FOULING IN HEAT EXCHANGERS : A STUDY OF THE MECHANISMS OF FORMATION OF KAOLIN DEPOSITS

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ABSTRACT

Fouling caused by a water-kaolin suspension in an annular heat exchanger was studied. Deposition seemed to be controlled by mass transfer for lower Reynolds numbers and by adhesion for higher Re. The data was satisfactorily described by the *generalized* model of Pinheiro.
The relative cohesion of the deposits was measured using a concentric cylinders apparatus, which also helped in confirming the existence of a *loose* and a *hard* layer in the kaolin deposits.

INTRODUCTION

Energy losses due to fouling

Industrial fluids tend to originate solid deposits on the adjacent walls, mainly in the presence of heat transfer. Fouling is, in fact, a widespread problem in the chemical industry, modifying the operating behaviour of sensible heat exchangers, boilers, chemical reactors, condensers and evaporators. Most deposits show a rather low thermal conductivity, causing significant reductions in the thermal efficiency of the equipment subjected to fouling.

Estimates of fouling costs in the United Kingdom and in the United States have been published (1,2) pointing out to about 0.25-0.3% of the Gross National Products; furthermore, 30-40% of these costs (that is, 0.1% of the G.N.P.) can be assigned to energy losses (2). In a country such as Portugal, the total economic penalties due to fouling will probably rise up to US $ 5 x 10^7 in 1984 and the energetic inefficiencies brought by the deposits will be around 1.5% of the energy consumption in industry. These figures undoubtely state the economic importance of such a phenomenon.

Contributions of particulate fouling studies

Fouling may involve several different processes such as mass transfer, heat transfer, chemical reaction, adhesion, crystal nucleation, biological growth, etc., depending on the kind of fluid and operating conditions in each specific case. The question is how to identify and control the phenomena that govern the build-up of deposits.

Particulate fouling - one of the so-called *types of fouling* - is caused by small particles suspended in fluids and its study can add some useful contributions to the understanding of the overall problem. In fact:

- It comprises the three individual processes that are common to almost every fouling situation: transport towards the wall, adhesion on the solid-fluid interface and removal of the deposit by fluid action.

- It is an *inert* type of fouling, making it possible to study those processes without having to face the additional complexities of chemical reactions, bacteria growth, etc.

- It occurs frequently in many industrial processes, either isolated or associated with other types of

fouling, such as precipitation and biological fouling. In this paper an experimental study of particulate fouling caused by a water-kaolin suspension on copper tubes is reported, in which the effects of fluid velocity were examined and the steps controlling the growth of deposits were identified.

FOULING MODEL

The basic theory of fouling follows the ideas suggested by Kern and Seaton (3), who assumed that deposits grow as a result of the competion between a deposition rate (ϕ_d) and a removal rate (ϕ_r). Considering that ϕ_d remains constant during the fouling process and that ϕ_r increases with the deposit thickness (or its thermal resistance), the authors obtained an integrated equation of the following type:

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

where R_f is the thermal resistance of the deposit at time t, R_f^∞ is the maximum (asymptotic) value of the R_f (at t = ∞) and β is the proportionality constant between ϕ_r and R_f :

$$\phi_r = \beta \cdot R_f \qquad (2)$$

According to Kern and Seaton, β will be directly proportional to the wall shear stress, which is a function of the square of the fluid velocity. It should be noted that for equal R_f, a higher value of β means that the removal of the deposit will proceed at a higher rate; hence, $1/\beta$ can be considered as a measure of the deposit's resistance, or of its *cohesion*.

It can also be shown that:

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

The ideas of Kern and Seaton were further developed by several authors, mainly in what concerns the deposition term, although all the models maintained the basic form

of equation 1. An unifying approach was presented by Pinheiro (4,5), involving the particulate fouling model of Watkinson and Epstein (6), the chemical reaction fouling model of Crittenden and Kolaczkowski (7) and the precipitation fouling model of Taborek et al (8). The concepts of Cleaver and Yates (9,10) regarding the removal process were also included in Pinheiro's *generalized* model, its fundamental assumptions being the following (for the case of particulate fouling):

(i) The deposition process involves the transport of particles (by turbulent diffusion) to the deposition surface, followed by a surface interaction mechanism (adhesion). If u is the mean fluid velocity, C the suspension concentration, T_s the surface temperature and f the friction factor, the deposition rate will be:

$$\phi_d = \cfrac{C}{\cfrac{1}{k_1 \sqrt{f}\, u} + \cfrac{u^b}{k_0 \exp(-E/RT_s)}} = \cfrac{C}{\rho_f \cdot k_f \left[\dfrac{1}{k_t} + \dfrac{1}{k_r}\right]} \qquad (4)$$

where E is an *activation energy* associated to the adhesion process, R is the ideal gas constant and k_0, k_1 are proportionality constants. k_t and k_r are the transport and the adhesion rate coefficients, while ρ_f and k_f are the density and thermal condutivity of the deposition. Parameter b depends essentially on the individual processes that control the deposition phenomenon:

– If the mass transfer step is much slower than the surface phenomena process ($k_t \ll k_r$), $\phi_d = \dfrac{1}{\rho_f \cdot k_f} \cdot k_t\, C$ and b = 0, which means that the deposition rate increases with fluid velocity.

– If the transport rate is much greater than the adhesion rate, then $\phi_d = \dfrac{1}{\rho_f \cdot k_f} \cdot k_r\, C$ and, as suggested by data from several authors (4), $0 \le b \le 1$. In this case, ϕ_d will decrease with increasing fluid velocity.

(ii) The removal rate is a function of the hydrodynamic forces acting on the deposit and of the cohesive

properties of the latter. As Cleaver and Yates (9) pointed out, there will be a *minimum fluid velocity*, or shear stress, necessary for removal to occur. Based on experimental observations of several authors (11,12,13), Pinheiro assumed that the structure of the deposit is not uniform, consisting of (at least) two layers: the inner one, near the wall, is more hard and adherent, while the outer one, in contact with the fluid, is composed by more or less loose particles and is, thus, more easily removable by the fluid. Hence the *minimum fluid velocity* will be determined by the resistance to removal of the outer layer: the higher the cohesion of this layer, the higher will be u_{min}.

ϕ_r is taken as proportional to the shear stress, i.e., to $f \cdot u^2$, but considering, as Taborek et al (8) did, that higher velocities originate harder deposits, ϕ_r will also vary inversely with u^a, where a is an empirical parameter depending on the cohesive properties of the deposit. The removal term in Pinheiro's model is then:

$$\phi_r = k_2 f \left(\frac{u}{u_{min}}\right)^{2-a} \cdot R_f \tag{5}$$

where it is probable that $0 < a \leq 2$ (4).

Table 1 summarizes the dependencies of ϕ_d, β and R_f^∞ on the fluid velocity, as given by the model of Pinheiro; in this table, the Blasius correlation for the friction factor ($f \sim u^{-0.25}$) was taken into account.

Table 1 – Effects of fluid velocity on fouling, as predicted by Pinheiro's model.

Controlling Process	ϕ_d	β	R_f^∞
Transport (Turbul. diffusion)	$(u)^{0.875}$	$(u)^{1.75-a}$	$(u)^{-0.875+a}$
Adhesion	$(u)^{-b}$	$(u)^{1.75-a}$	$(u)^{-1.75+a-b}$

EXPERIMENTAL EQUIPMENT AND METHODS

Fouling tests, each one lasting several weeks, were carried out in an horizontal annular heat exchanger in order to study the buid-up of kaolin deposits at Reynolds numbers between 2300 and 11040.

The cohesive characteristics of the deposits obtained in the annular heat exchanger were compared using a concentric cylinders apparatus similar to the one described by Visser (14), who measured the adhesion forces of particles to clean surfaces.

a) The annular heat exchanger consists of a 2 meters long external perspex tube (ID=36 mm) and a removable inner copper tube (OD=25 mm) heated by an electrical resistance placed inside it. Thermocouples are located in the internal upper wall of the copper tube at five different positions in the axial direction (A,B,C,D,E), the distances from the inlet of the fluid being: A-20 cm; B-45 cm; C-78.5 cm; D-111.5 cm; E-145 cm. Fluid temperatures are also measured at the same five positions and pressure drop is monitored in the central zone of the annulus.

The water-kaolin suspension (mean particle diameter = 16 microns) is cooled and stirred in a 250 liters vessel, pumped through PVC tubes to the test section and back to the reservoir. Flow rates are controlled by two valves, one of them located in a by-pass tube, and are measured with a rotameter. Voltage and current intensity are registered in order to evaluate the heat flux. Therefore, overall heat transfer coefficients can be determined at each one of the five positions, knowing the local wall and fluid temperatures as well as the heat flux.

All fouling tests were run at constant heat flux (3000 W/m^2), constant kaolin concentration (2.2 kg/m^3), constant bulk water temperature (12°C) and constant

pH (7.5). Samples of fluid were periodically withdrawn for analysis of kaolin concentration and suspension pH. After the tests, the thickness of the deposits was measured using a micrometer inserted in an appropriate electrical circuit, following a technique described by Harty and Bott (15) and adapted by Melo and Pinheiro (16).

b) The concentric cylinders apparatus has a removable inner cylinder (2 cm long, OD=25 mm) placed inside an outer rotating perspex cylinder (8 cm long, ID=36 mm). A Variac controls the input voltage to the alternate motor connected to the outer cylinder, the rotation speed of the latter being measured with a stroboscope.

Samples of the fouled copper tubes obtained in the annular exchanger tests are cut and used as the inner cylinder in the apparatus. Before placing them inside the device, filled with water at pH = 7.5, they are dried and weighed. The outer cylinder is then rotated at a low velocity for 3 minutes, after which the sample is removed, again dried and weighed. This procedure is repeated at increasing speeds of rotation in order to measure the effect of hydrodynamic forces on the deposit, which will serve as a means for assessing its relative cohesion.

The hydrodynamic force can be evaluated using the correlations developed by Wendt (17) – also referred by Visser (14) – that relate the rotation speed to the shear stress at the surface of the inner cylinder.

RESULTS AND DISCUSSION

Annular heat exchanger

By carrying out tests with clean water at different Reynolds numbers, overall heat transfer coefficients with the clean surface (U_0) were determined and, using an adaptation of the Wilson method (18), the associated convective heat transfer coefficients (h_0) were also evaluated. U_0 and h_0 are related through the following equation (for the case of a plane wall):

$$\frac{1}{U_0} = R_w + \frac{1}{h_0} \tag{6}$$

where R_w is the thermal resistance between the point where the wall thermocouple is located and the clean deposition surface.

During the fouling tests, the overall heat transfer coefficient changes as the deposit builds-up. If, at a given time t, the overall coefficient is U and h is the convective coefficient, the thermal resistance of the deposit at the same time (R_f) will be:

$$R_f = \frac{1}{U} - \frac{1}{U_0} + \frac{1}{h_0} - \frac{1}{h} \tag{7}$$

Supposing that there are no blockage effects (which in the present case is pratically true because the thickness of the deposits is much less than the annulus diameter), changes in h will be due to changes in the roughness of the deposition surface as the particles adhere to it. Melo and Pinheiro (16) described a technique, based on pressure drop measurements, that can be used to evaluate the relationship between h and h_0 at the solid/fluid interface in a fouled annulus, at any instant.

Fouling curves (R_f versus t), similar to the one shown in Figure 1, were then obtained from tests conducted at Reynolds numbers (Re) 2300, 2760, 4140, 6900 and 11040. By fitting equation 1 to the data, values of R_f^∞ for positions A,B,C,D, and E were determined as a function of Reynolds numbers (see Figure 2); final thickness (y_f) versus Re curves were also drawn (see Figure 3) indicating the same trends.

Values of ϕ_d were calculated with equation 3 and are shown, as a function of Re, in Figure 4 for positions D and E, and in Figure 5 for positions A and B.
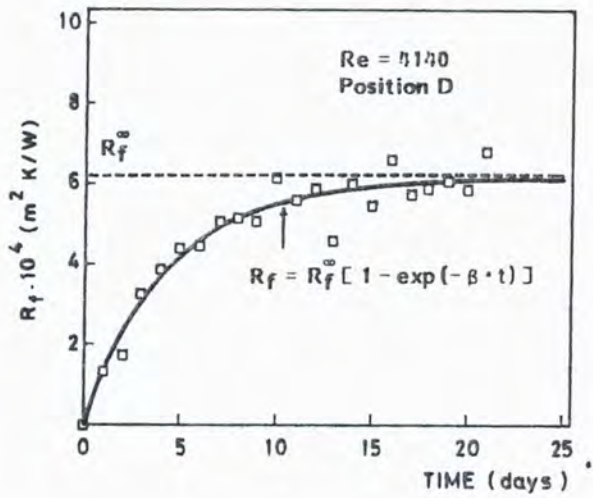
Figure 6 shows the *resistance to removal* of the deposits
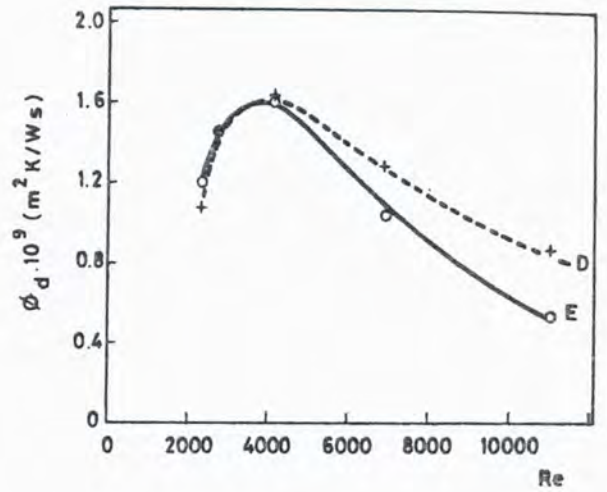
Figure 1 - Typical fouling curve

$Re = 5140$
Position D

R_f^∞

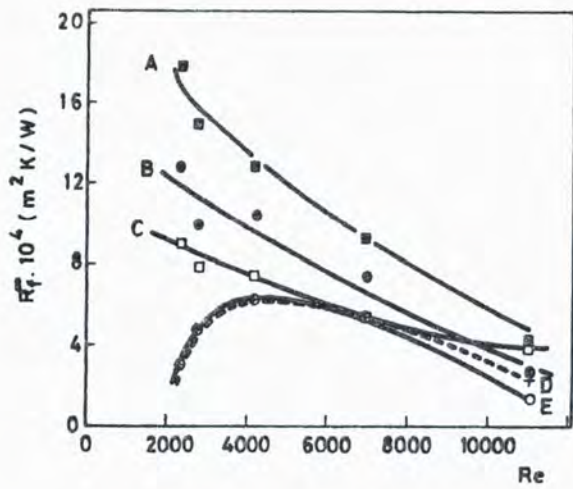$R_f = R_f^\infty [\, 1 - \exp(-\beta \cdot t) \,]$

$R_f \cdot 10^4 \ (m^2 K/W)$

TIME (days)

Figure 2 - R_f^∞ versus Reynolds No.

$R_f^\infty \cdot 10^4 \ (m^2 K/W)$

Re

Figure 3 - Final thickness versus Reynolds No.

Y_f (microns)

Re

Figure 4 - Deposition rate versus Reynolds No.

$\phi_d \cdot 10^9 \ (m^2 K/Ws)$

Re

Figure 5 - Deposition rate versus Reynolds No.

$\phi_d \cdot 10^9 \ (m^2 K/Ws)$

Re
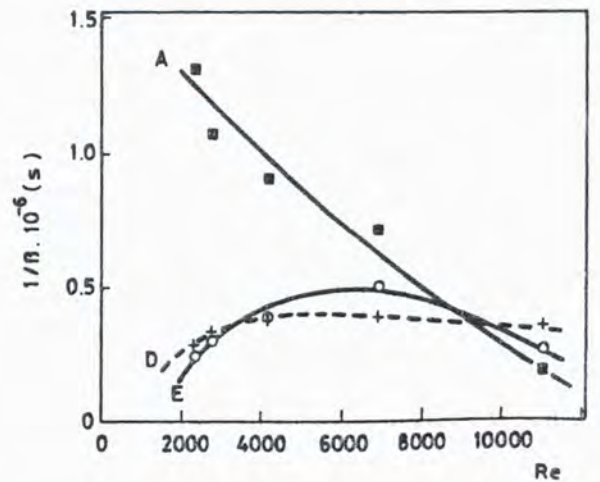
Figure 6 - Resistance to removal versus Reynolds No.

$1/\beta \cdot 10^{-6}$ (s)

Re

$(1/\beta)$ as a function of Reynolds numbers for positions A, D and E.

Striking differences between the amount of fouling obtained at the various positions in the exchanger can be readily noted in Figures 2 and 3. Previous studies (19) have shown that for the lower Reynolds numbers (below 7000, approximately), positions A, B and, partially, C are in developing laminar flow region where the removal forces are weaker, which explains the thicker deposits obtained in this entrance region. In the fully developped non-laminar region (positions D and E), R_f^∞ (or y_f) increases with fluid velocity up to Re $\simeq$ 4000, the trend being inverted for higher Re values. A possible explanation for this behaviour, at D and E, is the following:

- For low fluid velocities (Re < 4000), mass transfer rates are small, meaning that particles transport could be the process controlling deposition. In this case, increasing the Reynolds numbers would not only increase ϕ_r, but also ϕ_d (see Figure 4). If, simultaneously, there is an increase in the cohesion of the deposit (see Figure 6), thicker deposits will be obtained with higher Reynolds numbers. This feature is predicted by Pinheiro's model, when a > 0.875 (see table 1).

- For even higher fluid velocities, a change in control will occur between Re > 4000 and Re $\simeq$ 6000, and the depostion process will be governed by adhesion. Consequently, ϕ_d ceases to increase with Re, while the fluid removal forces continue to grow overcoming the cohesion effect. Figure 4 shows that, as predicted by Pinheiro's model, ϕ_d decreases with increasing Reynolds numbers.

In what concerns the upstream positions, laminar effects will prevail as far as those points remain in a developing flow region. In such a case, an increase in the velocity will not result in a significant increase in the transport rate, because molecular (and not turbulent) diffusion will be the mass transfer mechanism. Furthermore, gravitational effects can also play a role in the laminar region and, if so, transport rates will be independent of fluid velocity (see Figure 5). In any case, if the shear stress is increased, the final amount of deposit will decrease, as shown in Figures 2 and 3 for positions A and B.

For the higher range of Reynolds numbers, similar trends for all the five positions can be observed in Figures 2 and 3. At A and B, however, the curves in Figure 5 (ϕ_d versus Re) seem to indicate that mass transfer still controls the deposition for Re > 6000; but, as the cohesion of the deposits (Figure 6, curve A) decreases, lower thicknesses are obtained as Re is increased.

The model of Pinheiro was fitted to the data of Figure 2, 4 and 6, at positions D and E, in order to test the proposed fluid velocity dependencies for the two limiting cases of deposition control presented in Table 1. Parameters a and b were also evaluated. The results of the fitting procedure are presented in Table 2 and appear to support reasonably well the proposed model, although the values of a and b are, in some cases, beyond the limits suggested by Pinheiro.

Concentric cylinders apparatus

Figure 7 shows the results of the removal experiments carried out in this apparatus using samples of the annular exchanger fouled tubes at position D.

These results seem to indicate that:

- The deposit obtained with Re = 4140 has a higher cohesion than the one obtained with Re = 2300, confirming the results of Figure 6 and the explanation suggested in Annular heat exchanger

Table 2 - Fitting of Pinheiro's model to data from the annular heat exchanger (positions D and E).

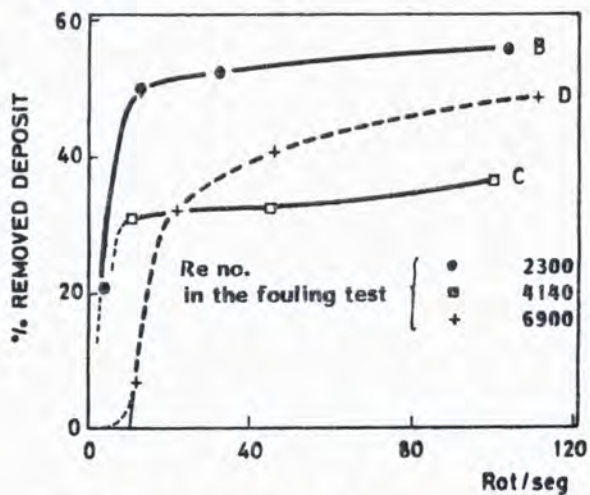| Position	Range of Reynolds No.	Effects of fluid velocity			Parameters	
		ϕ_d	β	R_f^∞	a	b
D	2300- 3300	$u^{1.03}$	$u^{-0.62}$	$u^{1.78}$	2.6-2.8	0
	6900-11040	$u^{-0.83}$	$u^{0.25}$	$u^{-1.09}$	1.75	0.83
E	2300- 3300	$u^{0.70}$	$u^{-0.73}$	$u^{1.47}$	2.1-2.5	0
	6900-11040	$u^{-1.43}$	$u^{1.44}$	$u^{-2.83}$	0.35	1.43

Figure 7 - Results from the concentric cylinders apparatus

for the increase in R_f^∞ with fluid velocity.

- All the curves in Figure 7 present a similar shape, showing a *critical point* (c.p.) above which the fluid velocity has a minor effect on the amount of deposit removed. This *critical point* could represent, according to the hypothesis of a two-layer structure in the deposits, the transition from the *loose* to the *hard* layer. Hence, the deposit obtained with the lowest Reynolds number (Re = 2300) would contain around 50% of hard layer, while the deposits obtained with Re = 4140 and Re = 6900 would contain a higher proportion of hard layer (about 70%). For Re = 6900, the hard

layer appears to have a lower cohesion than for Re = 4140, and the inverse seems to occur with the loose layer.

- A value for u_{min} can be determined in the case of Re = 6900. Extrapolating the curve to 0% removal, the minimum speed rotation will be 8 rot/seg, corresponding to a mean fluid velocity of 0.09 m/s (17). This is much lower than the mean fluid velocity in the annular heat exchanger when Re = 6900 (u = 0.79 m/s), showing that the removal of the loose layer is easily accomplished.

- The hard layer is practically unremovable even at the highest velocities.

CONCLUSIONS

Particulate fouling tests were carried out in an annular heat exchanger at several Reynolds numbers using a water-kaolin suspension. The data can be satisfactorily described by the *generalized* model of Pinheiro, and the following conclusions can be drawn up for the case of non-laminar fully developped flow:

- At low Reynolds numbers, mass transfer controls the deposition process and, since the cohesion of the deposits is relatively high, the thickness of the deposits increases with the Reynolds numbers.

- At higher fluid velocities, adhesion is the controlling step, resulting in a decrease in the amount of deposit as Re is increased.

Tests carried out in a concentric cylinders apparatus (with a rotating outer cylinder) supported the hypothesis concerning the relative cohesion of the deposits and, furthermore, confirmed the predicted existence of a *loose* and a *hard* layer in the deposits, the latter being a substantial fraction (50-70%) of the total mass of the deposit.

In the entrance zone of the heat exchanger, where a laminar developing flow exists, the results show a quite different behaviour, R_f^∞ always decreasing with increasing Reynolds numbers.

ACKNOWLEDGEMENT

NOMENCLATURE

a,b	-	empirical parameters in Pinheiro's model
C	-	suspension concentration (kg/m^3)
E	-	activation energy for adhesion (J/kg mole)
f	-	friction factor of the inner surface of the annulus
h	-	convective heat transfer coefficient ($W/m^2 \cdot k$)
h_o	-	convective heat transfer coefficient, clean wall ($W/m^2 \cdot k$)
k_o, k_1, k_2	-	proportionality constants
k_f	-	thermal conductivity of the deposit (W/mk)
k_r	-	adhesion coefficient (m/s)
k_t	-	transport coefficient (m/s)
R	-	ideal gas constant (J/kg mole $\cdot$ k)
Re	-	Reynolds number
R_f	-	fouling resistance at time t ($m^2 \cdot k/W$)
R_f^∞	-	asymptotic fouling resistance, at time $t = \infty$ ($m^2 \cdot k/W$)
R_w	-	thermal resistance between the wall thermocouple and the clean surface ($m^2 \cdot k/W$)
t	-	time (s)
T_s	-	surface temperature (k)
u	-	mean fluid velocity (m/s)
u_{min}	-	minimum fluid velocity necessary for removal to occur (m/s)
U	-	overall heat transfer coefficient ($W/m^2 \cdot k$)
U_o	-	overall heat transfer coefficient, clean wall ($W/m^2 \cdot k$)
y_f	-	final thickness of the deposit (microns)
β	-	constant in equation 1 (s^{-1})
ϕ_d	-	deposition rate ($m^2 \cdot k/J$)
ϕ_r	-	removal rate ($m^2 \cdot k/J$)
ρ_f	-	density of the deposit (kg/m^3)

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