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ABSTRACT

An experimental study is carried out to determine biofouling characteristics for enhanced surfaces. As a part of the OTEC biofouling project, two types of heat-transfer enhanced surfaces are used; spirally indented and fluted tubes. The experimental program is carried out at the Natural Energy Laboratory of Hawaii. The results are compared to plain-surface fouling data and key differences are identified. The experimental results show that for enhanced surfaces, the rate of fouling is comparable to that for plain surfaces. Moreover, the rate of chlorination required for maintaining the fouling resistance within an acceptable value is more-or-less the same. Manual brush cleaning and chlorination for removal of film of fouled surface is possible, provided excessive fouling buildup is not allowed. The interactive effects of thermal-hydraulic phenomena and fouling mechanisms are examined. The literature data are evaluated along with the present results to explain the fouling behavior of enhanced surfaces.

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INTRODUCTION

Enhancement of heat transfer has been one of the most active research and industrial development area. Many kinds of enhancement surfaces have been proposed and commercialized for single-phase, condensation, flow boiling and nucleate boiling heat transfer applications. However, such enhanced surfaces are considered exclusively for applications where no fouling deposition is expected. The reason for such an approach is that very little research work has been done to characterize the fouling behavior of enhanced surfaces. It can be argued that understanding of fouling mechanisms for plain surfaces is poor, however, it is important to extend the basic knowledge of fouling to enhanced surfaces. Without such a research work, it would be difficult to exploit the potential of enhanced surfaces for augmenting the heat exchange equipment efficiency.

Fouling of enhanced surfaces has been recognized as a key area of research. However, little work has been carried out, especially to determine the interactive effects of thermal-hydraulic conditions of enhanced surfaces on the deposition and growth of fouling. The previous studies have been mostly exploratory type work, in which selected commercial enhanced surfaces were tested for possibility of serious fouling. There is significant experience and some experimental data for particulate fouling of finned-tubes for gas-side heat transfer applications. However, the present study is related to fluid flowing inside the channel, and the heat transfer enhancement is achieved by modifying the wall surface. Kornbau (1983) tested spirally indented (Korodence) tubes for naval-vessel applications. They used coastal water at the LaQue Center for Corrosion Technology in North Carolina. Their basic conclusion was that the difference between fouling of plain and enhanced tubes is insignificant. However, they reported uneven distribution of fouling film between enhancement ridges. Boyd (1983) reported field experience for power plant condensers. They retubed a 300 MW power plant condenser with Korodence tubes, and reported the overall performance. Their results showed that after about 1 year the enhanced tube condenser performance dropped to that of a plain tube unit. They did not use any cleaning method during this test period. Later the condenser was cleaned and they reported that Korodence tubes could be cleaned easily with manual-bristle brushes. The friction factor increased by about 43% compared to unfouled surface values for both enhanced and plain tubes.

Mussalli (1984) identified potential of enhanced tubes for power plant condensers, however, fouling was identified as the major barrier for commercial acceptance of enhanced tubes. Webb (1984) examined a typical power plant and evaluated potential improvement in the overall system efficiency by installing enhanced tubes in the power plant condensor. Later, Webb (1985) discussed general cleaning methods for controlling fouling of commercial units. Watkinson (1988) has reported several case studies in which finned tubes were tested for general evaluation of fouling behavior of extended surfaces. The results seemed to indicate that under certain conditions finned-surface might have an advantages for achieving higher overall performance under fouled conditions as compared to that for a plain surface. Watkinson (1988) reanalyzed Katz (1954) data for fouling of radial outer-fin tubes for fuel oil fouling. The reanalyzed results showed that the heat transfer coefficient ratio (enhanced to plain) for the finned-surface under fouled conditions was greater than that for a clean surface. It indicated that the fouling effects were more significant for a plain surface than that for the radially finned-surface. Muller-Steinhagen (1988) carried out a particulate fouling study for externally threaded tubes. The results showed that the fouling resistance for the radially finned-surface was lower than that for a plain surface under comparable flow conditions. In an earlier study, Watkinson (1974) found that the asymptotic scaling fouling for the spirally indented surface was comparable to that for a plain surface. However, due to a higher value of the heat transfer coefficient, the relative effects was more significant for the enhanced surface than that for a plain surface.

In summary, the previous work shows that fouling of enhanced surfaces may be controllable. However, no definite conclusion can be derived for the interactive effects of enhancement geometry on the rate of deposition and growth of fouling. These studies represent isolated case studies. The present study examines the possible fouling mechanisms for enhanced surfaces and analyzes the experimental data on biofouling for two enhanced surfaces for tropical seawater. The results are compared with fouling behavior of a plain surface. The objective of this study is to understand the biofouling deposition and growth behavior as compared to that for a plain surface. In addition, mechanical and chemical methods to remove the biofouling film are studied. The experimental results provide information that may be used to design enhancement surfaces to mitigate the fouling effects.

INTERACTIONS OF THERMAL-HYDRAULIC CONDITIONS WITH FOULING

The previous studies discussed in the Introduction have shown that enhanced surfaces in general did not foul worse than plain surfaces. The main question arises is that whether the fouling film distributes evenly as shown in Fig. 1a or unevenly as shown in Fig. 1b. It should be noted that even for a plain surface, some degree of randomness exists initially until the whole surface is covered with the fouling film. However, for enhanced surfaces, the local wall temperature and wall shear stress are not uniformally distributed. Therefore, it can be argued that for enhanced surfaces the fouling deposition cannot be uniform. Significant work has been done to determine the turbulence intensity for two dimensional enhanced surfaces i.e. repeated ribs or spirally indented surfaces. The analysis of Hijikata and Mori (1987) shows that the turbulence intensity is maximum at the enhancement crest and at the point of reattachment of boundary layer, which lies in the region of about 6 to 10 time rib height downstream of enhancement. The local shear stress and heat transfer coefficient could be of the order of magnitude higher than that for a plain surface at comparable flow conditions. Therefore, if the net deposition rate (deposition minus removal of fouling) is a function of wall shear stress e.g. particulate fouling, one would expect minimum fouling in the region of maximum turbulence intensity. Alternatively, the rate of fouling deposition would be high in the region of low turbulence intensity.

At low rate of fouling deposition it may be possible to develop a prediction model to calculate the local rate of deposition on the basis of turbulence intensity known for the clean surface and fouling model for a plain surface. However, when the fouling film thickens, the effective shape of geometry that gives heat transfer enhancement could change. Subsequently, the flow mechanism would be affected leading to a different shear stress distribution pattern (see Figs. 1a and 1b). In an extreme case, enhancement ridges can be completely covered up with the fouling film, especially for small size enhancement. In that case, there will be a total loss of enhancement and the effective fouling resistance could be greater than that for a plain surface. However, the literature data discussed earlier indicate that in general the enhancement efficiency is not lost. The results show that the thermal-hydraulic phenomena that contribute to the heat transfer enhancement may not have been significantly affected. This argument is supported by the friction factor data reported by Boyd (1983) for the spirally indented tubes under fouled condition. The pressure drop data indicate that uniform increase in micro-roughness should have contributed to the increase in friction factor. The relative increase in friction factor for plain and enhanced tubes were comparable. Therefore, the fouling film was not able to render the enhancement ineffective. It can be argued that the fouling film deposition follows the shear stress distribution pattern. Therefore, the analysis of fouling film distribution should provide necessary information for designing enhancement shapes.

In some fouling mechanisms, the temperature at the interface of fluid and wall or fouling film is an important parameter, e.g. crystallization (scaling) fouling. Distribution of the local heat transfer coefficient should certainly affect the interface temperature. As a result, the fouling potential would be minimum at a point where the heat transfer coefficient is maximum for the case where fouling is proportional to the temperature gradient. In the case of retubing of the power plant condenser discussed by Boyd (1983), by an appropriate selection of enhanced tubes, the mean temperature difference between wall and cooling water could have been reduced from about 7°C to 3.5°C. If the fouling mechanism is controlled by crystallization kinetics at the interface, this reduction in mean temperature difference should reduce the fouling potential. Based on the data of Dunqui and Knudsen (1987), Epstein (1988) has developed a model for cooling water fouling as shown below.

$$\frac{R^{*}f}{\theta_c} - 7.14\times10^{28} \exp\left(\frac{-Ea}{Rg\ Ts} \right) \quad (1)$$

where

- Ea = activation energy, 221 kJ/mol
- Rg = gas constant, 0.008324 kJ/mol K
- Ts = interface temperature, K
- $R^{*}f$ = asymptotic fouling resistance, m^2 K/W
- θ_c = time constant, days

The left hand-side term, $R^{*}f/\theta c$ represents the initial rate of change of fouling resistance in the Kern-Seaton equation. The effects of change of interface temperature by enhancing the water-side heat transfer coefficient for the case discussed above can be found by substituting the appropriate temperature in Eqn. 1. The calculated results show that for the enhancement factor of 2 and corresponding reduction in interface temperature by about 3.5°C, the initial rate of fouling could be reduced by a factor of 2.8.

If the fouling mechanism is controlled by diffusion of salt ions to the wall, the enhancement would increase the rate of fouling. On the other hand, if precipitation of salts occurs in the boundary layer followed by deposition, the mechanism would be characterized as particulate fouling. In that case the distribution of shear stress should have direct effect on the fouling characteristics of enhanced surfaces. It should be noted that Katsman (1983) has reported that the rate of fouling for plain tubes was one and half time greater than that for spirally indented tubes in a power plant condenser experiment. However, for a highly mineralized circulating water (dissolved solid concentration of 3000 mg/L), spirally indented tubes fouled faster than plain tubes. Moreover, the fouling film analysis showed that the bond between deposition and wall was stronger for plain tubes than that for spirally indented tubes. It can be argued that the shear stress distribution might have affected the fouling film deposition and growth. This experiment shows that for better understanding of fouling for enhanced surfaces, it is essential to characterize the film in addition to measure the fouling resistance as change in the heat transfer coefficient.

It should be noted that the fluid-flow mechanisms near the wall vary depending upon enhancement geometry. For two dimensional enhancement (shown in Fig. 2a as spirally indented tube surface) separation and reattachment of the boundary layer has been identified as an enhancement mechanism. On the other hand, swirling flow or secondary flow near the wall has been considered to be the contributor to the enhancement for the spirally fluted tube surface (see Fig. 2b). The swirling flow mechanism is also achieved for twisted ribbon insert, however, the flow mechanism near the wall would be different for twisted ribbon and spirally fluted tube surfaces. The swirling or secondary flow mechanism is expected to have noticeable effect on the fouling mechanism. However, in the absence of any systematic investigation, no definite conclusion can be drawn whether the secondary flow would increase or reduce the deposition and growth rate for different fouling mechanisms i.e. crystallization, biological, chemical reaction, and particulate.

EXPERIMENTS

Fouling experiments were conducted as a part of the OTEC program at the Natural Energy Laboratory of Hawaii, and details are given elsewhere (Panchal et al., 1986). The test facility is equipped for continuous supply of warm-surface and deep-ocean-cold waters. Several series of experiments were run with parallel test loops. each experiment consisted of a test section on which a heat transfer monitor (HTM) was installed. Figure 3 shows a photograph of such a HTM system and details are given in the report by Panchal et al. (1986). Each test section was equipped with a chlorinator designed to chlorinate the flowing seawater in situ, by electrolysis. The seawater was sampled immediately after the test section and the sample is introduced directly into the buffer solution to inhibit further reaction of hypochlorous and hypobromous acids with ammonia and other organic constituents of seawater. The concentration of total oxidants was determined by backtitration of the buffer solution. For the present study of fouling of enhanced surfaces, four test sections (2 in warm and 2 in cold waters) were installed and experiments were conducted in parallel. Operating conditions and details of test sections are given in Table 1. For the purpose of comparison the fouling results for a reference plain test section is also included in the present study.

The warm water temperature varied from about 25°C in winter days to 30°C for the summer period. The cold water temperature remained relatively steady at about 7°C. The pH for warm and cold waters were about 7.9 and 8.2 respectively. The total organic carbon (TOC) for deep-ocean cold water was nearly half of that for surface-warm water. The total organic carbon (TOC) for warm water was in the range of 0.6 to 1.0 mg/L, with slight increase during the summer period. For more detailed water chemistry measurements, reference should be made to the Argonne report (Panchal et al., 1986).

DISCUSSION OF RESULTS

Comparison of Free Fouling

In this series of experiments, the test section was allowed to foul freely without application of control methods. Figure 4 shows the first free fouling curves for the spirally indented and spirally fluted test sections. It should be noted that in the original measurement the fouling resistance for the spirally fluted tube was based on the projected area. The fouling results are corrected for the area ratio in the present study. As a result the free fouling cycle was continued until R_f reached to 0.156 m^2 K/kW which was higher than a normal value of 0.09 m^2 K/kW used for other test sections before a clanning method was applied. Moreover, the tube material was aluminum Al-6061, and corrosion film was also developing in parallel. It has been observed that the rate of corrosion film development for most aluminum alloys is comparable (Panchal 1988). Therefore, if the corrosion fouling for the first fouling cycle period is subtracted, the biofouling growth would be slightly lower. However, the corrosion fouling is relatively small for the initial period of 50 days as compared to the biofouling growth, and no correction was applied to the spirally fluted tube data.

For both test sections, the induction period was present. The spirally fluted tube took about 9 days before fouling growth was noticeable in terms of change in the heat transfer coefficient as compared to about 5 days for the indented tube. The growth rate calculated for fouling curves in Fig. 4 is shown in Table 2. For comparison, the fouling data for a reference plain surface (Panchal 1984) is also shown. The results showed that the rate of growth for all three test sections was comparable within the experimental uncertainty. The growth rate started at a low value initially, but it reached to a constant value of about 0.0032 to 0.0034 m^2 K/kW per day. For some unexplained reasons, the growth rate slowed down for both enhanced surfaces after about 10 and 20 days of test period for the indented and fluted tube, respectively. Later the fouling growth continued at a constant rate.

The biofouling growth represents complex phenomena, which include deposition of new microorganisms, growth of colonies, transport of nutrients from bulk flow to the film, and removal of microorganisms. The analysis is further complicated by the dynamic nature of newly deposited microorganisms that have not developed any colony. However, the above results show that the initial deposition and subsequent biofouling growth (measured as change in heat transfer coefficient) for enhanced tube surfaces are comparable to that for a plain surface. The observed fouling behavior for enhanced surfaces indicate that the fouling film may not be uniformly distributed, but the effects on the average heat transfer coefficient are insignificant. Alternatively, the enhanced surface does not foul worse than a plain surface. It was not possible to conduct a detailed film analysis for the spirally fluted surface. Limited film analysis was carried out for the indented surface, and it was observed that the upstream of the ridge surface was clear of fouling film, but the immediate downstream of ridges had larger concentration of biofouling colonies. This observation supports the discussion of the effects of shear stress distribution on the film growth. Kornbau et al. (1983) in a similar series of experiments with temperate coastal seawater, found that the dry-film weight gain for spirally indented surface was 18.5 mg/day as compared to 12.3 mg/day for a plain surface. Nevertheless, the rate of fouling resistance measured using the same HTM device showed comparable rate of fouling resistance for both surfaces. Subsequent film analysis showed that the enhancement ridges were free from fouling but both side of ridges had heavy colonies of biofouling. These results seem to indicate that the biofouling growth occurs unevenly, however, high growth in certain areas of enhanced surface is compensated by maintaining low growth in the region of high shear stress and local heat transfer coefficient.

Effectiveness of Brush Cleaning

It is of practical interest to know the tenacity of the biofouling film for enhanced surfaces, and the effectiveness of mechanical cleaning system. In the present experiment, the spirally indented test section was allowed to foul freely until the Rf value reached to about 0.09 m^2 K/kW, and then it was cleaned using soft nylon brushes of effective diameter of 0.5 mm larger than inside diameter of the test section. Table 2 shows that after one pass (to and fro) of manual brush cleaning, the Rf value was reduced from 0.106 to 0.0025 m^2 K/kW, i.e., 97% reduction in the fouling resistance. After five passes, the Rf value was negligible. For the plain surface test section, a similar observation was made. It should be noted that the reference plain test section was being tested for nearly 3 years before the enhancement experiment was started, and the plain surface in this cycle of cleaning showed some residual fouling that could not be easily removed. However, brush cleaning for other fouling cycles of plain-surface produced negligible residual film resistance after five passes. No brush cleaning was performed for the spirally fluted surface, because it was assumed that such cleaning might not be effective for a complex geometry. A new brush-cleaning device needs to be developed for the spirally fluted tubes, in which the brush-system will rotate to follow the spiral grooves.

Repeated film analysis has been carried out for the plain tube test section. Two sample sections were withdrawn at the time of brushing, one before and one after brushing. Dry weight for the fouled test section (Rf about 0.09 m^2 K/kW) was in the range of 100 to 160 micro gram/cm^2. After brush cleaning, the value was reduced to about 20 micro gram/cm^2. The SEM pictures showed that a thin layer of scattered microorganisms stayed after brush cleaning. Similar results were observed for the enhanced tube section. Before cleaning, the biofouling film was more concentrated on the downstream of ridges. Due to forward and backward motion of brush cleaning, part of the fouling film moved on both side of ridges.

The results of this series of tests suggest that mechanical cleaning, manual or on-line, should be able to remove the biofouling film and maintain a low Rf value for the spirally indented tube surface. However, it is important to study the effects of a given mechanical cleaning device on redistribution of the fouling film as a function of enhancement geometry i.e. pitch and ridge height. The Taprogge Company (1985, 1986) has evaluated the sponge ball cleaning technique for the spirally indented and spirally ribbed surfaces similar to those used in the present study. However, their tests included physical examination (photographs) only without fouling resistance measurements. Their results showed that the ball cleaning produced uneven removal of simulated fouling film from the spirally indented tube surface. After 2 ball passes, thicker film was observed downstream of ridges compared to the upstream region. After 50 passes, the tube surface was nearly restored to the prefouled condition. The ball cleaning was not effective for the spirally ribbed surface.

Chlorination as a Cleaning Method

Removal of an established biofouling film by chlorination has been shown to be effective for plain surfaces (Panchal et al., 1984). A similar series of experiments was conducted for both enhanced surfaces, in which the test section was allowed to foul, followed by chlorination. Figures 5 and 6 show the rate of removal of fouling film for indented and spirally fluted tube surfaces respectively. For comparison corresponding data for the plain surface test section from an earlier study (Panchal et al., 1984) are reproduced. For the indented tube surface, 70 ppb of chlorination was applied for 1 hour everyday after the fouling resistance reached to about 0.093 m^2 K/kW, and the plain surface had a comparable Rf value at the beginning of chlorination. The results show that after high rate of removal initially, it decreases to a lower value and remains nearly linear until the Rf value reached to about 0.02 m^2 K/kW. After that, the chlorination was not able to reduce the fouling resistance. On the other hand, the rate removal for the plain surface remained constant until the Rf value reached to about zero. Summary of the rate of removal results are shown in Table 2. It is interesting to note that the rate of fouling removal, for the indented and plain surfaces, was identical. However, it was not possible to bring down the Rf value to zero even after prolonged chlorination. It was necessary to brush the surface to remove the residual fouling film. Examination of the test sample showed that the fouling film downstream of ridges was not effectively removed.

The observed results indicate that the major portion of the biofouling film from spirally indented surfaces can be removed. However, chlorination followed by film breakup by the wall shear stress could not remove fouling from bottom part of the ridge area. It can be argued that the recirculation flow downstream of ridges may not be able to lift the film that is already oxidized by chlorination. However, it is not a conclusive analysis, and additional research work is required to understand the film removal mechanism for the spirally indented surface.

Figure 6 shows the rate of fouling removal for the spirally fluted and plain surfaces for a comparable chlorination schedule. In the original experiment, 70 ppb of continuous chlorination was used. However, the area ratio for the enhanced surface was 1.64, therefore, the effective chlorination when normalized to the total surface could be interpreted as 43 ppb. Chlorination schedule for the plain surface test section was 50 ppb applied continuously. Similarly, the Rf measurement was based on the inside projected area, therefore, its reported value in the present study i.e. based on total inside area, was relatively high (0.156 m^2 K/kW) at the beginning of chlorination schedule.

Figure 6 and Table 2 show that the initial rate of removal for the enhanced surface was relatively high. However, it slowed down and became slower that that for the plain surface. It took an extended period of about 456 hours of continuous chlorination to lower the Rf value to a level value of 0.02 m^2 K/kW. Due to the complexity of the surface brush cleaning was not used. The results indicate that chlorination can effectively remove the initial fouling film. However, it is difficult to remove the fouling film from the valley area of the enhanced surface. It might have been possible that chlorination could not diffuse into the valley area. Alternatively, the turbulence intensity was not able to remove the film from the valley area after oxidized by chlorination. The deposition of fouling in the valley area might have modified the local flow phenomena in the fluted surface to make the chlorination less effective at low values of Rf. It will be shown later that once the fouling film is effectively removed it was possible to keep the whole surface area free from significant fouling.

The present study shows that it is possible to remove the biofouling film by chlorination. However, the enhanced surface should be designed to minimize low shear stress areas. Very low local values of local heat transfer coefficient means low mass diffusion for chlorine ions and such enhancement geometry should be avoided, even if it leads to a lower value of the overall coefficient. The present study clearly shows that the local thermal-hydraulic flow phenomena plays an important role in removing the biofouling film by chlorination.

Chlorination for Fouling Control

After completing the initial experiment for determination of the effectiveness of mechanical and chemical cleaning methods, daily chlorination was started for both test sections. Seventy ppb of chlorination was applied everyday for 1 hour. However, as discussed above, the effective chlorination for the spirally fluted surface should be interpreted as 43 ppb due to the area ratio of 1.64. In general, the chlorination scheduled mentioned above was maintained, but occasionally the schedule is skipped for a day due to problems with the chlorinator or accidentally a continuous-overnight chlorination was applied. This kind of practical problems and sudden change in microorganism concentration due to strom conditions were detectable in the general behavior of fouling curves. Nevertheless, the overall fouling results were not affected significantly, and it was not difficult to derive major conclusions for the effectiveness of low level chlorination for controlling biofouling growth.

Figure 7 represents the complete experiment for the spirally indented tube section. After brushing the test section to bring Rf value to nearly zero, the daily chlorination schedule was started. It shows that the fouling resistance increased to about 0.01 m^2 K/kW and remained steady. Later at about 350 days of test period, the Rf value started to increase, and leveled off at about 0.02 m^2 K/kW. This test period represented summer months, when microorganism activity has been found to change leading to an increase rate of deposition and growth. This increased microorganism activity affected all experimental results equally. During the winter month period, the fouling resistance decreased to a pre-summer value. Figure 7 shows a similar seasonal trend during the test period of about 700 days. On the day of test period of 821, sudden change in water chemistry was observed after a storm passed by the test site in Hawaii. All test sections showed sudden increase in the fouling resistance. However, the fouling deposition was removed by the routine chlorination schedule and normal Rf value was regained. The effects of increased growth activity of microorganisms during the summer period is observed in Fig. 7 at the time of conclusion of experiment.

Figure 8 shows the results for the spirally fluted surface including the initial free fouling and continuous chlorination as a fouling removal method. At the conclusion of the initial test, the test section was accidentally free fouled for a short period before the daily chlorination schedule was started. It might have caused the Rf value to increase, however, it stabilized at about 0.029 m^2 K/kW. At that point, the storm conditions mentioned above affected the results, and the Rf value suddenly rose to about 0.047 m^2 K/kW. The routine chlorination was not able to lower the fouling resistance, and it stayed in the range of 0.035 to 0.042 m^2 K/kW. On the day of test period of 613, the chlorinator was accidentally left on for 16 hours. As a result, the fouling resistance dropped from about 0.033 to 0.023 m^2 K/kW. Subsequently, the fouling resistance stayed at about 0.02 m^2 K/kW. Towards the end of test period, slight increasing trend was observed which could be attributed to the increased biological activity in summer months.

Although the surface may not be totally free from the biofouling deposition when daily chlorination was used (Berger, 1986). However, the results reported by Panchal (1988) for plain aluminum surfaces in warm and cold seawaters showed that the corrosion film represents the major heat transfer resistance. It was shown that for aluminum Al-3003 test section, the Rf value was about 0.035 m^2 K/kW after 600 days of testing and with 100 ppb of daily chlorination. The weight loss due to corrosion followed the fouling trend. The fouling resistance in cold water reached to about the same value after 800 days, however, no biofouling was present for cold water experiments. Berger (1986) reported that for warm water experiments, sparsely distributed microorganism colonies exist imbedded in the hydrated corrosion product layer. Such biofouling film increases the wall roughness and enhances the heat transfer coefficient which has been observed for other series of tests. This observation for plain aluminum surfaces can be extended to the spirally fluted surface, and it can be concluded that the leveled value seen in Fig. 8 represents the corrosion fouling with little if any contribution from the biofouling film.

The results reported in the present study show that biofouling can be controlled for enhanced surfaces with periodic chlorination for tropical seawater. It is however important to compare the fouling behavior for enhanced surfaces with that for a plain surface. It is believed that the enhanced surface facilitate the chlorine diffusion to the film and oxidize it. For the spirally fluted surface the shear stress distribution was adequate to lift the oxidized film from the wall surface when no significant deposition was allowed to occur. For the spirally indented surface, the flow recirculation area may not be as effective as other part to remove the film. As a result, residual film could stay near the bottom part of ridges and contribute to the fouling resistance.

CONCLUSIONS

In the present study, the literature results are evaluated and possible interactions between thermal-hydraulic phenomena and fouling deposition are examined. Possibility of designing an enhanced surface for minimization of fouling deposition is identified. An experimental study is carried out to characterize biofouling of two kinds of enhanced surfaces for tropical seawater. The study includes free fouling, removal of the biofouling film using chlorination, effectiveness of brush cleaning, and periodic chlorination for fouling control. The experimental results show that in general chlorination is effective for controlling and removing the biofouling film. However, bottom part of ridges for spirally indented surface may be difficult to keep free from fouling deposition due to recirculation flow in that area.

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Table 1. Details of test sections and experimental conditions

	Indented Tube	Fluted Tube	Plain Tube
TEST SECTION			
Material	AL-6X SS	Al-6061	Titanium
Inside diameter, mm	24	26.8	24
Inside area ratio	1	1.64	1
EXPERIMENTAL CONDITIONS			
Water velocity , m/s	1.83	1.83	1.83
Heat transfer enhancement (including area ratio)	1.50	2.68	1.0
Test duration, days	1080	820	1832

Table 2. Summary of experimental results

	Indented Tube	Fluted Tube	Plain Tube
<u>Free fouling</u>			
Induction period, days	5	9	3
Rate of growth, m^2 K/kW/day			
Initially	0.0028	0.0026	0.0019
Linear growth	0.0032	0.0034	0.0034
<u>Brushing</u>			
Fouling resistance, m^2 K/kW			
Before brushing	0.1064		0.0930
After 1 pass	0.0025		0.0086
After 5 passes	0.0014		0.0042
<u>Chlorination of 70 ppb applied 1 hour/day</u>			
Fouling resistance, m^2 K/kW			
Before chlorination	0.0932		0.0942
After 5 hours of chlorination	0.0662		0.0616
After 24 hours of chlorination	0.0267		0.0251
At end of chlorination	0.0139		-0.0176
Total chlorination time, hours	63		53
Rate of fouling removal, m^2 K/kW/hr			
Initial	0.0054		0.0065
Linear removal	0.0021		0.0019
<u>Continuous chlorination</u>			
Concentration, ppb		70	50
Fouling resistance, m^2 K/kW			
Initial		0.1563	0.0933
After 24 hours of chlorination		0.1040	0.0570
After 72 hours of chlorination		0.0777	0.0233
At end of chlorination		0.0162	0.0014
Total chlorination time, hours		456	192
Rate of fouling removal, m^2 K/kW/hr			
Initial		0.0022	0.0015
Linear removal		0.0005	0.0007

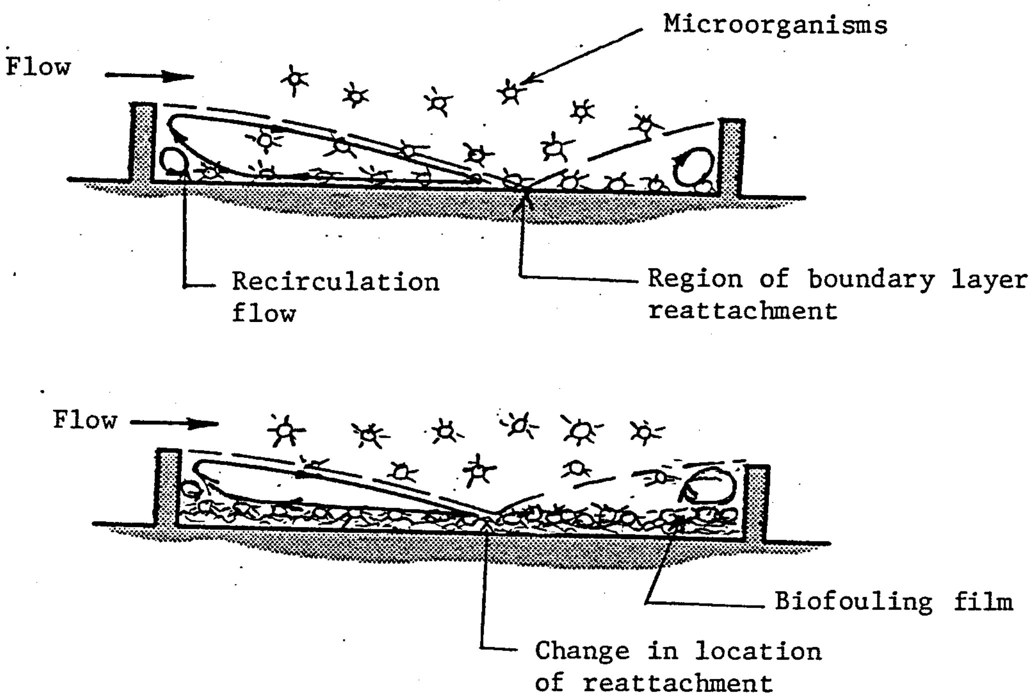

Fig. 1a. Deposition and growth of biofouling assuming uniform film distribution.

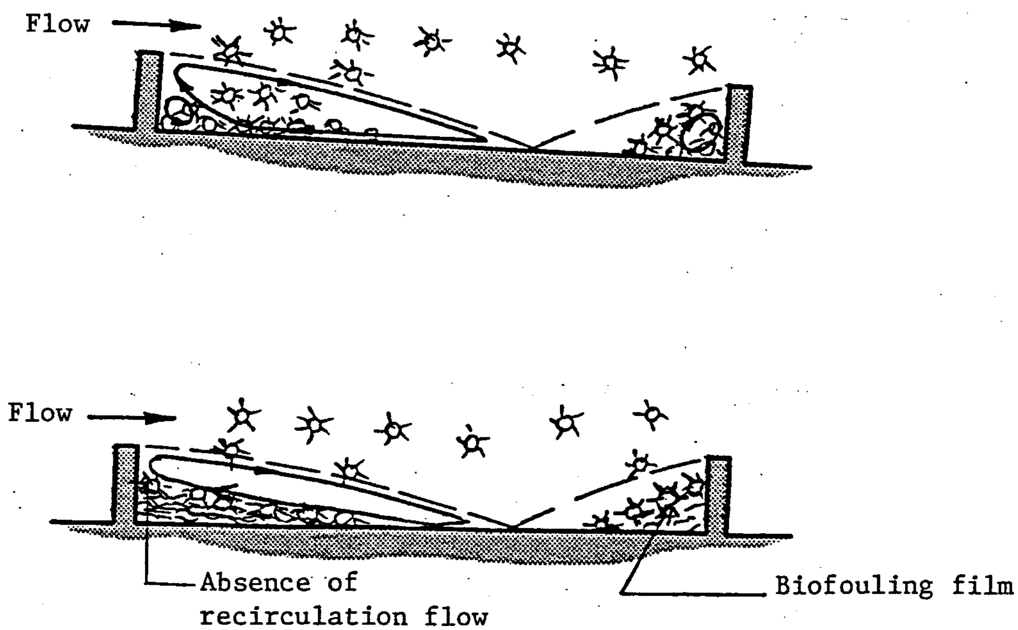

Fig. 1b. Deposition and growth of biofouling assuming nonuniform film distribution.

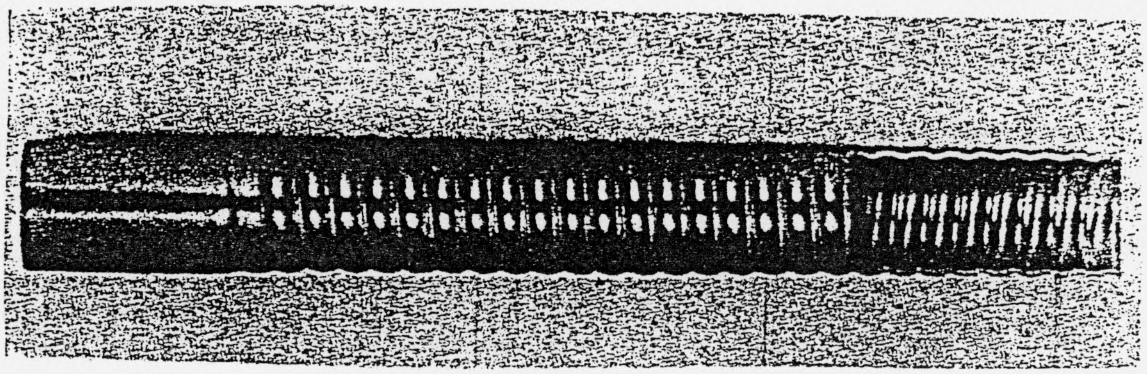

Fig. 2a. Spirally indented tube section.

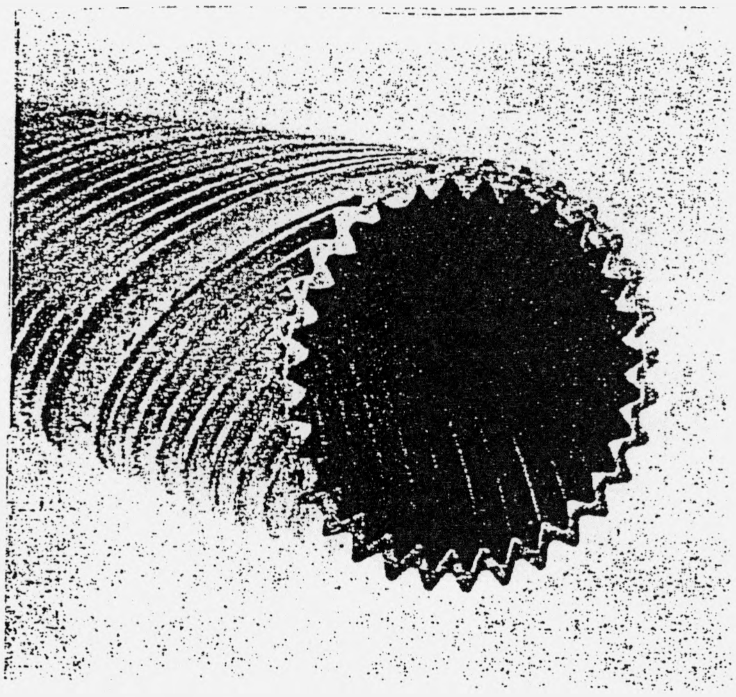

Fig. 2b. Spirally fluted tube section.

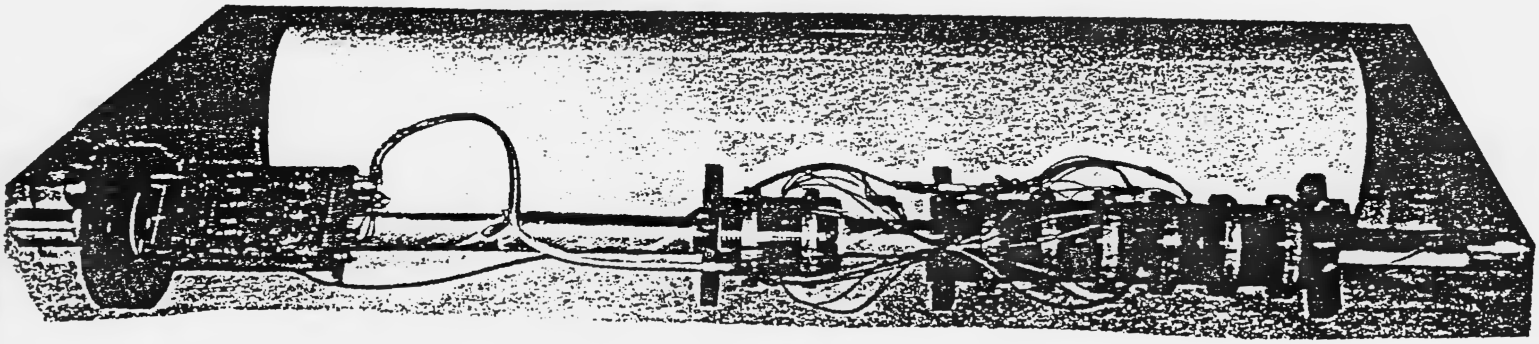

Fig. 3. Heat transfer monitor (HTM) for fouling measurements.

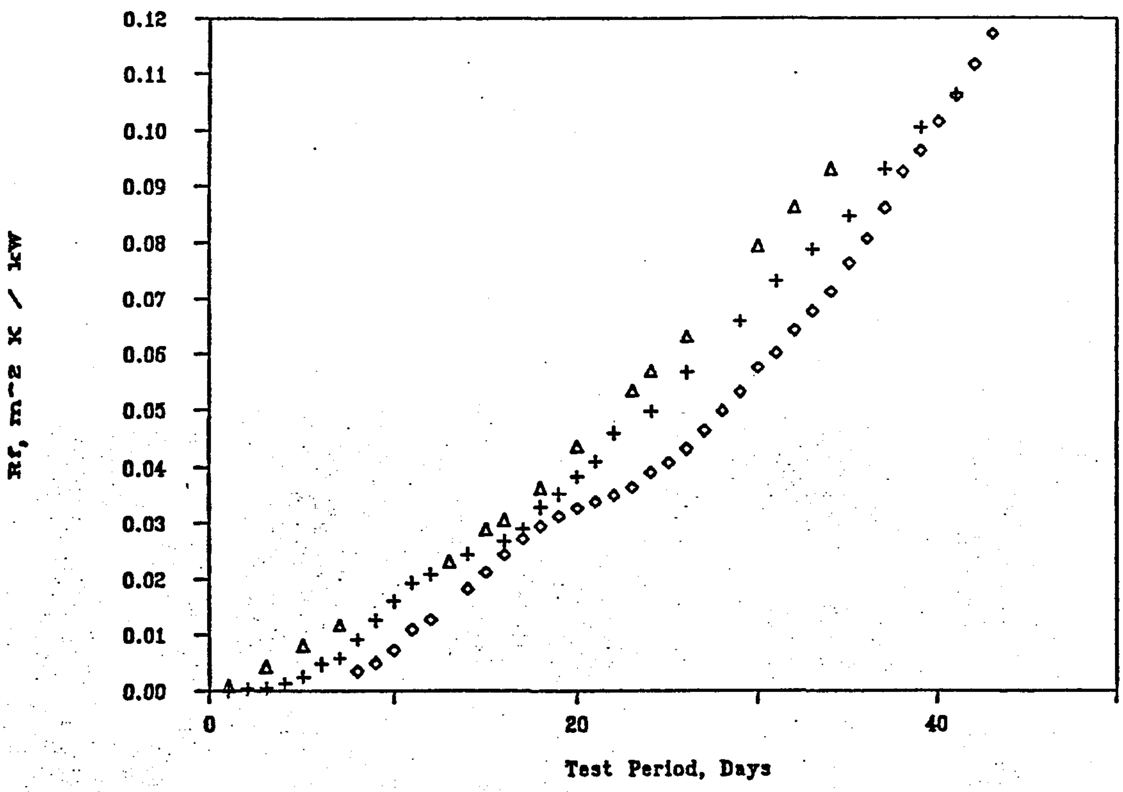

Fig. 4. Free fouling for plain (Δ), spirally indent (+), and spirally fluted (◇) test sections.

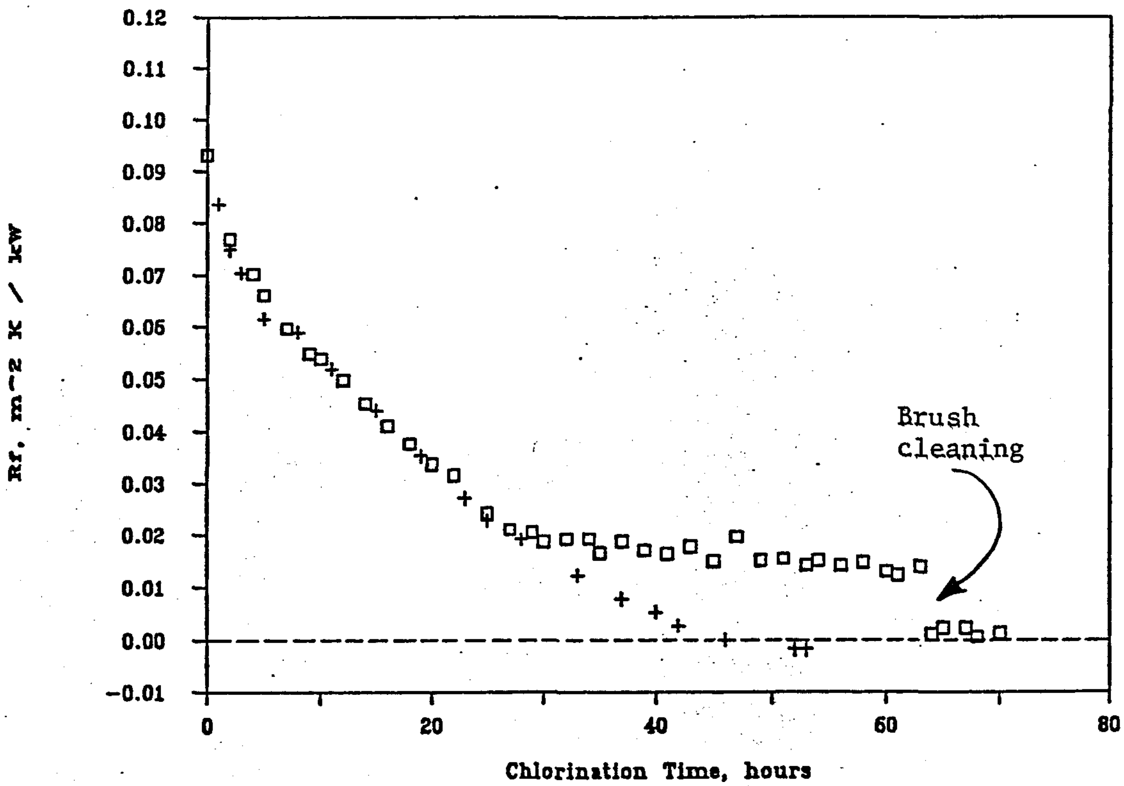

Fig. 5. Rate of removal of biofouling film by chlorination by plain (+) and spirally indented (□) test sections.

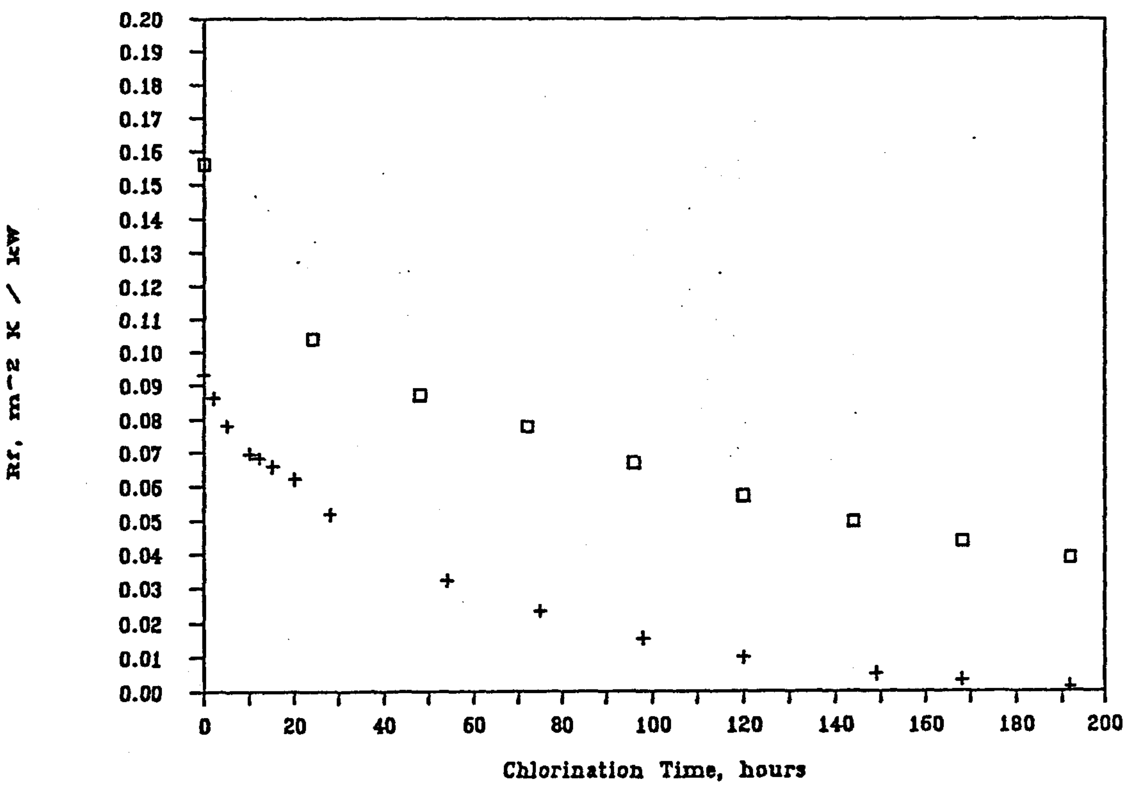

Fig. 6. Rate of removal of biofouling by chlorination for plain (+) and spirally fluted (□) test sections.

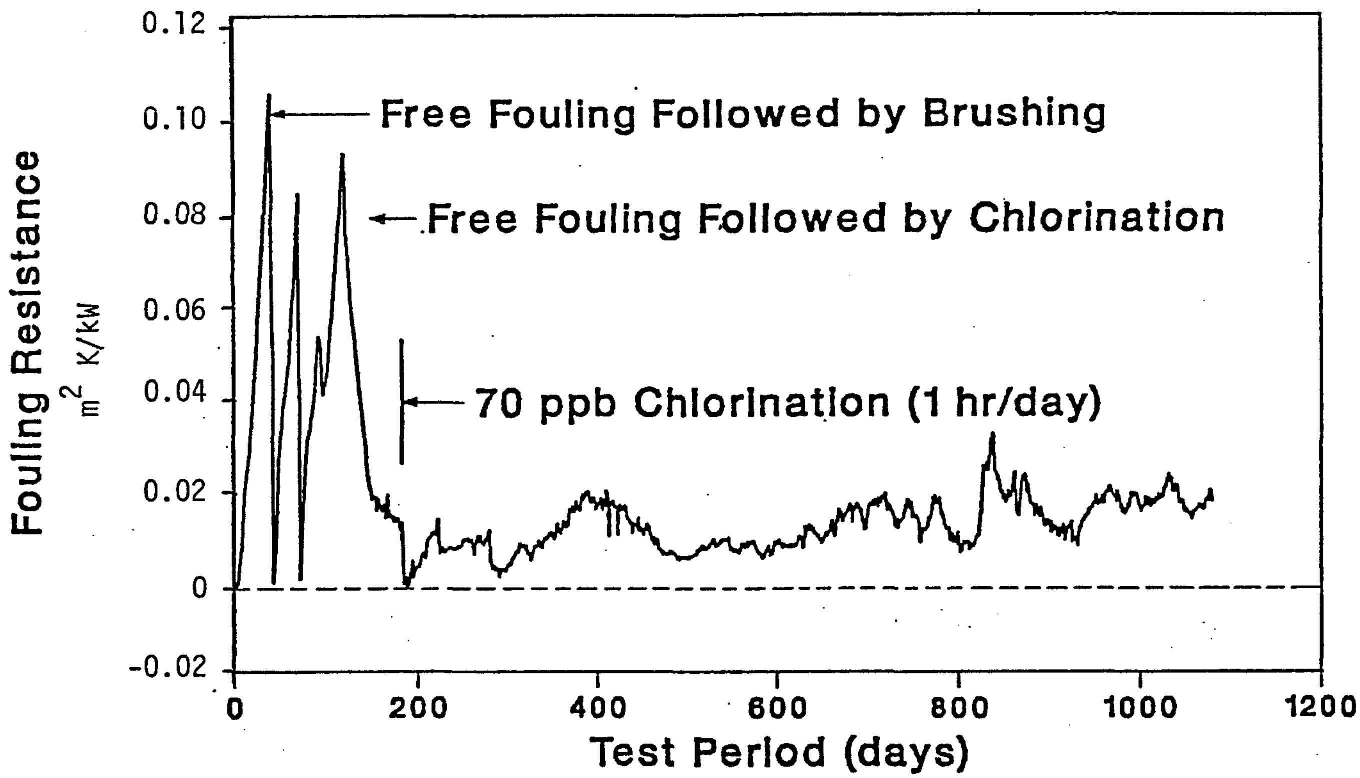

Fig. 7. Fouling behavior of spirally indented test section.

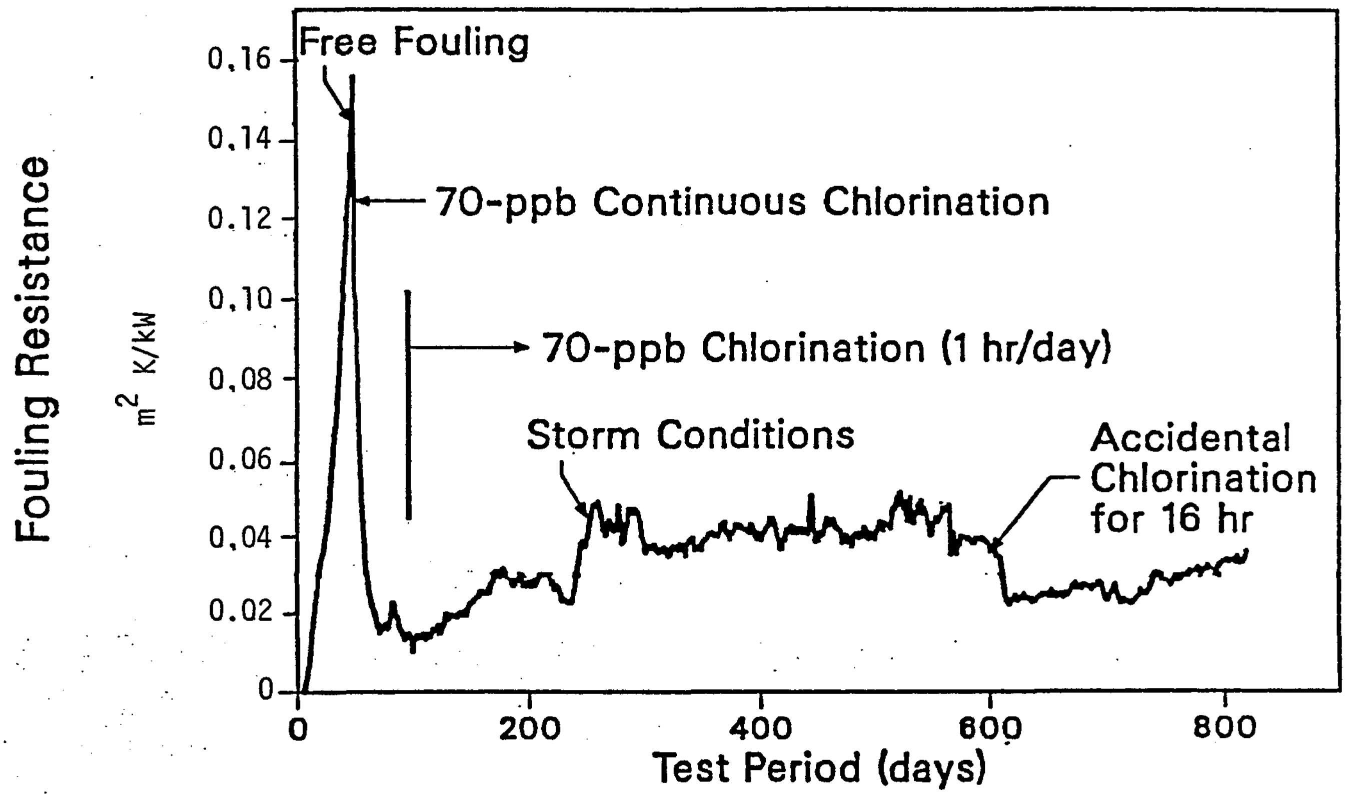

Fig. 8. Fouling behavior of spirally fluted test section.