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ENHANCED HEAT EXCHANGER TUBES: THEIR FOULING TENDENCY AND POTENTIAL CLEANUP

George F. Hays[1], Edward S. Beardwood[2], Steven J. Colby[1]
[1]Ashland Specialty Chemical, Drew Industrial, One Drew Plaza, Boonton, NJ 07005
[2]Ashland Canada Corporation, Drew Industrial, 525 Finley Avenue , Ajax, Ontario, Canada L1S 2E5

ABSTRACT

Biofouling of enhanced heat exchanger tubes has been a significant problem for industry ever since their introduction. Prior research has indicated that the intensity of biofouling problems is a function of the number of flutes in the enhanced tubes. Field and laboratory data indicate that enhanced tubes biofoul more rapidly and to higher fouling factors than do traditional smooth tubes. Enhanced tubes have also been found to clean up more rapidly than smooth tubes when comparable cleaning programs are employed.

A novel monitor has been developed to evaluate biomass deposition and removal under operating heat exchanger conditions utilizing an enhanced tube. Traditional oxidizing biocides have been found to be relatively inefficient for removal of biofilm from enhanced heat exchanger tubes. The use of biodispersants in conjunction with oxidizing biocides has demonstrated a significant reduction in enhanced tube biofouling. This paper will review prior research and present findings from recent pilot cooling tower studies.

KEYWORDS

biofouling, enhanced heat exchanger tubes, oxidizing biocides, bromine, chlorine dioxide, chlorine, annular heat transfer test section, biodispersants, inorganic crystallization fouling, biofilm monitoring

INTRODUCTION

Prior research on smooth heat transfer tubes indicates that biofouling has two effects on heat transfer. Biofilms form insulating layers on the heat transfer surface and the elasticity of a biofilm layer significantly increases the pressure drop across the tube, thus reducing the fluid flow rate and its ability to remove heat.[1,2,3] This paper extends prior research on smooth tubes to enhanced tubes.

Heat exchanger tubes with enhancements on the exterior have long been used in fin-fan coolers and refrigeration machines to increase the heat transfer area and thus reduce the size of the heat exchanger. During the early 90s, tubes with tube water-side enhancements were introduced into the market in an effort to further reduce the size of condensers in refrigeration service. Internal enhancements are similar to rifling in a gun barrel. They are helical flutes (i.e., grooves). Initially, the number of flutes was small, in the range of 10 to 20, and the effect was a measurable increase in heat transfer area and heat transfer rates, which allowed the length of refrigeration machines to be reduced. With initial success, tube manufactures began to increase the number of flutes, which shrank the spacing between the ridges to the point where today's enhanced tubes form steep and narrow grooves. The increase in the number of flutes has had a dramatic effect on water velocity within the flutes. Typically, today's refrigeration equipment is designed for mean water velocities in the range of 1.6–2.3 m/s (5–7 ft/sec). However, the greatly diminished cross section of each flute has significantly increased the friction factor of the stream within the flute to the point of being laminar at the base of the flute. These conditions, in turn, promote the precipitation of solids from the aqueous stream and provide an ideal environment for the growth of biomass. In fairly short order, flutes may become fouled with a biomass-rich foulant layer to such an extent that most or all of the benefits of the tube enhancement become neutralized. The first inclination of both the operator and manufacturer is to suspect that the problem is caused by poor water treatment.

Throughout the 90s, Professor Ralph Webb of Penn State University studied the problem. Dr. Webb has written numerous papers on the subject.[4,5,6] Much of his research has been in the study of enhanced tubes in operating heat exchangers. He reports that the rate of fouling on

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enhanced tubes is associated with a number of variables that are related to tube enhancement geometry. Enhanced tube fouling potential increases with:

- The number of starts (n_s), wherein n_s 30 are more susceptible[4].
- Helix angle ( ), wherein ≥ 35 are more susceptible.
- Lower rib axial pitch (P) to rib height (e) ratio, wherein $P/e < 4.0$ ratios are more susceptible.
- Lower rib height (e) to tube diameter to the base of the enhancement (D).

The water velocity within the grooves is significantly reduced as the groove narrows to its base due to the restriction in flow area and the combined effect of the shear stress on adjacent surfaces. The increase in the number of starts further narrows the flow channel within the grooves. Hence the enhancement increases deposit rate, and the drag profile associated with the roughness element does not contribute to the deposit removal process. Conventional knowledge has suggested particulate (i.e., suspended solids) fouling can be used as an accelerated method to evaluate long-term crystallization/precipitation fouling potential and that the typical foulant found in the field is a combination of these two.

Numerous attempts were made to adapt standard treatment chemistries for use with enhanced tube heat exchangers. Unfortunately, results were inconsistent. The absence of laboratory devices to emulate enhanced tube conditions and the large number of variables from application to application made field data unreliable.

Field reports have indicated that enhanced tubes fouled faster than smooth tubes. Much of that information came from open recirculating cooling systems in which two or more refrigeration machines were installed. Typically, one or more of these refrigeration machines had smooth tubes and one or more had enhanced tubes. Reports indicated that the machines with enhanced tubes were losing efficiency significantly faster than those with smooth tubes. The difference appeared to be related to the level of biomass in the deposits. It was also noted that localized corrosion susceptibility was greater with enhanced tubes due to the foulant nature whereby under-deposit corrosion cells are created by said fouling.

In the late 90s, Wieland Werke[7] provided Ashland with a sample of a tube enhancement on the exterior of the tube, which when installed in a test device with the water flowing in an annular space, provides a means to emulate internal conditions in tube-side enhancements. The tube enhancements present for the annular heat transfer test section were as follows:

Helix angle ( ):	29.3 degrees
Rib height (e):	0.287 mm
Rib axial pitch (P):	5.944 mm
Number of starts (n_s):	31
P/e value:	21.3
e/D value:	0.021

One of Ashland's proprietary on-line heat exchanger monitors[8] was adapted to use the externally enhanced tube. Calculations were modified for the change in the mean diameter of the enhanced tube, thus allowing for experimentation with an enhanced tube under the following operational regimes:

- Inorganic crystallization/precipitation fouling conditions
- Biological fouling conditions
- Biological foulant removal conditions

The annular fouling test section has been employed extensively to study fouling of various fluids used on the tube-side of tubular heat exchanger.[9] The question arises as to whether the fouling results obtained in an annular test section are applicable to predicting the fouling in a circular tube. The fouling process is highly dependent on the quality of the flowing fluid and the thermal hydraulic conditions existing at the heat transfer surface.

The annular test section is an annular duct in which a short section of the inner concentric core is electrically heated and temperature sensors in the wall are used to measure the wall temperature. This central core is called the heater rod. The annular test section offers several advantages over a tubular test section in which a short length is heated and temperature sensors are placed in the wall of the tube. In a majority of situations, a glass outer tube may be used on the annular section, so the progress of fouling may be visually observed. The central heating

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[4] Number of starts equals the number of flutes or grooves counted around the tube circumference on a plane perpendicular to the axis of the tube.

rod may be removed and the fouling deposit studied in situ or removed for further analysis. The rod may be easily cleaned for subsequent tests. This cannot be done with tubular test sections.

In the range of annular equivalent diameters that are in use (½-inch to ¾-inch equivalent diameter), the fluid mechanics near the surface where the fouling occurs are predictable and are identical both for the annular test section and for the circular tube. It is, therefore, possible to simulate, in the annulus, the thermal hydraulic flow conditions existing in the tube. Heat transfer conditions for a fluid flowing through a tube in a heat exchanger (i.e., wall surface temperature and wall shear stress in the fluid flowing adjacent to the surface) can be duplicated in the annular test section and the fouling characteristics of the fluid may be determined. Studies have shown that if a fluid is tested simultaneously under identical conditions of wall temperature and wall shear stress in a tube and in an annular test section, identical fouling results are obtained.[10]

TESTING AND RESULTS

A laboratory system was adapted to have two test heat exchanger sections run in parallel in the same cooling system (Figure 1). One test section was equipped with an enhanced tube. The other test section used a standard smooth tube. The test protocol called for both tubes to be of the same copper metallurgy and to emulate the same tube-side flow conditions, which were a velocity of 1.6 m/s (5 ft/sec) and a surface temperature of 35-37.8 °C (95-100 °F). Initially, a baseline test was run with city water that was not permitted to concentrate. This test was performed to prove that the protocol was properly constructed. Subsequent tests were run with city water that was naturally concentrated by the system to a level of 5 cycles of concentration.

The test system consists of a cooling tower, a circulating pump, a small water-to-water heat exchanger, which is used to supply a heat load to allow the tower water to concentrate, and a laboratory version of Ashland's online cooling water monitor, which consists of three parallel independent heat transfer test sections (Figure 2). The system has an operating volume of 0.22 m^3 (58 gallons), a cold water temperature of 33° C (92° F) and a temperature drop of 2.8° C (5° F) across the tower. Maximum circulation is 76 L/min (20 gpm). During these tests, a portion of the circulating water was bypassed to the tower basin to maintain the cold water temperature (Table 1). The system is automated. The concentration of circulating water is maintained by conductivity control. In addition, fouling factor, pH and ORP are constantly monitored.

Initially, tests were conducted to determine the relative fouling tendency of enhanced tubes versus smooth tubes in the presence of inorganic foulants, such as calcium carbonate and calcium phosphate in the absence of biomass. An organic deposit and corrosion control additive blend was also present in the cooling water. The chemistry under which the tests were performed is listed in Table 2. Under those conditions, with a velocity of 1.6 m/sec. (5 ft/sec.) and a surface temperature of 65.5 °C (150 °F) on the smooth tube, fouling resulted within 7 days (standard water chemistry concentrated 5 times). At a lower surface temperature of 54.4 °C (130 °F), fouling of the smooth tube was not observed until the 14th day at which time the standard water chemistry was concentrated to 9.0 times with an additional 1.5 mg/L of orthophosphate present. The enhanced tube required an increase in skin temperature to 63 °C (145 °F) in conjunction with concentrating the standard water chemistry by a factor of 9.5 and an additional presence of 1.9 mg/L of orthophosphate. Under these conditions, the

Figure 1: Heat Transfer Section

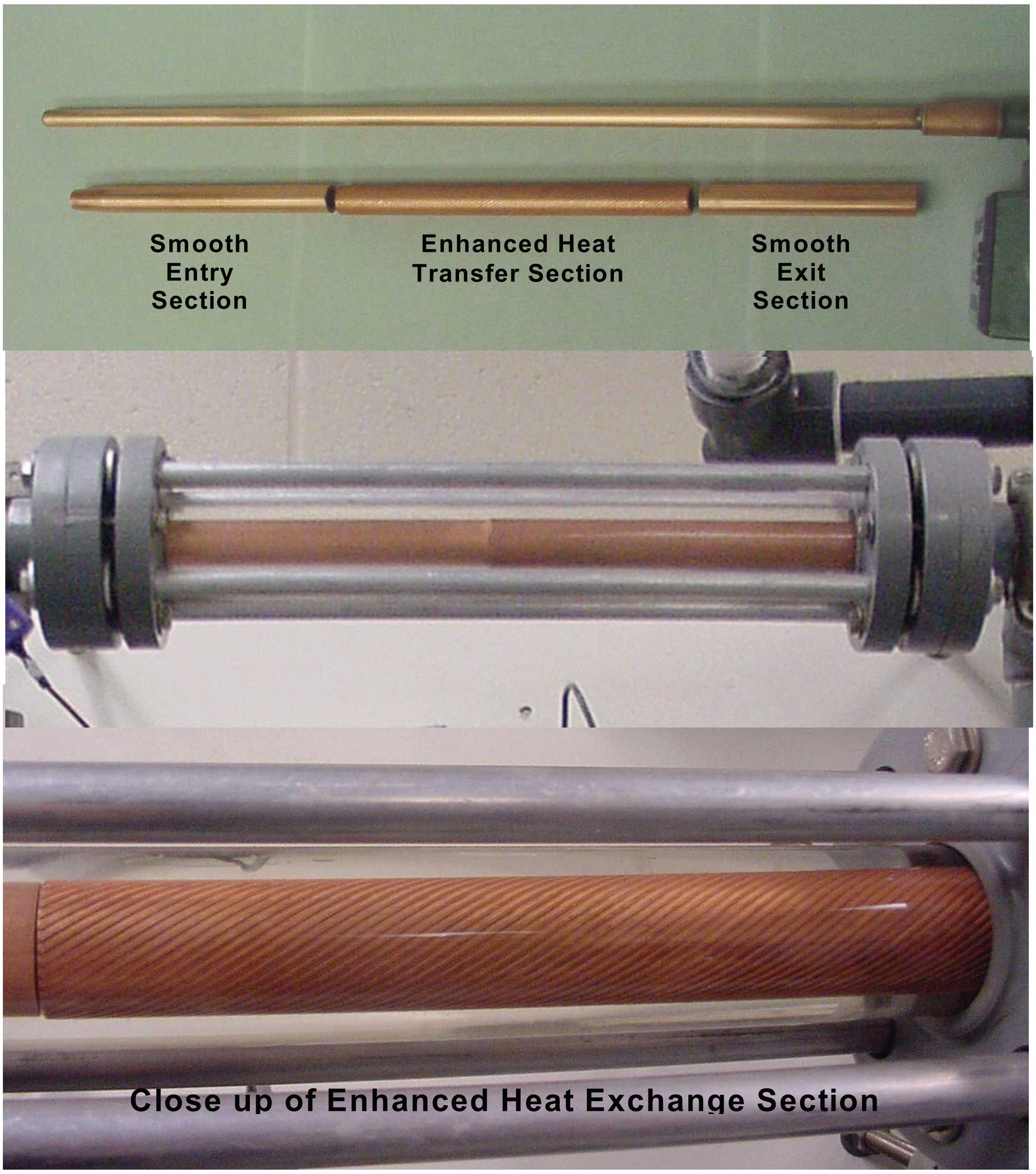


Figure 2: Pilot Cooling Tower Test Rig

Figure 2A

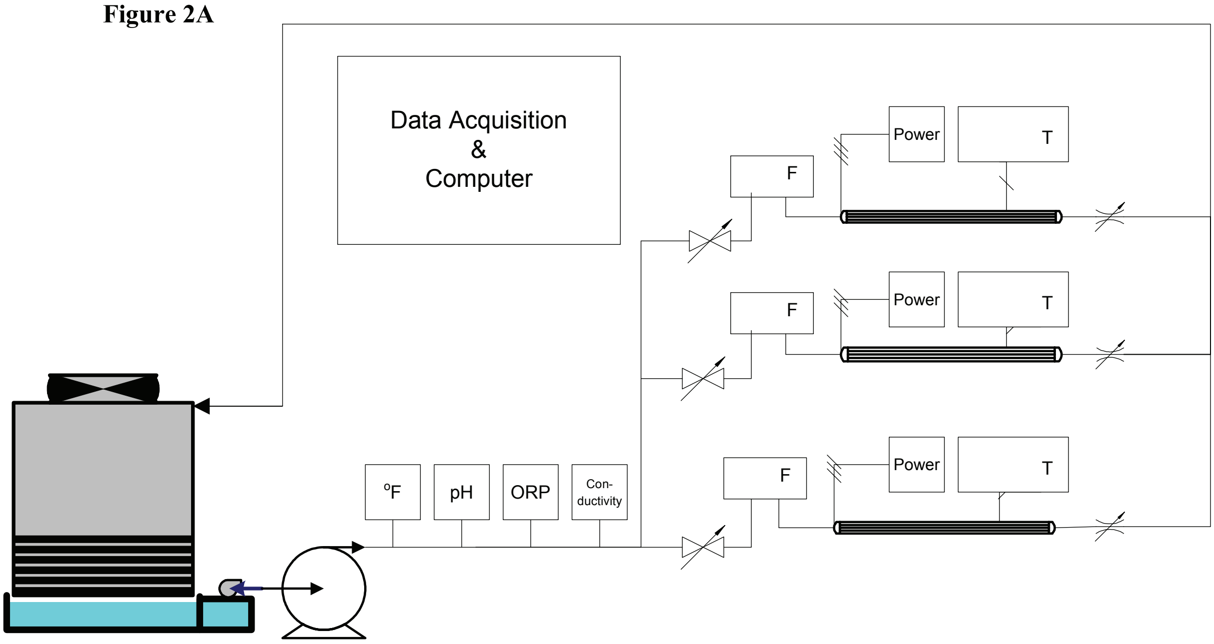


Table 1: Pilot Cooling Tower Test Rig Operating Design Conditions

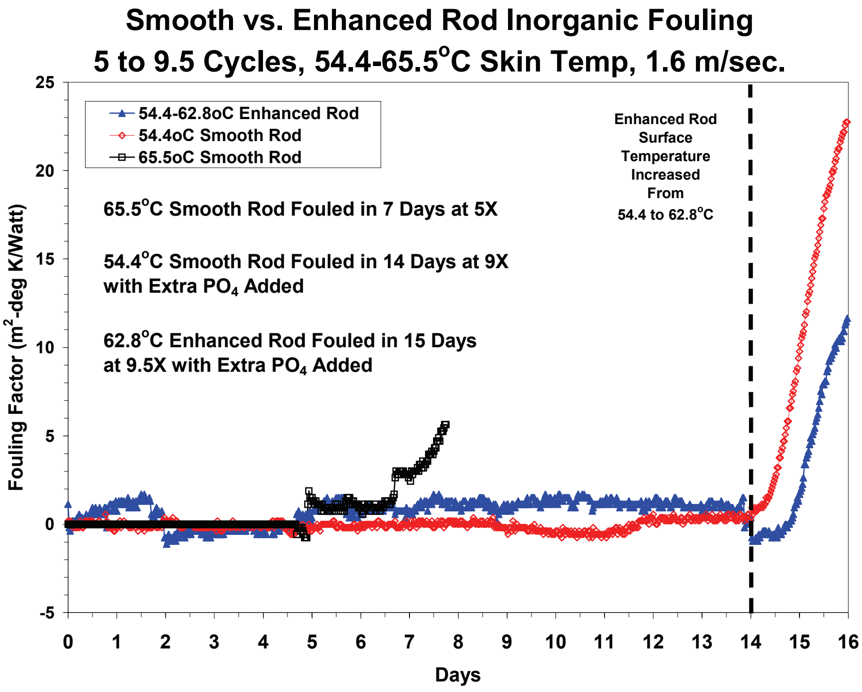
Pilot Cooling Tower Test Rig Operating Design Conditions	
System Volume:	0.22 m^3 (58 gallons)
Recirculation Rate:	4.542m^3/hr (20 gpm)
Volume to Recirculation Ratio:	3:1
Cooling Tower Temperature Drop (ΔT):	2. 8° C (5° F)
Cooling Water Apparent Retention Time in Test Rig:	Approximately 22 to 23 hours
Standard Uncycled Makeup Water Chemistry	
Calcium, mg/L as $CaCO_3$	81
Magnesium mg/L as $CaCO_3$	48
Total Alkalinity, mg/L as $CaCO_3$	96
Bicarbonate Alkalinity, mg/L as $CaCO_3$	96
Chloride mg/L as Cl	58
Sulfate, mg/L as SO_4	46
pH	7.4

Table 2: Inorganic Crystallization Test Run Water Chemistry & Data

Inorganic Crystallization Test Run Water Chemistry and Data			
Standard Water Cycled	5 Cycles	9 Cycles	9.5 Cycles
pH:	8.8	8.8	8.3
"P" Alkalinity, mg/L as $CaCO_3$:	52	73	0
Carbonate, mg/L as $CaCO_3$:	104	146	0
Total Alkalinity, mg/L as $CaCO_3$:	420	579	578
Bicarbonate, mg/L as $CaCO_3$:	316	433	578
Calcium Hardness, mg/L as $CaCO_3$:	397	404	400
Magnesium Hardness, mg/L as $CaCO_3$:	265	575	628
Chloride, mg/L as Cl:	354	639	697
Sulfate, mg/L as SO_4:	415	514	526
Ortho Phosphate, mg/L as PO_4:	2.5	4.0	4.4
Conductivity, μS/cm^2:	2340	4770	5200
Tube Velocity, m/sec. – 1.6			
Skin Temperatures °C – 54.4, 62.8, 65.5			
Deposit Control Additive -150 mg/L, (12.5 mg/L active deposit control compounds)			

enhanced tube took approximately twice as long to foul in the presence of almost double (i.e., 1.9x) the amount of inorganic impurities than the smooth tube. The results are illustrated in Fig. 3.

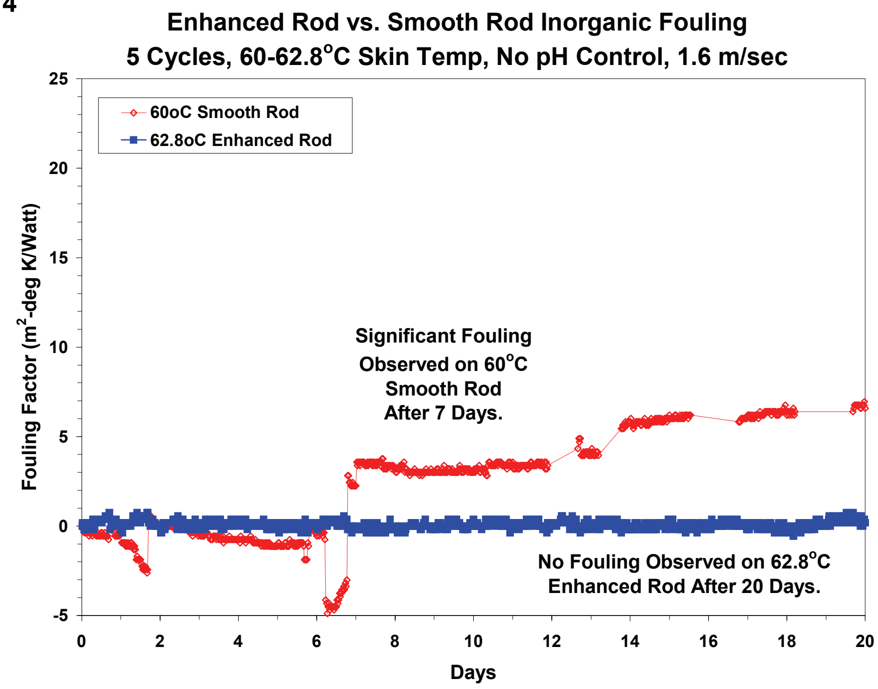
Figure 3



This test was repeated with one enhanced tube (63 °C) and one smooth tube (60 °C) with the standard water chemistry concentrated to 5 cycles.

The smooth tube fouled in 7 days, but the enhanced tube did not foul in the 20 days when the test was terminated as illustrated in Figure 4. Subsequent tests confirmed these results.

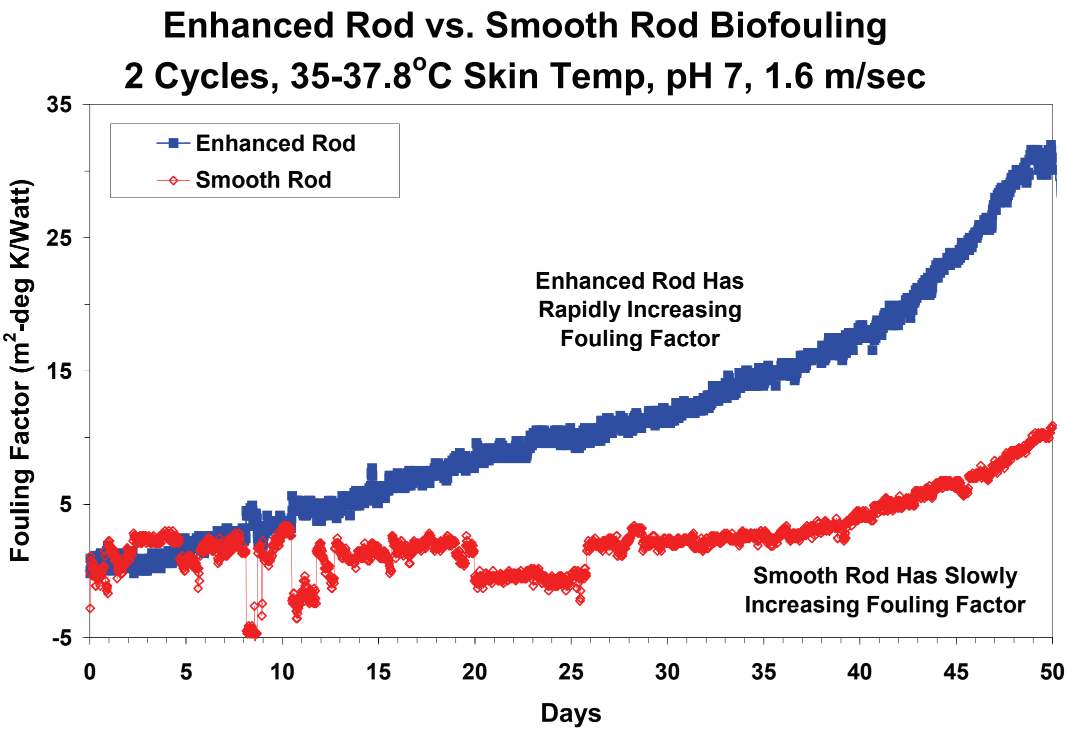
Figure 4



Further experiments were focused on fouling associated with biomass and to discover an efficient means to remove accumulated biomass. A blank biofouling run was performed where the cooling water was inoculated with *Pseudomonas aerigenosa* (ATCC 27853), a known slime-forming aerobic bacterium.

Nutrient broth was added to the tower daily at a dose of 50 mg/L. Chemistry and data associated with this test run are provided in Table 3. Although biofouling was observable with the naked eye by the seventh day into the run, it was actually detected as an increasing trend on the third and fifth day by the enhanced tube and smooth tube respectively. The enhanced tube fouled at a linear rate of 0.439 m^2 - °K/Watt-sec., while the smooth tube fouled at a rate of 0.097 m^2 - °K/Watt-sec., as illustrated in Figure 5.

Figure 5



All subsequent tests were run until the enhanced tube flutes were filled with foulants, then various chemistries were employed to clean the tubes. The smooth tube never did foul as fast as the enhanced tube, nor did it foul to the extent seen with the enhanced tube. Surprisingly, when a cleaning chemistry was found to be effective on the enhanced tube, it was also found to clean the enhanced tube faster and to a greater degree than the smooth tube. Biodispersants were slug fed daily during this testing phase. These biodispersants can be generically categorized as follows:

Dispersant A – Biodegradable terpene dispersant
Dispersant B – Nonionic ester dispersant
Dispersant C – Amide based dispersant
Dispersant D – Nonionic ethoxylated dispersant

The water chemistry for these experimental runs is listed in Table 3.

The various oxidants slug fed daily to various ORP values over a 4-hour period/day during the testing periods were:

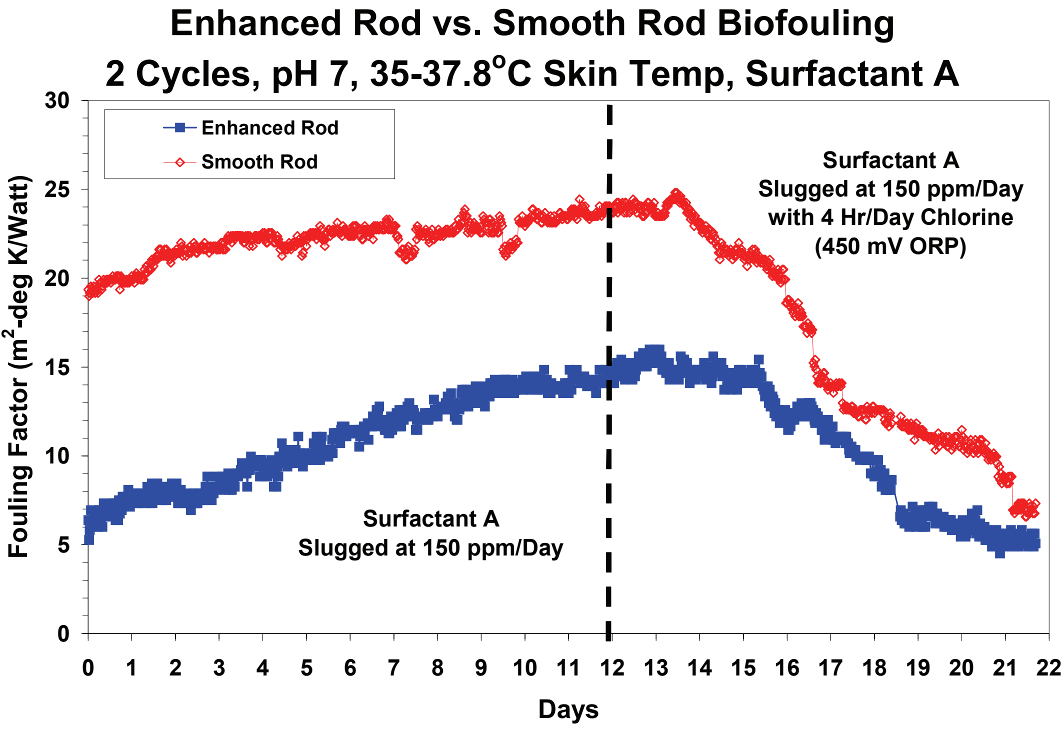
Chlorine (sodium hypochlorite)
Bromine (activated bromide)
Chlorine dioxide
Stabilized bromine

Table 3: Generalized Experimental Biofouling Runs – Water Chemistry

Generalized Experimental Biofouling Runs-Water Chemistry and Data	
PH:	8.5
"P" Alkalinity, mg/L as $CaCO_3$:	14
Carbonate, mg/L as $CaCO_3$:	28
Total Alkalinity, mg/L as $CaCO_3$:	186
Bicarbonate, mg/L as $CaCO_3$:	158
Calcium Hardness, mg/L as $CaCO_3$:	243
Magnesium Hardness, mg/L as $CaCO_3$:	144
Chloride, mg/L as Cl:	174
Sulfate, mg/L as SO_4:	240
Conductivity, □S/cm^2:	1404
Note: Aerobic bacteria, nutrient broth, tube velocity and skin temperature data remain the same as shown in Table 2	

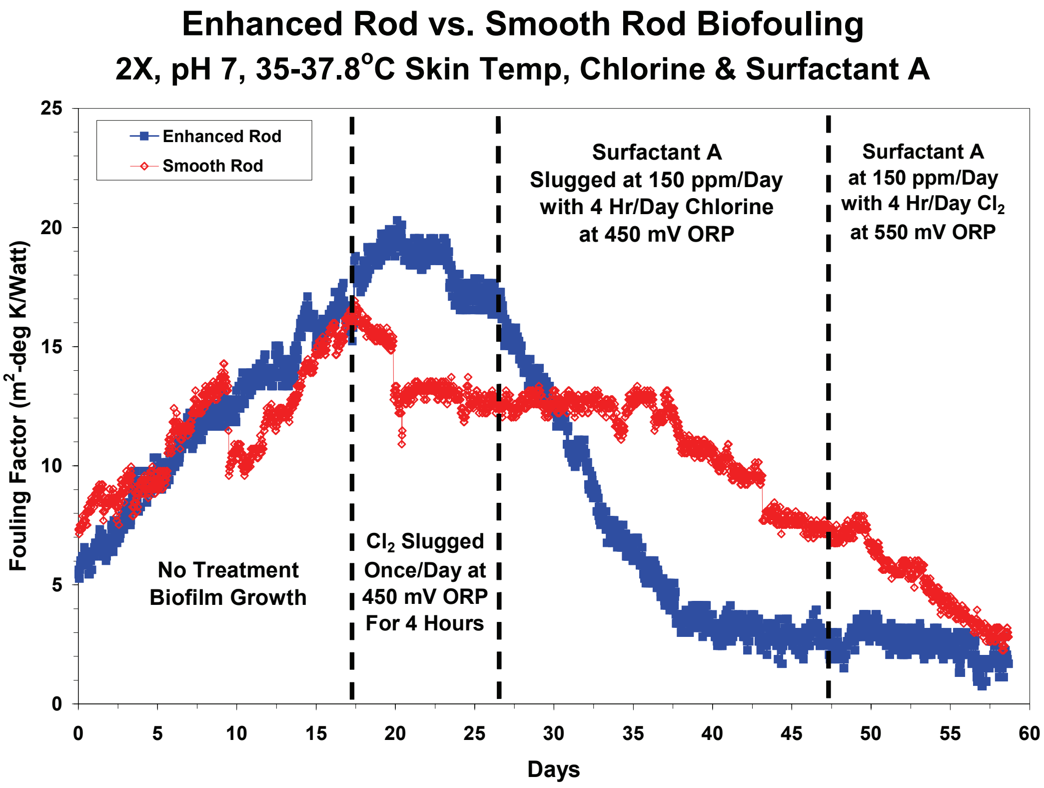
After the blank biofouling run, Dispersant A was slug fed at 150 ppm daily. After 12 days, both the enhanced and smooth tubes continued to foul, though at a slower rate. Beginning on the 13th day, chlorine was slugged over a 4-hour period/day to maintain an Oxidation-Reduction-Potential (ORP) of +450 mV. The fouling factors on both tubes dropped, though neither one returned to satisfactory conditions for a refrigeration machine as illustrated in Figure 6.

Figure 6



At this point, the biofilm was allowed to build up once again in the absence of dispersant or oxidant. On the 17th day, chlorine addition was re-instituted. Oxidant alone was able to contain the fouling on the enhanced tube and reduce the fouling on the smooth tube by 25% over the succeeding 10-day period. For the final 25 days, Dispersant A was again slug fed daily at 150 mg/l along with the daily slug of chlorine. Cleanup rates of the remaining biofoulant were 82% for the enhanced tube and only 50% for the smooth tube. At this point, it was hypothesized that increased turbulence from the tube enhancements was a principal factor in the cleaning efficiency. This biofouling run is illustrated in Figure 7.

Figure 7



Differences in applied oxidants were investigated next. Biofilm growth was again promoted prior to bromine oxidant slug feed for 4 hours per day to +550 mV ORP for 9 days followed by the slug feeding of Dispersant A at 150 mg/l per day. The same trend as the previous run (Figure 7) was experienced and illustrated in Figure 8. Chlorine dioxide was utilized as the next oxidant. Chlorine dioxide was slug fed for 4 hours/day to maintain an ORP of +400mV. The results are illustrated in Figure 9. Quite surprisingly, chlorine dioxide alone gave equivalent performance to the combination of either bromine or chlorine with a biodispersant in the equivalent time period. These treatments were found to lower fouling factors to levels that are very acceptable for refrigeration equipment.

Finally, a proprietary stabilized bromine oxidant was tested at a slug feed of 4 hours per day without dispersant. Initially, the oxidant slug feed was performed to maintain +325 mV ORP, which did not halt biofilm growth on the heat transfer rod (Figure 10). An increase in oxidant feed to maintain +425 mV ORP followed (Figure 11). At this oxidant residual, the fouling associated with biofilm growth was terminated, which resulted in an on-line cleanup of the heat transfer rod. These results and the cleanup profile were similar to chlorine dioxide. However, the cleanup rate was about twice the duration as chlorine dioxide.

Figure 8

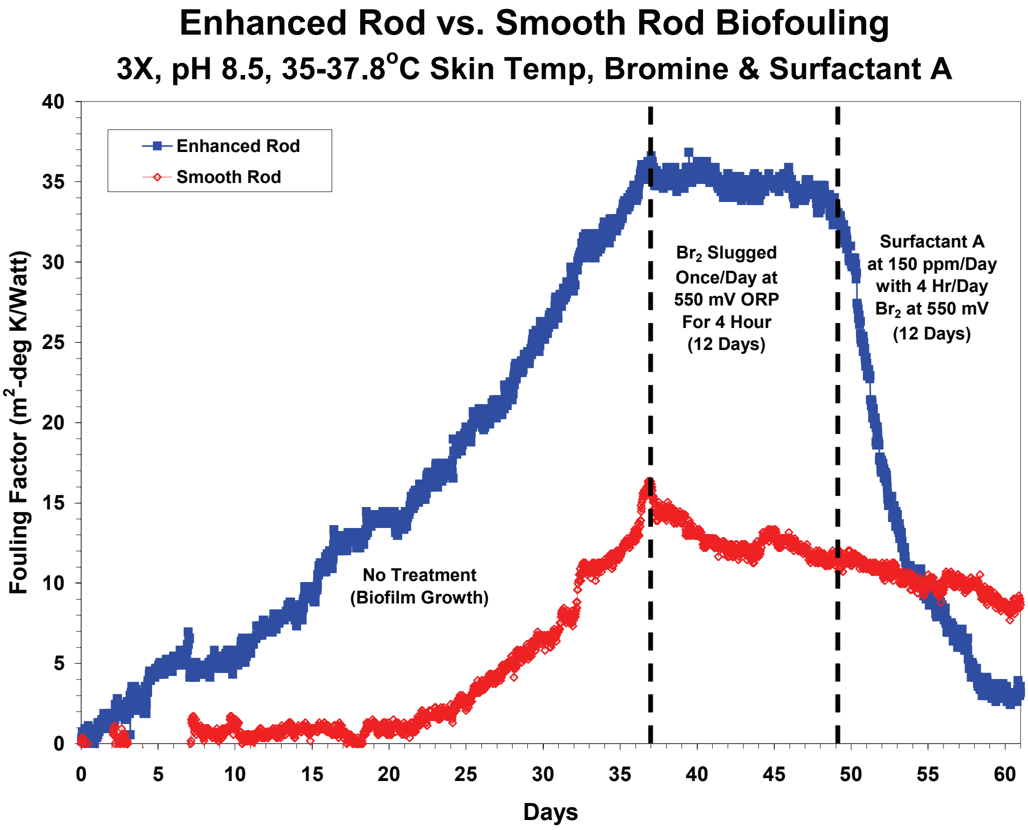


Figure 9

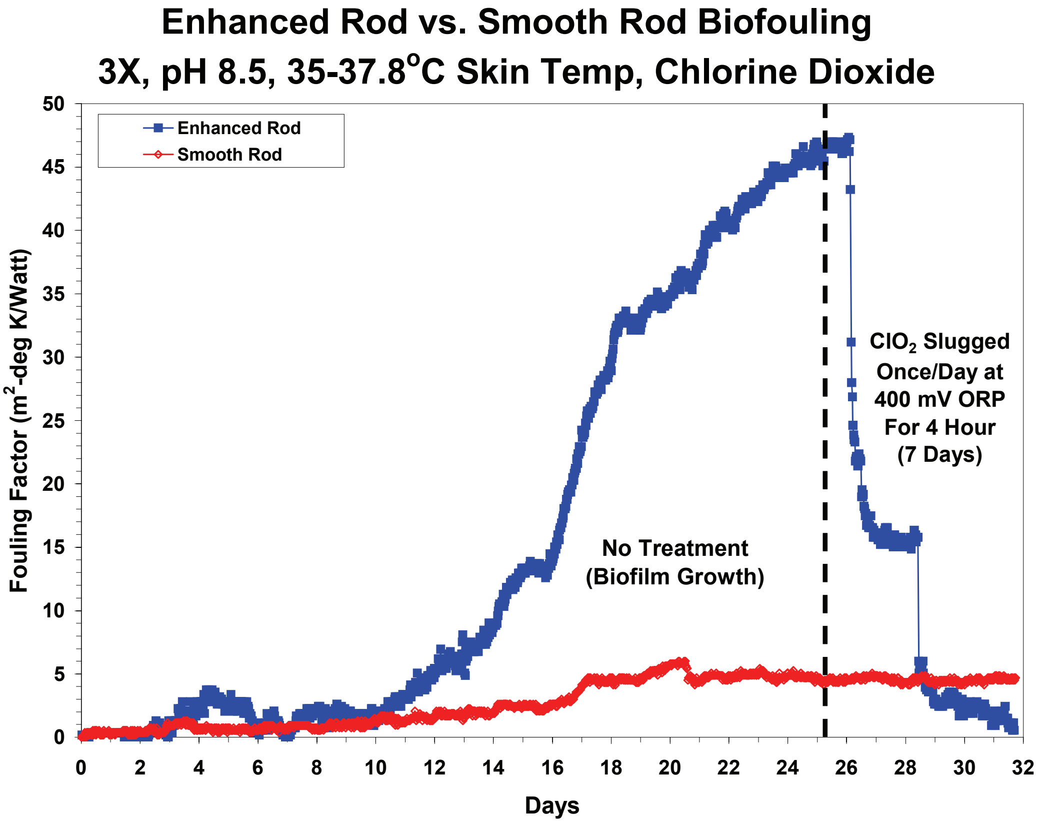


Figure 10

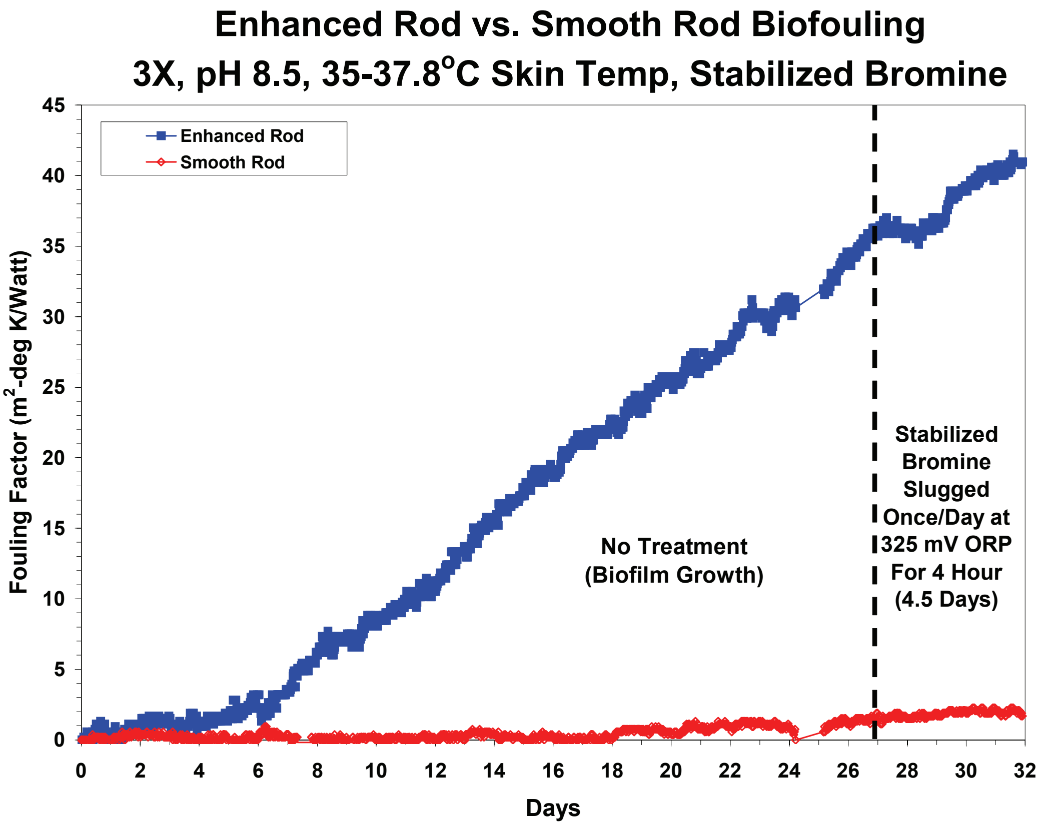
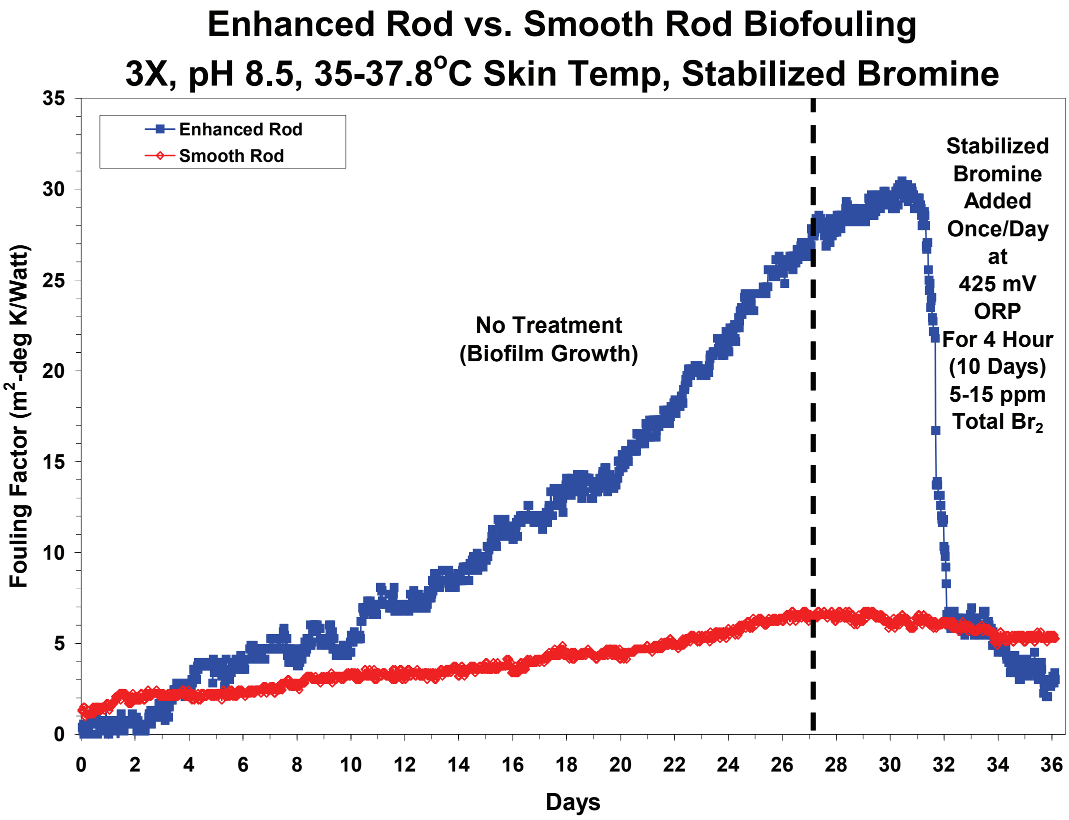


Figure 11



Cleanup ability and efficiency of three other biodispersants with inherently different chemistry were investigated. Bromine oxidant was slug fed 4 hours per day to maintain +475 to +550 mV ORP. During this time, biodispersant was slug fed daily. Biofilm removal profiles of these biodispersants are illustrated in Figures 12, 13, 14. Overall, these results and the results revealed in Figure 8 indicate that different chemistries do not produce equivalent cleanup rates. The Dispersant C cleanup profile suggests biofilm penetration followed by foulant release while the Dispersant D foulant removal is very gradual. An initial foulant conditioning time period was revealed with Dispersant B and Dispersant C applications. Biofoulant cleanup rates on an equivalent active solids basis were as follows:

Biodispersant	Dosage, mg/L	Time to Clean, Days
Dispersant B	200	5
Dispersant C	50	6
Dispersant A	150	7
Dispersant D	200	12

Figure 12

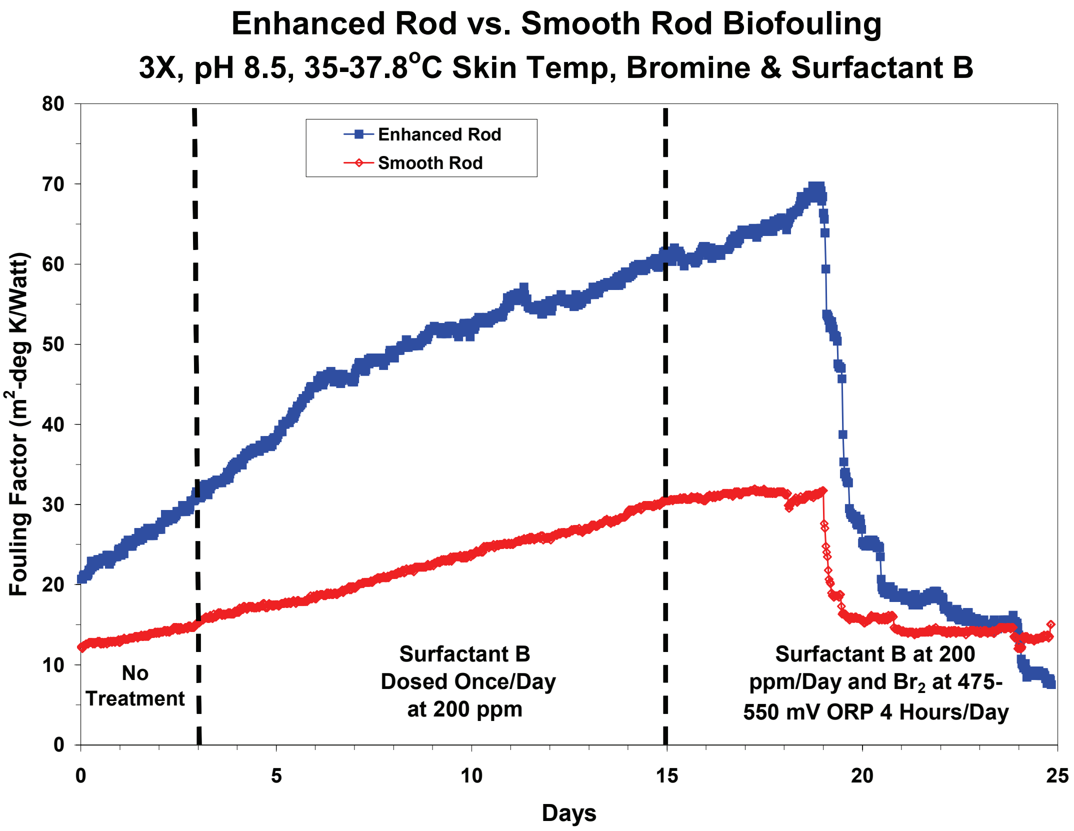


Figure 13

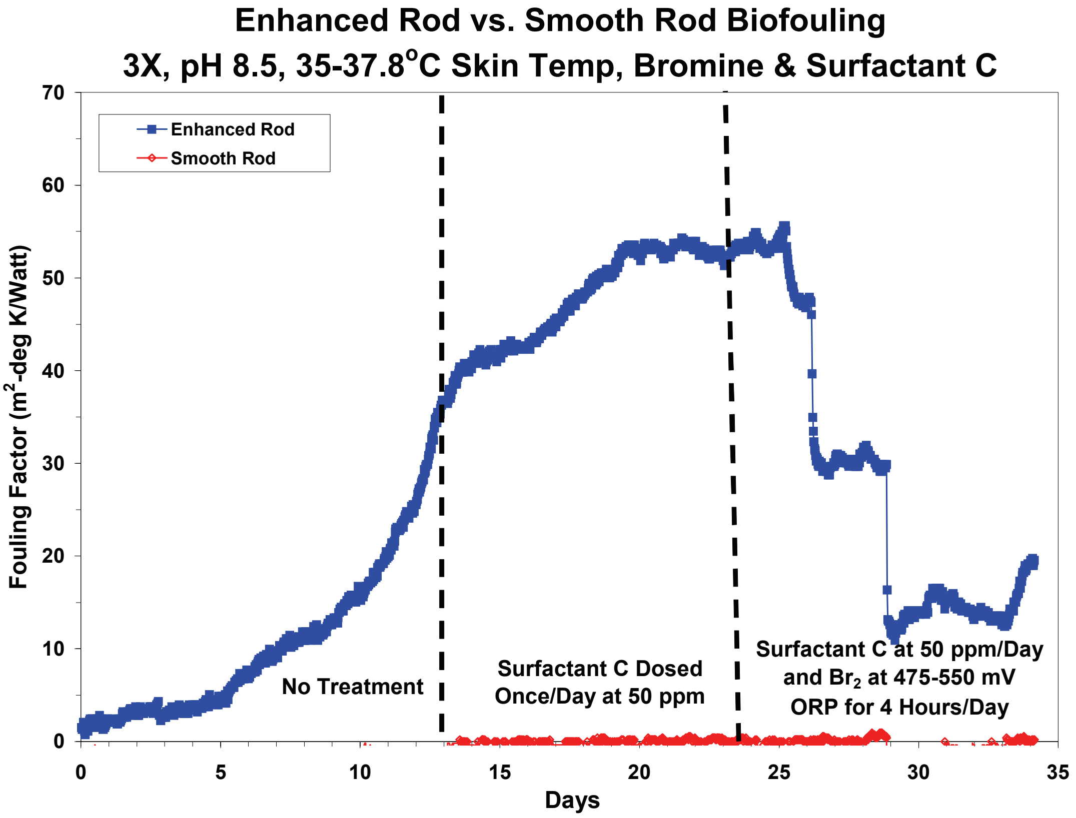
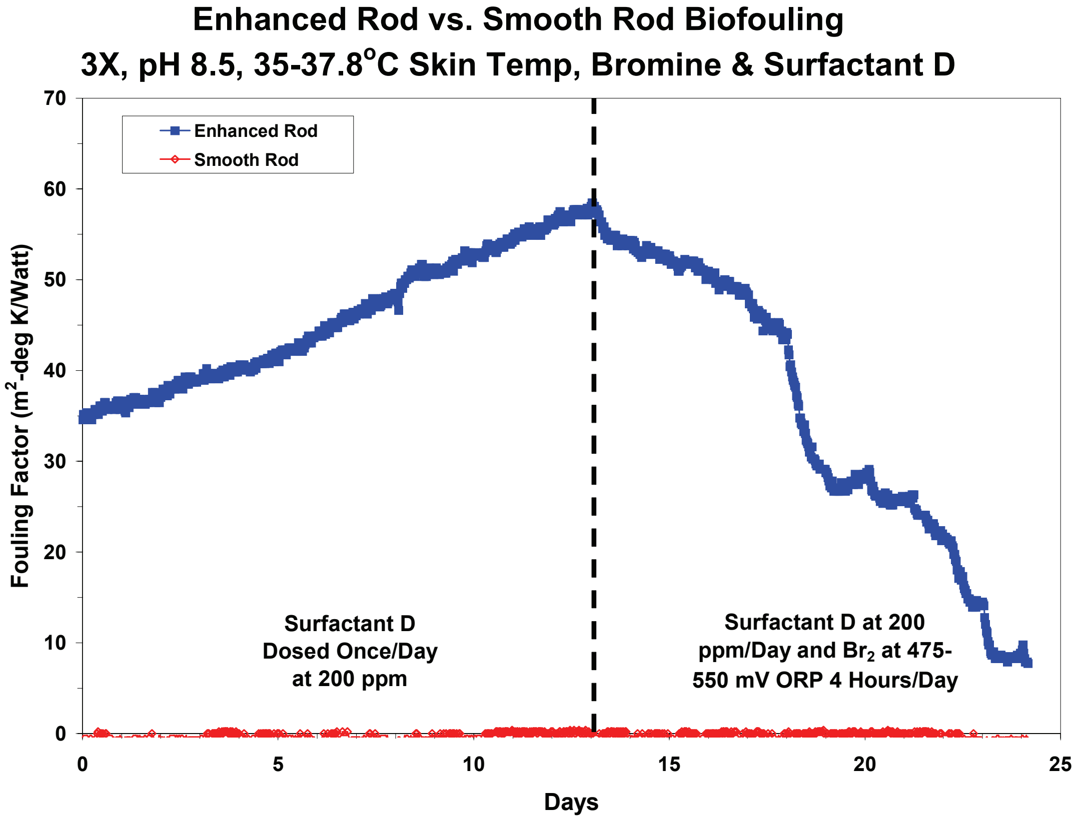


Figure 14



SUMMARY

Simulation of cooling waters under fouling conditions was achieved with the dynamic pilot system in the laboratory. Experimental investigations provided further insight in regard to the fouling behavior of enhanced tubes compared to smooth bore tubes. A brief summary is provided in Table 5. In particular, it was noted from the laboratory work that:

Inorganic crystallization/precipitation fouling potential is lower for enhanced tubes.

Enhanced tubes foul faster and to a higher degree than smooth bore tubes when the potential for biofouling is present.

Biodispersants alone are not as effective in the reduction of biofoulants on heat transfer surfaces.

Conventional oxidants such as chlorine or bromine usage at dosing rates that afford planktonic bacteria control while avoiding the potential to initiate localized corrosion of copper alloy heat exchanger tubes are not effective in reducing biofoulants (sessile bacteria) alone when present on heat transfer surfaces. Increasing the ORP from +450 to +550 mV produced only marginal improvements in biofilm removal efficacy. The supplemental use of biodispersants greatly enhances the biofouling removal efficacy of oxidizing biocides.

Chlorine dioxide or proprietary bromine oxidant chemistry provides equivalent clean-up of biofoulants without the use of supplemental biodispersants. The application of chlorine dioxide alone provides the fastest biofoulant removal times compared to all other clean-up processes investigated.

The annular test section fitted with the enhanced tube geometry detects the onset of biofouling in about 2 to 3 days compared to the smooth bore tube which reveals such by the fifth day as seen in Table 4.

Table 4

Fouling of Heat Transfer Tubes

Foulant	Time Delay Prior to Fouling (t_D)	General Fouling Rate of Heat Transfer Tubes	
		Smooth Bore	Enhanced Surface
Suspended Solids (Particulate)	No	Slow	Fast
Crystallization (Precipitation)	Yes	Fast	Slow
Biofilm Formation	Yes	Slow	Fast

CONCLUSIONS

A non-corrosive method has been developed to remove biological and biologically entrapped foulants from enhanced tubes without jeopardizing the integrity of the tubes. The addition of a supplemental biodispersant was observed to significantly improve foulant removal when utilizing conventional oxidants at concentrations below where localized corrosion can be initiated. The importance of dispersant chemistry is secondary. Dispersants with biofilm removal efficacy[11,12] will differ in the amount of time required to reduce the foulant loading on the tube surface. Chlorine dioxide was shown to have the fastest cleanup rate and does not require biodispersant assistance.

An enhanced tube incorporated in a side stream heat transfer test section can be employed to detect fouling occurrence rapidly as well as tracking the cleanup improvements to completion. This capability can provide enhancements to performance-based monitoring control for cooling waters. If used in conjunction with a smooth bore tube monitor in parallel, an enhanced tube monitor can allow for categorization of the type of foulant that is detected. Thus, the appropriate mitigation method and chemistry selection can be implemented.[13,14,15,16]

These monitoring capabilities provide rapid foulant detection/characterization and allow for proactive corrective treatment measures that can prevent excessive heat transfer losses and the development of localized corrosion. This monitoring and foulant control technology should allow for a broader acceptance and applicability of the use of enhanced tubes in the cooling water industry.

ACKNOWLEDGEMENTS

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