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BIOFOULING GROWTH ON TUBULAR HEAT EXCHANGERS. MATHEMATICAL MODEL AND SIMULATION

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ABSTRACT

Biofouling is one of the most serious problems to face numerous industrial processes. In the case of a tubular heat exchanger, biological deposits adhered to the inside surface of the tubes reduce heat transfer and therefore the thermal performance of the equipment. By virtue of this, control of this phenomenon is fundamental for both sea and land-based equipment to operate under optimal running conditions. A set of equations have been developed for this purpose which have enabled a mathematical model to be drawn up that is capable of predicting substrate and cell concentrations in the formation of biofilm over time, at any point in the tube. The said mathematical model serves as the basis for the creation of a computer simulation program that enables prediction of biofilm thicknesses and concentrations inside the tubes. It likewise allows experimentation with the heat exchanger under different working conditions and enables optimal down and cleaning times to be established.

Keywords: Biofouling, Heat exchanger, Mathematical model, Simulation.

INTRODUCTION

Biofouling may be defined as the undesirable phenomenon of adherence and accumulation of biotic deposits on an artificial surface that is submerged or in contact

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with seawater. This accumulation consists of an organic film composed of micro-organisms embedded in a polymer matrix they themselves create (biofilm) that inorganic particles can reach and be retained (salts and/or corrosion products), which are the outcome of other types of fouling undergone in the process. This biofilm composed of micro-organisms (microbial biofouling or microfouling) may give rise to the accumulation of macro-organisms (macrobial biofouling or macrofouling) (Eguia et al., 2004).

The process whereby biofilm accumulates on a surface may be considered as the net result of several physical, chemical and biological processes (Characklis, 1990): The transport of soluble components and particles to the wet support medium, adsorption by the wet support medium, chemical or microbial reaction in the support medium or inside the deposit and separation, detachment or splitting of portions of the deposit layer.

The final outcome of this sequence of events is usually characterized by a sigmoid shaped progression or curve, in which three periods are clearly distinguishable (Eguía, 1998): In the first, known as induction, small changes are observed in the biofilm accumulation process; however, it is very difficult to appreciate any variation in representative parameters during this phase; the second, entitled exponential increase, is characterized by a logarithmic progression in the biofilm accumulation; and the third, called the asymptotic or flat phase, shows the stabilization of the biofilm accumulation process.

From the biofouling viewpoint, for a heat exchanger the following parameters should be considered:

— *Fluid parameters.* The type of fluid, its features and the conditions under which it fosters biofouling settlement are two of the most important factors to be taken into account in an industrial process. The factors relating to the fluid that should be taken into consideration for heat exchanger design are (Knudsen, 1991): Fluid purity and the absence of pollution; treatment of the fluid for the prevention of biological growth; treatment of the fluid to reduce biofouling; the influence of internal and external fluid flows and their velocity and temperature.

— *Heat exchanger parameters.* The exchanger parameters that exert a direct influence on biofouling settlement are: wall surface area and temperature, the material and coating used for the inside of the tube, geometry and protection systems.

— *Factors applied in heat exchanger design*. The consequences of the biofilm accumulation process on the tube walls are disastrous for heat exchanger performance; therefore in the design phase this phenomenon must be taken into account in the form of a fouling factor (Chenoweth, 1990).

A mathematical model is then constructed taking these variables into account, to predict substrate and cell concentrations over time, both in the liquid and biofilm phases, at any point in the heat exchanger tubes. The mathematical model enables a

computer simulation program to be created in which it is possible to assess biofilm thicknesses and concentrations in the tubes under different working conditions. Thus, we can forecast the best down-times and cleaning times for keeping a seawater-cooled heat exchanger free of the biofouling phenomenon.

The growth simulation module for biofouling in heat exchangers is part of a computer design, simulation and analysis program that allows:

— The design and choice of the optimum tubular heat exchanger for a particular industrial process. The definition of the said heat exchanger is reached by following international standards, the recommendations of the classifying societies and current design methods used in modern industry today.
— The simulation of normal and abnormal operation in real, extreme working conditions to thus analyze and forecast to what point it can carry the process out without going into losses.
— The simulation of biofouling growth on exchanger walls and a forecast of the effects of the scale on exchanger performance.
— The forecast of the optimum operating time without losses in performance and the optimum down and cleaning periods.

MATHEMATICAL MODEL

The development of our mathematical model can be divided into four, well defined parts: the substrate concentration profile in the liquid phase; the substrate concentration profile in the solid phase; the cell concentration profile in the liquid phase; and the biofilm thickness.

The study was broached under the following assumptions (Characklis and Marshall, 1990): a.) The heat exchanger tubes are considered as a microbial tubular reactor; b.) Due to the high flow velocity in the tube, it was assumed that there is no cell reaction in the liquid phase; c.) In the biofilm formation process a liquid phase is clearly differentiated from a solid phase; d.) Matter in the liquid is transported by convection (transport of mass by fluid movement) and in by diffusion in the solid phase (transport of mass through a difference in concentration); e.) All the substrate considered in the liquid-biofilm interface is consumed by the organisms, therefore the wear by convection in the liquid phase is equal to the wear by diffusion in the solid phase; f.) Substrate transport and its concentration in the biofilm depends on the following variables: concentration in the liquid phase, flow velocity, resistance at the interface, substrate diffusion velocity in the biofilm, the velocity by which the organisms consume the substrate, cell mass concentration per unit of volume in the biofilm, the rate at which substrate is converted into cells and biofilm thickness; g.) Substrate diffusion velocity in the biofilm is very fast, therefore growth is at its maximum and the substrate reaction rate is the same in both the liquid and solid phases.

Mass Balance in the Liquid and Solid Phases (Biofilm)

By applying the Conservation of Mass Principle to the biofilm system, it is possible to determine the mass balances both in the liquid and solid phases where the substrate mass balance and the cell mass balance are taken into consideration for each of the phases. Thus, we can obtain the substrate and cell concentration at any point in the tube, in any phase and at any moment in time (Kotake and Hijikata, 1993). To obtain the substrate mass balance we apply the equation below

$$\frac{\partial S}{\partial t} + v\nabla S = D_s \nabla^2 S - r_s \tag{1}$$

and likewise for the cell mass balance

$$\frac{\partial X}{\partial t} + v\nabla X = D_x \nabla^2 X + r_x \tag{2}$$

The process states may be transitory when substrate and cell concentration at a particular point vary over time

$$\frac{dS}{dt} \neq 0, \frac{dX}{dt} \neq 0 \tag{3}$$

or stationary when the concentration does not vary over time

$$\frac{dS}{dt} = 0, \frac{dX}{dt} = 0 \tag{4}$$

Resolving equations (1) and (2) for each phase, substrate and cell concentration can be obtained at any point in the tube at any particular moment in time.

Substrate Concentration in the Liquid Phase

Taking equation (1) in a stationary state and given that in this phase, for a high flow velocity, transport by convection is much greater than by diffusion ($v\nabla S >> D_s \nabla^2 S$)

$$v\nabla S = -r_s \tag{5}$$

where

$$r_s = \frac{\mu_{máx}}{Y_s} X_f = q_{s_{máx}} X_f \tag{6}$$

therefore the substrate concentration at any point of the tube axis is

$$v\frac{dS}{dz} = -\frac{\mu_{máx}}{Y_s} X_f \tag{7}$$

By integrating equation (7) using the dimensionless variable method, where

$$S^* = \frac{S}{S_i}\ ,\ z^* = \frac{z}{L} \tag{8}$$

then

$$\frac{dS^*}{dz^*} = -\frac{\mu_{máx}}{Y_s}\frac{L}{vS_i} X_f = -k_m \tag{9}$$

therefore

$$\int_0^1 dS^* = \int_0^1 -k_m dz^* \tag{10}$$

We, thus, obtain the substrate concentration along the tube axis in the liquid phase and under stationary conditions, the process being represented by a straight-line graph with a gradient of $-K_m$.

The coefficient K_m represents the energy microorganisms require in their life process or the maintenance coefficient.

$$k_m = \frac{\frac{\mu_{máx}}{Y_s} X_f}{\frac{S_i}{L} v} = \frac{\text{consump}}{\text{transport}} \tag{11}$$

When $k_m = 1$, all the substrate entering the tube is consumed by the microorganisms.

When $k_m < 1$, there is sufficient substrate to fulfill the growth process.

When $k_m > 1$, the cell reaction is incomplete because there is insufficient substrate for all the organisms.

Substrate Concentration in the Solid Phase (Biofilm)

In the solid phase substrate is transported by diffusion (v = 0) and it is fully used up in the cell growth process, fulfilling Monod's saturation equation, which describes

the relationship between microbial growth and substrate concentration

$$\mu = \frac{\mu_{máx} S}{k_s + S} \tag{12}$$

if $S = k_s$, then $\mu = \mu_{max}$, and growth does not depend on S.

if $S = k_s$ then $\mu = \frac{\mu_{máx}}{k_s}$, and growth is exponential and depends on S.

By applying equation (1) in a stationary state to the solid phase

$$D_s \frac{d^2 S}{dx^2} - r_s = 0 \tag{13}$$

assuming that $\mu = \mu_{max}$,

$$\frac{d^2 S}{dx^2} = \frac{\mu_{máx} X_f}{D_s Y_s} \tag{14}$$

And introducing the dimensionless variables

$$S^* = \frac{S}{S_b},\ x^* = \frac{x}{L_f} \tag{15}$$

then

$$\frac{d^2 S^*}{dx^{*2}} = \frac{2}{\Omega^2} \tag{16}$$

where Ω is the coefficient of substrate penetration in the biofilm, considering that if Ω >1, substrate penetration in the biofilm reaches the support medium and is complete and if Ω <1, penetration is incomplete; therefore in the layers furthest from the biofilm surface no microbial reaction takes place due to the lack of nutrients.

$$\Omega = \left[\frac{D_s S_b}{q_s X_f L_f^2} \right]^{1/2} \tag{17}$$

By integrating equation (17) for $\Omega > 1$ between $x^* = 0$ ($S^* = 1$) and $x^* = 1$ ($dS^*/dx^* = 0$)

$$S^* = \frac{x^{*2}}{\Omega^2} - \frac{2x}{\Omega} + 1 \tag{18}$$

and for $\Omega < 1$ between $x^* = 0$ ($S^* = 1$) and $x^* = x_A$ ($S^* = 0$)

$$S^* = \frac{x^{*2}}{x_A^{*2}} - \frac{2x^*}{x_A^*} + 1 \tag{19}$$

where

$$x_A^* = \frac{L_{fA}}{L_f} \tag{20}$$

Cell Concentration in the Liquid Phase

If a flocculation process takes place in the liquid phase, we will have an increase in the microbial population in the core of the liquid and thus a higher concentration of the said population. In the case of heat exchangers this process is not taken into consideration, due to the fluid velocity and the short time of residence available for completing the cell division; cell concentration is assumed only to vary due to adsorption, which consists of temporary or permanent immobilization of the cells contained in the fluid.

By applying equation (2) in a stationary state to the liquid phase, considering the flow speed in the tube axis to be z and making $r_x = r_{ax}$,

$$r_x = r_{ax} = k_{ax} X_L \left(1 - \frac{x_f'}{k_{ax}'}\right) \tag{21}$$

the cell mass balance in the liquid phase is

$$\frac{dX_L}{X_L} = \frac{k_{ax}}{v_z}\left(1 - \frac{x_f'}{k_{ax}'}\right)dz \tag{22}$$

Integrating for the condition $z=0$ ($X_L = X_{L0}$)

$$\ln X_L = -\frac{k_{ax}}{v_z}\left(1 - \frac{X_f}{X_{\max}}\right).z + \ln X_{L0} \tag{23}$$

and exponentially

$$X_L = X_{L0} EXP\left[-\frac{k_{ax}}{v_z}\left(1 - \frac{X_f}{X_{\max}}\right)z\right] \tag{24}$$

where

$$z = z^{*} L \tag{25}$$

then for $0 < z^{*} < 1$

$$X_L = X_{L0} EXP\left[-\frac{k_{ax}}{v_z}\left(1 - \frac{X_f}{X_{\max}}\right).z^{*} L \right] \tag{26}$$

Equation (26) enables us to calculate the cell concentration in the liquid phase along the tube axis of a heat exchanger while bearing only the adsorption process in mind and assuming that there is no growth in the liquid.

The cell adsorption process is calculated as the difference between cell mass at the inlet and outlet of the tube for $z^{*} = 0$ and $z^{*} = 1$

$$\Delta X_L = X_L\big|_{z^{*}=0} - X_L\big|_{z^{*}=1} \tag{27}$$

where this value is the cell concentration adhered to the internal surface of the tube that will go to form part of the biofilm formed on the support medium.

Cell Concentration in the Solid Phase. Biofilm Formation

Supposing that the cell mass per unit of biofilm volume remains constant over time, the accumulation of organisms and their growth contributes to increasing the biofilm thickness instead of increasing their concentration.

By applying equation (2) in a stationary state to the solid phase, the mass balance is

$$r_x = \frac{dX_f^{*}}{dt} = \frac{d}{dt}\left(\frac{A}{V} L_f X_f\right) \tag{28}$$

where

$$X_f^{*} = X_f \frac{AL_f}{V} \tag{29}$$

and the cell concentration at any moment in time is

$$X = \frac{X_0 e^{t\mu_{\max}}}{1 - \frac{1}{X_{\max}} X_0 (1 - e^{t\mu_{\max}})} \tag{30}$$

In equation (28) if $\frac{A}{V} = \text{constant}$

$$r_x = \frac{A}{V}\left(L_f \frac{dX_f}{dt} + X_f \frac{dL_f}{dt}\right) \tag{31}$$

and if X_f is constant

$$r_x = \frac{A}{V} X_f \frac{dL_f}{dt} \tag{32}$$

given that

$$r_x = \mu X_f \tag{33}$$

then

$$\frac{dL_f}{dt} = \frac{\mu V}{A} \tag{34}$$

Resolving this differential equation for $t = 0$ and $L_f = L_{f0}$

$$L_f = \frac{\mu . V}{A} t + L_{f0} \tag{35}$$

this allows us to calculate the microbial growth process reflected in the increase in biofilm thickness at any moment without taking detachment due to fluid action into account.

SIMULATION OF THE BIOFOULING ACCUMULATION PROCESS IN A TUBULAR HEAT EXCHANGER

The formation of the biofilm on the submerged surface is an unavoidable consequence of a series of events that begin with the adsorption of organic molecules by the support medium surface, followed by bacterial adhesion, cell growth and reproduction and formation of extracellular polymers, finally constituting the biofilm matrix. For there to be a fast biofilm development, cell adhesion and reproduction levels must exceed those for detachment and death.

The development of a biofilm on a surface in contact with a fluid is the net outcome of various physical, chemical and biological processes, such as: transport of

soluble components and particles from the fluid to the support medium; adsorption of cells on the support medium; chemical reactions on the support medium; production of exopolymers and other metabolic processes; and lastly the separation, detachment or splitting of portions of the deposit by the cutting force of the fluid or due to cell death.

If all these processes take place in series, the slowest stage of the sequence, called the determinant value stage or limiting value stage, may exert most influence and limit the value of the entire process. If the total process comprises a number of parallel processes and series-parallel processes, the slowest process then becomes the stage controlling value. It is necessary to identify the controlling value and the stage limiting value in order to correctly interpret the results of the experiment.

Description of the Simulation Module

The simulation and analysis process took place in a central tube of the heat exchanger, which was virtually fully insulated, and in which its dimensions and all its thermal-hydraulic flow parameters are maintained.

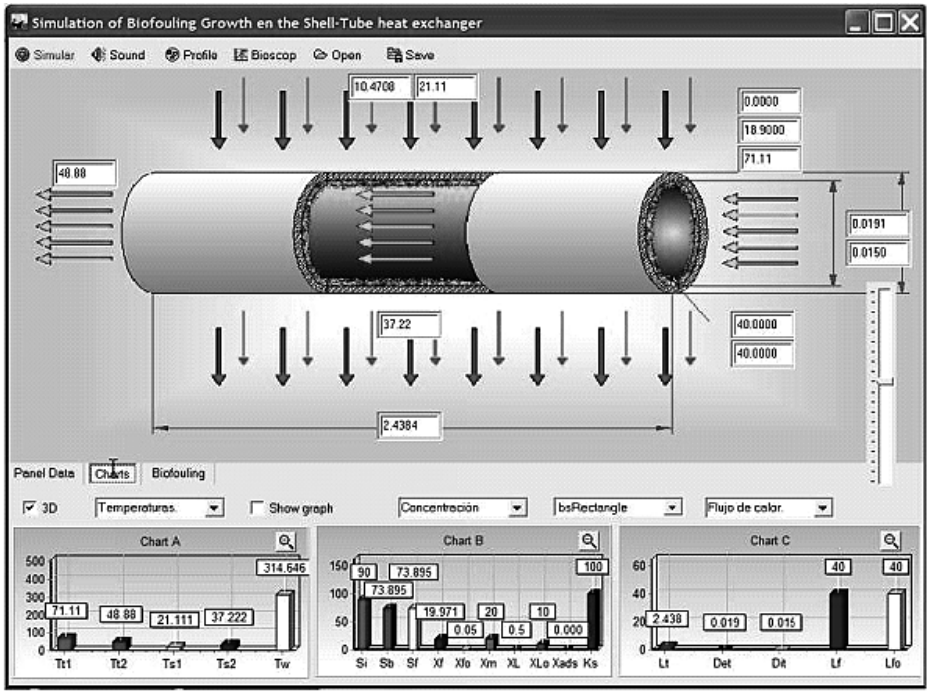

Figure 1. Main window of the simulation module

Figure 1 shows the main window of the simulation module, which offers the following alternatives:

— A virtual tube through which the heat transmission process takes place between fluids, and inside which a microbial growth and accumulation process occurs, giving rise to biofilm formation.
— The data cells on the drawing indicate the internal and external flow parameters and the dimensions of the tube.
— The data panel indicates the physical properties of the fluid from the tube (viscosity, density, specific heat and conductivity) and the flow's thermal-hydraulic parameters (heat transmission coefficients, heat transmitted, Reynolds Number and velocity).
— The graph panel provides a graph representation of how the biofouling accumulation parameters and the thermal-hydraulic flow parameters all evolve.
— The biofouling panel shows the simulation data and results referring to the accumulation, growth and elimination of the biofilm in the tube, such as substrate and cell concentration, growth rate, biofilm thickness and all the coefficients associated with microbial growth in a biofilm system. We only have to use the dropdown menus (see Figures 2a and 2b) to select the variable to be shown on the abscissa and ordinate axes to see a graph representation of their evolution.

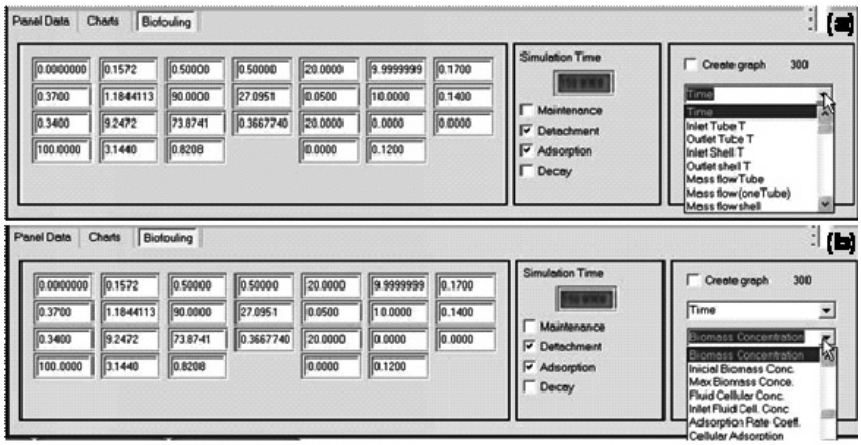

Figure 2. List of the parameters graphically represented on the abscissa axis (a) and the ordinate axis (b).

Simulation Process for Biofouling Accumulation

— Upload heat exchanger data. The program has a database which stores the characteristics of the heat exchangers designed which are going to be submitted to a simulation process for biofouling growth inside their tubes (see Figure 3).

— Biofilm Parameters. When a heat exchanger is simulated for the first time, it is necessary to put in the features of the fluid that circulates inside the tubes. The program automatically assumes the characteristics for the biofilm growth process.
— The "Bioscope" option enables us to forecast the variation in substrate and cell concentrations, as well as that of the biofilm over time. This is illustrated in Figure 4 for some specific initial conditions and a particular experiment period.

The program offers a wide range of possibilities. To be able to extract all the information it can provide and thus to understand the biofouling accumulation process and its effects on heat exchanger performance, we need at least a basic understanding of the processes of microbial transformation and growth in an aquatic medium, together with biofilm accumulation processes and mechanisms in heat exchangers and the effects of biofouling on their performance.

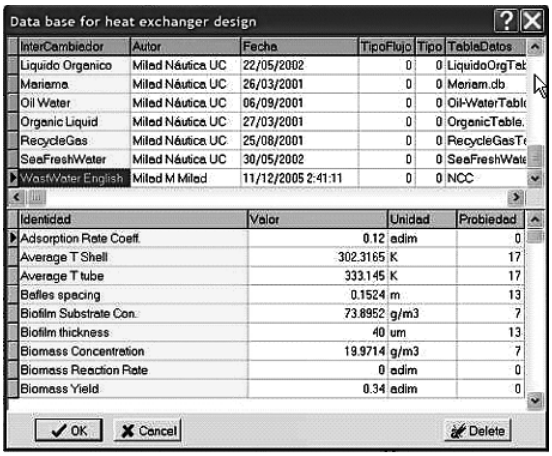

Figure 3. Database of designed heat exchangers.

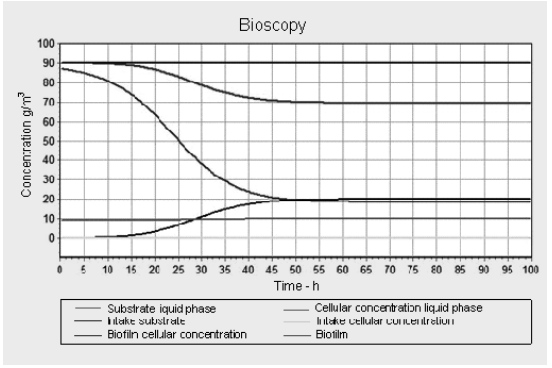

Figure 4. Evolution of substrate and cell concentration and the biofilm over time.

RESULTS

Figure 4 shows that the variation in substrate concentration in the liquid phase along the length of the tube for fifteen hours barely varies because the microbial population is very low and hence there is no consumption. From this point substrate consumption increased markedly at the same rate as the biofilm increases, to reach a stationary state after 60 hours where the substrate concentration no longer varies along the tube.

In the solid phase, substrate concentration varies from the liquid-biofilm interface to the tube wall because it is consumed by the organisms that comprise part of the biofilm. The curve gradient becomes steeper, which implies that there is a notable difference between the concentration on the biofilm surface and on the

support medium. In some cases this may reach zero before reaching the support medium. This takes place when the biofilm is thick or cell metabolism is high and all the substrate arriving through the fluid is consumed. As time goes by, the substrate concentration in the biofilm tends to stabilize and reaches a stationary state, which depends on the cell concentration reaching its maximum saturation value.

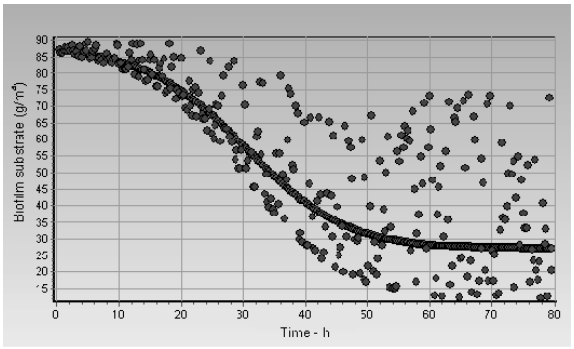

Figure 5. Evolution of substrate concentration at every point in the biofilm (●) and at its mid point (●●●●) from the surface to the support medium.

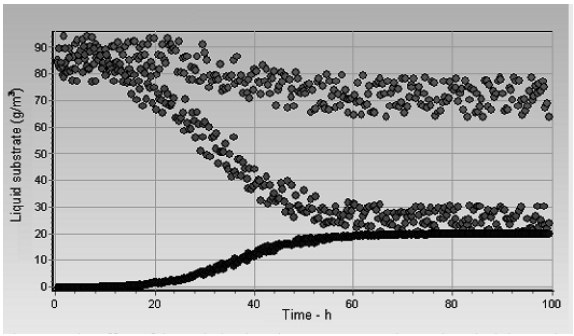

Figure 6. The effect of the variation in substrate concentration at the tube inlet on the concentration of substrate in the liquid (●), in the biofilm (●) and in the biofilm cell concentration (●●●●).

Figure 5 shows the simulation process of the evolution of biofilm substrate from the surface to the support medium, differentiating between substrate concentration at all the biofilm thickness points and the concentration in the middle of the biofilm.

Substrate concentration at the tube inlet has a direct effect on microbial activity and therefore on the organism population. To see the effect of the substrate concentration at the inlet, a variation is simulated from 80 to 95 g/m^3 for 100 operating hours. The results are shown in Figure 6, where we can see the effect of the said variation on substrate concentration at the tube inlet, on substrate concentrations in the liquid, in the biofilm and on concentration in the biofilm. We can see that cell concentration is only affected in the exponential growth phase, broadening the curve in the maximum growth phase to stabilize on reaching cell saturation concentration.

As far as the evolution of cell concentration is concerned, Figure 4 shows it develops through a slow linear phase followed by an exponential phase to the stationary state where concentration reaches its maximum. This state of maximum concentration depends on the organisms and on the nutrient concentration in the core of the liquid entering the tube. If the cell concentration is at its maximum, the increase in the microbial population increases the biofilm thickness and keeps the

concentration constant. For small biofilm accumulations, the concentration increases exponentially whereas thickness increases with a smaller gradient. After a certain time saturation point is reached and cell concentration does not increase any further, however thickness does undergo an exponential increase.

The increase in the biofilm thickness depends on factors such as cell concentration, the specific growth rate, the concentration of organisms in the core of the liquid entering the tube and on substrate concentration. Biofilm thickness may rise slowly or exponentially depending on cell detachment or growth. These features may be simulated on the program producing the results shown in Figure 7. We can observe that when the detachment effect is unappreciable, biofilm thickness increases exponentially. On the other hand, whether there is a considerable detachment effect, it is especially detected early on in the process giving rise to a reduction in biofilm thickness until cell activity increases, thus leading biofilm thickness to rapidly increase. If the detachment effect is very large, either due to turbulences or to biofilm fragility, its thickness will stabilize and barely increase after some 60 hours.

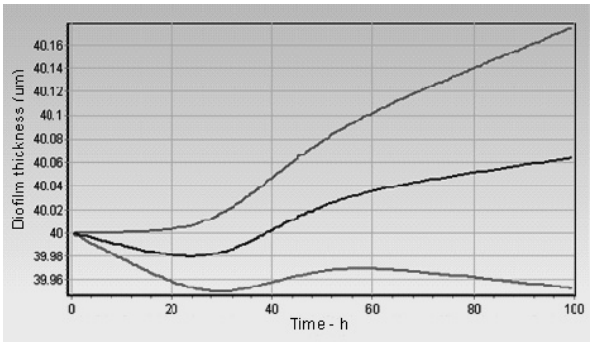

Figure 7. The comparative evolution of biofilm thickness over time: without detachment, with detachment, and with detachment in a stationary state

The effects of other parameters on biofilm thickness, such as specific growth rate, for example, can likewise be simulated to produce numerous graphs that provide a wealth of information.

CONCLUSIONS

This paper has applied an easily understandable mathematical model to one of the greatest problems facing seawater cooled industrial equipment –biofouling. This has enabled forecasts for substrate and cell concentrations to be made for the different phases of biofilm formation over time, at any point in the tube. Based on the mathematical model, the computer simulation program allows the thicknesses and concentrations of the biofilm in the tubes to be predicted and experiments to be carried out on the heat exchanger for different operating conditions. This, in turn, enables optimum down and cleaning times to be determined. The examples of the simulated effect caused by the variation in the biofilm formation process show the potential the simulation module offers. A variety of results and graphs can be obtained that enhance understanding of the biofouling accumulation process and its effects on heat exchanger performance.

NOMENCLATURE

A	biofilm surface
D	diffusion coefficient
K'_a	saturation coefficient per unit of volume
k_a	adherence coefficient
k_m	maintenance coefficient
k_s	saturation coefficient
L	tube length
L_f	biofilm thickness
q_s	specific consumption rate or consumption per mass cell unit and time unit in saturation state
r	reaction rate
r_a	specific adsorption rate
S	substrate concentration at a certain instance in time t
t	time
v	flow velocity
V	tube volume
X	cell concentration at a certain instance in time t
x	co-ordinate perpendicular to the tube axis
x'	cell concentration per unit volume
X_f	cell mass per unit of biofilm volume
Y	microbial mass produced per unit of substrate
z	co-ordinate in the direction of the tube axis

Greek-symbols

μ	specific growth rate
Ω	coefficient of substrate penetration in the biofilm

Subscripts

0	initial
A	biofilm thickness penetrated by the substrate
b	liquid-biofilm interface
f	solid phase
i	effluent
L	liquid phase
max	maximum
s	substrate
x	cell
z	direction of tube axis

Superscripts

*	dimensionless variable

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CRECIMIENTO DE BIOFOULING EN INTERCAMBIADORES DE CALOR TUBULARES. MODELO MATEMÁTICO Y SIMULACIÓN

RESUMEN

El *biofouling* es uno de los problemas más graves con que se enfrentan numerosos procesos industriales. En el caso de un intercambiador de calor tubular, los depósitos biológicos adheridos en la superficie interior de los tubos disminuyen la transferencia de calor y, por lo tanto, el rendimiento térmico del ciclo. Debido a esto, el control de este fenómeno resulta fundamental para que los equipos, tanto marítimos como terrestres, operen en condiciones óptimas de funcionamiento. Por ello se desarrolla un conjunto de ecuaciones que han permitido elaborar un modelo matemático con el que poder predecir las concentraciones de sustrato y celulares en las diferentes fases de formación de la biopelícula en el tiempo, en cualquier punto del tubo. Basándose en el modelo matemático elaborado se crea un programa de simulación informático que permite predecir espesores y concentraciones de biopelícula en los tubos pudiendo experimentar el intercambiador de calor en diferentes condiciones de funcionamiento y así conocer los tiempos de parada y limpieza óptimos.

MODELO MATEMÁTICO

En el desarrollo del modelo matemático se diferenciaron cuatro partes bien definidas: el perfil de la concentración del sustrato en la fase líquida, el perfil de la concentración de sustrato en la fase sólida, el perfil de la concentración celular en la fase líquida y el espesor de la biopelícula.

El estudio se abordó considerando los siguientes postulados (Characklis and Marshall, 1990): a.) los tubos del intercambiador de calor se consideraron como un reactor tubular microbiano, b.) debido a la alta velocidad del flujo en el tubo se supuso que no hubo reacción celular en la fase líquida, c.) en el proceso de formación de la biopelícula en los tubos se diferenció entre una fase líquida y una fase sólida, d.) la materia en el líquido se transporta por convección (transporte de masas por movimiento del fluido) y en la fase sólida por difusión (transporte de masas por diferencia de concentraciones), e.) todo el sustrato considerado en la interfase *líquido-biopelícula* es consumido por los organismos, por lo que el gasto por convección en la fase líquida es igual al gasto por difusión en la fase sólida, f.) el transporte del sustrato y la concentración en la biopelícula depende de las siguientes variables: concentración en la fase líquida, velocidad del flujo, resistencia en la interfase, velocidad de difusión del sustrato en la biopelícula, velocidad de consumo del sustrato por los organismos, concentración de masa celular por unidad de volumen en la biopelícula,

tasa de conversión de sustrato en células, espesor de la biopelícula, g.) la velocidad de difusión del sustrato en la biopelícula es muy rápida, por lo que el crecimiento es máximo, siendo la tasa de reacción del sustrato la misma en la fase líquida que en la sólida.

SIMULACIÓN DEL PROCESO DE ACUMULACIÓN DE BIOFOULING EN UN INTERCAMBIADOR DE CALOR TUBULAR

Descripción del módulo de simulación

El proceso de simulación y análisis se realizó en un tubo central del intercambiador de calor, virtualmente aislado, en el que se mantienen sus dimensiones y todos los parámetros del flujo termohidráulico. En la Figura 1 se presenta la ventana principal del módulo de simulación, la cual ofrece las siguientes posibilidades:

- Tubo virtual a través del cual se produce el proceso de transmisión de calor entre fluidos, en cuyo interior se experimenta el proceso de crecimiento y acumulación microbiana que origina la formación de biopelícula.
- Las celdas dispuestas en el dibujo indican los parámetros del flujo interno y externo y las dimensiones del tubo en cuestión.
- El panel de datos indica las propiedades físicas del fluido del tubo (viscosidad, densidad, calor específico y conductividad) y los parámetros termohidráulicos del flujo (coeficientes de transmisión de calor, calor transmitido, número de Reynolds y la velocidad).
- El panel de gráficos presenta de manera gráfica la evolución de los parámetros del proceso de acumulación del biofouling y de los parámetros del flujo termohidráulico.
- El panel biofouling presenta los datos y resultados de la simulación referentes al proceso de acumulación, crecimiento y eliminación de la biopelícula en el tubo, tales como, la concentración del sustrato y celular, tasa de crecimiento, espesor de la biopelícula y todos los coeficientes asociados al crecimiento microbiano en un sistema biopelícula. Basta con seleccionar en los "desplegables" (ver Figura 2a y 2b) la variable a representar en los ejes de abscisas y ordenadas para ver gráficamente su evolución.

Proceso de simulación de acumulación de biofouling

- Carga de los datos del intercambiador de calor. El programa dispone de una base de datos en la que se almacenan las características de los intercambiadores de calor diseñados, a los que se va a someter al proceso de simulación de crecimiento de biofouling en el interior de sus tubos (ver Figura 3).
- Parámetros de la biopelícula. Cuando se simula un intercambiador de calor por primera vez es necesario introducir las características del fluido que circula por el interior de los tubos. Las características propias del proceso de

crecimiento de la biopelícula las asume el propio programa de manera automática.

— La opción "Bioscopio" permite predecir la variación de la concentración de sustrato y celular, así como de la biopelícula en el tiempo, tal y como se muestra en la Figura 4 para unas condiciones iniciales dadas y un periodo de experimentación determinado.

Las posibilidades del programa son amplias y para poder extraer toda la información que puede aportar y así comprender el proceso de acumulación de biofouling y sus efectos en el rendimiento del intercambiador de calor hay que tener un mínimo conocimiento sobre el proceso de transformación y crecimiento microbiano en el medio acuático, así como de los procesos y mecanismos de acumulación de la biopelícula en los intercambiadores de calor y de los efectos del biofouling en su rendimiento.

CONCLUSIONES

Este trabajo ha aplicado un modelo matemático fácil de comprender a uno de los mayores problemas con que se enfrentan los equipos industriales refrigerados con agua de mar: el biofouling. Esto ha permitido predecir las concentraciones de sustrato y celulares en las diferentes fases de formación de la biopelícula en el tiempo, en cualquier punto del tubo. Basándose en el modelo matemático el programa de simulación informático permite predecir espesores y concentraciones de biopelícula en los tubos pudiendo experimentar el intercambiador de calor en diferentes condiciones de funcionamiento y así conocer los tiempos de parada y limpieza óptimos. Los ejemplos de simulación del efecto de la variación de algunos parámetros en el proceso de formación de la biopelícula, muestran las posibilidades del módulo de simulación. Pueden obtenerse una variedad de resultados y gráficos que ayudan a la compresión del proceso de acumulación del biofouling y sus efectos en el rendimiento del intercambiador de calor.