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Effect of Flow Rate on the Enhancement of Particulate Fouling in the Presence of a Developing Biofilm

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RÉSUMÉ

La vitesse de dépôt de la magnétite sur une section d'essai chauffée a fait l'objet de recherches en utilisant des méthodes de radiotraçage en fonction du débit en l'absence et en la présence d'un biofilm croissant de *Pseudomonas fluorescens*. Le débit a été ajusté pour couvrir la plage des nombres de Reynolds de 2 200 à 9 600. Pour tous les débits, il y avait une augmentation de la vitesse de dépôt de la magnétite en présence du biofilm croissant. En plus, la vitesse de dépôt était 10 fois supérieure pour un nombre de Reynolds de 6 400 par rapport à celle observée à des débits inférieurs et supérieurs avec des nombres de Reynolds respectivement de 2 200 et 9 600. Les résultats sont examinés en fonction de l'effort de cisaillement sur le biofilm et de la vitesse de transport des nutriments.

Technologie des échangeurs thermiques
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ABSTRACT

The rate of magnetite deposition on a heated test section was investigated using radiotracing methods as a function of flow rate in the absence and presence of a growing biofilm of *Pseudomonas fluorescens*. The flow rate was adjusted to span Reynolds numbers from 2200 to 9600. For all flow rates, there was an increase in the rate of magnetite deposition in the presence of the growing biofilm. In addition, the rate of deposition was 10 times greater for a Reynolds number of 6400 than that observed at lower and higher flow rates with Reynolds numbers of 2200 and 9600, respectively. The results are discussed in relation to the shear stress on the biofilm and to the rate of transport of nutrients.

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1. INTRODUCTION

The costs associated with heat exchanger fouling in the process industries are well documented (Pritchard 1988). In the nuclear industry, forced plant outages result in significant costs associated with both lost generation revenue and replacement energy costs. In CANDU® nuclear reactors, several heat exchangers serve critical functions in safety-related systems. For example, the moderator heat exchangers control the temperature of the heavy-water moderator, which—in turn—dictates the maximum reactor power that can be achieved. Reduced heat-transfer efficiency can result in reactor derating, thereby reducing generating capacity and revenues. In addition, shutdown coolers are used to safely lower the temperature of the primary (heavy water) coolant during both scheduled and emergency shutdown of the reactor. Obviously, the integrity of these heat exchangers and their efficient operation are critical for continued reactor operation. Conventional on-line mechanical cleaning methods for fouling deposit control are limited with these heat exchangers because the flow of cooling water is on the shell side (the process water is on the tube side in order to reduce the costly heavy-water inventory).

Field experience has shown that heat exchangers cooled by Lake Ontario water contain deposits composed of approximately equal volume fractions of silt, calcium carbonate and biological material (Gendron and Turner 1995). Deposit analysis suggests that the foulants may deposit because of interactions or synergisms between the different fouling modes. For example, biofilms on tube surfaces appear to enhance silt and particulate deposition.

In this report, we determine the effect of flow rate on the enhancement of particulate fouling on heat exchanger surfaces in the presence of a developing biofilm. Biological fouling experiments were performed using *Pseudomonas fluorescens*. This species was chosen as a model slime-forming bacterium to simplify interpretation of the data and because pseudomonads are among the earliest colonizers of engineered materials when present in mixed populations.

2. EXPERIMENTAL

Figure 1 shows the heat exchanger fouling loop facility. The entire loop, including the heated test section, is constructed of 304 stainless steel. Automatic controllers are used to regulate the loop flow rate, inlet temperature to the test section, and applied heat flux. The deposition experiments were performed using radioisotope-tracing techniques. The radiotracer was magnetite (particle diameter of ~0.25 μm) irradiated in the NRU reactor at the Chalk River Laboratories. In each experiment the flow rate was first set and then magnetite was added to the fouling loop. Deposition on the heat-transfer surface was monitored continuously using an on-line gamma ray detector. The tests were performed at an inlet temperature of ~20°C, an initial surface temperature of ~35°C at the midpoint of the test section, a pH of ~7, and at Reynolds numbers from 2200 to 9600 (linear fluid velocities of 0.21 to 0.81 $m \cdot s^{-1}$). Following an

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initial period (~15 h) to establish the deposition rate in the absence of a growing biofilm, growth medium was added followed shortly (~5 h) by an inoculum of *Pseudomonas fluorescens*. The growth medium was a pyrrolidine/yeast-based broth containing a number of inorganic constituents. The concentration of magnetite and bacteria in suspension were monitored throughout the experiment. At the conclusion of each test, the test section was cut into 30-mm sections, and the mass deposited on each section was measured using an off-line gamma ray counting facility. Details of the methodology for measuring and calculating deposit masses from radiotracing data are described elsewhere (Turner and Smith 1998). The rate constant for particle deposition (K) was calculated assuming linear kinetics; that is,

$$\frac{M}{A} = cKt. \qquad (1)$$

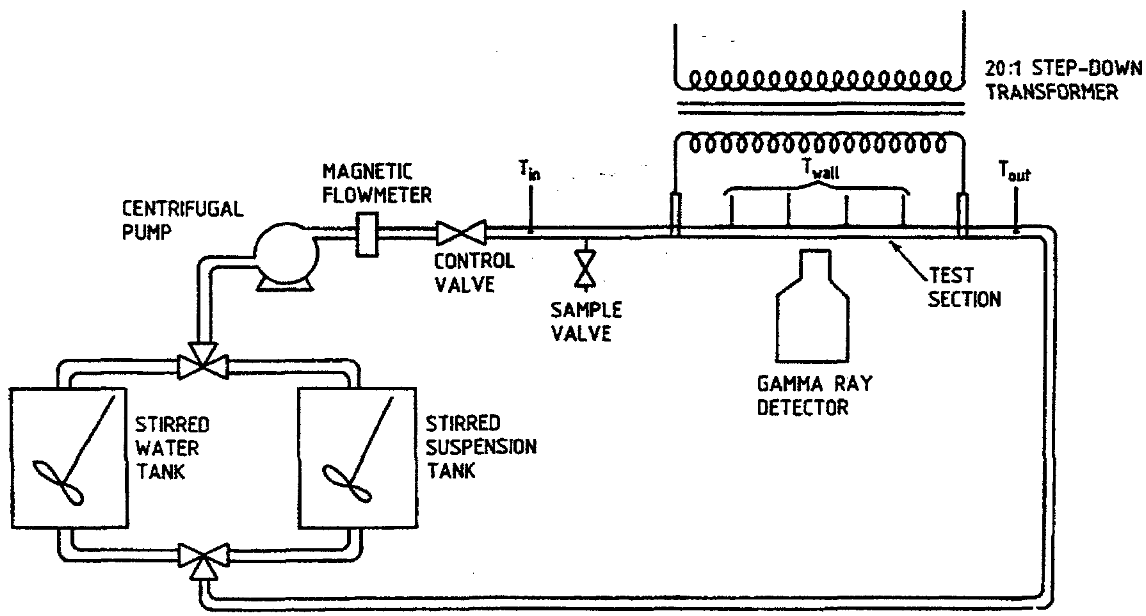

Figure 1 The heat exchanger fouling loop.

3. RESULTS

The deposition rate of magnetite in the presence of a developing biofilm was found to be strongly dependent on the flow rate. The time dependence of the deposit mass of magnetite is shown in Figure 2 for Reynolds numbers of 2200, 6400, and 9600. The deposition rate constant is the slope of the graph in Figure 2. It can be seen from Figure 2 that the shape of the deposition profile is the same, regardless of flow rate. This finding suggests that in systems where particle deposition and biofouling are occurring simultaneously, it can be expected that, within limits, the interactions will be similar regardless of the flow conditions. The deposition rate is essentially constant during the initial period of each experiment in the absence of any bacterial growth. There may be a slight variation in the deposition rate when the medium is added, and then a significant increase in the deposition rate after the inoculation of the loop with *P. fluorescens*.

Table 1 summarizes the experiments that were performed and lists the flow rate, Reynolds number, deposition rate constant prior to and after inoculation, and the related enhancement factor. Some of these data have been reported previously (McGarvey and Turner 1997). For comparison, the deposition rate constant for a 0.25-μm particle at 0.54 $m \cdot s^{-1}$ for eddy diffusion is calculated to be 1.7E-7 $m \cdot s^{-1}$, a value that agrees well with the present measurements.

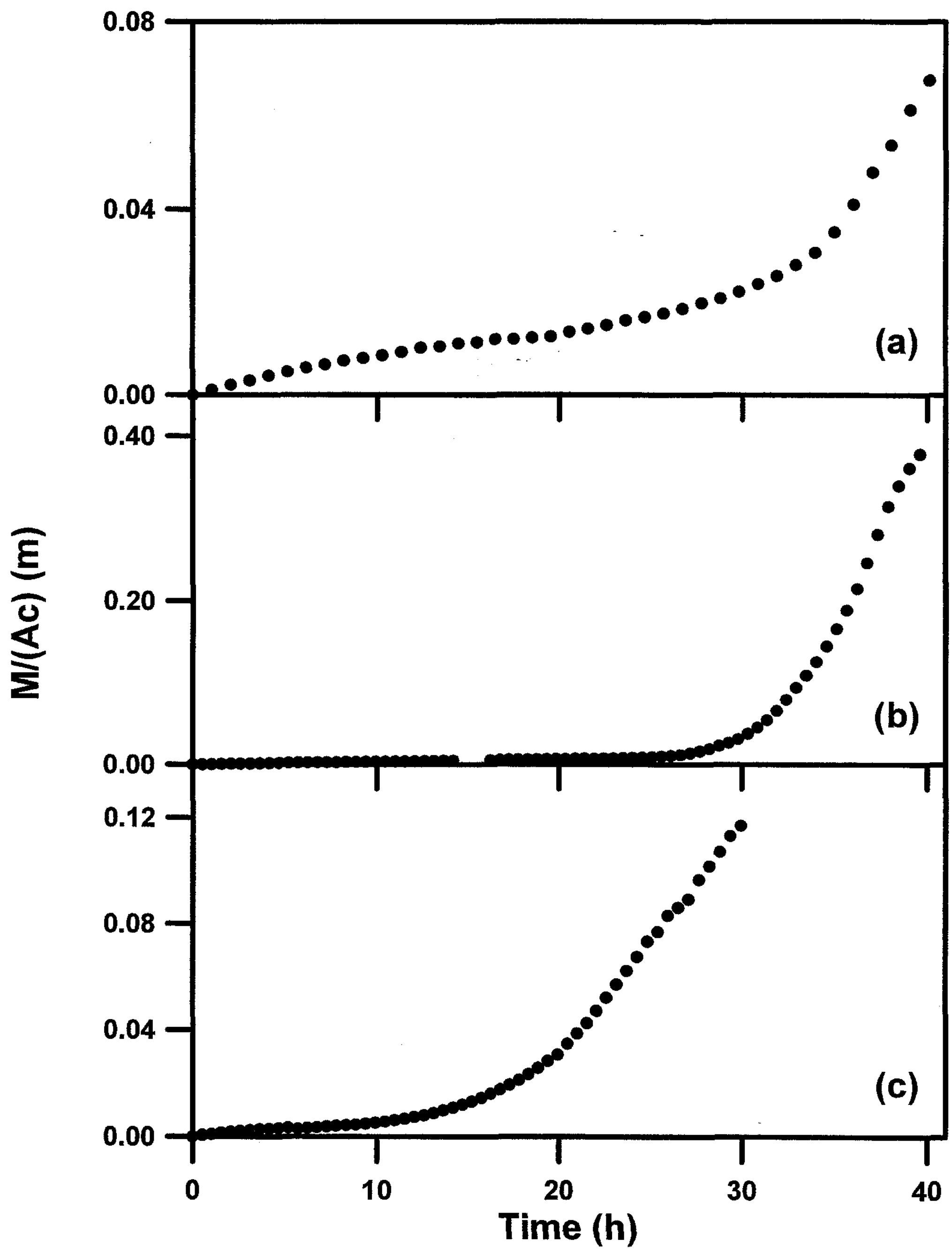

Figure 2 Time dependence of deposit mass of magnetite per unit concentration: (a) Reynolds number of 9600, (b) Reynolds number of 6400, and (c) Reynolds number of 2200.

The variation of the enhancement factor (the ratio of the deposition rate constant after inoculation to that prior to inoculation) with flow rate (Reynolds number) is shown in Figure 3. Figure 3 shows that except at a Reynolds number of 6400 the enhancement factor for the deposition of magnetite is approximately 10. However, the enhancement factor at a Reynolds number of 6400 is greater than this value by a factor of 15. These results would indicate that under the experimental conditions used in the present work the deposition of magnetite is extremely sensitive to flow rate in the presence of a developing biofilm.

4. DISCUSSION

For particle deposition alone, the deposition profile generally displays a linear behaviour in the early stages, followed by the tendency towards asymptotic behaviours as the deposit increases in mass and ages (Turner and Smith 1992). In the case of pure biofouling containing planktonic, slime-forming bacteria, the fouling process begins with the formation of an organic layer on the surface of the substrate (Characklis and Marshall 1990). Early colonizing bacteria are transported by eddy diffusion to the metal surface where they can attach. With time, the bacteria use nutrients that are transported in the flowing water to reproduce and excrete an extracellular polymeric substance that binds the consortium of cells together. There is, therefore, an induction period associated with the transport and initial colonization steps. A more rapid increase in biofilm mass is associated with the reproduction of the bacteria and biofilm growth. A maximum biofilm size will be achieved once removal processes, such as sloughing, balance biofilm growth.

Table 1
Summary of results to determine the variation of the deposition rates of magnetite before and after inoculation with *P. fluorescens*

Experiment	Flow Velocity ($m{\cdot}s^{-1}$)	Reynolds Number	Deposition Rate Constant Before Inoculation ($m{\cdot}s^{-1}$)	Deposition Rate Constant Following Inoculation ($m{\cdot}s^{-1}$)	Enhancement Factor
1	0.19	2000	9.2E-7	9.6E-6	11
2	0.19	2100	3.6E-7	2.8E-6	8
3	0.19	2000	1.4E-7	2.4E-6	17
4	0.25	2600	4.0E-7	3.4E-6	9
5	0.29	2900	6.5E-7	1.0E-6	2
6	0.29	3100	3.2E-7	1.7E-6	5
7	0.29	3100	3.9E-7	4.0E-6	10
8	0.45	5400	6.9E-8	2.0E-7	3
9	0.54	6400	8.9E-8	1.5E-5	170
10	0.54	6400	1.8E-7	2.2E-5	120
11	0.63	7500	3.4E-7	8.3E-6	24
12	0.72	8500	4.8E-7	4.3E-6	9
13	0.81	9600	2.4E-7	1.8E-6	7

Under the lowest flow conditions examined in the present work, several processes will be occurring simultaneously, namely, transport of particles (both magnetite and bacteria) to the tube surface, transport of nutrients to the surface, bacterial reproduction and growth, and transport of bacterial wastes from the surface. It is probable that the growth of the biofilm is limited by the transport of nutrients to the surface under these conditions (Re = 2200). Under the highest flow conditions examined (Re = 9600), biofilm shearing and compression rather than transport by eddy diffusion will likely be the dominant factor that limits biofilm growth. It appears that, in the present study, very specific intermediate flow conditions provide adequate turbulence to ensure efficient mass transport of nutrients to the developing biofilm, while not being so aggressive as to have a negative effect on the biofilm structure.

The observations in this study are consistent with observations made by Bott (1991). In one study, the velocity of a *P. fluorescens*–water mixture through a test section was varied, and the biofilm thickness was measured. The biofilm thickness was found to increase with increasing flow velocity up to approximately 1 $m \cdot s^{-1}$, after which a significant decrease in thickness was observed with further increases in fluid velocity. It should be noted that the biofilm thickness reached a plateau at the higher velocities, which suggests that the rate of nutrient transport to the surface equalled the rate of removal of biofilm material from the surface.

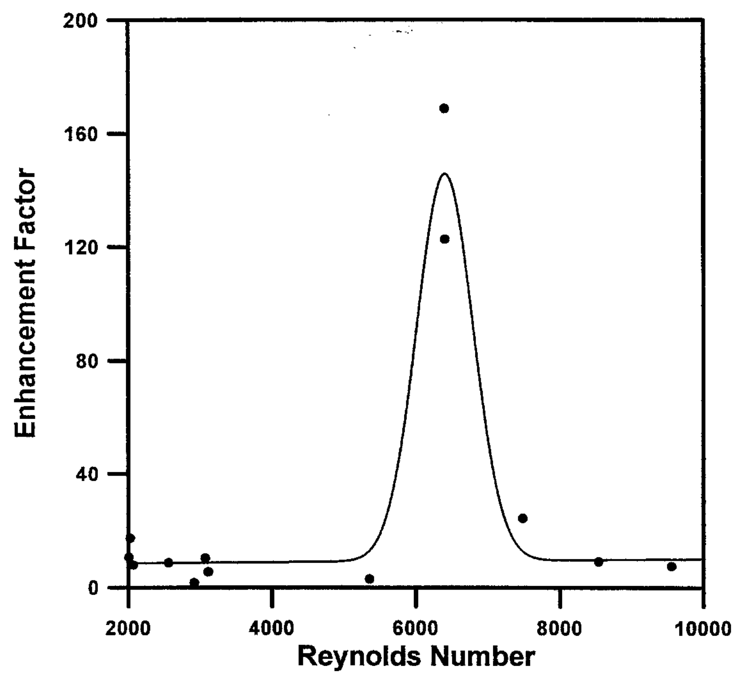

Figure 3 The deposition rate enhancement factor for magnetite as a function of Reynolds number resulting from the inoculation of the fouling suspension with *Pseudomonas fluorescens*, a model slime-forming bacterium.

Lewandowski and Walser (1991) reported that the thickness of a mixed population biofilm passes through a maximum value as the fluid flow conditions were increased from the laminar region through the transition zone to fully developed turbulent flow. Their interpretation of the system behaviour suggested that the maximum thickness represented a balance between transport limitations (nutrients) and biofilm erosion (related to increased shear stress).

Pinheiro et al. (1988) discussed their measurement of deposition fluxes to the surface of a heat exchanger in terms of physical processes such as transport and adhesion of micro-organisms, and biological processes such as nutrient transport and biological growth. Their approach was to separate the deposition flux into contributions from two simultaneous parallel processes (physical and biological). The composite plots indicate that the overall deposition rate is determined primarily by the transport and attachment (both bacteria and particles). Interestingly, the deposition flux associated with the biological processes was found to pass through a maximum as the Reynolds number was increased. The increase was attributed to enhanced nutrient transport to the surface, whereas the subsequent decreases at still higher Reynolds numbers were attributed to changes to the biofilm structure that are introduced by changing hydrodynamic conditions. We argue that higher flow rates will lead to a denser biofilm that restricts the diffusion of nutrients.

5. CONCLUSIONS

The deposition of magnetite on a simulated heat exchanger test section has been shown to increase by at least 10 times in the presence of a developing biofilm at all flow rates used in the present work. The deposition was found to increase by over 2 orders of magnitude under very specific and sensitive flow conditions. Further experimentation is underway to measure the enhancement factor at Reynolds numbers on either side of the observed maximum. The results will be incorporated into a service-water fouling model for use in the nuclear industry.

6. ACKNOWLEDGEMENTS

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