Investigation of Technologies to Improve Condenser Heat Transfer and Performance in a Relevant Coal-Fired Power Plant

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ABSTRACT

Improvements in thermal power-generating plant performance is correlated directly to societal benefits including lower cost of reduced fuel consumption, resulting in lower cost of electricity for the consumer and reduced carbon emissions to the atmosphere. Warm steam exhausted from low-pressure steam turbines is condensed to liquid water on the exterior of thin-walled metal condenser tubes with cooling water passing through the tube interior. The condensation of steam creates a vacuum that supports turbine rotation and the concurrent generation of electricity. This vacuum is optimized when heat transfer across the wall of condenser tube is maximized. Common hindrances to heat transfer include foulants in cooling water that may form and adhere to the interior of condenser tubes, including mineral scale, microbiological films, and particulate deposition. Flowing cooling water may also include a laminar layer at the interior metal surfaces that travels more slowly than bulk water flow, serving to impede heat transfer. On the tube exterior, condensing steam forms an insulating layer of water that flows down the tube and reduces the effectiveness of cooling. Both the interior and exterior barriers to optimal heat transfer may be alleviated to some extent by surface treatments. On the tube interior, hydrophobic coatings may be applied that can reduced the adherence of foulants and of the laminar flow layer to the tube surface. On the tube exterior, hydrophobic coatings or mechanical treatments can be applied that may result in the termination of droplet growth and the departure of droplets from the surface rather than coalescence into a continuous layer of flowing water. Fourteen surface treatments were applied to condenser tubes in this study, including eight interior coatings and six exterior treatments, five of which were coatings and one a microstructural texture. Heat transfer measurement equipment simulating conditions in the condenser of an operating power plant was used to determine heat transfer coefficients by measuring sufficient flow, temperature, water chemistry and other data. Several of the tubes with interior surface treatments showed improvement in heat transfer coefficients compared with a plain (uncoated) tube, and several of the tubes with exterior surface treatments also showed enhanced heat transfer coefficients.

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Condenser / water-cooled condenser (WCC)
Hydrophobic / hydrophobicity
Heat transfer coefficient
Cooling water

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PRIMARY AUDIENCE: Thermal Electric Generating Station Owners and Operators

SECONDARY AUDIENCE: Vendors and Consultants to Thermal Electric Generating Stations

KEY RESEARCH QUESTION

Will hydrophobic surface modifications to condenser tubes improve heat transfer by anti-fouling properties or promotion of dropwise condensation?

RESEARCH OVERVIEW

Condenser tubes with modifications applied (coatings or physical alterations to surfaces) were tested in heat transfer measurement equipment designed to closely simulate the environment in an operating condenser at a thermal power plant. The heat transfer coefficient for steam cooling was measured in modified tubes and compared with an unmodified tube. Modifications were applied on both the interior (cooling water side) and exterior (steam side) of individual tubes, and testing was performed on each.

KEY FINDINGS

- Certain internal modifications applied to condenser tubes had limited indication of improved heat transfer in a biofouling environment.
- Several internal modifications resulted in improved heat transfer apart from biofouling or other fouling issues.
- Several external modifications resulted in improved heat transfer.

WHY THIS MATTERS

Improved heat transfer is directly correlated with improved power plant efficiency and reduced fuel use. Reduced fuel use correlates with lower electricity costs for end-users and lower carbon emissions.

HOW TO APPLY RESULTS

The project essentially conducted pilot-scale testing in an environment designed to be representative of that in an operational thermal power-generating plant. Additional pilot-scale testing may be desirable for confirmation of results herein and other factors required for successful full-scale operation.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- The results obtained during this research will be made available and communicated via technical presentations, conference presentations and journal entries to all relevant communities of interest.

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ABBREVIATIONS, ACRONYMNS, INITIALISMS, AND DEFINITIONS

°C. Degrees Centigrade.

°F. Degrees Fahrenheit.

Biofilm. A mucous layer formed by micro-organisms, commonly found on metal or other surfaces exposed to natural water sources when a disinfectant is not used, or is not effective.

Blowdown. Water discharged from the system to control concentrations of salts or other impurities in the circulating water (units – gallons per minute [gpm]).

Cooling Water Makeup. Source water added to replace the sum of all evaporation, blowdown, and drift loss.

Cycles of concentration. Ratio of dissolved solids in circulating water to the dissolved solids in makeup water; will greatly affect makeup water needed; lower cycles of concentration equates to more makeup water.

Disinfectant. A chemical such as bleach used to kill micro-organisms.

gpm. Gallons-per minute.

Heat load. Amount of heat dissipated in the cooling system (units - British thermal units per hour [Btu/hr] or megawatt thermal [MWth]).

Heat transfer. The movement of thermal energy across a barrier in the direction that supports an equilibrium temperature between materials on either side of the barrier.

Heat transfer coefficient. A numerical value describing the rate of heat transfer across a barrier; for a thermal power plant condenser tube calculated as [BTU/hr-ft^2-°F] or [J/s•m^2•K].

MDCT. Mechanical-draft cooling tower.

MW. Megawatt.

Open cycle. A cooling system configuration consisting of a cooling loop that it is not continuous and includes system water losses and water replacement.

Scale / Mineral Scale. Mineral compounds that can form on surfaces when the concentration of certain dissolved constituents in water exceeds the saturation point for precipitation.

Steam Surface Condenser (SCC). In thermal power generation, a heat exchanger that receives exhaust steam from the low-pressure turbine and condenses the steam on the exterior of horizontal tubes with cooling water flowing through the interior of tubes.

Water-Cooled Condenser (WCC). An SSC that is cooled by water, as opposed to an ACC that is cooled by air.

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1
INTRODUCTION

Electricity is integral to delivering diverse services to all sectors of today's global economy. Fossil fuels (coal, natural gas, petroleum) have traditionally provided the energy source for the bulk of electricity generation worldwide, with significant input from nuclear and hydrodynamic energy in some regions. In recent years, a focus on reducing carbon dioxide (CO_2) emissions into the atmosphere has led to a shift towards renewable energy sources, particularly wind and solar. Nevertheless, fossil fuels continue to play a significant role in providing the world's electric energy.

Operation of thermal power-generating stations with optimized thermodynamic efficiency results in reduced fuel requirements and consequently lower costs to the end-user and power generator, as well as lower CO_2 emissions per unit of electricity generated. Improving efficiency has been an engineering objective for thermal power-generating station design for decades, and current fossil power plants incorporate many of these design improvements. One of the key drivers of thermal plant efficiency is the steam surface condenser (SSC), which has been largely optimized with respect to design, but can suffer significant efficiency losses due to operational factors.

The purpose of an SSC is to receive exhaust steam from the low-pressure (LP) turbine and to convert the steam to liquid water. This is accomplished by flowing cooling water through the interior of thousands of thin-walled, horizontal tubes while steam condenses on the exterior surface. This process creates a vacuum in the condenser that has a major effect on unit efficiency by supporting steam flow through the turbine. If the condenser vacuum is inadequate, increased fuel and steam flow are required to maintain generating capacity. Therefore, any factor that reduces heat transfer efficiency across the condenser tube wall will affect the rate of steam condensation and lower the vacuum, posing a risk to efficient unit operation. The condensed steam is returned to the boiler, providing an additional benefit in that costly high-purity water is maintained in the system for repeated use.

Condenser tubes are subject to internal surface fouling by four primary mechanisms: mineral scale formation, microbiological film growth, adherence of particulates, and formation of base metal corrosion products. These issues are well-known in power generation and other industries and are managed by various approaches, but failures of equipment, changes in water supply, and human error frequently result in fouled surfaces. In addition, the steamside of condenser tubes can experience a type of "fouling" by condensed steam that coats the tube with a layer of water, limiting the rate of steam condensation. Both internal and external fouling are an impediment to heat transfer and therefore to achieving an optimal condenser vacuum.

Surface treatments have been considered a promising approach to limit fouling on both the interior and exterior of condenser tubes. In particular it has been anticipated that treatments that impart hydrophobic properties to the surfaces will reduce fouling and improve optimal heat transfer.

Previous Related Research

Several projects have been directed at evaluating the effect of surface treatments on condenser tubes, as follow:

A sound theoretical basis exists for improving heat transfer for steam condensation by surface treatments. The potential for efficiency benefit from coatings tailored for the purpose is promising [1].

Two different steamside coatings were applied to 2 sets of 10 copper-alloy tubes which were then installed after removing existing tubes in an operating power plant. The tubes were instrumented for flow rate and temperature rise. Results did not indicate any difference between the coated and uncoated tubes [2].

Criteria were evaluated and described for testing the effectiveness of surface modifications on heat transfer, including (1) condenser performance metrics, (2) coating attributes, (3) commercial coatings and (4) validation testing [3].

Several 304 stainless steel tubes with the internal surface modified by application of a thin nanocoating, reportedly 1-2 nanometers in thickness, were installed in test heat exchangers for fouling comparison with unmodified tubes. The test ran continuously for 8 months under conditions representative of those in a thermal power plant, with untreated river water supplied for cooling. Cooling water flow and temperature rise were measured to evaluate heat transfer performance. Post-exposure examination and testing of the tubes did not identify any significant differences between the coated and uncoated tubes [4].

Current Research

The inability to control conditions in a power plant condenser and inadequate controls for the test condenser utilized were significant limitations in evaluating the effectiveness of surface treatments on condenser tubes. It was determined that to advance the research it would be necessary to design and construct equipment specifically designed to measure heat transfer operated under simulated conditions closely matching those in a power plant condenser.

2
EQUIPMENT AND EXPERIMENTAL DESIGN

A Heat Transfer Loop (HTL) was designed to closely simulate conditions matching an operating thermal power plant condenser, with the objective of testing condenser tubes with surface modifications that enhanced hydrophobicity (Figure 2-1 and Figure 2-2).

Figure 2-1
Heat Transfer Loop, condenser side

Figure 2-2
Heat Transfer Loop, boiler side

Characteristics of the HTL included:

- Variable-speed pump to recirculate cooling water (CW) through a loop including an evaporative cooling tower
- Interchangeable positions for four fifteen (15) foot long, ¾ to 1” outside diameter, titanium test condenser tubes side-by-side in the test condenser
- Flow and temperature measurements for CW in each test condenser tube
- Bulk flow and temperature measurements for CW
- Backwashable sand filter in the cooling loop, optional flow path
- Sidestream flow path for test coupons
- Chemical feeds for CW pH and biocide control, additional optional
- Inline CW chemistry measurements, conductivity, pH, additional bench testing
- Steam generator (boiler) to provide steam to condense and generate a vacuum
- Automated flow-balancing and conductivity-based CW blowdown
- Vacuum pump to support air removal

It was necessary to monitor and occasionally identify and correct ambient air leaks into the condenser vacuum.

In all cases three modified tubes were installed in the HTL condenser along with one unmodified tube as a control / baseline.

Experimental Conditions: Internal Modifications

Internal modification testing was directed towards biofouling reduction, as this was deemed the easiest internal fouling mode to create with consistency. The HTL was operated under the following conditions for monitoring heat transfer:

- Steam generation to achieve CW temperature rise of ~15°F from inlet-to-outlet of the test condenser tubes
- CW flow rate ~3.5 fps through condenser tubes
- CW blowdown to maintain conductivity of <700 µS/cm
- pH maintained at ~7.8 with sulfuric acid addition as needed
- No biocide feed
- Stagnant periods (~2 days) and addition of microbiological ‘seed’ solution if needed to promote biological film growth
- Continuous operation other than occasional stagnant periods to promote biological growth
- Measurements suitable for heat transfer coefficient determination taken approximately every 2 days, for a period of about an hour
- Test duration at least 30 days unless circumstances dictated earlier termination
- Periodic monitoring of mesh coupon and microbiological presence

For internal modification testing, the first two or three tests were representative of heat transfer affected by only the modification, since a period of time is required for a biofilm to become established. This allowed identification of the extent to which an internal coating itself inhibited heat transfer, apart from any subsequent fouling.

Experimental Conditions: External Modifications

Testing of external modifications was performed in a shorter time frame because no incubation period was required as for microbiological film formation. For external modification testing it was important to avoid any internal fouling to ensure consistency in heat transfer testing, and considerations were given to support this objective.

To include variations in exhaust steam and cooling water flow, the following matrix of conditions was developed and used for this testing.

Table 2-1
Test Conditions Matrix for Steamside Modifications

Test Run Number	Cooling Water Flow Through HTL	CW Temperature Rise Along 15-foot Tube
1	55 gpm	10˚F
2	55 gpm	5˚F
3	55 gpm	3˚F
4*	25 gpm	15˚F
5	30 gpm	10˚F
6	30 gpm	5˚F

*Test run 4 matched conditions for internal modification testing.

Other HTL operating conditions for external modification heat transfer testing included the following:

- CW blowdown increased to reduce the likelihood of internal scale formation*
- pH reduced to 7.2-7.4 with sulfuric acid addition to minimize the likelihood of scale formation*
- Biocide feed to limit the possibility of biofilm development*
- Continuous operation to avoid stagnant periods that could promote biological growth
- Measurements suitable for heat transfer coefficient determination initiated as soon as temperature and flow conditions stabilized, for a period of about an hour, in triplicate for each of the matrix settings*
- Test duration typically 1 to 2 weeks

*These conditions were prescribed as precautionary but not necessarily followed strictly, as no evidence of biofilm growth was determined in any external modification testing.

3
SURFACE MODIFICATIONS FOR TESTING

The project included testing of fourteen (14) surface modifications overall, eight (8) internal and six (6) external. The selection process for the modifications to test included the following criteria:

Priority selection criteria:

- Supplier experience with applying the technology to heat exchanger surfaces
- Technical characteristics of the product
- Existing market availability or a simple path to commercial deployment within three to five years
- Environmental and system compatibility
- Other factors that appeared beneficial or detrimental to performance of the product in the intended application

Secondary selection criteria:

- Whether a coating material can be supplied in quantities for large-scale applications
- How the coating or surface modification process is accomplished
- Whether the technology is suitable for application on existing condenser tubes in the field or is limited to tube replacement or new construction installations
- Whether new tubes modified in a supplier facility can be installed without disturbing the modification
- Whether routine tube cleaning and non-destructive inspections will disrupt the modification
- Whether a coating material, if disrupted, can be re-applied to surfaces

The criteria above were supported with screening of modified coupons via ASTM tests for relevant coating characteristics. The following tests were utilized for this screening process:

ASTM C1624: Standard Test Method for Adhesion Strength and Mechanical Failure Modes of Ceramic Coatings by Quantitative Single Point Scratch Testing (*coating / substrate adhesion strength*)

ASTM G133: Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear (*abrasion resistance*)

ASTM E1461: Standard Method for Thermal Diffusivity of Solids by the Flash Method (*measure related to thermal conductivity*)

ASTM D7334: Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement (*hydrophobicity, including thermal stability by heating coated coupon prior to a second test*) (Figure 3-1)

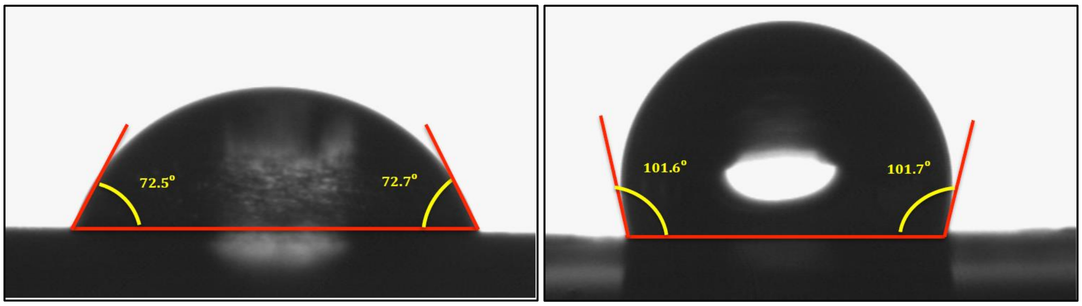

Figure 3-1
Hydrophobicity test with water drop on unmodified (left) and modified (right) surfaces.

Modification Technologies Selected

Tube modification technologies are generally proprietary with limited categorization of the modification type. For the purposes of this report, the modifications are labeled “A” through “H” for internal tube (cooling water) application, and “I” through “N” for external tube (steamside) application.

Limited characterization of these modifications is listed in Table 3-1 and Table 3-2.

Table 3-1
Internal Modification Technologies Selected for Testing

Internal Modification	Type	Estimated Thickness	Application Method
A	Epoxy with copper oxide	~ 12 micrometers	Wipe / spray
B	Hybrid epoxy with nanocomposite	< 25 micrometers	Wipe / spray
C	Nano surface treatment	< 1 micrometers	Circulate water-based solution
D	Functionally graded superhydrophobic coating	5-20 micrometers	Spray / airbrush
E	Thin-film nanocomposite (polymer base + additive)	< 2 micrometers	Spray
F	Chemically functionalized silicon oxide	< 2 micrometers	Chemical vapor deposition
G	Nano metal oxide	~ 5 nanometers	Dipping or spraying
H	Carbon-silicon polymer	~10 micrometers	Recirculate through tubes; heat to cure

Table 3-2
External Modification Technologies Selected for Testing

External Modification	Type	Estimated Thickness	Application Method
I*	Physical surface modification	N/A	Tubing as-manufactured
J*	Physical surface modification	N/A	Tubing as-manufactured
K*	Physical surface modification	N/A	Tubing as-manufactured
L	Functionally graded superhydrophobic coating	5-20 micrometers	Spray / airbrush
M	Fluoro-molecular surface treatment	Not specified	Chemical vapor deposition
N	Nano metal oxide	~ 5 nanometers	Dipping or spraying

*I, J and K are essentially the same physical modification under slightly different forming conditions.

Titanium condenser tubes, 17 feet in length and 1.0" outside diameter, and 0.028" wall thickness, were supplied to each coating vendor in triplicate for application of the coatings, with the following exceptions:

- Internal modification C was applied to titanium tubes onsite at the test facility
- External modifications I through K were supplied by the vendor as-manufactured, along with an unmodified tube for comparison; these tubes were composed of the alloy UNS S44660, a high-alloy corrosion resistant stainless steel (Figure 3-2).

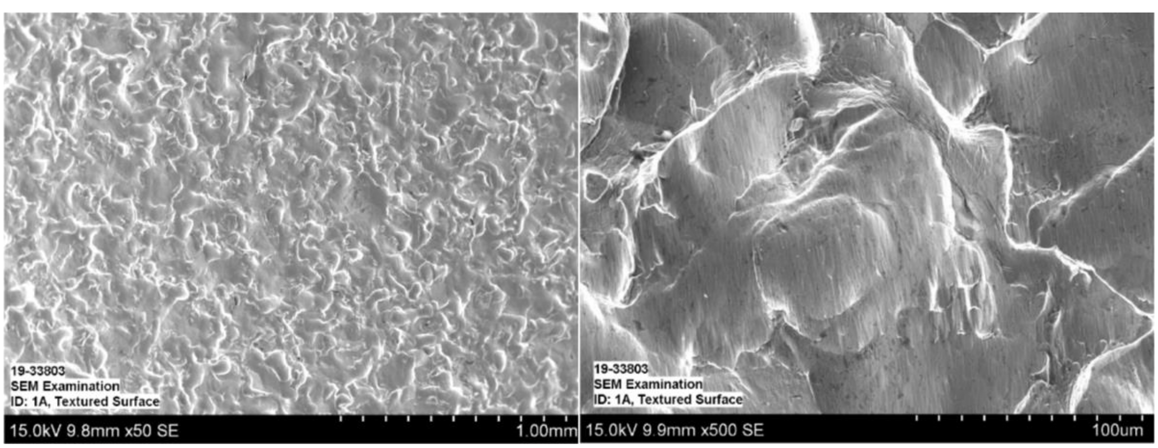

Figure 3-2
Physical modification on exterior surface of modified tube I, 50X magnification (left) and 500X magnification (right).

4
TEST RESULTS

The primary criteria used for evaluating heat transfer in this project was the heat transfer coefficient Udot, calculated as [BTU/hr-ft^2-ºF] or metric equivalent [J/s•m^2•K]. The primary data collected for this determination included the following:

- Time of data collection
- Temperature of cooling water in each of four tubes, inlet and outlet
- Flow rate of cooling water through each of four tubes.
- Steam temperature

Internal Modifications: Summary Results

Results for internal modifications are presented as a ratio of the heat transfer coefficient (HTC) of the modified to unmodified tube. The data for the modified tubes is an average for the three tubes, compared with a single unmodified tube. Summary data includes the initial stabilized ratio, the final ratio, and the minimum and maximum ratio during the measurements period.

- A ratio that is greater than 1 indicates that the modified tube exhibited better heat transfer than the unmodified tube.
- The initial ratio indicates the performance of the modification with respect to heat transfer “as-applied,” i.e. independent of microbiological fouling.
- The final ratio indicates the performance of the modification after exposure to a biologically fouling environment, in comparison with an unmodified tube.
- The ‘minimum’ and ‘maximum’ numbers provide consideration of the variance in data under conditions of the test, and may be subject to further interpretation.

Table 4-1
Results, HTC Ratios for Internal Modifications

Modification	Initial Ratio	Final Ratio	Minimum	Maximum
A	0.88	0.95	0.84	0.96
B	0.93	0.91	0.90	0.95
C	1.02	1.02	1.00	1.05
D*	1.01	1.02	1.01	1.03
E	0.92	0.91	0.89	0.94
F	1.03	1.03	1.02	1.04
G	1.03	1.03	1.02	1.04
H	0.83	0.75	0.73	0.83

*Results invalid due to rapid coating degradation.

Comments, Internal Modifications

The following general results interpretations are provided for each test result. Additional considerations of the data may lead to more detailed interpretations and conclusions.

Table 4-2
Comments on Internal Modification Results

Modification	Comments
A	A clear trend was demonstrated towards reduction of biofouling on the modified tube compared with the unmodified tube over the duration of the test, with an initial HTC deficit of 12% for the coated tubes and a final deficit of 5%.
B	No definitive trend was present regarding the effect of the modification on biofouling over the duration of the test, with an initial HTC deficit of 7% for the coated tubes and a final deficit of 9%.
C	There was no evidence of change in HTC ratio with biofouling, but every measurement for the duration of testing showed the modification to provide equal or better heat transfer than the plain tube. The initial and final improvements were both 2%.
D	While the data showed improved heat transfer with the modification, only four readings were taken before the coating was observed to be significantly detaching from the tube. Therefore, no significance is attached to these very limited results.
E	The modification resulted in an initial HTC deficit of 8% and a final deficit of 9%. No significant change in the HTC Ratio was observed over the duration of the test.
F	The modification resulted in an initial and final HTC improvement both at 3%, with very little fluctuation during the test period. No significant change in the HTC Ratio was observed over the duration of the test. However, there was no correlation between the HTC improvement and biofilm formation.

Table 4-2 (continued)
Comments on Internal Modification Results

Modification	Comments
G	The test results were somewhat obscured because both the interior and exterior surfaces were modified. An attempt to distinguish the effects suggests that the initial HTC improvement of 5% would be a combination of internal plus external effects, whereas the improvement from 5 to 8% over test duration would result from biofouling mitigation. Overall the results were clearly positive but isolating internal effects from external was not entirely possible.
H	The initial HTC ratio showed a HTC loss of 17% with the initial measurement, deteriorating to a final loss of 25% after nine days. The test was discontinued at that point due to the poor modification performance.

External Modifications: Summary Results

Results for external modifications are presented as a ratio of the heat transfer coefficient (HTC) of the modified to unmodified tube. The data for the three modified tubes is an average, compared with a single unmodified tube. Summary data includes the average for tests from each of the six test conditions in Table 2-1.

- A ratio that is greater than 1 indicates that the modified tube exhibited better heat transfer than the unmodified tube.

Table 4-3
Results, HTC Ratios for External Modifications

Modification	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
I				0.91		
J	1.04	1.04	1.08	1.04	1.03	1.03
K	1.05	1.08	1.12	1.04	1.04	1.08
L*	0.95	0.90	0.87	0.94	0.93	0.91
M	1.03	1.05	1.07	1.02	1.03	1.05
N	1.05	1.08	1.11	1.04	1.04	1.07

* Results invalid due to rapid coating degradation.

Comments, External Modifications

The following general results interpretations are provided for each test result. Additional considerations of the data may lead to more detailed interpretations and conclusions.

Table 4-4
Comments on External Modification Results

Modification	Comments
I	The HTC was significantly poorer for the mechanically modified tubes, with a 9% deficit. Only one test matrix was used for this initial testing.
J	The HTC was significantly improved for the mechanically modified tubes under all test matrices, ranging from 3 to 8%.
K	The HTC was significantly improved for the mechanically modified tubes under all test matrices, ranging from 3.5 to 11.5%.
L	The modified tubes had a significant HTC deficit (4.3 to 12.6%) for all test matrices. After test conclusion it was observed that the coating had significantly detached from the tube exterior.
M	The modified tubes showed significant HTC improvement (1.5 to 6.8%) for all test matrices.
N	The test results were somewhat obscured because both the interior and exterior surfaces were modified. An attempt to distinguish the effects suggests that the initial HTC improvement of 5% would be a combination of internal + external effects, whereas the improvement from 5 to 8% over test duration would result from biofouling mitigation. Overall the results are very positive but isolating internal effects from external is not entirely possible.

5
DISCUSSION

The project results demonstrated that surface modifications on both the interior and exterior of condenser tubes can affect the rate of heat transfer from steam to cooling water. On the cooling water side (interior), it was somewhat surprising that three of the eight coatings (C, F and G) showed improved heat transfer ranging from 2 to 5% simply by the presence of the coating, apart from the presence of biofouling or any other fouling. Since all modifications were hydrophobic in nature, it is possible that reduced surface wetting by the flowing cooling water served to disrupt the laminar flow layer of water that tends to adhere to the tube surface and move at a reduced flow rate. This slower-moving layer creates a barrier to optimal heat transfer, and disruption or removal of the layer should enhance heat transfer.

One internal modification (C) showed significant impedance to heat transfer (12% deficit compared with an unmodified tube) upon initial testing, but under biofouling conditions over 2-3 months its relative performance improved (5% deficit). This was the only coating to show a clear indication of biofouling reduction.

On the steam side of the tube (exterior), four of the six tube modifications tested (J, K, M, N) showed improvement in heat transfer compared with the unmodified tube ranging from 2 to 12%, depending on the test conditions. Any actual benefit in an operating power plant would clearly depend on the specific conditions in effect, but the tendency for better performance with hydrophobic modifications was clear.

Only one coating, used for both internal testing (D) and steam side testing (L), failed to adhere to the tube surfaces after a relatively short time in the test condenser. However, several of the modifications were so thin that coating adherence problems would not have been visibly apparent. In addition, with desirable field performance of years or decades, there was no confirmation that any coating had suitable durability. The only durability exceptions were steamside physical modifications I, J and K, in which the surface modification would not be expected to change structurally over the life of the tube in a condenser.

The feasibility of applying certain treatments to thousands of tubes in a steam surface condenser for a moderately-sized thermal power plant was beyond the scope of the project. It is evident that some modifications are more suited to retrofit application than others, and the cost for application will also vary considerably.

6
SUMMARY AND CONCLUSIONS

Based on the modified tube samples received and the testing performed, four of eight interior modifications and four of six exterior modifications showed significant and consistent improvement in the rate of heat transfer. These results indicate a significant potential for surface modifications to improve condenser efficiency with a consequent reduction in fuel requirements and air emissions from thermal power plants fueled with coal, natural gas oil.

7
FUTURE RESEARCH

This research was conducted in a test condenser designed to simulate conditions in the condenser of a thermal power plant and measure heat transfer in individual condenser tubes. While the design was well-engineered and conditions controllable for the research plan, it is not possible to directly project results obtained from a four-tube condenser to field operation where more than 20,000 condenser tubes may be in service. Scale-up would be a meaningful next step, perhaps to a small condenser in actual service, whether in power generation or other industrial application. This will provide confirmation of the results herein as well as inspiring confidence with potential end-users.

There is a need to determine the durability (life expectancy) of coatings that showed improvements in heat transfer during this research. Since suitable durability is measured in years, a long-term trial application in a small condenser or a section of a large condenser would be an appropriate action to evaluate the status of a coating over an extended period. This trial would ideally include heat transfer testing in order to evaluate the continuing performance of the coating over an extended period of time.

Suppliers of the coatings who are seeking to bring their technology to market will need to closely examine the feasibility of both retrofit and new tube applications, with associated cost-benefit evaluation. Environmental considerations must be included in such an evaluation as there is typically a need for an environmental impact study prior to the end-user receiving regulatory approval for installing a technology that may affect the discharge to a receiving body of water.

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