INTERACTION BETWEEN DIFFERENT FOULING AGENTS IN WATER SYSTEMS

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Most of the fouling studies have been up to now focused on the build up of deposits caused by only one foulant. Although this type of research allows a more clear identification of the mechanisms involved in the formation of deposits, the study of more realistic situations is now needed.

The paper reports the results of fouling tests where different fouling agents were present in water: kaolin plus magnetite particles, and bacteria (*Pseudomonas fluorescens*) plus kaolin particles. Deposit formation was monitored through heat transfer measurements. The tests were performed with water flowing at several velocities and the data were compared with previous results obtained using a single foulant, in an attempt to determine possible changes in the processes controlling the fouling rate.

Increased fouling resistances and rates were observed when kaolin particles were suspended in the bacteria - - water system.

The kaolin - magnetite interaction seems to decrease the final amount of deposit and, at the same time, to increase its mechanical strength.

Modifications in the metabolic processes or in the adhesion forces may account for the observed changes.

1. INTRODUCTION

Research on fouling has been mostly devoted to the study of the deposition / removal mechanisms of individual foulants (particles, dissolved ions or molecules, bacteria, etc.). The progress so far obtained in this type of work stimulates the analysis of more complex and more realistic situations, such as the cases where more than one fouling agent is present. Fouling in cooling water systems, for instance, may be caused by a variety of foulants, such as suspended particles, microorganisms and inorganic salts, acting simultaneously.

The literature concerning research on the mechanisms involved in mixed fouling situations is scarce [1, 2, 3, 4, 5]. The interaction effects between different foulants are not easily predictable and, frequently, they can control the overall fouling behaviour.

This work presents a set of results obtained in tests with kaolin - magnetite and bacteria - kaolin aqueous suspensions, in a first approach to simulate fouling caused by "real water" systems. The data are compared with the ones obtained in tests with pure kaolin or pure bacteria systems. A simple analysis of the fouling curves was carried out using the basic model of

Kern and Seaton [6]:

$$\frac{dR_f}{dt} = \emptyset_d - \emptyset_r \qquad (1)$$

$$R_f = R_f^\infty [1 - \exp(-\beta t)] \qquad (2)$$

where the asymptotic thermal resistance (R_f^∞) is related to the deposition flux ($\emptyset_d$) through:

$$\emptyset_d = R_f^\infty \cdot \beta \qquad (3)$$

2. EXPERIMENTAL METHODS AND EQUIPMENT

2.1. Kaolin - Magnetite Interactions

The tests were performed with a kaolin - magnetite suspension at pH=7.5, bulk water temperature 10 °C, flowing at velocities between 0.53 m/s (Re=4150) and 1.05 m/s (Re=8300), the concentrations of kaolin and magnetite being respectively 2.2 g/l and 0.4 g/l.

The test section (Figure 1) is an annular duct, 2 metre long, placed horizontally, consisting of a copper tube (OD=25mm) inserted in a perspex tube (ID=36mm). Hot water flows inside another perspex tube which is tightly inserted in the copper tube.
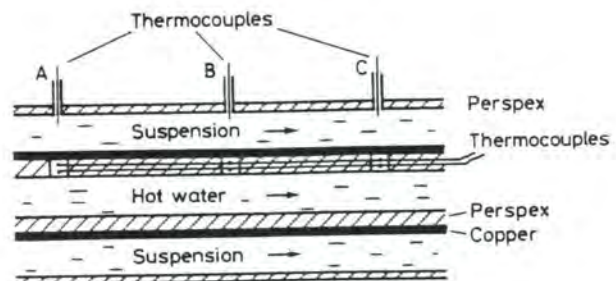

Figure 1 - Longitudinal section of the test cell for experiments with kaolin and kaolin-magnetite.

The heat flux, between the inner hot fluid and the outer cold suspension, is determined from temperature measurements using three thermocouples at each of the three different positions, A, B and C, along the test section.

The test section is part of an experimental rig mainly composed by two closed loop circuits, one with a heating tank of 100 liter, the other having a well stirred cooling tank of 250 liter and PVC tubes of 25 mm diameter.

The average equivalent diameters of the particles are respectively 12 μm and 20 μm. The magnetite particles have a density of 5200 kg/m^3, which is twice the value for kaolin.

The final deposit thickness was measured by a micrometer coupled to an electrical circuit [7].

2.2. Bacteria - Kaolin Interactions

A glass tank of 12 liters was continuously fed with water at 27 °C and contaminated with a pure culture of *Pseudomonas fluorescens*, grown in a 4 liters fermenter. The glucose concentration in the system was kept at 0.03 g/l by a constant flow of nutrient (glucose, peptone and yeast extract). The fouling fluid contained 6×10^7 bacteria/ml. [8, 5]. In some tests, this fluid was mixed with kaolin particles (final concentration = 150 mg/l). The kaolin particles used were the ones referred in 2.1.

The test sections were semi circular perspex ducts (with 1.8 cm equivalent diameter), where the fouling fluid circulated at a constant velocity. The velocity was changed from test to test between u=0.28 m/s and u=0.87 m/s. The deposit accumulated on an aluminium plate, heated by water at 60 °C. (Figure 2).
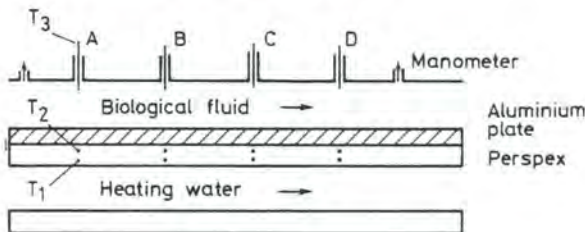
Figure 2 - Longitudinal section of the test cell for experiments with bacteria and bacteria-kaolin.

Heat flux was measured at four different positions in the heat exchangers (Positions A, B, C and D) using two thermocouples (T_1 and T_2) placed in the perspex wall adjacent to the aluminium plate, and one thermocouple (T_3) placed in the fluid [8, 5].

3. RESULTS AND DISCUSSION

Based on temperature measurements, local heat transfer coefficients and thermal resistances were calculated. Roughness effects were taken into account in the evaluation of fouling factors.

3.1 Kaolin - Magnetite Interactions

Values of R_f as a function of time were determined for positions A, B and C. Figure 3 presents the "average fouling curves" obtained from these values.
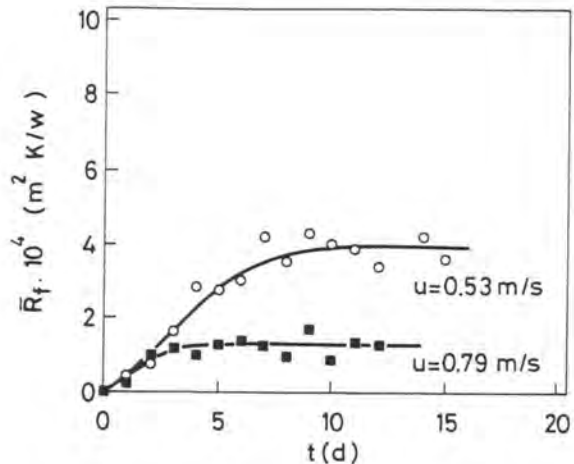
Figure 3 - Fouling curves for kaolin-magnetite system.

Figure 4 shows the values of R_f^∞ (at A, B and C) as a function of fluid velocity. It also includes the data obtained by Melo [9], in the same experimental rig, with a kaolin suspension having a concentration of 2.2 g/l. As can be seen comparing both data, they show a similar trend - a decrease in R_f^∞ with increasing fluid velocity, but the R_f^∞ values for the case of pure kaolin are higher than the corresponding values for the mixed suspension, although the latter has a higher overall concentration.

Another similar set of tests had been already carried out using a mixed suspension with 1.5 g/l of kaolin and 0.7 g/l of magnetite. The final thicknesses of the deposits were referred and compared elsewhere [4] with the values obtained with the pure kaolin suspension. Once more the mixed deposits were smaller than the pure kaolin ones. No significant differences were found between the thicknesses of mixed

deposits obtained from suspensions containing different kaolin - magnetite ratios. It seems that the relative proportions of the two fouling agents can be changed, within some limits, without having a detectable effect in the formation of the deposits.
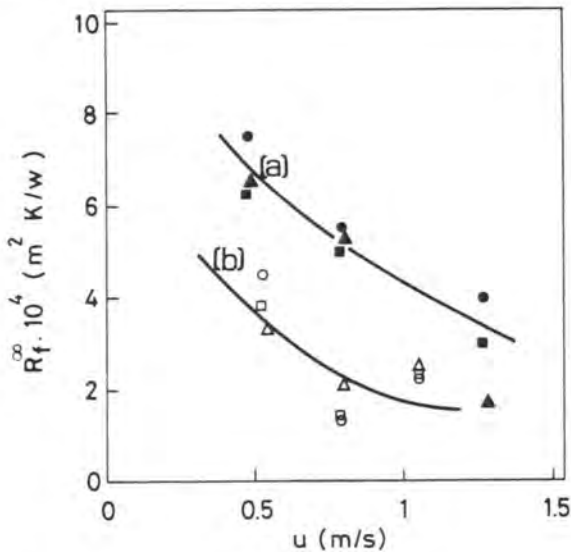

Figure 4 - Dependence of R_f^∞ on velocity for

kaolin (a) and kaolin-magnetite (b).
□ ■ Position A
△ ▲ Position B
○ ● Position C

All the experiments confirmed that the presence of magnetite inhibits the deposition of kaolin and this must be due to the interaction between the two different types of particles.

It was suggested that in the presence of magnetite and for the range of fluid velocities studied, the deposition is governed by the adhesion process [4]. This could be confirmed by comparing values of the deposition fluxes, as it was done in the case of pure kaolin [8]; however, in the present case there is a practical limitation to determine those values. As can be

seen from Figure 3, the value of R_f^∞ is attained

very early, specially for high velocities, and the number of points in the initial part of the curve is too small to enable a reasonably accurate fitting.

An explanation for the behaviour of the mixed system, in what concerns the interaction between the two different types of particles and the copper surface, can possibly be found in the DLVO theory [10]. According to this theory the interaction forces depend on the values of: electrokinetic potentials, Hamaker constants and distances of closest approach.

At pH=7.5 the electrokinetic potentials of kaolin, magnetite and copper are all negative,

having values ranging from about -30 mV to -50 mV [9]. This is not inhibitory of deposit formation, otherwise no single deposits of kaolin or magnetite would also be formed. Furthermore, it was theoretically proved that even in the case of electrokinetic potentials of the same sign an overall attractive effect is possible [11].

The variation of the Hamaker constant affects the value of the energy barrier (which the particles have to surmount before reaching the surface) and the existence of one or two minima [12]. The Hamaker constant for the interaction kaolin - magnetite is more than 20 times greater than the value for the interaction kaolin - kaolin [9]. This can result in the lowering of the energy barrier with the formation of a deeper primary minimum and a shallower secondary minimum. In this case, the stabilization of the particles in the secondary minimum is more difficult, and only those that reach the primary minimum may be able to form solid layers resistant to the hydrodynamic removal forces. This is somewhat in accordance with the low thicknesses and hardness [4] showed by the mixed deposits.

The distance between particles is greatly influenced by their sizes and shapes. As the kaolin and magnetite particles are quite different, mainly in shape, this fact can also have a significant role in the adhesion process.

These explanatory hypotheses emphasize the contribution that a deeper investigation in the adhesion field can give to the understanding and control of fouling.

3.2. Bacteria - Kaolin Interactions

Figures 5 and 6 present the averages values of R_f^∞ versus time obtained in the four positions.
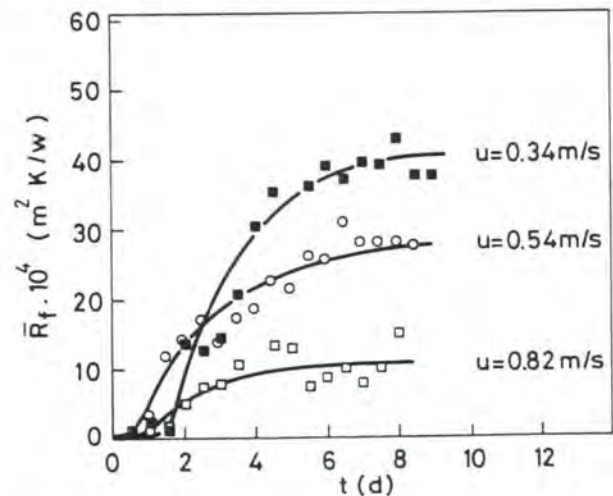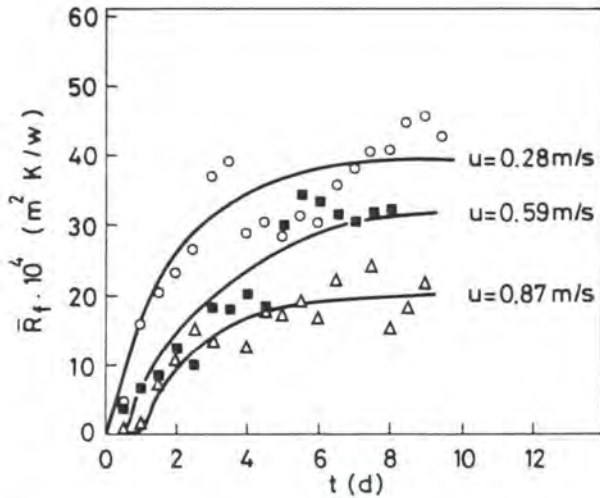

Figure 5 - Fouling curves for bacteria suspensions.

Figure 6 - Fouling curves for bacteria-kaolin
suspensions.

In both cases (bacteria and bacteria - kaolin)
an asymptotic behaviour of R_f versus time was
observed but the fluctuations around the value of
$\overline{R}_f^\infty$ are more pronounced in the case of the
bacteria - kaolin system.

The curves of the biofilm average asymptotic
thermal resistance versus velocity show a
similar trend in the two cases (Figure7),
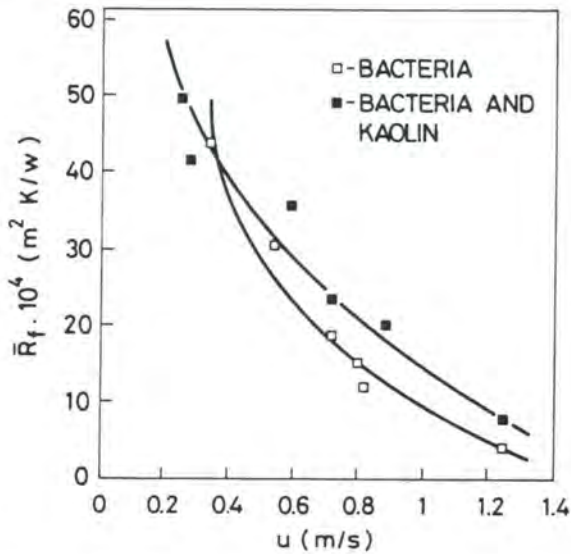although higher fouling resistances were
observed in the presence of kaolin.

Figure 7 - Dependence of $\overline{R}_f^\infty$ on velocity for
bacteria and bacteria-kaolin
suspensions.

Values of the deposition flux ($\emptyset_d$) were
obtained by fitting the basic Kern and Seaton
equation to the experimental data. Figures 8 and
9 present values of $\emptyset_d$ for pure bacteria and
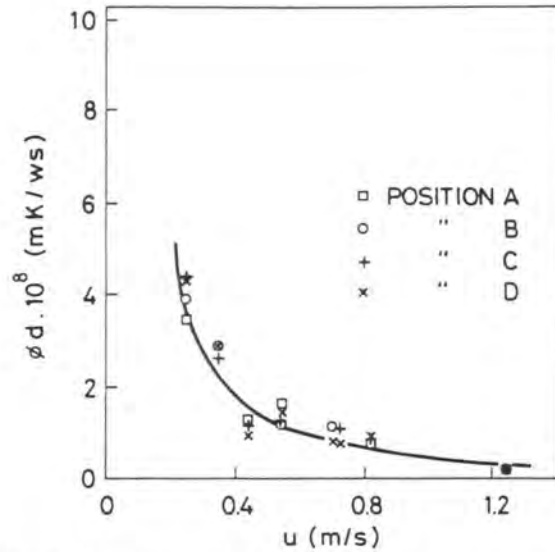bacteria - kaolin suspensions, respectively.

Figure 8 - Deposition flux rate versus velocity
for the bacteria suspensions.

The presence or the absence of kaolin
particles leads to the same kind of variation of
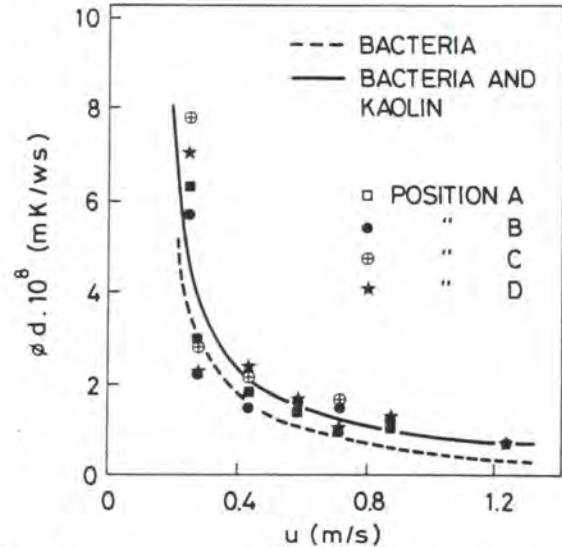the deposition flux with velocity (Figure 9).

Figure 9 - Deposition flux rate versus velocity
for the bacteria and bacteria-kaolin
suspensions.

106

A decrease of $\emptyset_d$ with u is observed in both cases, but in the presence of kaolin particles higher values of $\emptyset_d$ are obtained. A number of hypotheses can be suggested to explain this phenomena.

In the presence of kaolin particles the growth and reproduction rates of the biofilm seems to increase. This may be due to the fact that:

-biofilms produced in the presence of kaolin are more porous, making easier the diffusion of nutrients [5] and of metabolism products.

-some kinds of clays have an expanded surface area particularly suitable for the adsorption of water, nutrient ions and other macromolecules [13]. When these particles are in the deposit, they are a source of nutrients for the inner layers of biofilm. Other type of clays do not adsorb nutrients, but have the ability to remove inhibitory products of metabolism from the bacterial surface [13], which favours microbial growth.

Furthermore, the transport of microorganisms to the deposition surface may increase since bacteria in the bulk fluid may become associated to kaolin particles through the exopolymers they produce [13].

The adsorption of water by the kaolin particles may also contribute to an increase in the deposit thickness and, thus, to the higher values of $\overline{R_f^\infty}$ found in biofilms containing kaolin (the thermal conductivities of water and biofilms are similar).

4. CONCLUSIONS

Fouling tests were carried out with aqueous suspensions of kaolin [9], kaolin-magnetite [4], bacteria and bacteria-kaolin [5], at different fluid velocities.

From these tests, values of asymptotic thermal resistance (R_f^∞), thickness and deposition flux ($\emptyset_d$) were obtained.

From a comparison of kaolin and kaolin--magnetite systems it becomes clear that:

- at the same fluid velocity the values of R_f^∞ and deposit thickness are higher for the pure kaolin system than for the mixed one;

- increasing the fluid velocity of the kaolin--magnetite suspension decreases the value of R_f^∞ and of the deposit thickness. This behaviour was also observed in the simple kaolin suspensions;

- the presence of magnetite reduces the amount of deposit and this quantity does not seem to be greatly influenced by the kaolin/magnetite concentration ratio.

Bacteria and bacteria-kaolin tests demonstrate that:

- increasing fluid velocity, $R_f^\sim$ and $\emptyset_d$ decrease in both cases;

- in the presence of kaolin, higher values of R_f^∞ and $\emptyset_d$ are obtained;

- fluctuations of the thermal resistances around R_f^∞ are higher when bacteria-kaolin suspensions are used.

The tests showed that the effects caused by the interaction of different fouling agents do not present similar patterns. At the present state-of-knowledge,prediction of such effects is not feasible, since they may be governed by complex phenomena occurring in the bulk fluid or within the deposit itself. Much more experimental results are thus required in order to be able to draw a first picture of the variety of effects that may occur in industrial situations

ACKNOWLEDGMENTS

NOMENCLATURE

$\overline{R_f^\infty}$	- average asymptotic thermal resistance, m^2 K/W
t	- time, days
T_1, T_2	- wall temperature, k
T_3	- fluid temperature, k
U	- velocity, m/s
β	- parameter related to the strenght of the deposit, s^{-1}
$\emptyset_d$	- deposition flux, m^2k/ws
$\emptyset_r$	- removal flux, m^2k/ws

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