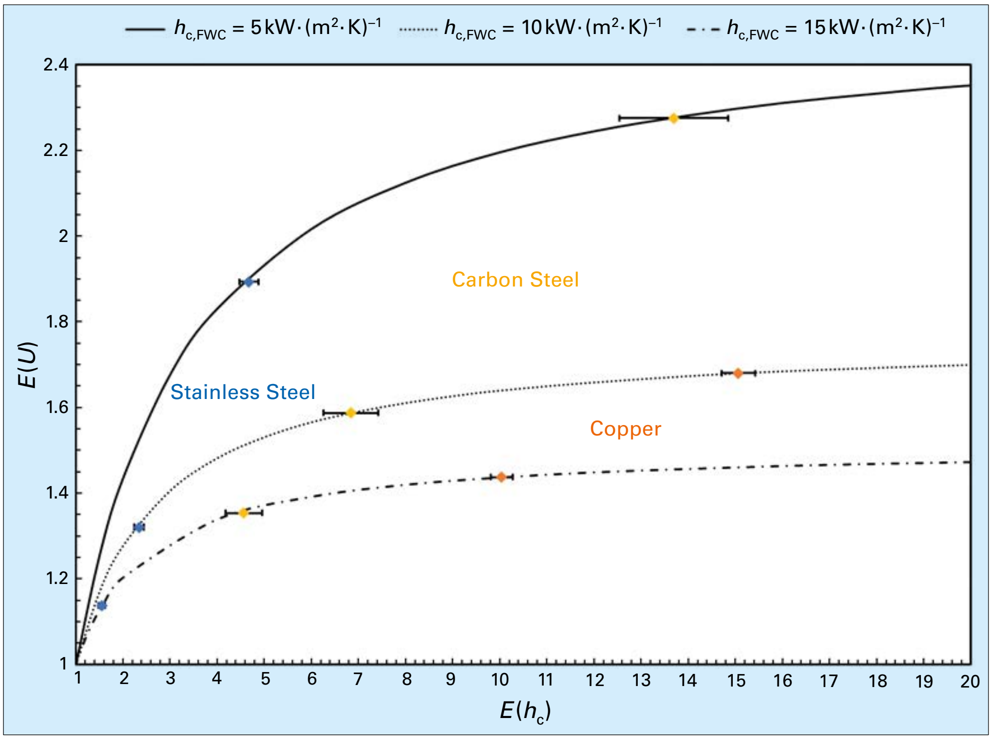

Figure 6:
Enhancement ratio of the overall heat transfer coefficient, U, as a function of the enhancement ratio of the condensation heat transfer coefficient, h_c. The data points represent the experimental enhancement of h_c superimposed on the results for the modeling curves. The font color for each condenser material corresponds with the accompanying data points of the same color.

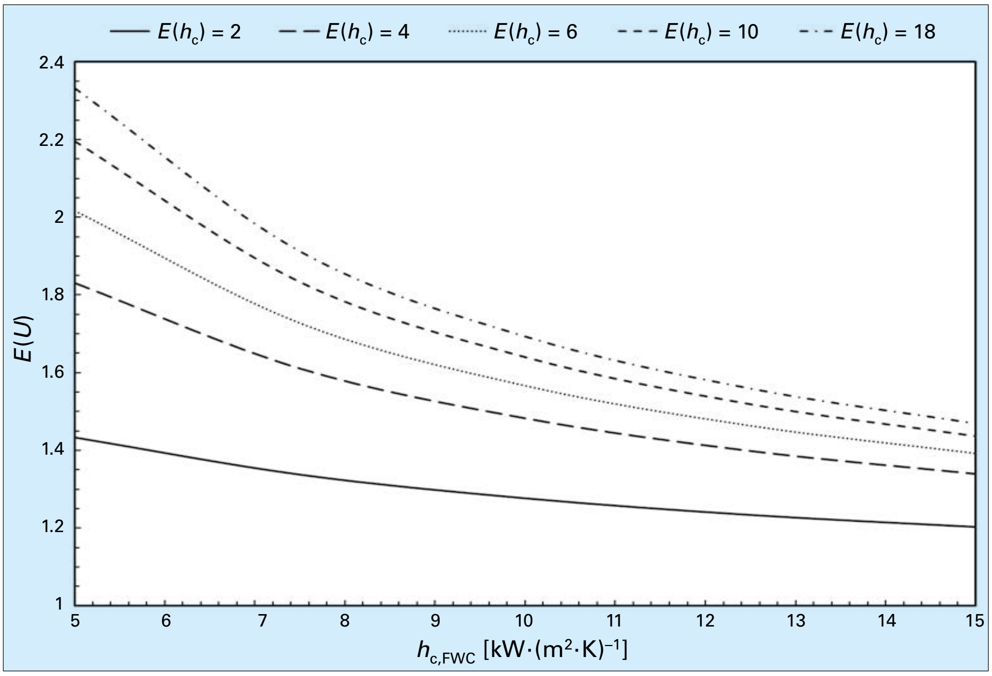

Figure 7:
Modeling results for the enhancement in the overall heat transfer coefficient, U, as a function of the filmwise condensation heat transfer coefficient, $h_{c,FWC}$. With a known experimental enhancement in h_c determined for a steam surface condenser, the range of improvement in U can be quickly determined as a function of $h_{c,FWC}$.

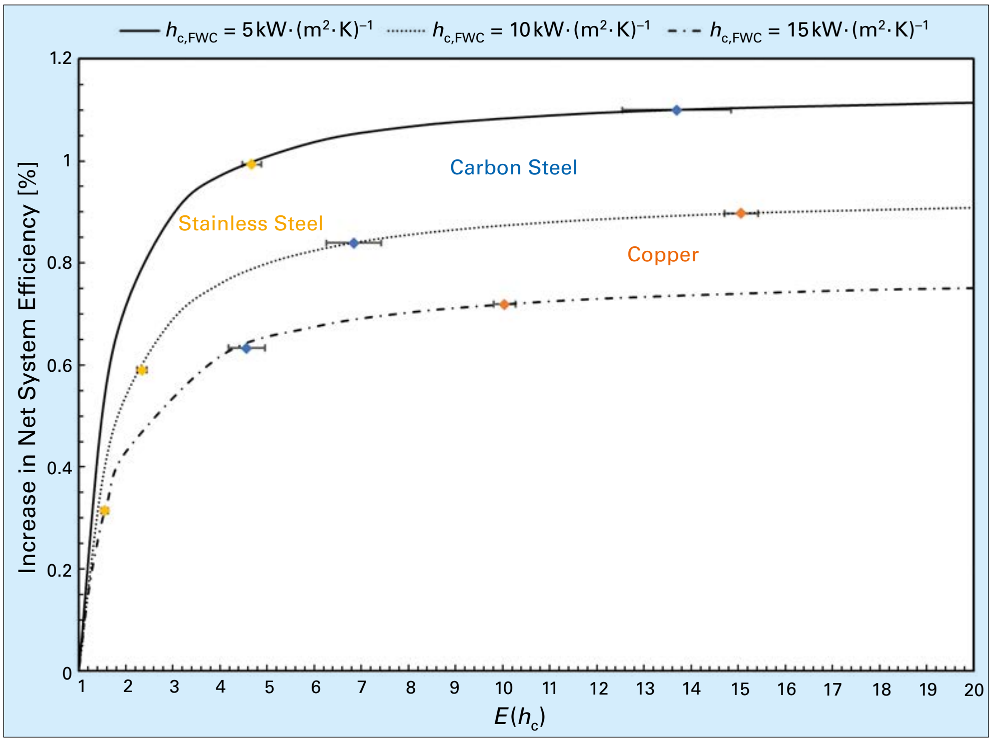

Figure 8:
Increase in net system efficiency as a function of the enhancement ratio of the condensation heat transfer coefficient. The font color for each condenser material corresponds with the accompanying data points of the same color.

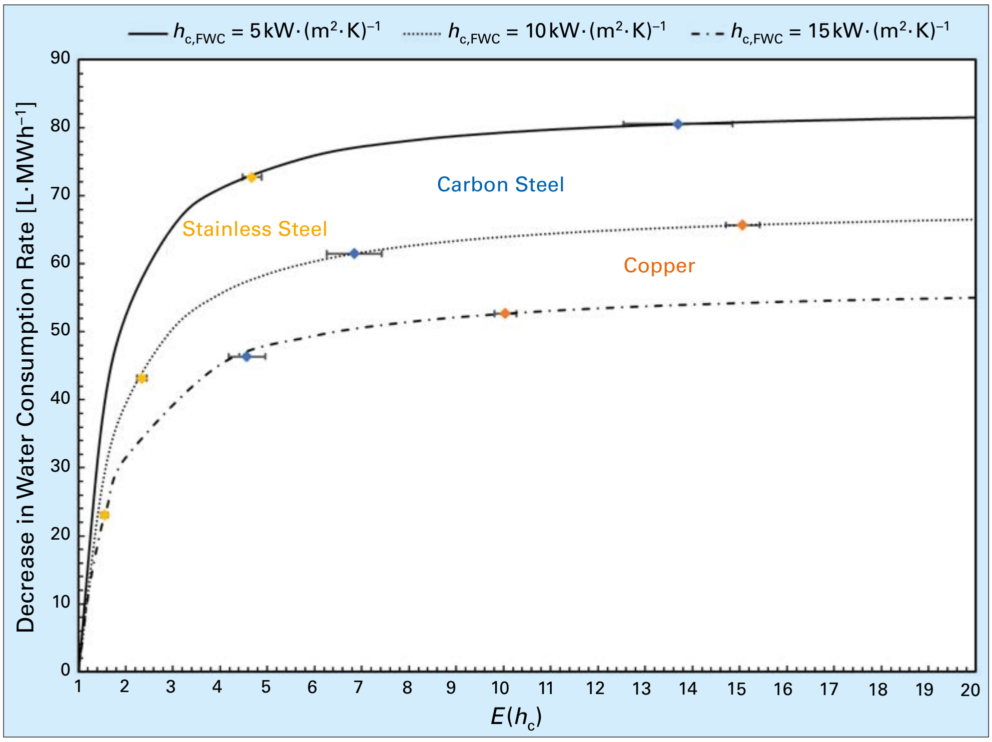

Figure 9:
Decrease in water consumption rate as a function of the enhancement ratio of the condensation heat transfer coefficient. The font color for each condenser material corresponds with the accompanying data points of the same color.

While the enhancement in U reveals the thermal performance benefits of DWC, the improvement in plant process parameters directly demonstrates the value for key performance indicators. To determine this improvement as outlined in Section 2, a model developed by NETL reveals the change in net system efficiency and water consumption as TTD changes for a representative coal-fired power plant [23]. The following figures are presented in the same manner as Figure 6 for relatability to the achievable experimental thermal performance enhancement in h_c. In Figure 8, the achievable increase in net system efficiency is between 0.3 and 1.1 %. The net system efficiency metric is defined for the entire plant energy use. In Figure 9, the achievable decrease in water consumption rate is between 22.7 and 79.5 L MWh^{-1}. The water consumption rate is defined as the cooling water usage rate on the tube-side of the steam surface condenser. Finally, in Figure 10, the decrease in turbine backpressure is determined using the change in the saturated pressure of steam at the condenser tube wall. The achievable decrease in turbine backpressure for this model is between 6.1 and 26.1 mbar. The introduction of replenishable FFS to the power plant steam-water cycle would lead to a measurable decrease in turbine backpressure for the power plant user to track and relate to energy cost savings on turbine operation. Ultimately, this reduction in turbine backpressure would allow additional power to be generated by the power plant with a smaller fuel penalty. These trends for key performance indicators can be used to relate to improvements in other power plants if the enhancement in h_c is known with promotion of DWC. All these findings are for the representative enhancement in h_c observed within the context of the aforementioned experimental results. The measurement of the initial performance ($h_{c,FWC}$) of the steam surface condenser will reveal the extent of improvement in these key performance indicators using replenishable DWC. Additionally, these benefits can be quantified as real cost savings for the power plant using a generic cost model.

HEAT EXCHANGER COST MODEL

To quantify the total cost reduction of a steam surface condenser within the context of the replenishable coating application costs, a heat exchanger cost model is proposed. This analysis is used to determine the economic benefits of replenishable DWC for a steam surface condenser with regard to overall performance and total cost. The goal of this exercise is to demonstrate the trend in total heat exchanger cost reduction, while taking into account the reduced

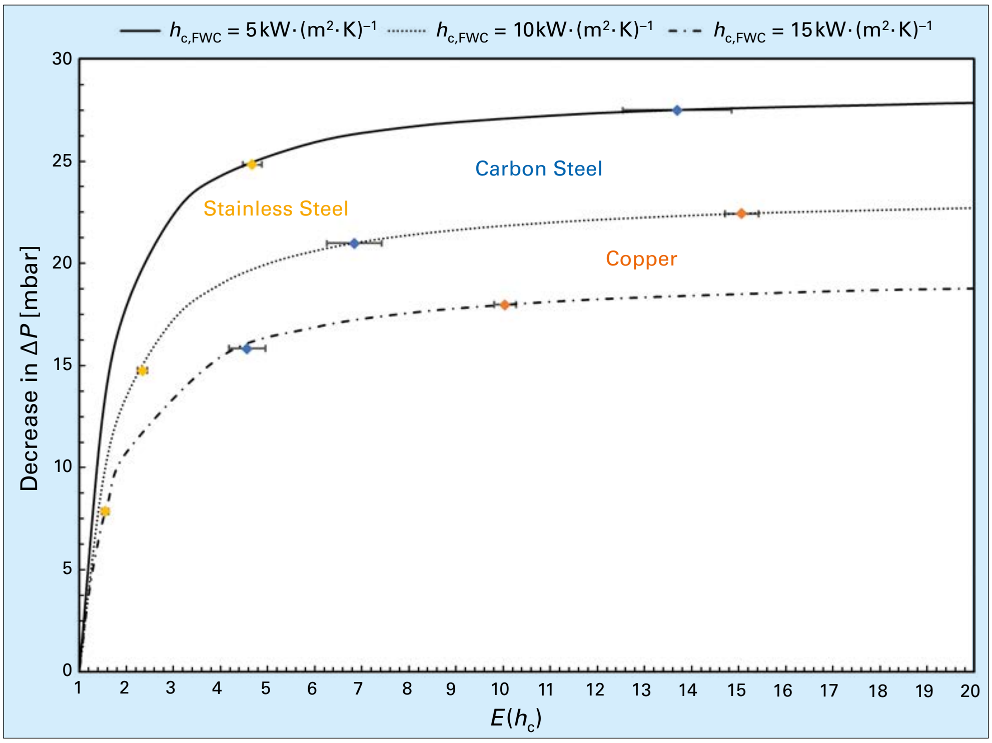

Figure 10:
Decrease in turbine backpressure as a function of the enhancement ratio of the condensation heat transfer coefficient. The font color for each condenser material corresponds with the accompanying data points of the same color.

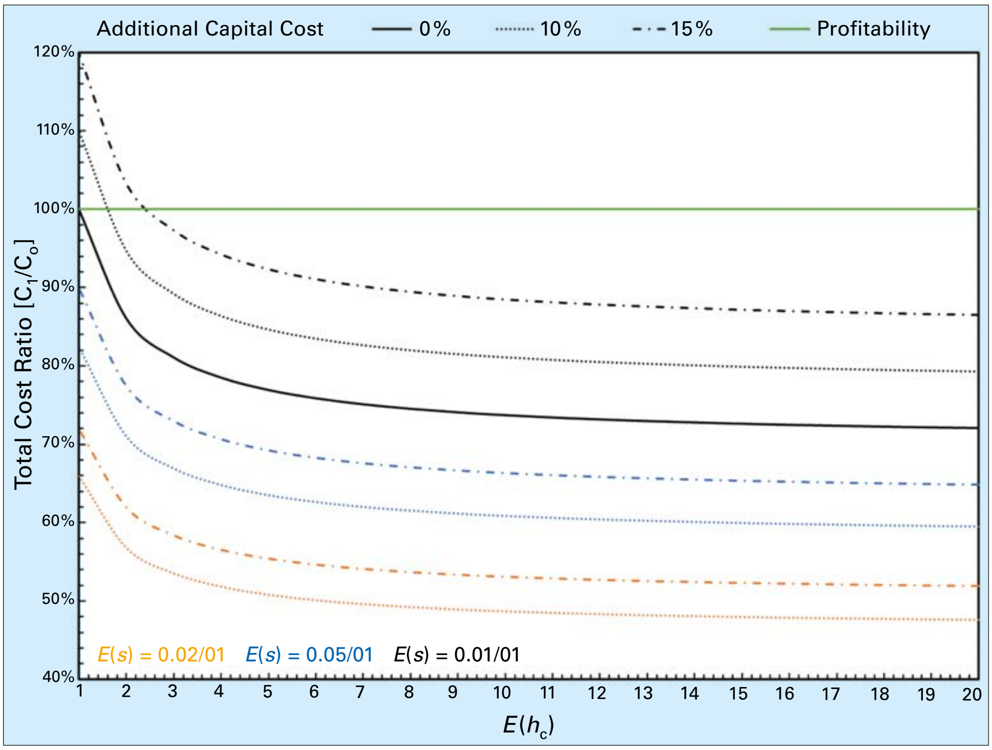

Figure 11:
The total cost ratio as a function of the enhancement of the condensation heat transfer coefficient for different maintenance cost ratios and additional capital cost requirements. Any value below the profitability line is a profitable scenario.

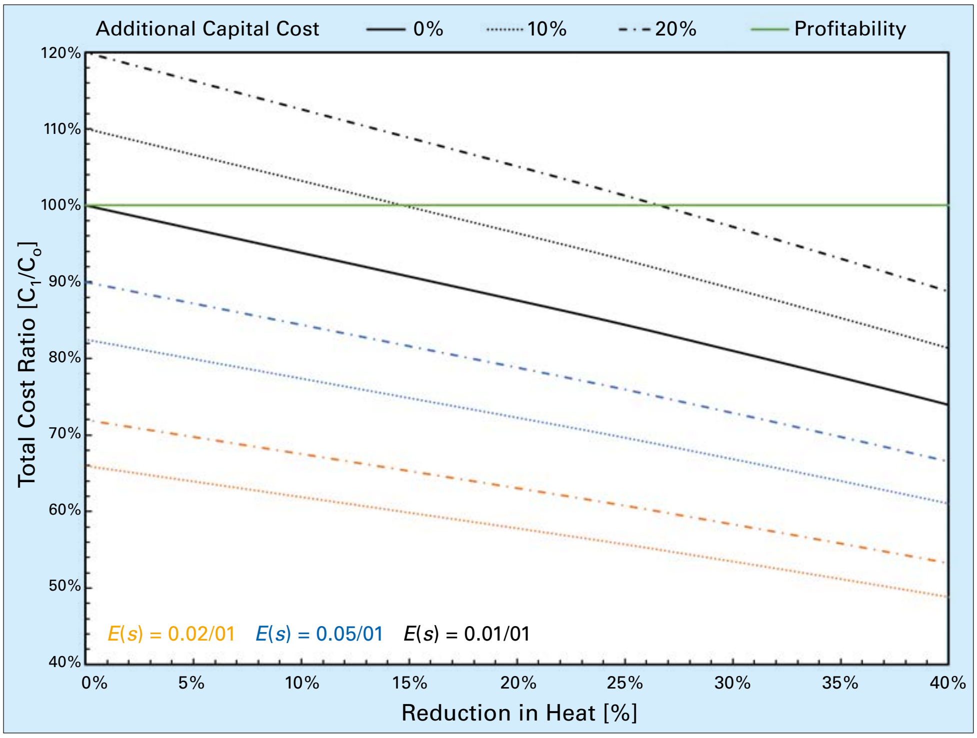

Figure 12:
The total cost ratio as a function of the reduction in tubing heat transfer surface area for different maintenance cost ratios and additional capital cost requirements. Any value below the profitability line is a profitable scenario.

thermal resistance (decrease in required tubing surface area) and increase in coating application costs. The key point is that the reduction in capital cost by reducing the tubing area required must not be exceeded by the cost of materials and application of the coating system on the reduced tubing surface area [21]. Therefore, a balance is required between the maintenance costs of the heat exchanger and the anticipated increase in thermal performance to ensure price competitiveness. With advancements in this technology, it could become facile to guarantee dropwise condensation behavior for improved thermal performance. In [21], Ahlers et al. outline a precise framework for a heat exchanger cost model, which is adapted here. Ahlers et al. concluded that generic condensers with very low maintenance requirements due to a low fouling propensity on the steam-side would maintain substantial cost savings (>15–25%) for scenarios where only 10–20% additional surface modification costs were required to sustain DWC. However, the study neglected to identify replenishable, self-healing FFS coatings as a solution for this identified scenario. The following cost model is defined to examine this scenario further. The total heat exchanger cost is defined in Eq. (5) as:

$$C_{\text{total}} = C_{\text{cap}} + C_{\text{e}} + C_{\text{m}} \tag{5}$$

The capital costs, C_{cap}, include the heat exchanger itself and the coating materials. The energy costs, C_e, include the cooling water pump operation and steam generation. The maintenance costs, C_m, are related to tube fouling and the coating replenishment (i.e. feed rate). The energy cost terms can be neglected since it is process-specific and difficult to generalize. For this reason, the cost benefits of reduced turbine backpressure are not included. The capital cost is a function of the reference price of the heat exchanger with a given surface area and the amortization factor, *a*. The maintenance costs are a function of the purchase price ($I_{hx,o}$) and a fouling factor, *s*. After substituting new terms, Eq. (5) is rearranged into Eq. (6) as:

$$C_{\text{total}} = C_{\text{cap}} + C_{\text{m}} = aI_{\text{hx,o}} + sI_{\text{hx}} = (a+s)I_{\text{hx,o}}\frac{A}{A_{\text{o}}}^{m_{\text{hx}}} \tag{6}$$

where the degression exponent m_{hx}=0.59, *s*=0.02–0.05 for low fouling risks, and the amortization factor *a* = 0.1 [21].

An additional definition is the total cost ratio, which is the total heat exchanger cost for DWC, C_1, compared to the original total heat exchanger cost for FWC, C_o. This total cost ratio determines the value of using replenishable FFAP coatings, which is due to their low maintenance requirements and improved heat transfer performance (reduced surface area), even with their additional capital cost requirements. If profitability is defined as unity (C_1/C_o=100%), then any value below this provides cost benefits to the power plant user due to improved thermal performance (reduced tubing surface area) and lower maintenance requirements.

COST PERFORMANCE RESULTS

The main findings are demonstrated in Figure 11, which shows the total cost ratio as a function of the enhancement in h_c. The base case (solid black line) is a hypothetical scenario with no additional coating costs or reduced maintenance requirements. With improvement in h_c, the results show reduced total cost due to the decrease in required tubing surface area. This means that if the coating application was free, the reduced tubing surface area alone would lead to at most a 22% reduction in the total cost ratio due to the promotion of DWC. For scenarios where s is reduced to 0.05 or 0.02, the improvement in the total cost ratio is even more substantial since this term represents a reduction in maintenance requirements due to reduced fouling risk. The additional capital cost curves (10%, 20%) demonstrate the degree of improvement in the total cost ratio and can be extrapolated if the exact increase in coating application costs is known. Since it is difficult to specifically account for the precise reduction in maintenance costs, a 10–40% reduction in the total cost ratio is found for $s=0.02$–0.05. In Figure 12, the same data is examined for the total cost ratio as a function of the reduction in tubing surface area. When examined with Figure 11, it is clear how the reduction in tubing heat transfer surface area leads to substantial total cost savings.

CONCLUSIONS

A thermal resistance network model was established using representative power plant operational parameters, materials, and assumptions for a steam surface condenser. This was completed to quantify the technical and economic benefits of replenishable FFAPs used to promote efficient DWC on the steam-side. Although the convective condensation thermal resistance is notably smaller than the more dominant cooling water-side thermal resistance, an improvement in U of 15 to 120% is an attainable bound given recently discovered experimental improvement in h_c ($E(h_c)=2$–15). Similarly, the increase in net plant efficiency (0.3 to 1.1%), decrease in water consumption (22.7 to 79.5 $L \cdot MWh^{-1}$), and reduction in turbine backpressure (6.1 to 26.1 mbar) demonstrate additional value for the power plant user in energy cost savings, fuel cost reductions, and additional power generated with incorporation of FFAPs. The operational conditions for every power plant vary and these results are not definitive; however, the trends provide a clear basis for comparison. Finally, a total heat exchanger cost model was adapted to understand the trade-off in reduced tubing surface area and increase in coating application costs, specifically for the application of replenishable FFAPs. With a reduced maintenance requirement, a 10–40% reduction in the total cost of the heat exchanger can be realized even with a 10% to 20% increase in coating capital costs. The benefit of a reduction in tubing surface area outweighs the increase in costs to supply and use the coating for most scenarios. To further understand these benefits, additional experimental results for h_c at low vapor pressure are required for a more precise bound on h_c, U, plant operational parameters, and total cost ratio. These new h_c results would demonstrate benefits on the lower end of the bounds for these terms, due to the increased interfacial vapor resistance.

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