Portable pilot plant for evaluating marine biofouling growth and control in heat exchangers-condensers

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Abstract: Biofouling frequently involves a serious impediment to achieving optimum operating conditions in heat exchangers-condensers. The economic cost and energy losses associated with this phenomenon are significant and the environmental impact of biocides must satisfy stringent regulations. A portable pilot plant has been designed in order to carry out *in-situ* experimental study as biofilm is formed under thermal and hydrodynamically controlled conditions. The pilot plant has an automatic monitoring, control and data acquisition system, which automatically processes data from indirect measure of fouling in terms of increased fluid frictional and heat transfer resistances. A particular method is used and proposed for direct measuring and biofilm characterization. Once we know the actual film thickness, we can calculate the effective thermal conductivity of the layer by using the appropriate heat transfer equations.

Keywords Biofilm characterization; biofouling monitoring and control; cooling water fouling; heat exchanger-condenser fouling; seawater biofouling

Water Science and Technology **Vol 47 No 5 pp 99–104**

Introduction

Seawater is employed for refrigerating purposes in many heat exchangers-condensers in the process industry, ships and in conventional and nuclear power plants. Fouling biofilms that form on surface condensers reduce heat transfer and lower plant efficiency. A common method of controlling biofilm accumulation is continuous or periodic chlorination. In order to reduce both economic and environmental costs of the antifouling treatment, it is necessary, first of all, to establish the specific characteristics of the circulating water that affect the biofilm growth and that will vary, for a given site, in a seasonal way. Additionally, it is necessary to know how the actual hydrodynamic and thermal conditions can influence the aforementioned phenomenon. For this purpose, a pilot plant has been designed and operated to simulate biofilm development in heated tubes, as might occur in a condenser or heat exchanger, as close as possible to real systems. In addition, the pilot plant must provide the necessary information to predict the biofilm formation under controlled conditions and different biocide dosage patterns for, finally, optimizing its application schedule. This research work deals with the understanding and study of the fouling biofilm development and its influence on heat transfer so that the impact of new regulations on a particular power plant and site can be evaluated.

Material and methods

Experimental system

Taking into account that the type and rate of biofouling will be dependent on the specific characteristics of the cooling water, climatology and other operating conditions of every ship or industrial plant, *in situ* studies must be accomplished and, consequently, to facilitate transportation has been an important requirement. In order to fulfill both requirements, the whole plant has been installed inside a 20 ft standard container.

All the equipment is fixed to the soil and/or walls by means of suitable bedframes and supports, in order to avoid damage during transportation. The shell-and-tube heat exchanger is faced to the container door so that the tubes can be easily removed for replacement or maintenance operations. The container base has been reinforced to support the total weight of the equipment. It also has a light slope towards one of the corners, where there is a drainpipe for evacuation of any liquid spill. The floor is protected with a neoprene carpet. The container is equipped with a compact air conditioner. An exhaustive list of the different components of the plant is the following (see Figure 1).

- Seawater feed system which consists of feed pump (B-10) and seawater feed tank (TA).
- Seawater circulation system to force sea water through all the circuit, and consisting of seawater circulation pump (B-20), chlorination tanks (DC – A/B/C/D) and the distribution system for supplying the required flow to each test tube.
- PVC shell-and-tube heat exchanger (ICCT) 3,100 mm in length and specially designed to avoid galvanic corrosion.
- Biocide dosage system, including the biocide tanks (TH – A/B) and the dosage PLC controlled pumps (B-30 A/B/C/D).
- External heating system for the PVC heat exchanger, including the mixing tank (TM), the plate heat exchanger (ICP), the electric boiler (CE), the circulating pump for the primary heating fluid (B40), the circulating pump for the secondary fluid (B50) and the expansion pressure vessel (DE) and circulating pump for the tertiary fluid (B60).
- Seawater discharge collecting system (PD).
- Control and data acquisition systems: for the control, processing and measurement of flow, temperature, chlorine (REDOX potential) and pressure drop.
- Cabinet for electrical and power components, PLCs, displays.
- Cabinet for computer, monitor, keyboard and printer.

A diagram of the experimental system is presented in Figure 1, where the different circuits can easily be followed and the aforementioned elements can be recognized.

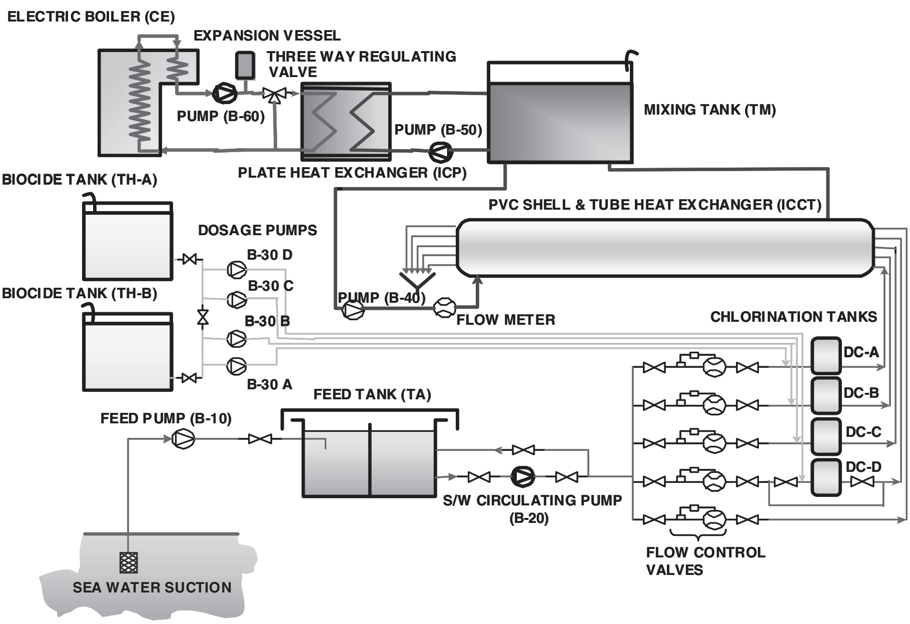

Figure 1 Diagram of experimental system

Advantages of this pilot plant for *in-situ* field experimentation include the fact that the adaptability and full automation of the pilot plant make possible a wide range of experimentation possibilities.

The plant, in a portable container, enables "on site" field studies taking into consideration the specific characteristics of the circulating water that affects the biofilm type and growth, and that will vary for each particular location throughout the year.

The design of the main heat exchanger and the whole plant makes it easy to carry out studies with different tube materials, diameters, biocides and dosage patterns, which is very useful for optimizing biofouling control procedures. Wireless remote control, monitoring and data transmission of the pilot plant can be carried out via a modem.

Biofouling evaluation methods

Indirect measures. By monitoring the effects of the biofilm on transport properties: heat transfer resistance and frictional resistance (Characklis *et al.*, 1981, 1982; Von Rège and Sand, 2000). In our study, indirect measures of transport properties are employed and changes in them are computed and monitored. The overall heat transfer resistance (sum of conductive and convective resistances) is expressed by the reciprocal of the overall heat transfer coefficient and will be determined for each tube. Also, increased frictional resistance is measured as the effective diameter of the tube diminishes and roughness increases. This will result in an augmented pressure drop of water through the tubes. Frictional resistance is conveniently expressed by the Darcy dimensionless friction factor. Our pilot plant uses a SCADA system to calculate the friction factor and the resistance to the heat transmission, according to the current values of the measured variables (pressure drop, flow rate and temperature), and represents graphically their evolution versus time for every tested tube.

Direct measures. These concern the determination of the quantity of the biofilm directly from the fouled support. Frequently, these type of procedures can be cataloged either as *non-destructive methods*, like direct observation using optical microscope or determining some specific activities, or as *destructive methods* involving previous biofilm removal or direct measure over the support (Lazarova and Manen, 1995; García-Morales, 1997).

A stainless steel tool, which is shown schematically in Figure 2, has been designed to collect the inner deposit, allowing us to carry out direct measures of the fouling layer. Even though this is done at the end of the experiment, it provides valuable information and gives us the possibility of contrasting with the indirect measurements and also to check the sensitivity of the indirect method used. We have used this device as follows and good results have been achieved.

Prior to opening the tubes that were tested, heating is turned off and the cooling water flow rate is gradually lowered. In this way we prevent the fouling from drying and from

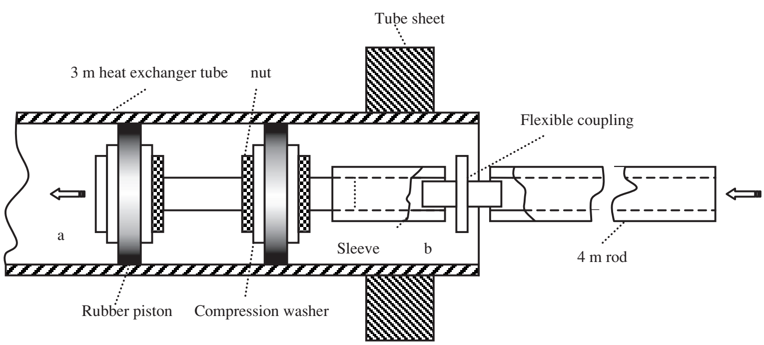

Figure 2 Fouling collecting tool

detachment. Previous tests had confirmed, by filtering the discharged water, that any significant mass of film was eliminated, following the aforementioned procedure.

Once we have removed the set of sensors connected at the end of each tube, we can tighten the nuts, and compress the rubber rings until they fit properly into the inner surface of the tube. The tube is then completely cleaned (zone b) by the double rubber piston as it is pushed through the 3.2 m heat exchanger tube, by means of the 4 m rod. Owing to the second piston, any remaining fouling layer after the first one has functioned is collected and also acts as a guide maintaining the concentric position of the set, not disturbed by the pushing rod due to the flexible coupling. The deposit is easily collected (zone a) at the other end of the tube for the subsequent laboratory measures.

Experimental method

The study was accomplished in seawater where biofilm presents very particular characteristics. Taking into account that characteristics of cooling water and other environmental factors clearly influence the type of fouling and development rate, the pilot plant was located at the suction point of the power plant to conduct the experiment using the same cooling water as in the real system. The experiment lasted 98 days, from 7th December to 14th March (winter season), and seawater temperatures recorded during this period ranged between 13.8–19.2°C.

Two aluminium-brass (ASTM–B111 79 alloy 687) tubes 12/15 mm in diameter and 3,200 mm in length were used. The flow rate through the tubes was established and automatically controlled at 800 l/h resulting in a flow velocity of 1.98 m/s. One of them, tube 1, received the chlorine dosage necessary to obtain a concentration of 0.20 mg/l of residual chlorine in cooling water discharge, the other, tube 2, had been maintained in no dosing conditions.

In order to simulate power plant condenser conditions, tubes were heated on the shell side by hot water to maintain an inner tube surface temperature equal to that in the real condenser. The heating water temperature set point was 35°C with a difference through the shell of only 0.4°C, this being achieved by employing a flow rate of 35 m^3/h through the shell.

Temperatures were measured and monitored with thermistors (accuracy to $\pm$ 0.1°C) and the seawater initial temperature difference through the tubes was 4.5°C.

Results and discussion

Overall heat transfer resistance (indirect measurement)

From temperatures and cooling water flow rate automatically recorded and controlled, the calculated values of the overall heat transfer resistance for each tube are plotted versus time. As shown in Figure 3, R_f values show that tube 1 was appreciably less susceptible to fouling than tube 2 due to the effects of biocide.

Observed overall heat transfer resistance (R_f) values increased throughout the experiment from 0.62 to 0.93 m^2 °C/kW for tube 1 (0.20 ppm residual chlorine) and from 0.69 to 1.32 for tube 2 (with no biocide). Thus fouling factors (r_f) i.e. $R_f - R_{fo}$ are 0.31 and 0.63 m^2 °C/kW for tubes 1 and 2, respectively.

According to the equations employed in heat transfer calculations we can determine the theorical thickness of the fouling film as follows:

$$\text{Since } d_i - 2\,\delta = d_i \exp^{-2\pi k_f l r_f}, \text{ then } \delta = 0.5\, d_i\,(1 - \exp^{-2\pi k_f l r_f}) \quad (1)$$

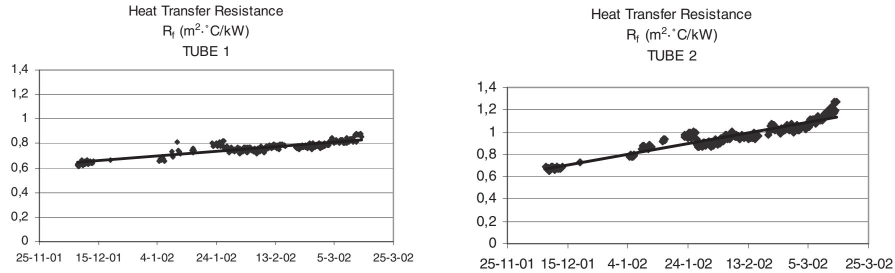

Figure 3 Overall heat transfer resistance for tubes 1 and 2

Table 1 Summary of experimental results

Tube	Residual chlorine mg/l	Carbon mg/cm^2	Fouling volume (wet) cm^3	Film thickness µm	Total solids (mg/cm^2)	Organic solids (mg/cm^2)	Inorganic solids (mg/cm^2)
1	0.2	0.027	8.0	66.31	0.227	0.056	0.170
2	0	0.053	19.0	134.04	0.403	0.113	0.290

where:

d_i = inner diameter of tube
δ = film thickness
k_f = effective thermal conductivity of the layer
l = length of heat exchanger tube
r_f = fouling factor

However, for the previous calculation we need reference values for k_f that introduce some uncertainty in the results.

Direct measurement

Results of laboratory measurements on collected inside deposit are given in Table 1.

We can see the wet volumes (4 h settling) after 98 days of experimentation for both tubes. The color of the removed inside deposit was brown. The slime was easily removed and no signs of pitting or oxide inner layer were observed. Thus any thermal resistance due to *in situ* corrosion fouling was negligible for the material used.

From experimental data recorded during our research, once we knew the actual film thickness, we calculated the effective thermal conductivity of the layer solving Eq. (1) for k_f. By doing this we get, with the stated conditions for flow velocity and temperatures, 0.283 and 0.262 W/m K for the effective thermal conductivity of the layers in tube 1 and 2, respectively. It is necessary to consider that the fouling layer is not only composed by biological material, but also of an important inorganic contribution, as we can see in the data of solid concentration (total, organic and inorganic) which are included in Table 1.

Consequently, we could assume a mean value of 0.273 W/m K for the effective thermal conductivity which allow us to estimate the film thickness from an indirect measure: the overall heat transfer resistance R_f. Nevertheless, this conductivity value has been obtained in very particular conditions (see Experimental Method), and it is not possible to extrapolate to other fouling situations.

Conclusions

A portable pilot plant for evaluating marine biofouling has been designed and made. This pilot plant, makes possible "on site" field studies taking into consideration the local characteristics of the cooling water, which largely affect any specific fouling process.

The design of the main heat exchanger and the whole plant makes easy to carry out studies with different tube materials, diameters, biocides and dosage patterns, which is very useful for optimizing biofouling control procedures. Wireless remote control, monitoring and data transmission of the pilot plant can be carried out via modem.

A winter study over a period of 98 days, has been accomplished to evaluate the chlorine effect on biofilm development. Also this research has permitted us to establish direct and indirect methods for monitoring the fouling process. As an indirect measure, overall heat transfer coefficient is considered a suitable non-destructive on-line method. In combination with the proposed direct method to obtain the actual film thickness, it is possible to determine the effective thermal conductivity of the layer (k_f), finding a mean value of 0.273 W/m K. The effective thermal conductivity, calculated as stated before, allow us to estimate the film thickness from an indirect measure: the overall heat transfer resistance R_f.

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