STUDIES OF PARTICULATE FOULING FOR A WATER-KAOLIN SUSPENSION FLOWING IN A HORIZONTAL SQUARE SECTION CHANNEL

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ABSTRACT

Experimental particulate fouling studies were carried out for an aqueous suspension of kaolin at a concentration of 6 kg/m^3, flowing at 2.99 x 10^{-3} m^3/s in a square section horizontal channel and using stainless steel deposition plates. Fouling resistance curves obtained for three positions on the bottom deposition plates showed an initial enhancement of heat transfer, but as the deposition process continued, the fouling resistance increased until it reached a constant value. Measurements of the mass and the thickness of the dry kaolin deposits on the plates at the end of the experiment (144 days) showed that deposition was higher for the bottom plates than for the top ones.

KEYWORDS

Particulate fouling, kaolin, square section channel, horizontal

INTRODUCTION

Fouling is a universal problem that affects the design and operation of a diverse range of equipment by increasing the resistance to heat transfer, thus reducing the efficiency of heat recovery, and by increasing the pressure drop of the fluids across the apparatus. Systematic investigations into fouling have only begun in the last three decades, with a particular emphasis in recent years, increasingly due to the concerns about the way fouling affects the environment and about the scarce energetic resources. Fouling has several origins, which can be classified according to the mechanism responsible for the generation of deposits: crystallisation fouling, particulate fouling, chemical reaction fouling, corrosion fouling, biological fouling and freezing fouling. In particular, particulate fouling is due to the accumulation of solid particles, suspended in the fluid, onto the surface in contact with the moving fluid. Many studies have been carried out for particulate fouling in conditions of single-phase flow and reviews of these works have been presented by Bott (1995).

Kaolin, a type of clay that is primarily composed of aluminium-silicate, is usually found in suspension in the water of rivers, especially in the Northern and Central regions of Portugal (Melo (1985)). When this water is used in industrial cooling systems, it presents a significant potential for inducing particulate fouling alone or in conjunction with other types of fouling (crystallisation, biological and corrosion).

Fouling studies for kaolin-water suspensions flowing through an annular heat exchanger with an inner tube in copper, were performed by Melo and Pinheiro (1988). During the tests, the fluid temperature, pH and the particle concentration (2.2 kg/m^3) were maintained constant. Several runs were conducted for different flow rates, with Reynolds numbers based on the equivalent diameter varying between 2300 and 11040. The tests lasted for less than 30 days and the fouling curves obtained were well fitted by the asymptotic fouling equation of Kern and Seaton (1955).

It is the purpose of the present work to experimentally study particulate fouling for an aqueous suspension of kaolin at a concentration of 6 kg/m^3, flowing in a square section horizontal channel and using stainless steel deposition plates. In this work some preliminary results are reported for a flow rate of suspension of 2.99 x 10^{-3} m^3/s.

EXPERIMENTAL

Experimental apparatus

The experimental apparatus used to obtain the results consisted of a horizontal perspex tube with an ID of 0.032 m and a length of 5.15 m, followed by a square cross-section channel, also in perspex, with a side of H = 0.02425 m and a length of 2.3 m, where the fouling experiments were performed. This apparatus is fully described by Ferreira (2004). The aqueous suspension of kaolin was stored in a 0.1 m^3 tank equipped with an agitator and a refrigeration unit to maintain its temperature at a constant value of 13°C. The suspension circulated through the system by means of a centrifugal pump, and was metered by a calibrated rotameter before entering the horizontal tube and the test section channel. The suspension returned than to the stock tank through a section of PVC tube, where it was re-circulated.

Both ends of the square section channel, schematically represented in Figure 1, included converging pieces that allow a smooth transition from the circular to the square geometry, and back again. In the last 0.7 m of the square channel, four stainless steel deposition plates with a length of 0.198 m, a width of 0.016 m wide, and a thickness of 0.006 m were inserted (two each at the top and bottom of the channel). Heating was provided by circulating hot water at a flow rate of 4 x 10^{-5} m^3/s through each of the two chambers at the top and bottom of the channel. The heating chambers were connected to the top and bottom of the square channel by using a series of metal clamps. The space between contacting walls was always filled with a high conductivity paste. The heating water was supplied from a water tank, maintained at 55 °C by a heating system with temperature control "Digiterm 100".

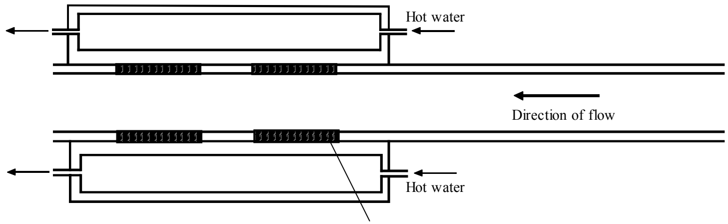


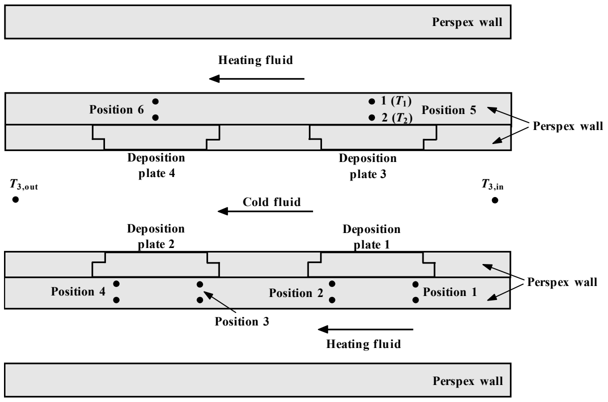
Figure 1
Test section used in the fouling experiments (longitudinal view).

Determination of the heat transfer coefficient under no fouling conditions

The objective of this part of the work was to determine the overall heat transfer coefficient without fouling (U_o), the heat transfer coefficient between water flowing inside the channel and the wall (h_o), and the resistance of the wall (R_W), for each of the deposition plates. This preliminary work is necessary before the fouling experiments, as will be explained in the next section.

The heat transfer coefficients and the resistance of the wall were calculated from temperature measurements using the method described by Vieira *et al.* (1993). It was considered that heat transfer is unidirectional and perpendicular to the fluid flow, and that the variation of the temperature of the cold fluid is linear as it flows inside the heated part of the channel (the longitudinal distance between two deposition plates was short (0.03 m)). Several sets of two temperature sensors aligned in the vertical direction were inserted into the Perspex wall above the deposition plates (top of the channel) or below (bottom of the channel), as shown in Figure 2. The mean temperature of the fluid inside the channel (T_3) was also determined by measuring the temperature at points $T_{3,\text{in}}$ and $T_{3,\text{out}}$.

Figure 2
Longitudinal view of the square section channel with the heating system.



As an example, to calculate the overall heat transfer coefficient for position 5 (Figure 2), the following heat balance equation was used:

$$U_0 = \frac{k_{perspex}\left(T_1 - T_2\right)}{\Delta x\left(T_2 - T_3\right)} \quad (1)$$

where k_{perspex} is the thermal conductivity of the perspex wall, T_1 and T_2 the temperatures at levels (1) and (2) of the perspex wall, T_3 the fluid temperature and Δx the distance between levels (1) and (2).

When there is no deposition, the resistance to heat transfer between level (2) and the fluid is due to the thermal diffusive resistance through the wall and to the convective resistance between the wall of the channel and the fluid. Thus the overall heat transfer coefficient - without fouling, U_o, is given by:

$$\frac{1}{U_o} = \frac{1}{h_o} + R_W \quad (2)$$

where R_W is the thermal resistance of the wall, which is composed by the resistance of the perspex, from level (2) up to the point of contact with the metal plate, by the resistance of the metal plate, and by the resistance of contact between the metal plate and the perspex wall.

The value of h_o was obtained from several thermal experiments carried out for different velocities of the fluid circulating in the channel and for a constant value of the fluid temperature Melo (1985). Under these circumstances, the heat transfer coefficient varies with the Reynolds number according to:

$$h_o = a \operatorname{Re}^n \quad (3)$$

where *a* and *n* are constants to be determined experimentally. If equation (3) is substituted into equation (2) then:

$$\frac{1}{U_o} = \frac{1}{a\,\mathrm{Re}^n} + R_w \tag{4}$$

Using equation (4) and an appropriate optimization method (Solver package in Microsoft Excel®) the values of the constants *a* and *n* and of the thermal resistance of the wall, R_w, were calculated from the experimental data. For the other positions (1, 2, 3 4 and 6) a similar procedure was followed.

To measure the temperature in the perspex wall several little holes were drilled to insert the thermocouples below the bottom deposition plates and above the top deposition plates, as shown in Figure 2. Before the thermocouples were placed inside the holes, they were filled with a high thermal conductivity paste, to avoid bubbles of air in contact with the temperature sensors. The temperature of the flowing fluid was also measured by thermocouples inserted in the flow at the beginning and at the end of the heated part of the channel (in the previous example T_3 represents the average temperature). During the thermal experiments, the tube and the test section were thermally isolated.

The thermocouples were linked to a data acquisition system consisting of a PC-LABCard-818HG data acquisition board connected to a computer. Each temperature was recorded at a frequency of 100 Hz for a period of 120s, using Labtech data acquisition software. The number of temperature measuring points was limited by the available connections in the data acquisition board.

Determination of the overall heat transfer coefficient under fouling conditions and of the fouling thermal resistance

When an aqueous suspension of kaolin flows in the channel, particulate fouling occurs, and a deposit appears on the metal deposition plates. The overall heat transfer coefficient under these conditions, U_{fouling}, is determined by the method described in section 2.2. U_{fouling} is obtained from equation (1) substituting U_o by U_{fouling}. The overall heat transfer coefficient is then given by:

$$\frac{1}{U_{fouling}} = \frac{1}{h_{fouling}} + R_W + R_{fouling} \cong \frac{1}{h_0} + R_W + R_{fouling} \tag{5}$$

where R_{fouling} is the thermal resistance of the kaolin deposit and h_{fouling} is the heat transfer coefficient between the flowing aqueous suspension and the deposition plate. In equation (5), it was assumed that $h_o \cong h_{\mathrm{fouling}}$. This is an approximation since the hydrodynamic conditions for both situations could be relatively different, in particular the roughness of the surface. The value of R_{fouling} at a given instant *t* can, therefore, be calculated by:

$$R_{fouling} = \frac{1}{U_{fouling}} - \frac{1}{U_0} = \frac{1}{U_{fouling}} - \frac{1}{a\,\mathrm{Re}^n} - R_w \tag{6}$$

The experimental arrangement and conditions used for the thermal experiments were maintained in the fouling experiment. During this run the flow rate of the suspension of kaolin was 2.99×10^{-3} m^3/s and the average concentration 6 kg/m^3. It lasted for 144 days, and the overall heat transfer coefficient and the fouling resistance were determined on a daily basis. The pH and the concentration of kaolin in the suspension were also monitored daily.

The particle size of the kaolin used in the experiment was determined by a laser diffraction technique at the " Instituto Geológico e Mineiro". The analysis showed that 90% of the particles presented a characteristic dimension inferior to 24.03 μm and 13.6% of the particles had a dimension inferior to 1 μm. The average of the characteristic dimension was 11.40 μm. The density of the kaolin particles was 2579 $kg/m^{3,}$ determined using a picnometer.

2.4 Measurement of the mass and thickness of the dry fouling deposit

At the end of the fouling experiment, the deposition plates were withdrawn and allowed to dry. After drying, the plates were weighed and the mass of deposit per plate was determined by subtracting the original plate weight. In addition, the thickness of the fouling deposit was measured using a micrometer.

RESULTS AND DISCUSSION

Determination of the heat transfer coefficient and of the resistance of the wall under no fouling conditions

Overall heat transfer coefficients were calculated for positions 1 to 6 (Figure 2), for water flowing in the square section channel with Reynolds numbers varying between 2471 and 13931. From these results and equation (4) and by applying an optimization method (the Solver package in Microsoft Excel®), the constants *a* and *n* of equation (4) and the resistance of the wall, R_W, for each position were calculated. The results are shown in Table 1.

Table 1
Calculated values of the constants a and n of equation (4) and of the resistance of the wall.

	a (W/(m² K))	*n*	R_w* 10³ (m² K/W)
Position 1	0.754	0.802	13.44
Position 2	1.002	0.798	5.80
Position 3	0.924	0.747	17.85
Position 4	0.643	0.815	7.70
Position 5	1.034	0.753	12.80
Position 6	0.760	0.832	17.76

In published correlations (for example, Colburn (1933), Dittus-Boelter (1930) and Sieder-Tate (1936), as mentioned by Incropera and DeWitt (2002)), when calculating the heat transfer coefficient, the exponent of the Reynolds is defined as $n = 0.8$. The experimental values obtained for *n* for positions 1 to 6 varied between 0.747 and 0.832, showing good agreement with the published results.

If the correlation of Colburn is considered, $h = 0.023\left(k/d_{eq}\right)\mathrm{Pr}^{1/3}\,\mathrm{Re}^{0.8}$, then the constant *a* of equation (4) corresponds to $a = 0.023\left(k/d_{eq}\right)\mathrm{Pr}^{1/3}$, where Pr is the Prandtl number. Considering the properties of the water at 15°C (average temperature of the water in the test section during the experiments) and the equivalent diameter of the channel $d_{eq} = 0.02425$ m, the value obtained for *a* is 1.127 W/(m² K). This value is slightly higher than the experimental values, that range from 0.643 to 1.034 W/(m² K).

Determination of the overall heat transfer coefficient under fouling conditions and of the fouling thermal resistance

As previously mentioned, a fouling experiment was run with a kaolin-water suspension at a concentration of 6 kg/m³ for 144 days. During this time, the pH of the suspension varied in the range of 8.0-8.5 and the concentration of kaolin was maintained between 5.5 and 6.5 kg/m³.

The variation of the overall heat transfer coefficient with time is shown in Figure 3 for positions 1, 2, 3 and 6. The results for positions 4 and 5 are not presented because they were not coherent. By observation of the graph and for positions 1, 2 and 3 (bottom plates), it is seen that initially there is an increase in the overall heat transfer coefficient followed by a decrease and, at the end of the experiment, U_{fouling} tends toward a constant value. The behaviour of the curve for position 6 (top plate) is different. The initial increase is not observed, and U_{fouling} decreases with time until it reaches a constant value. As mentioned in section 2.3, the overall heat transfer coefficient under fouling conditions is influenced by the thermal resistance of the wall, by the heat transfer coefficient between the wall and the aqueous suspension and by the thermal resistance of the deposits. For positions 1, 2 and 3, the initial increase in the U_{fouling} could be explained by an increase in the heat transfer coefficient, h_o, or in the area of heat transfer. The increase in h_o can be caused by an increase in the roughness of the wall created by the deposits.

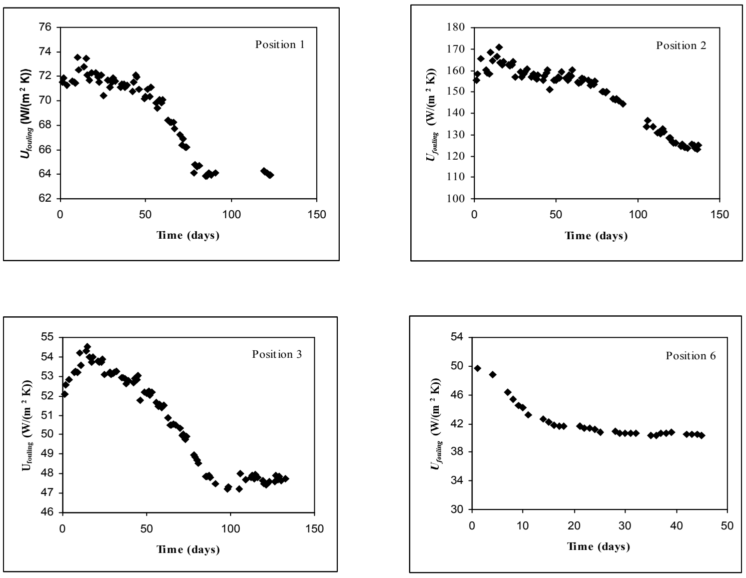


Figure 3
Variation of the overall heat transfer coefficient with time.

Figure 4 presents the fouling resistance *versus* time for positions 1, 2, 3 and 6. Initially the graphs for positions 1, 2 and 3 show negative values for the fouling resistance, due to an enhancement of heat transfer. This behaviour is a consequence of an initial increase in the overall heat transfer coefficient observed in the corresponding graphs of U_{fouling} versus time, for the same positions. A similar result was reported by Gudmundsson and Bott (1979), when studying the deposition from hot geothermal water onto cooled heat exchanger surfaces. Then, the fouling resistance increases with time and, by the end of the experiment, it reaches a constant value. For positions 1 and 3 the constant value of fouling resistance was attained around the 85th day and for position 2 around the 126th day of the experiment.

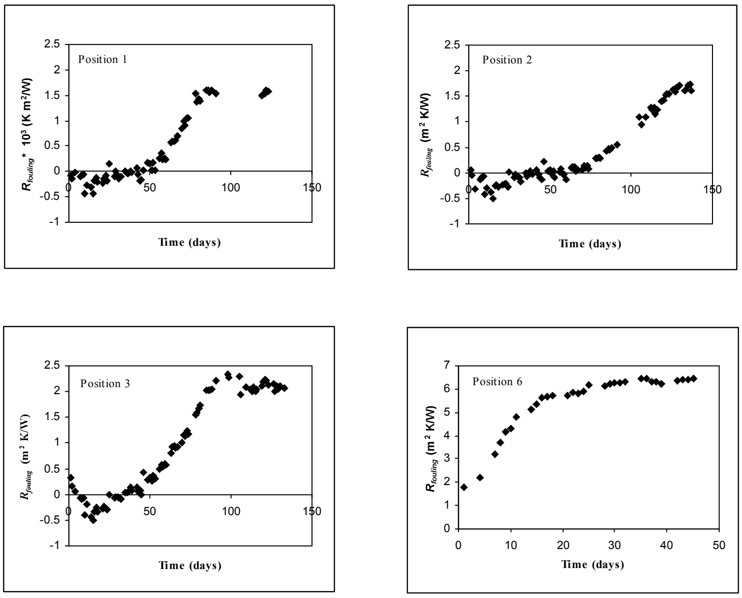


Figure 4
Fouling resistance versus time for the positions studied.

The graph in Figure 4 corresponding to position 6 (top deposition plate) shows that the fouling resistance increases with time until it reaches a plateau. This asymptotic behaviour has been previously reported in several studies. However, when comparing the values of the thermal resistances at the plateau level for the positions at the bottom of the channel with the one at the top, it is seen that R_{fouling} at the top plate is approximately three times larger than at the bottom, contrary to what was expected. Previous experiments carried out by Ribeiro *et al.* (2005) for kaolin deposition in the same test section, but for a shorter period, showed that the mass of kaolin deposited on the bottom plates was higher than for the top plates. This behaviour is also confirmed by the results that will be presented in the next section.

Mass and thickness of the dry fouling deposit

At the end of the 144 days of the experiment, the deposition plates were withdrawn and the mass of the dry deposit and its thickness were measured. Table 2 shows these measurements for the deposition plates 1 to 4 in addition to the calculated density of the dry deposit.

Table 2
Mass, thickness and calculated density of the kaolin deposits.

	Deposition plate 1	Deposition plate 2	Deposition plate 3	Deposition plate 4
Mass (kg/m^2)	0.3426	0.2737	0.0424	0.0322
Thickness * 10^3 (mm)	0.626	0.530	0.204	0.208
Density of the deposit (kg/m^3)	547	517	208	155

These measurements indicate that fouling is higher for the bottom plates than for the top ones, as all the plates had the same area available for the particles to deposit.

The mass deposited per unit area on the bottom plates was one order of magnitude higher than for the top plates. Also, the density of the dry deposit, calculated from the mass of deposits and its volume, is higher (more than double) for the kaolin deposits at the bottom than at the top of the channel. These effects point out that gravity has an influence in the deposition process of the kaolin particles. Yantsios and Karabelas (1998) suggested that sedimentation may affect the deposition process of micron-sized particles in liquids flowing in turbulent flow. Further investigation of this deposition process is necessary.

CONCLUSIONS

In the present work, particulate fouling was studied for a kaolin-water suspension flowing in a horizontal square section channel, at a concentration of 6 kg/m^3 and at a flow rate of 2.99 x 10^{-3} m^3/s. The following conclusions can be drawn:

- for the bottom stainless deposition plates, the curve of $U_{fouling}$ *versus* time showed an initial increase in the overall heat transfer coefficient, followed by a decrease and, finally, $U_{fouling}$ reached a constant value;
- the corresponding curves of the fouling resistance showed that initially the resistance of fouling reaches negative values, due to an enhancement of heat transfer. This can be explained by an increase in the heat transfer coefficient, h_o, or in the area for heat transfer, due to the presence of the kaolin deposits. Following this, the fouling resistance increased and reached a constant level. This behaviour of the fouling curves is a consequence of the way $U_{fouling}$ changes with time;
- from the measurements of the mass and thickness of the dry kaolin deposits on the stainless steel plates at the end of the experiment, it can be concluded that deposition is higher for the bottom plates than for the top ones. This indicates that gravity plays a role in the deposition process.

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