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BIOFOULING CONTROL USING ULTRASONIC AND ULTRAVIOLET TREATMENTS*

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ABSTRACT: Experiments were conducted at the Natural Energy Laboratory of Hawaii to determine the effectiveness of non-chemical techniques to control biofouling. The two techniques investigated were ultrasonic and ultraviolet. The colonization of microorganisms attracts higher order organisms; therefore, deactivation of microorganisms to prevent colony should reduce the fouling propensity. The major objective of the present investigation was to develop a biofouling model and analyze the experimental data to show the effects of reducing the microorganism activation in the incoming water. The results show that reducing the microorganism activation in the incoming water increases the induction period of low fouling rate, but the growth is not affected.

INTRODUCTION

Biofouling is a complex process of attachment of microorganisms, growth, and removal of biofilm. Several studies [e.g., Characklis, 1991] have been carried out to understand steps associated with biofouling. The development of an effective fouling-mitigation method requires understanding of a governing step(s). It is well recognized that biofouling is very sensitive to physical, chemical, and biochemical parameters. Typically, biofouling is associated with crystallization and/or particulate fouling. The later being the most common, because crystallization fouling occurs at higher temperatures at which biofouling is significantly reduced. Although mathematical expressions have been developed [Characklis, 1991], it is not possible to predict the rate of biofouling on the basis of water properties and operating conditions. It is however possible to estimate the biofouling propensity for a given water, and thereby evaluate control methods. The major uncertainty is the interactive effects of biofouling and particulate fouling for corrosion-resistance material and biofouling and corrosion fouling for corrosion-susceptive materials.

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DISCLAIMER

The most common biofouling-control method is chlorination; however, there is an increasing pressure to reduce or eliminate the use of chlorine. The utility industry developed so called "target chlorination" in order to comply with the environmental regulations [Mussalli, et al., 1985]. Further reduction in chlorination may or may not be effective to control biofouling; therefore, alternate methods need to be developed. The mechanical methods, such as sponge-ball cleaning [Renfftlen, 1989], are used in selected places, but for the reasons of costs, pressure-drop penalties, and uncertainty of their effectiveness to control biofouling, they are not widely used. Flemming [1991] provided a summary of current and potential biofouling control methods. Among them were ultraviolet [UV] and ultrasound [US] methods.

The UV irradiation is shown to be effective for destroying certain class of microorganisms; therefore, it is commonly considered for disinfecting water. However, it is not commonly used for controlling biofouling. Referring to the early investigations [Meltzer, 1987; and Kreft, et al., 1986], Flemming [1991] indicated that the effectiveness of the UV irradiation for removing an established biofilm may be low due to entrapped particles and opaque biofilm may shield microorganisms. No long-term data are reported to determine the effectiveness of the UV irradiation of incoming water for preventing microorganisms from depositing on the surface. Photoinactivation or photostunning of the marine microorganisms to prevent their attachment to the heat-exchanger surface is the desired result of the UV irradiation. Photoinactivation in single cell organisms is expected primarily due to the interaction of photon with the DNA molecule [Jagger, 1979; and Yang, 1976]. Some of the DNA alternations are irreparable, while the others are reparable in a given time [Calkins, 1971]. Cruver [1981] presented the UV dosage, expressed as W-sec/cm^2, required for different microorganisms for 90% and 100% inhibition of colony development. The natural water, depending upon sources, contain many classes of microorganisms; therefore, determination of the effects of the UV irradiation on the overall biofouling process under prototype flow conditions is important.

The US treatment is commonly used for removing deposits from the surface by producing cavitation. The previous investigations [Hill, et al., 1981; Zips, et al., 1990; Pandolfini, et al., 1979; Burton, et al., 1984] showed promising results of biofilm removal; however, the lack of understanding to predict the energy requirement and scale-up to industrial heat exchangers are two major technical issues. Determination of the physical structure and chemical make up of an established biofilm is essential to evaluate the effectiveness of the US treatment for removal of biofilm with an acceptable energy level. No data available to evaluate the effectiveness of the US treatment of the incoming water for preventing microorganisms from depositing on the surface. The US treatment may not destroy microorganisms but it may temporarily inactivate them, and thereby prevent them from depositing on the surface.

An investigation was carried out to determine the effectiveness of the UV and US treatments of the incoming water. The experimental data were presented by Takahashi et al., [1986]. The present analysis was carried out to quantify the effects of reducing microorganisms in the incoming water on the fouling rate.

EXPERIMENTS

A long-term biofouling program at the Natural Energy Laboratory of Hawaii was conducted for a period of about 10 years [Panchal et al., 1985, Panchal et al. 1990]. A detailed description of the test facility is given by Panchal et al. [1990]. The warm-water intake is located about 100 meters offshore in a water depth of 20 meters. The water quality at the test facility represented tropical open-ocean water without significant changes for the whole year. The water temperature ranged between 25 °C during winter and 29 °C during summer. Average properties of the water are given in Table 1. The fouling resistance was measured by a heat-transfer monitor [HTM] with an accuracy of 0.0035 m^2 K/kW.

TABLE 1
Average water properties.

Water Parameters	Value
Temperature, °C	25 to 29
pH	8.2
Salinity, mg%	34.7
TOC, microgram-atom/L	0.75
TDN, microgram-atom/L	4.23
Dissolve oxygen, mL/L	5.0

The UV unit consisted of mercury lamps irradiating through a Teflon pipe. Four UV lamps were installed around a column of four Teflon tubes to obtain a full coverage of the passing water. Figure 1 shows a schematic view of the UV unit. The interior of the enclosure acted as a reflector to ensure maximum UV dosage. The total system features a maximum UV dosage of 30 mW-sec/cm^2 at 113 L/m water flow. The power requirement of this unit was 200 watts. The model number was 30H and it was manufactured by Ultraviolet Technology of Sacramento. An overall flow diagram for the UV tests is shown in Figure 2.

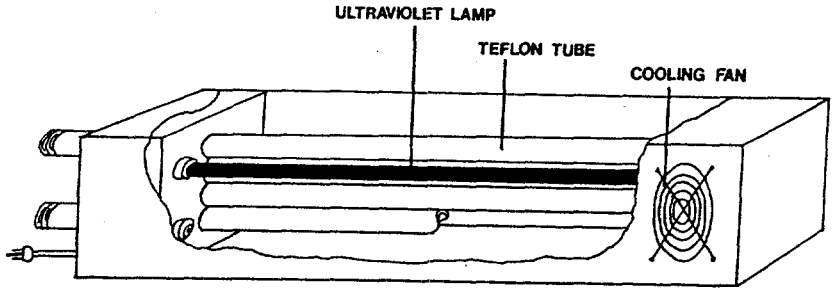

Figure 1. Ultraviolet unit.

The schematics for the flow loop and the US transducer are shown in Figure 3 and 4, respectively. A PVC chamber was equipped with a stainless steel US transducer designed to produce cavitation at 22 kHz in the chamber with a volume of 1.13 liters. An average sound density was about 1 W/cm^2 at the transducer surface. Seawater entered through the bottom port and exited from the top port. The water-flow volume was 0.92 liters giving an average residence time of 1 second. The power consumption was about 50 watts. The delay-tank volume was 25.4 liters, which provided a residence time of 30 seconds for the water flow of 50.5 L/m that gave flow velocity of 1.83 m/s in the test section.

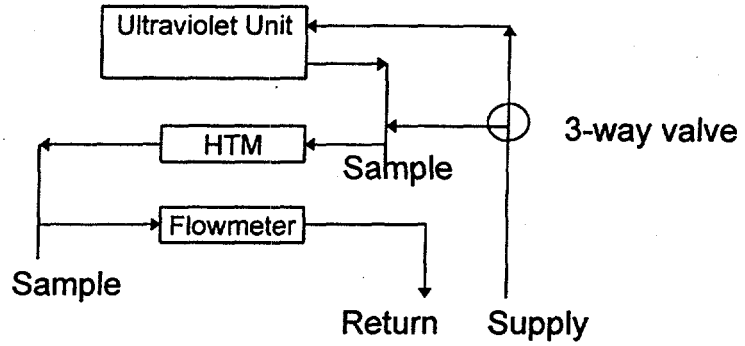

Figure 2. Flow loop for ultraviolet tests.

A control test loop was used to monitor the rate of fouling without any treatment. The free-fouling loop was run in parallel with the other two flow loops, and thereby a direct comparison of the fouling data could be made. The water velocity was typically maintained at about 1.8 m/s for control tests. The test section was brush cleaned when the fouling resistance reached to about 0.1 m^2 K/kW.

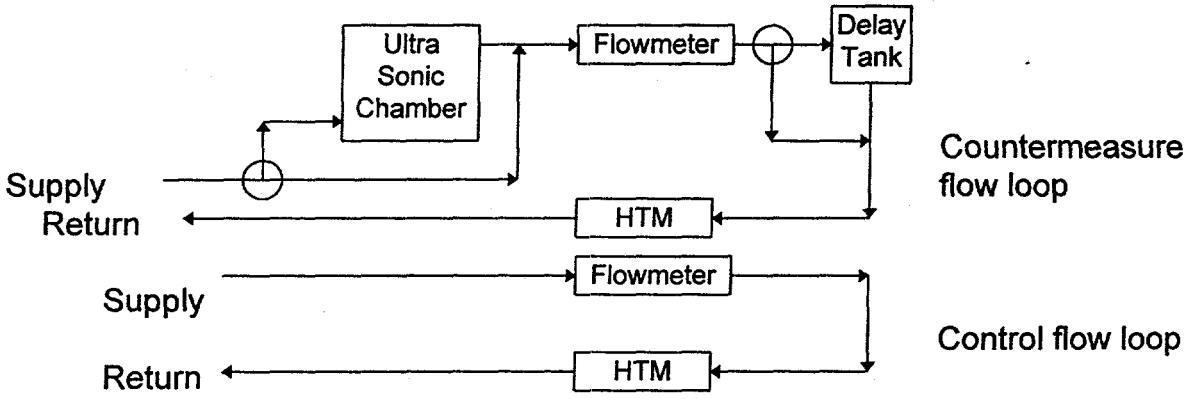

Figure 3. Flow loop for ultrasound tests.

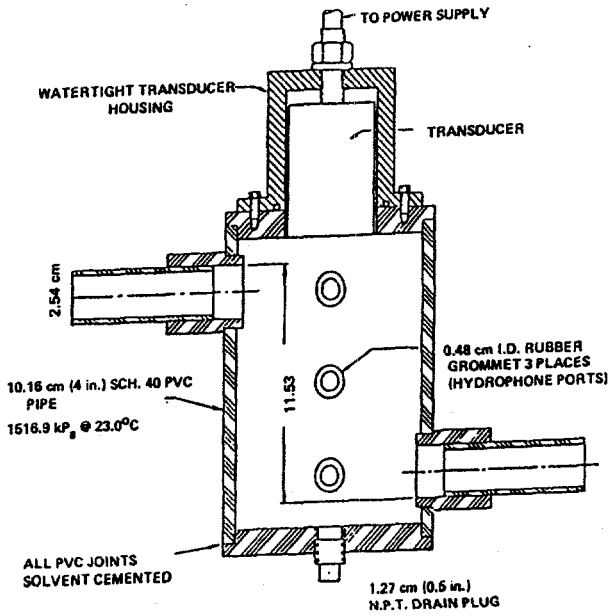

Figure 4. Ultrasound cavity unit.

BIOFOULING MODEL

The biofilm growth is affected by many physical and chemical parameters and it can be highly sensitive to a slight change in water chemistry, surface conditions, and operating conditions such as water velocity and temperature. Characklis [1991] discussed steps taking place in the biofouling process. He presented a comprehensive physical model for biofouling; however, the development of mathematical expressions for each of the biofouling steps is quite difficult. It is therefore important to under the governing step[s] and develop a simplistic expression that can characterize the overall process. The mathematical expressions can then be incorporated in a model that can predict the effects of physical and chemical parameters. Such a model can not only quantify the effects of physical and chemical parameters on the biofouling rate, but it should help to develop effective control methods.

Development of Biofouling Model

According to Characklis [1991], biofouling consists of three stages, 1) induction, 2) growth, and 3) plateau. Each stage consists of 1) transport of microorganisms and nutrients, 2) deposition, 3) surface growth, and 4) detachment and re-entrainment of biofilm. The biofouling resistance at the plateau stage is unacceptably high; therefore, the induction and growth stages are of major interest for the most industrial applications.

Characklis [1991] proposed the following expression to describe the biofouling process:

$$dR_f/dt = k\, R_f\, (1 - k'\, R_f) \qquad (1)$$

where

k	=	growth constant
k'	=	removal constant

This expression was developed on the basis of an assumption that biofouling is the net effects of growth and removal of biofilm. Equation 1 does not have the deposition term; therefore, it does not show the effects of reducing the living microorganisms by applying ultraviolet or ultrasound treatments to the incoming water. An equation is proposed in the present analysis to include the following three steps:

1. Deposition of microorganisms,
2. Growth, and
3. Removal of biofilm.

$$dR_f/dt = km\, F(v)\, Cm + k(T,x)\, R_f - \gamma\, \tau_w\, R_f \qquad (2)$$

where

km	=	transport coefficient for microorganism
F(v)	=	fraction of microorganisms re-entrained (function of velocity v)
Cm	=	concentration of microorganisms in the incoming water
k(T,x)	=	growth coefficient (function of the interface temperature T and nutrient concentration x)
γ	=	biofilm removal coefficient
τ_w	=	wall shear stress

The first term represents the net deposition of microorganisms. It is assumed that a fraction of microorganisms is re-entrained when they are in the transient stage. The second term assumes that the growth is first order with respect to biofilm. The third term represents removal of an established biofilm due to the wall shear and weakness of the film is proportional to the film thickness. It is quite difficult to obtain experimental data to calculate individual coefficients. However, it has been shown that there is good correlation between biofilm mass and fouling resistance [Panchal et al., 1985]. The surface roughness produced by the biofilm can be measured by change in the friction factor [Characklis, 1991]. It is also shown that there is a direct relationship between concentration and temperature with the growth [Panchal, 1985; Novak, 1981]. The film removal term is difficult to develop and the proposed third term in Equation 2 should be refined with the data obtained from controlled experiments.

For constant velocity and the interface temperature during a test, Equation 2 can be simplified by grouping coefficients as shown below.

$$dR_f/dt = \alpha\, Cm + \beta\, R_f \qquad (3)$$

where

$$\alpha = km\, F(v)$$
$$\beta = [k(T,x) - \gamma\, \tau_w]$$

Equation 3 is integrated to calculate R_f as a function of time.

$$R_f = (\alpha\, Cm)/\beta\, [\exp(\beta\, t) - 1] \qquad (4)$$

The two undetermined constants, α and β, were calculated from the fouling data. The model is then used to determine the effects of microorganism concentration, Cm.

RESULTS AND DISCUSSION

Biofouling experiments were conducted at constant velocity and at an isothermal condition of water temperature which remained within about 1 °C during a given test. The fouling curve for the control test without US or UV treatment is shown in Figure 5. It is a typical fouling curve obtained with tropical-ocean water. The test section was brush cleaned when the fouling resistance reached to a value in the range of 0.09 and 0.15 m^2 K/kW. A longer induction period was observed for the first cleaning cycle after which the fouling rate was comparable for each cycle. The fouling curve shown in Figure 5 represents the third cycle; therefore, it does not have the long induction period.

A regression analysis was used to determine constants, α Cm together and β. The values are as follows:

$\alpha\, Cm = 1.765\ 10^{-5}$ $\quad (m^2K/kW)/hr$

$\beta = 0.00258$ $\quad hr^{-1}$

The resulting equation was used to predict the fouling curve shown in Figure 5. It shows that Equation 4 closely represents the fouling resistance for the induction and growth periods. It should be now possible to evaluate the effects of reducing the microorganism concentration on the overall biofouling process.

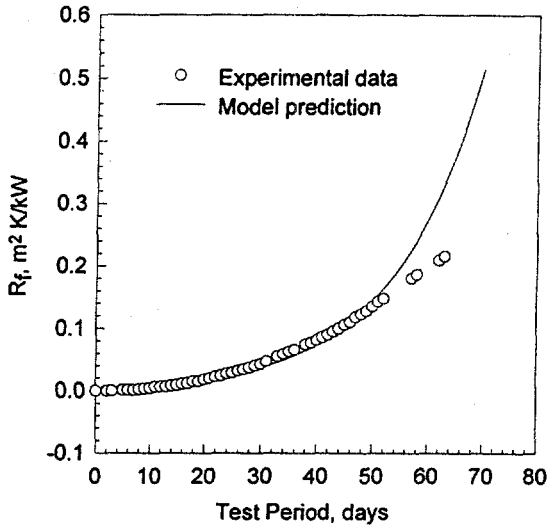

Figure 5. Experimental and predicted fouling curve.

Ultraviolet (UV) Irradiation

An experiment was carried out to determine the spore kill of microorganisms. In a laboratory set up, a collimated beam of UV at germicidal wavelength primarily of 253.7 nm was used. A detailed description of the spore test is given in the report [Takahashi, 1986]. The spore test was also carried out for seawater used for biofouling experiments at the Natural Energy Laboratory of Hawaii. In order to monitor the UV dosage that seawater received, B. Subtilis spores were injected into seawater preceding the UV unit. An analysis of the number of surviving spores after UV exposure compared to the number of spores in seawater determined the log survival values. The field data are presented in Figure 6; log survival as a function of exposure dose. Apparently stirring did not have much effects indicating the colony growth was not affected by the transport of nutrients. Note that E. Coli were effectively destroyed by UV irradiation. A linear regression of the data produced the following equation, where UV Dose was expressed in mW-sec/cm^2:

$$\text{Log Survival} = 0.06586 - 0.013483\ \text{UV Dose} \qquad (5)$$

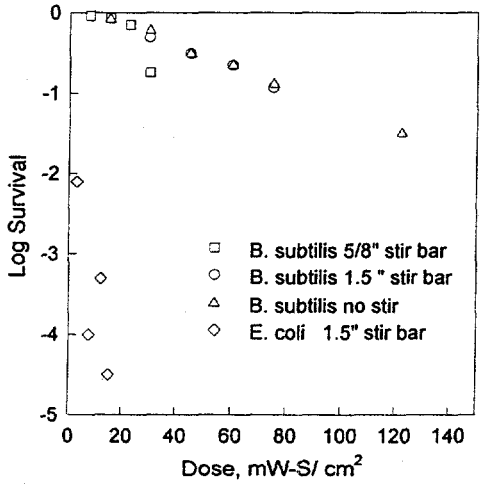

Figure 6. Plot of log survival as a function of UV dosage.

The exposure dose during biofouling experiments was in the range of 40 to 50 mW-sec/cm^2, which gave log survival of -0.54 for an average dose of 45 mW-sec/m^2. The resulting fraction of surviving microorganisms was 0.29 and it was used for analyzing the biofouling data. Equation 3 can be expressed in terms of surviving fraction of microorganisms as shown below, where F is surviving fraction of microorganisms.

$$dR_f/dt = F \alpha Cm + \beta R_f \quad (6)$$

Two separate experiments were carried out to determine the effects of UV irradiation. The water velocity for both tests was about 1.8 m/s. The surviving fraction of 0.29 was estimated on the basis of the spore test. The predicted fouling curves, along with the control test, for the two tests are shown in Figures 7 and 8. A good agreement between the predicted and experimental fouling resistances for the induction and growth periods indicated that the effects of reducing microorganisms can be explained with factor F equal to 0.29. Somehow, the fraction of surviving microorganisms was not below a threshold value to keep the rate of biofouling negligibly low. The results shown in Figure 7 indicated that the surviving fraction must be reduced to a low value of 0.01 or lower to prevent fouling. The predicted and experimental results show that the UV irradiation may not completely eliminate biofouling, but it will increase the induction period. The resulting effects can be used to reduce the total use of chlorine or ozone by increasing the time period between applications at lower dosage than the current level.

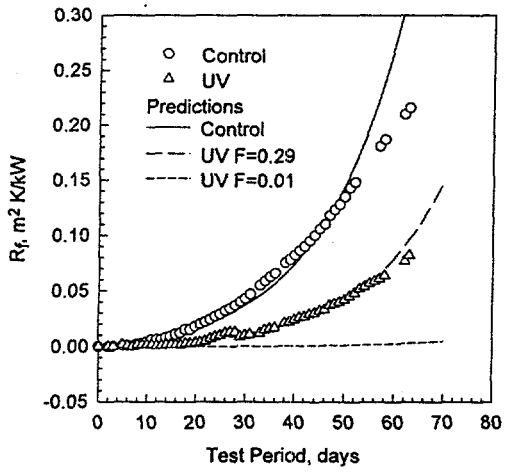

Figure 7. Experimental and predicted fouling resistances for control and UV - test 1.

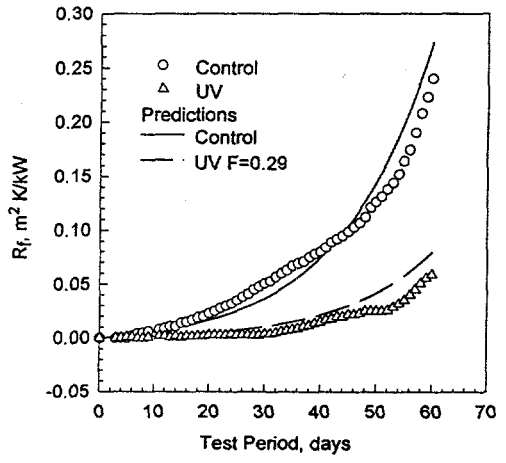

Figure 8. Experimental and predicted fouling resistances for control and UV - test 2.

Ultrasound [US] Treatment

Three separate tests were conducted along with the control test. The first two tests were carried out at water velocity of 1.83 m/s. The first test was carried out bypassing the delay tank (see Figure 3) simulating the inlet section of a heat exchanger. In the second test, the delay tank, with a residence time of 30 seconds, was used. The third test was carried out at a reduced velocity of 0.92 m/s and the delay tank was bypassed. No separate test was carried out to determine the survival or activity rate of microorganisms. As a result, the survival fraction of concentration Cm could not be independently determined. In order to understand the effects of the US treatment, F in Equation 5 was varied until a good curve fit is observed.

The test data along with the predicted fouling curve for the control and US treatment are shown in Figure 9. This test was carried out in winter during which the water temperature was about 25 °C. The growth rate during winter was observed to be about 25% lower than that during summer [Panchal et al. 1984]. Therefore, a lower value of 0.002 for α was used as compared to 0.00256 used for other two tests. F was assigned a value of 0.7 which indicated that the US effects to make organisms passive and prevent from deposition were significantly lower than those for the UV irradiation. The US effects were further reduced by the delay tank as seen in Figure 10. F was estimated to be about 0.9 for the data in Figure 10. By reducing the water velocity and thereby increasing the total dosage of the US treatment in test 3 had significant effects, Figure 11. F was estimated to be about 0.3 for test 3.

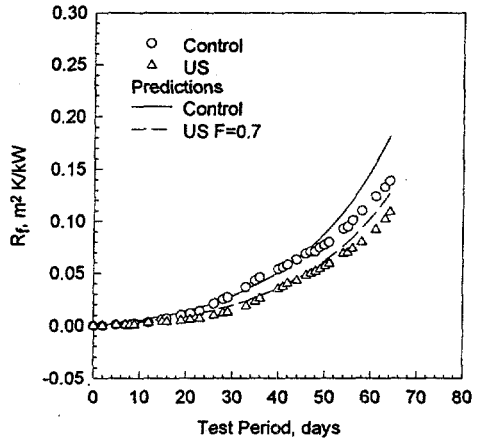

Figure 9. Experimental and predicted fouling resistances for control and US; test 1.

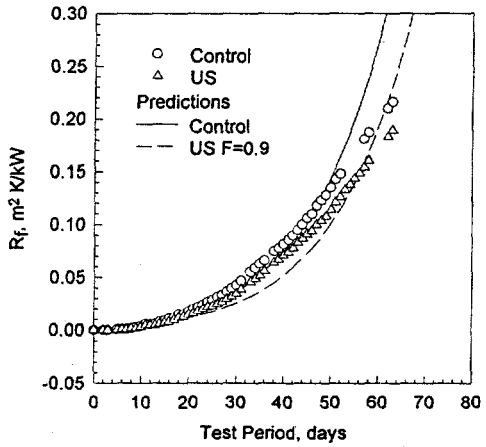

Figure 10. Experimental and predicted fouling resistances for control and US; test 2.

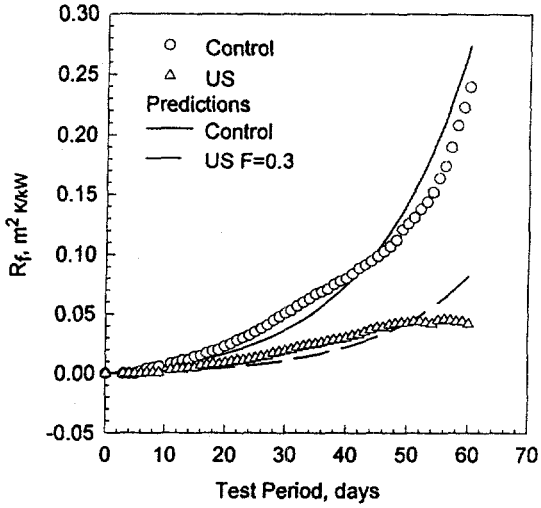

Figure 11. Experimental and predicted fouling resistances for control and UV; test 3.

Discussion

The fouling behavior in the presence of UV and US can be explained on the basis of inactivation and/or destruction of microorganisms in the incoming water. In a mathematical term, it can be represented by factor F in Equation 5. The experimental data and predicted results show that biofouling can not be totally controlled by treating the water with UV or US because these two treatments do not reduce the growth factor represented by the second term in Equation 6. One way to take advantages of the such treatments is to use them along with a chemical treatment. By reducing the deposition rate, the effectiveness of chemicals will be improved, which should result in reduced chemical consumption. The two major issues for both treatments are the energy consumption and scale-up to prototype water pipes.

The present analysis showed that the fouling model described by Equation 2 can be used to evaluate the effectiveness of biofouling control methods. The effects of water velocity, nutrient and oxygen concentrations, and turbulence promoters can be examined with the fouling model. Such a model needs selected experiments to evaluate constants. The model can then be used to determine the effects of biofouling control methods, including chemical treatments.

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REFERENCES

Burton, D.T., Richardson, L.B., and Taylor, R.J., 1984, "Control of Colonial Hydroid Macrofouling by Free-Field Ultrasonic Radiation," *Science,* Vol 223, P. 23.

Calkins, J., 1971, "A Method of Analysis of Radiation Response Based on Enzyme Kinetics," *Radiation Research,* Vol 45, pp. 50-62.

Characklis, W. G., 1991, "Biofouling: Effects and Control," In *Biofouling and Biocorrosion in Industrial Water Systems,"* H.C. Flemming and G. Gregory [Eds], Springer-Verlag Publisher, New York, pp. 7-28.

Cruver, J.E., 1981, "Ultraviolet Disinfection of Wastewater," Proceeding of the 25th Great Plains Waste water Design Conference, Omaha, Nebraska.

Flemming, H.C., 1991, "Biofouling in Water Treatment," In *Biofouling and Biocorrosion in Industrial Water Systems,"* H. C. Flemming and G. Gregory [Eds], Springer-Verlag Publisher, New York, pp. 47-81.

Jagger, J., 1979, *Introduction to Research in Ultraviolet Photobiology,* Prentice-Hall Inc., Publisher, New Jersey.

Hill, F.K., Pandolfini, P.P., Druger, G. L., and Avery, W. H., 1981, "Biofouling Removal by Ultrasonic Radiation," Corrosion 81, Int. Corr. Forum, April 6-10, Toronto, Paper No. 267.

Mussalli, Y.G., et al., 1985, "Targeted Chlorination," Proceedings: Condenser Biofouling Control- State-of-the Art Symposium, EPRI CS-4339, pp. 4.12-38.

Novak, L., 1981, "Comparison of the Rhine River and the Aresund Sea Water Fouling and its Removal by Chlorination," In *Fouling in Heat Exchange Equipment*, HTD-Vol. 17, pp. 61-66.

Panchal, C.B., Larsen-Basse, and Little, B., 1984, "Biofouling Control fro Marine Heat Exchangers Using Intermittent Chlorination," In *Fouling in Heat Exchange Equipment,* ASME Publication HTD-Vo. 35, pp. 97-104.

Panchal, C.B., et al., 1985, "OTEC Biofouling-Control and Corrosion Protection Study at Seacoast Test Facility," *Argonne National Laboratory Report,* ANL/OTEC-TM-5.

Panchal, C.B., et al., 1990, "OTEC Biofouling and Corrosion Study at the Natural Energy Laboratory of Hawaii 1983-1987," *Argonne National Laboratory Report,* ANL/ESD-10.

Pandolfini, P.P., Avery, W. H., and Hill, F. K., 1979, "Experiments on ultrasonic cleaning of a shelless folded-aluminum-tube OTEC heat exchanger," *Proceeding of the 6th OTEC Conference,* Vol 2, pp. 12.8-12.16.

Renfftlen, R.G., 1989, "Effectiveness of Sponge Ball Cleaning Against Typical Condenser Foulants," PWR-Vol. 6, October.

Takahashi, P.K., 1986, "Study of the Non-Chemical Methods of Biofouling Control in OTEC Heat Exchangers," Final Report submitted to Solar Energy Research Institute, Contract No. XX-4-0495-1.

Yang, S.Y., 1976, *Photochemistry and Photobiology of Nucleic Acids,* Vol II Biology, Academic Press Publisher, New York.

Zip, A., Schaule, G., Flemming, H.C., 1990, "Ultrasound as a Mean for Detachment of Biofilms, " *Biofouling,* Vol. 2, pp. 323-333.