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A model for the interpretation of biofouling

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The formation of biofilms on heat exchange surfaces was studied using water with Pseudomonas fluorescens as a contaminant and also a mixture of these bacteria and kaolin particles. In every case, increasing the fluid velocity resulted in a decrease in the final amount of deposit and in the deposition rate. The effect of the fluid velocity was interpreted using a mathematical model and it was found that cell adhesion and reproduction were the fundamental processes controlling the deposition rate.

The presence of inorganic particles in the deposit enhanced the biofilm growth rate. This result was explained by the differences in the structure of the fouling layers.

1. INTRODUCTION

Biological fouling on surfaces brought into contact with contamined fluids constitutes a yet unsolved problem especially in heat transfer equipment.

Several studies (1,4,7) have been undertaken in order to investigate the influence of variables such as fluid velocity, surface characteristics or nutrient concentration, but the existing mathematical models are not sufficiently developed to predict the rate at which this phenomenom occurs.

In the present work an extension of the generalized Pinheiro model (10) is introduced, taking into account the specificity of the processes which contribute to the biofilm formation. The results obtained when using water contaminated by a typical organism present in industrial cooling waters (8) (*Pseudomonas fluorescens*) and by a mixture of these bacteria and kaolin particles were interpreted on the basis of the referred model extension.

2. A MODEL FOR THE DEPOSTION FLUX IN BIOFOULING

Following Kern and Seaton's proposals (6), Pinheiro assumed that fouling is often the result of a competition between two basic phenomena - deposition (occuring at a constant rate) and removal (its rate increasing as the deposit builds up). In the case of the so-called "inorganic" fouling, deposition is considered to be a sequence of two distinct processes: transport of particles (or their precursors) to the surface, followed by an "incorporation" process such as adhesion, precipitation or chemical reaction. In a biological fouling situation some modifications have to be introduced in order to take into account the more complex set of processes that usually take place (3):

. Transport of microorganisms and nutrient molecules to the deposition surface.
. Adhesion of microorganisms at the deposition surface.
. Growth and reproduction of microorganisms in the deposit.

The processes occur either in series (as the arrows show) or in parallel (processes 1. and 2.), such as follows:

1. "Physical" processes $|\phi d_1|$:
   Transport of microorganisms ⟶ Adhesion
2. "Biological" processes $|\phi d_2|$:
   Transport of nutrients ⟶ Biological growth

The total deposition flux $|\phi d|$ is the sum of the fluxes of the two simultaneous parallel processes:

$$\phi d = \phi d_1 + \phi d_2 \qquad (1)$$

The following equation may be used to define, in thermal units, the deposition flux of the "physical" processes, ϕd_1 (10):

$$\phi d_1 = \frac{1}{\rho_f k_f} \cdot \frac{C_M}{\frac{1}{k_{tM}} + \frac{1}{k_a}} \qquad (2)$$

C_M is the concentration of microorganisms in the fluid, k_{tM} and k_a are the rate coefficients for the transport and the adhesion of microorganisms, respectively. ρ_f and k_f are the density and the thermal conductivity of the deposit. It is assumed that the probability of n particles adhering to the deposition surface in a certain moment increases linearly with the total number of particles that reach the surface per unit time, which in turn depends on the concentration of the suspension (at fixed fluid velocity and temperature).

A similar expression may be derived for the "biological" step, considering that the microbial growth process is described by a first-order reaction (2):

$$\phi d_2 = \frac{1}{\rho_f k_f} \cdot \frac{C_N}{\frac{1}{k_{tN}} + \frac{1}{k_g}} \qquad (3)$$

where C_N is the concentration of the limiting nutrient in the fluid, k_{tN} is the rate coeficient for the transport of nutrient and k_g is the rate coefficient for the production of biofilm due to microbial growth. The assumption of a first-order mechanism for the biological process is based on the well-known Monod equation (9) for the specific growth of microorganisms:

$$\mu_g = \mu_{g\,max} \cdot \frac{C_N}{k_S + C_N} \qquad (4)$$

In this equation, μ_g is the specific growth rate, $\mu_{g\,max}$ is the maximum value of μ_g (attainable for high availability of nutrients) and k_S is the "saturation constant" of Monod. Since the availability of nutrients in the inner layers of the deposit is low (or even nil), the average specific growth rate of the biofilm is considerably smaller than the maximum value, μ_{gmax}. In this case, $k_S + C_N >> C_N$, and $(\mu_g)_{average}$ can be considered to be linearly dependent on C_N.

The same reasoning can be applied to justify the assumption of the deposition flux being constant with time, particularly in the case of the biological growth term. In most biological processes, the higher the number of microorganisms, the higher will be the biomass growth rate. In the present case, however, the decrease of the average specific growth rate as the deposit builds up (due to the increasing difficulty of nutrient diffusion through the film) tends to compensate the first effect and results in a roughly time independent k_g.

The expression for the total deposition flux $|\phi d|$ can be simplified if one or two of the processes are considered to be "controlling" deposition. Different equations can then be obtained taking into account that when the processes are consecutive the slower step will control the overall phenomenon, and when they are parallel (simultaneous) the faster one will be the dominant (see Table 1). Suppose, for instance, that

Table 1 - Simplified equations for the deposition flux

Parallel Processes		Consecutive Processes		
Controlling step	Deposition flux	Controlling step	Deposition flux	Dependence on the fluid velocity (u)
"Physical" processes $\phi_{d1} >> \phi_{d2}$	$\frac{1}{\rho_f k_f} \cdot \frac{C_M}{\frac{1}{k_{tM}} + \frac{1}{k_a}}$	Transport of microorganisms $k_a >> k_{tM}$	$\frac{k_{tM} \cdot C_M}{\rho_f \cdot k_f}$	ϕ_d increases with u
		Adhesion $k_{tM} >> k_a$	$\frac{k_a \cdot C_M}{\rho_f k_f}$	ϕ_d decreases with u
"Biological" processes $\phi_{d2} >> \phi_{d1}$	$\frac{1}{\rho_f k_f} \cdot \frac{C_N}{\frac{1}{k_{tN}} + \frac{1}{k_g}}$	Transport of nutrients $k_g >> k_{tN}$	$\frac{k_{tN} \cdot C_N}{\rho_f k_f}$	ϕ_d increases with u
		Biological growth $k_{tN} >> k_g$	$\frac{k_g \cdot C_N}{\rho_f k_f}$	ϕ_d tends to increase with increasing u

adhesion and biological growth control the "physical" processes and the "biological" processes, respectively. The total deposition flux can then be evaluated by summing the adhesion flux and the biological growth flux, or by using only the larger of these values if their orders of magnitude are significantly different.

3. EXPERIMENTAL TESTS

Water was continuously introduced in a glass tank (10 litres) and contaminated by a continuous culture of *Pseudomonas fluorescens* maintained in a separated fermenter. A rich medium composed of glucose, peptone and yeast extract was used for the growth of the bacteria. The glucose concentration in the test cell was about 6g/l. The contaminated water, containing 6.10^7 bacteria/ml, at a temperature of 27°C and pH=7, was circulated at different velocities through a vertical test cell and returned to the glass tank.

The test cell, with a semi-circular cross section of 1.8cm diameter, contained a metal plate (aluminium) where the formation of biofilms was followed based on heat transfer measurements. The entry length was 50cm in order to allow for the development of the fluid hydrodynamics. The metal plate was heated by water at 60°C circulating in a rectangular cross section duct (Figure 1). Thermocouples placed in the fluid and on the heat transfer surface, in four different sections (A,B,C and D) allowed the measurements of temperatures. Pressure drop along the test cell was recorded as the biofilm developed by means of differential manometers.

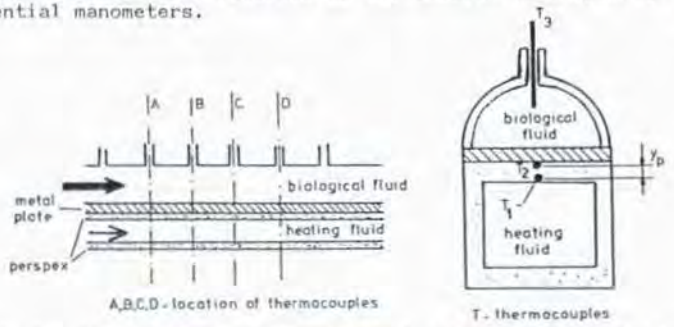

Fig. 1 - Longitudinal and transversal sections of the test cell

Similar tests were conduced with a mixture of water contaminated with bacteria (same concentration as before) and kaolin particles (concentration=150mg/l). The inorganic particles are similar to discs with thickness of about 1 micron and average diameter 16 microns.

4. RESULTS AND DISCUSSION

Temperatures T_1, T_2 and T_3 allowed the determination of the overall heat transfer coefficient U:

$$U = \frac{k_p}{y_p} \cdot \frac{T_1 - T_2}{T_1 - T_3} \qquad (5)$$

which was based on the heat transfer expressions (see Fig.1):

$$Q = UA\,(T_1 - T_3) \quad \text{and} \quad Q = \frac{k_p}{y_p} A\,(T_1 - T_2)$$

where k_p is the thermal conductivity of the material (perspex) between thermocouples T_1 and T_2, and y_p is the distance between them.

In order to characterize the heat transfer effects of biofilm roughness, the Norris correlation (5) was introduced and the heat transfer resistance of the biofilm, R_f, was calculated by Equation 6:

$$R_f = \left(\frac{1}{U} - \frac{1}{U_o}\right) - \frac{1}{h_o}\left[\left(\frac{f_o}{f}\right)^p - 1\right] \qquad (6)$$

where U_o is the initial value for the overall heat transfer coefficient, h_o is the initial convective heat transfer coefficient, f is the friction factor and $p=0.68.Pr^{0.215}$ (Pr=Prandtl number).

The experimental results of R_f along the time, t, allowed the fitting of the general equation for asymptotic fouling (6):

$$R_f = R_f^* \,(1 - e^{-\beta t}) \qquad (7)$$

where R^*_f is the asymptotic value of R_f and β is a factor depending on the hydrodynamic conditions of the system and on the mechanical "strength" of the deposit. Typical curves are represented in Figure 2 for the water-bacteria tests (11).

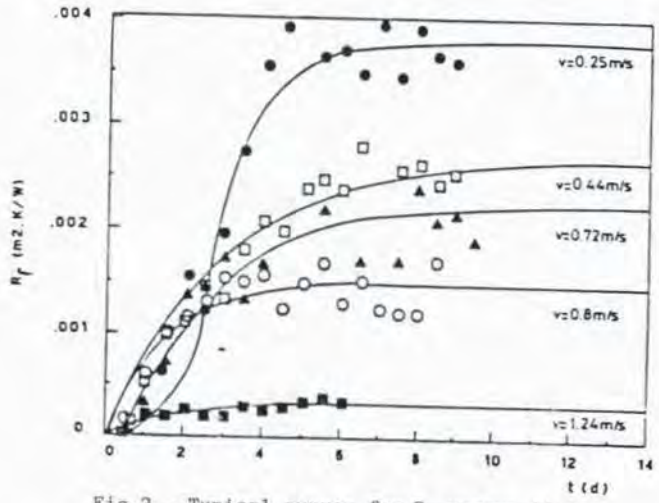

Fig.2 - Typical curves for R_f versus time
- section C in the test cell
- water contaminated with bacteria only
- Reynolds numbers between 3140 and 15570
- fluid temperature = 27°C.pH = 7

(Reproduced from the Canad. J. Chem. Engin.,1988, Refer.11)

The total deposition flux, ϕd, was obtained utilizing the relation:

$$\phi d = \beta \cdot R_f^* \qquad (8)$$

An "induction period" was observed for the lower fluid velocity (v=0.25 m/s). Here, β and ϕd were evaluated by fitting Equation 7 to the experimental values obtained after the induction period.

4.1 Fouling due to bacteria

The dependence of ϕ_d on the fluid velocity for the "pure" biological deposits is shown in Figure 3, which includes the data points from all the measurement positions (A,B,C and D) in the test cell.

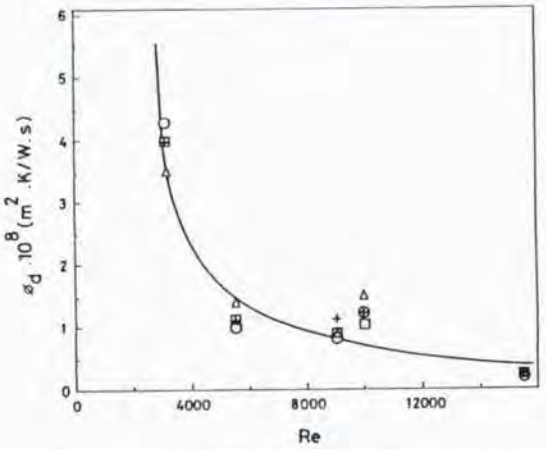

Fig. 3 - Dependence of on Reynolds number
- water contaminated with bacteria only
Δ - section A ◘ - section B
\+ - section C O - section D

As ϕ_d decreases with increasing Reynolds number (or with fluid velocity) it may be concluded (see Table 1) that adhesion will be controlling the overall deposition process.

A more detailed observation of the dependence of ϕ_d on the Reynolds number (Fig.3) suggests the existence of two different regions of the curve. In fact, for lower Reynolds numbers, until approximately Re = 5000, decreases very sharply, while the variation is much less sharp for higher Re.

It is expected that the two processes controlling the deposition flux have opposite effects with respect to the dependence of ϕd on the fluid velocity. In fact, the adhesion rate tends to decrease with increasing fluid velocity, whereas the growth and reproduction of microorganisms is favoured by higher fluid velocities due to the higher diffusion of nutrients to the surface. Thus, it can be considered that in the first part of the curve (Fig.3) the deposition flux ϕd is essentially controlled by the adhesion process. This means that for the range of Reynolds numbers considered (Re <5000), $k_a >> k_g$ and $\phi d \simeq \phi d_1 = C_n k_a \rho_f k_f$ In this case, the dependence of ϕd on Re can be expressed by the equation:

$$\phi_d \simeq \phi d_1 = k\ Re^{-b} \qquad (9)$$

where k and b are parameters that can be determined by regression analysis from the first part of the curve (Re < 4500) represented in Fig.3. The following values were obtained: $k = 58.2.10^6$ m^2.K/W.s and b=-2.05 .

For Re > 5000, the rate of growth and reproduction of microorganisms in the film seems to become important, with an order of magnitude similar to the adhesion rate. The deposition flux is then defined by:

$$\phi d = \phi d_1 + \phi d_2 = k\ Re^{-b} + \frac{1}{k_f\ \rho_f}\ k_g\ C_N \qquad (10)$$

ϕd_2 was calculated from the values of ϕ_d in Figure 3 and the values of ϕd_1 obtained with Equation 9 (Table 2).

Table 2 - Values of ϕd_1 and ϕd_2 as a function of Re (water + bacteria)

	Re						
	5500	6000	7000	8000	10000	13000	15000
$\phi d_1 \times 10^8$ (m^2 K/Ws)	1.25	1.05	0.76	0.58	0.37	0.21	0.16
$\phi d_2 \times 10^8$ (m^2 K/Ws)	0.23	0.29	0.35	0.40	0.31	0.27	0.24

4.2 Fouling due to bacteria and kaolin particles

The curve of ϕ_d versus Re for the case of water containing the same bacteria plus kaolin particles is represented in Fig.4 . As the curve shows a similar behaviour to the one shown in Fig.3, the same type of calculation was applied and the values obtained are indicated in Table 3. In this case the parameters in Equation 9 are $k=1.73.10^{8}$ $m^2.K/W.s$ and $b=-2.13$.

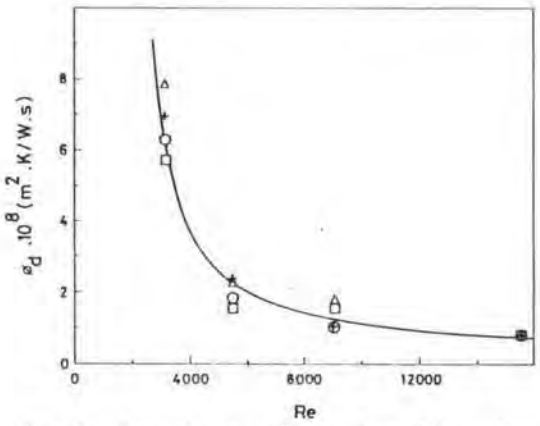

Fig.4 - Dependence of ϕd on Reynolds number
Water contaminated with bacteria and kaolin particles
O - section A □ - section B
Δ - section C + - section D

Table 3 - Values of ϕd_1 and ϕd_2 as a function of Re (water + bacteria) + + kaolin particles)

	Re						
	5400	6000	7000	8000	10000	13000	15000
$\phi d_1 \times 10^8$ (m^2 K/Ws)	1.87	1.55	1.12	0.84	0.52	0.29	0.22
$\phi d_2 \times 10^8$ (m^2 K/Ws)	0.34	0.42	0.47	0.58	0.56	0.52	0.45

Figure 5 represents the variation of the term ϕd_2 with Reynolds number for the two cases indicated before.

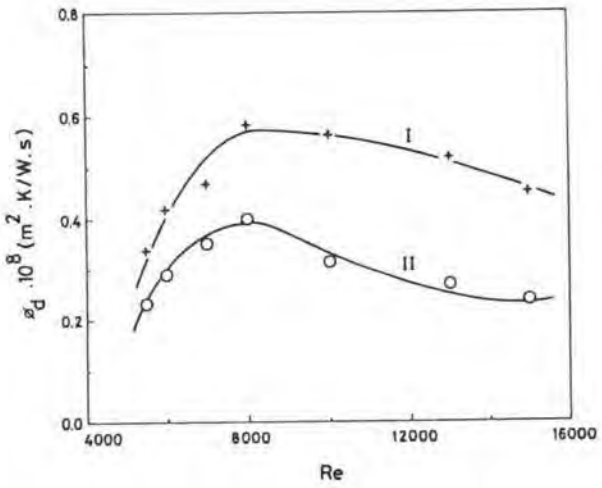

Fig.5 - Deposition flux due to microbial growth as a function of Reynolds number
I - mixture of bacteria and kaolin particles;
II - bacteria alone.

The curves obtained for ϕd_2 in the presence and absence of kaolin particles show in general the same shape. In the first part of the curves the growth and reproduction of microorganisms increases with Reynolds number, which can be related to the availability of nutrients near the surface. However, there is a decrease of that term for Reynolds numbers higher than 8000. It is thought that this behaviour is related to the structure of the films. As shown by some investigators (3,4) the film formed under higher velocities presents a more compact structure or, in other terms, a higher density. This fact tends to slow down the diffusion of nutrients and oxygen to the deeper parts of the film, resulting in a less active biomass and consequently a lower value of ϕd_2.

In the presence of kaolin particles the rate of growth and reproduction of biofilm is increased, as can be concluded from Fig.5. This fact is attributed to the favourable conditions of nutrient availability throughout the film due to the following facts:

- The structure tends to be more porous, favouring the diffusion of nutrients
- Kaolin particles may act as sources of nutrients in the film. In fact, before depositing, they tend to adsorb nutrient molecules in solution and, once deposited, they constitute a reservoir of nutrients that can be utilized by the cells for their metabolism.

The values of ϕd_1 in Tables 2 and 3 reflect expected changes in adhesion rates due to the presence of particles of different nature in

each type of test. Furthermore both transport and adhesion fluxes can be modified by probable formation of bacteria-kaolin agglomerates in the flowing suspension.

5. CONCLUSIONS

The use of a phenomenological model that includes the different processes involved in the formation of biofilms (transport, adhesion, bacteria reproduction and removal) allows the individualized study of these processes and the detection of the one that controls the deposition flux.

Such a model was applied to data obtained from biofouling tests, showing that for Reynolds numbers above ca. 5000 the growth and reproduction of microorganisms in the film played a significant role in the overall phenomenon. When analysing the term corresponding to the growth/reproduction process, it was found that within a certain range of fluid velocities, an increase in the flow rate leads to a higher production of biomass. However, for higher velocities, the biomass production tends to decrease, probably due to the formation of more compact films that hinder the diffusion of nutrients throughout the deposit.

The same type of analysis showed that the presence of kaolin particles results in higher rates of growth and reproduction of microorganisms in the deposit, which seems to be related to the more porous structure of the film and to the adsorption of nutrients in kaolin particle surfaces. Therefore, it is important to study in more detail the specific process of bacterial growth in the film under different operating conditions in order to understand the mechanisms that may help to reduce biofouling. At the same time, the experimental results of such a study allow the verification of the mathematical model.

NOMENCLATURE

A - area, m^2
b - empirical parameter
c - concentration of inorganic particles, kg/m^3
C_N - concentration of the limiting nutrient, kg/m^3
C_M - concentration of microorganisms, kg/m^3
f - friction factor
f_o - friction factor for clean surface
h_o - convective heat transfer coefficient, $W/m^2.K$
k_f - thermal conductivity of the deposit, W/m.K
k_a - rate constant of adhesion, m/s
k_t - constant rate for transport process, m/s
k_{tM} - rate coefficient for transport of microorganisms, m/s
k_{tN} - rate coefficient for transport of nutrients, m/s
k_g - rate of production of biofilm due to microbial growth, m/s
k_p - thermal conductivity for the material between thermocouples T_1 and T_2, W/m.K
k - constant
p - Norris factor

P_r - Prandtl number
Q_r - heat flux, W
R_e - Reynolds number
R_f - heat transfer resistance of film, $m^2.K/W$
R^*_f - asymptotic value of R_f, $m^2.K/W$
T - temperature, ^oC
t - time, s
U - heat transfer coefficient, $W/m^2.K$
u - fluid velocity, m/s
y - distance between thermocouples T_1 and T_2, m
α_p - constant
β - parameter (equation of Kern and Seaton)
ϕ_d - total deposition flux, $m^2.K/W.s$
ϕ_{d1} - deposition flux related to transport and adhesion of microorganisms, $m^2.K/W.s$
ϕ_{d2} - deposition flux related to transport of nutrients and growth of microorganisms, $m^2.K/W.s$
ρ_f - density of the deposit, kg/m^3

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