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PREVENTING BIOFOULING IN HEAT EXCHANGERS : AN EXPERIMENTAL ASSESSMENT OF THE EFFECTS OF WATER VELOCITY AND INORGANIC PARTICLES ON DEPOSIT DETACHMENT

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ABSTRACT

Biofouling is a costly problem in heat exchangers. Biocides can be used to minimize the formation of biofilms, but they are not always effective and, moreover, they are generally deleterious to the environment. The use of proper liquid velocities or of water jets in the exchanger tubes is also a means to prevent the build up of fouling deposits or to clean the surface once they are formed. Often, biofilms incorporate inorganic particles which modify the physical properties of the deposit and, thus, affect the effectiveness of anti-fouling measures. This paper presents experimental data that show the effects of the water velocity and of the presence of clay particles on the accumulation of biofilms and on their mechanical resistance to detachment caused by hydrodynamic forces. The results indicate that the fraction of dry biomass (micro-organisms plus extracellular biopolymers) in biofilms increases with the liquid velocity and that the deposits formed under higher hydrodynamic forces are more resistant to detachment. The resistance to detachment is even greater when the biofilms incorporate small (20 micrometer) clay particles.

1. INTRODUCTION

Cooling water, coming from rivers, lakes, bore holes, etc., is used in a number of industrial processes where hotter fluids must be cooled, or a phase change is needed such as in power plant condensers. Pre-treatment technologies do not eliminate all sources of organic and inorganic matter carried by the water into the heat exchanger tubes. These minor components are potential contributors to the growth of undesirable microbial films on the pipe walls (biofouling), that cause an increase in the thermal resistance and in the pressure drop in the heat exchanger. More often than desired, the operation of the industrial plant may have to be stopped in order to clean the equipment.

A "biofilm" is a matrix composed mainly by water (often, more than 90%), micro-organisms and extracellular polymers excreted by the microbial species. Biocides are frequently used to combat this unwanted biological growth, but they are not always efficient or acceptable from an environmental standpoint. Minimization of biofouling effects can also be achieved through good design and operating procedures, where fluid velocity stands as a key parameter. This physical variable has contradictory effects on biofilm development : in fact, an increase of the velocity enhances the transport of microorganisms and of nutrients to the deposition surface but, at the same time, it increases the hydrodynamic forces that contribute to the detachment of the biological layer. Some authors (Bott 1995) have reported that increasing the water velocity above 1 m/s reduces biofilm build up, although it was found that this reduction occurred also in the lower range of fluid velocities (Bott 1995, Characklis 1990, Pinheiro *et al.*, 1988). Such results were explained by the differences in the concentration of soluble nutrients, which caused the formation of biofilms with different characteristics : low concentrations lead to thin and firmly attached biofouling layers that are more difficult to remove from the surface than thicker and "fluffier" biofilms. Frequently, the water contains inorganic particles in suspension that become incorporated in the biological deposit; it is therefore important to determine the changes brought about by the presence of these particles as regards the detachment process.

The experimental work here reported was carried out with the purpose of assessing the effects of the water velocity and of the presence of clay particles on the development of microbial films in a lab-sacle heat exchanger, and also on the resistance of these deposits to detachment.

2. MATERIALS AND METHODS

A simulated vertical heat exchanger composed of two adjacent half-tubes separated by a wall was used to monitor the build up of the biofilm on aluminium surfaces. Two schematic views of this test apparatus (perpendicular and parallel to the flow direction) are shown on Figure 1. The hydraulic diameter of the half tube is 2.02 cm. Water at 27 °C and pH 7, containing a diluted suspension of bacteria (6.10^7 cells.ml^{-1} of *Pseudomonas fluorescens*) and nutrients (basically, glucose at the concentration of 20 $mg.l^{-1}$), circulated through one of the half-tubes of the test section (indicated as the "test fluid" side), separated from the other half-tube by the aluminium plate (50 cm long) and a perspex wall ("water" side). The "test fluid" was heated by water at 60 °C flowing in the "water side". The heat flux could be calculated from the measurement of three temperatures (T_1, T_2 and T_3) in each of the three sections indicated by A, B and C. Overall heat transfer coefficients were then calculated at different times during the growth of the biological deposit and, finally, the heat transfer resistances caused by the biofilm could be estimated at any instant of time. The results presented below refer always to the average values obtained in points A, B and C.

More detailed information on this test section and on the method used to evaluate the fouling resistances of the biofilm can be found elsewhere (Vieira *et al.* 1993, Vieira and Melo 1995).

Some runs were carried out using a mixed suspension of bacteria ("test fluid") and 150 $mg.l^{-1}$ of clay (kaolin) particles which had an equivalent diameter of about 20 micrometer. Different biofilms were formed (with and without clay particles) with the fluid circulating at velocities between 0.35 $m.s^{-1}$ and 1.2 $m.s^{-1}$, which correspond to Reynolds numbers between 4 200 and 15 000.

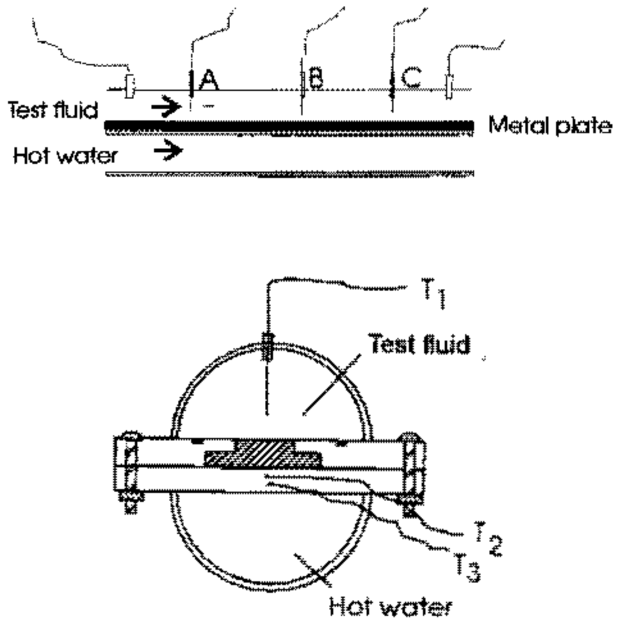

Figure 1 - Simulated heat exchanger used in the biofouling tests

3. RESULTS AND DISCUSSION

Figure 2 shows an example of a typical biofouling curve (fouling resistance as a function of time), while Figure 3 is a plot of the maximum (asymptotic) thermal resistance of the biofilm *versus* the Reynolds number. The latter confirms that the fouling resistance decreases as the Reynolds number or the flow velocity increases (in this work, two identical test sections were used in all runs). A similar trend was observed as regards the thickness of the deposits. This kind of result is usually found in many types of fouling (Bott 1995).

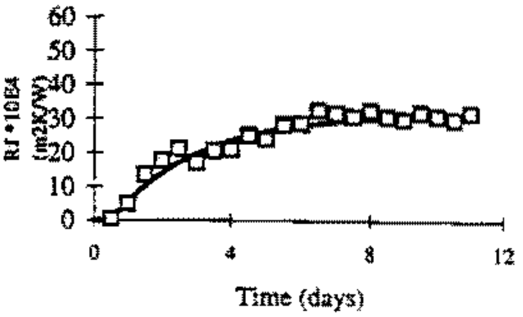

Figure 2 - Biofouling curve

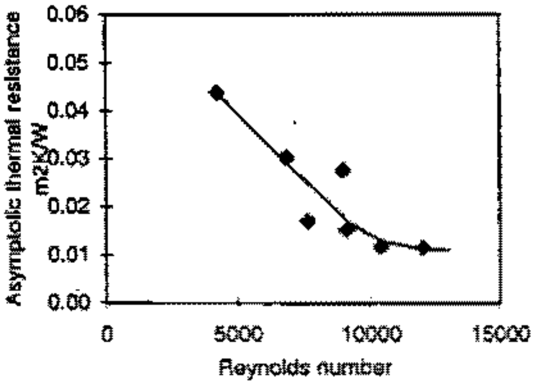

Figure 3 - Asymptotic thermal resistance as a function of fluid velocity

The amount of dry biomass (bacteria plus extracellular polymers excreted by them) was measured in biofilms formed under different velocities (Table 1).

The data of Table 1 show that higher fluid velocities, at least in turbulent flow conditions, result in more compact biofilms, containing higher percentages of dry matter.

The behaviour of the biofilms as regards their detachment from the surface was also different according to their previous "history" (Table 2): the deposits that were formed under lower hydrodynamic forces (Reynolds number = 9 200) were partially removed from the aluminium plate when the Reynolds number was increased up to 25 500; the films formed under higher hydrodynamic forces (Re=15 500) were not disturbed when an identical experiment was performed.

Tests were also carried out to assess the effect of clay particles within the biofilm matrix. For this purpose, biofilms were formed with and without clay particles, under different velocities. After the deposits had reached their asymptotic thermal resistance (steady-state), glucose was removed from the test fluid that was flowing through the experimental heat exchanger. Some time after the main nutrient was surpressed, the biofouling thermal resistance started to decrease and part of the biofilm was removed and carried away by the fluid. The response of the various biofilms to these drastic conditions was different depending on clay particles being incorporated in the deposit or not, as can be seen on Table 3.

Table 1 - Dry biomass (bacteria + polymers) *per* unit volume of wet biofilm (kg.m^{-3})

Fluid velocity (m.s^{-1}) Reynolds number	0.37 4 570	0.49 6 100	0.63 7 800
Dry biomass *per* unit volume of wet biofilm (kg.m^{-3})	14	20	28

Table 2 - Effect of increasing the Reynolds number on two biofilms formed under different hydrodynamic conditions

	Steady-state thermal resistance under initial Reynolds No. ($m^2.K.W^{-1}$)	Steady-state thermal resistance after increasing the Reynolds No. to 25 500 ($m^2.K.W^{-1}$)	**% of biofilm removed**
Biofilm formed under fluid Reynolds number of 9 200	25.10^{-4}	15.10^{-4}	**40%**
Biofilm formed under fluid Reynolds number of 15 500	16.10^{-4}	16.10^{-4}	**0%**

Table 3 - Loss of biofilm mass after glucose was suppressed from the test fluid

	Velocity of the fluid in contact with the biofilm ($m.s^{-1}$)	% of biofilm mass lost after suppressing the glucose supply
Biofilms **without** clay particles	0.34	21%
	0.72	91%
Biofilms **with** clay particles	0.34	15%
	0.73	83%

Although the results are not very expressive, it seems that the microbial films with clay particles were more resistant to removal when the nutrient supply was cut off. Table 3 also shows that the % of biomass removed was higher when the biofilms were formed under higher velocities. This may appear to be in contradiction with the results of Table 2. However, Table 2 describes a physical effect and Table 3 a metabolical one. In fact, since the biofilms formed at higher velocities are thinner, the nutrients are able to penetrate more deeply than in thicker biofilms. Thus, a higher fraction of the thinner biofilms is more dependent on the availability of nutrients and detachs from the deposit after the nutrient concentration is reduced to (practically) zero.

Another method, independent of the experiments reported in Table 3, was used to compare the characteristics of the biofilms with and without clay particles. The method relies upon the use of a simple and well known model that describes the build up of fouling layers (Kern and Seaton 1959). The model assumes that the fouling rate depends on the competition between the rates of two simultaneous phenomena: deposition and removal. The former is assumed to be constant with time, while the removal or detachment rate (Φ_r) is considered to increase proportionally to the thickness of the attached layer (here represented by its thermal resistance, R_f) :

$$\Phi_r = b.R_f \qquad (1)$$

The higher the value of b, the easier will be the detachment of the deposit. Therefore, 1/b can be interpreted as a "property" of the biofilm that is proportional to the "mechanical resistance" offered by the deposit to the removal forces of the fluid. The removal and deposition rates equal each other when the deposit reaches its steady state. In terms of thermal resistances, the integrated equation is (Kern and Seaton 1959) :

$$R_f = R_f^* [1 - \exp(-b.t)] \qquad (2)$$

where R_f is the thermal resistance of the fouling layer at any time t, and R_f^* is the asymptotic (steady-state) thermal resistance of this fouling layer. Values of 1/b for biofilms with and without clay particles were estimated by fitting Eq. (2) to biofouling curves obtained in different operating conditions (Table 4).

Table 4 - Resistance of biofilms to detachment (1/b)

	Fluid velocity ($m.s^{-1}$) and Reynolds number	1/b, "resistance to detachment" (s)
Biofilms without clay particles	0.62 (Re = 7 620) 0.97 (Re = 12 000)	$1.8x10^{-5}$ $2.5x10^{-5}$
Biofilms with clay particles	0.59 (Re = 7 505) 0.95 (Re = 11 763)	$2.2x10^{-5}$ $4.2x10^{-5}$

The results confirm that the presence of kaolin particles in the deposits makes them more resistant to detachment (higher 1/b, *i.e.*, higher residence time of a given portion of matter in the deposit) when subject to identical hydrodynamic conditions. The data of Table 4 are also in accordance with Table 2, since the value of the "mechanical resistance" parameter (1/b) is higher for biofilms formed under higher fluid velocities than in the case of biofilms subject to lower hydrodynamic stresses.

4. CONCLUSIONS

Proper choice of the fluid velocity in heat exchangers is of the utmost importance as a means of minimizing the build up of biofouling layers and of contributing to more efficient cleaning procedures. In fact, although higher velocities result in thinner biological deposits, these are more compact, more firmly attached and more difficult to detach from the surface by means of hydrodynamic forces. Obviously, a balance must be sought between using higher or lower velocities. The standard liquid velocities in heat exchanger design are 1.5-2 m/s, but designers should take into account the fact that the properties of the biological layer may determine the efficacy of cleaning procedures that often rely upon the use of water flows (containing detergents or other chemicals) to remove the deposit from the surface. Furthermore, when using biocides to reduce biofouling, it should be considered that thinner but more compact biofilms may not allow the complete penetration of biocides : in this case, a residual and "hard" layer can remain on the surface, which will eventually promote the rapid re-growth of the microbial film. The "history" of the biofilm (the conditions under which it was formed) should thus be known in order to choose the most adequate anti-fouling measures.

The results also indicated that the resistance to detachment is even greater when the biofilms incorporate very small clay particles. Therefore, elimination of these particles from the water can play a significant role in the prevention of biofouling effects.

ACKNOWLEDGEMENT

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NOMENCLATURE

b	parameter inversely proportional to the mechanical strength of the deposit, s^{-1}
Re	Reynolds number (dimensionless)
R_f	thermal resistance of the deposit at any time t, $m^2.KW^{-1}$
R_f^*	asymptotic thermal resistance of the deposit, $m^2.K.W^{-1}$
t	time, s
Φ_r	detachment or removal rate, $m^2.K.W^{-1}.s^{-1}$