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KINETICS OF DEPOSITION OF CARBON PARTICLES ON PLASTIC SPHERES

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ABSTRACT

The kinetics of particle deposition onto the surface of spherical collector particles suspended in a stirred batch vessel was investigated. The study considered monodisperse particle and monodisperse spherical collector particles. The Langmuir model for the deposition process was presented with model parametric study as well as model limiting cases of Smoluchowski analysis and equilibrium state. A method for obtaining the model parameters from model limiting cases was demonstrated. The model was experimentally tested by studying the deposition of small carbon particles onto plastic spheres. This is useful in the de-inking process of waste paper using plastic spheres. The obtained deposition curves are fitted to the model. The estimated parameters from model limiting cases are in agreement with those, obtained from the full deposition curves fitted to Langmuir kinetics. The maximum

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number of carbon particles that can deposit on plastic particles is estimated theoretically from geometrical analysis. The estimated value is very close to that determined from the model.

INTRODUCTION

De-inking is the most important step in waste paper recycling. Flotation and washing are the conventional methods used to remove the ink particles from recycled pulp suspension (1–4). A recent study conducted by Mousa and Qasaymeh (5) showed that the carbon particles (as ink model) could be collected on the surface of plastic particles with excellent removal ability. Their study was directed mainly towards equilibrium surface coverage. This paper investigates the kinetics of deposition of monodisperse carbon particles on the surface of monodisperse plastic spheres during the full deposition period.

Particle deposition onto surfaces has a wide industrial application. Among these is the deposition of small particles (e.g., clay, calcium carbonate, latex) onto pulp fibers for the purpose of paper filling. Other applications included the release and the re-deposition of corrosion products, deposition of cells onto surfaces in biological processes and transport of colloidal contaminants in ground water aquifers. Hence, developing theories for particle deposition kinetics has received a great attention in the literature in recent years (6–13). Models for deposition processes have taken two main directions: 1—Solving the general particle transport equation (either the convection–diffusion equation or the equation of motion) with the necessary boundary conditions (e.g., perfect particle sink at the collector surface) for obtaining particle concentration gradient in suspension around the collector. The flux of particles toward the surface of the collector from Fick's first law is then estimated which would give the deposition rate (13). 2—Assuming certain deposition kinetics such as the Langmuir type similar to that used for gas molecular adsorption (6). In this paper, Langmuir analysis is used since the existing models do not predict equilibrium or steady state particle deposition and detachment. Moreover, previous theories (13) assume that the surface is a perfect sink for particles while in this theory the surface has a maximum capacity beyond which it would not accommodate more particles. Finally, a parametric study for the effect of the constants of Langmuir kinetics on deposition curves has not been presented in previous publications. This paper shows such effects.

Particle deposition systems have been experimentally investigated in the literature under different flow conditions such as: 1—batch stirred vessels where both the collectors and the small particles are suspended and subjected to a shear flow (6,8,11); 2—deposition in packed beds of collectors with the continuous flow of suspension of small particles through the bed (7,10); and 3—deposition onto surfaces subjected to an impinging jet flow of small particle suspension (14–16). This paper deals with particle deposition in a stirred vessel where both carbon and plastic particles are kept suspended in the vessel by being subjected to a rotational flow at fixed revolutions per minute. The reason for using stirred vessel to study deposition is that: in the process of ink removal by plastic particles during waste paper recycling, both the paper pulp and the plastic particles are beaten together. Hence the study was performed in a stirring vessel to mimic the real de-inking process.

THEORY

Deposition Kinetics

The rate of deposition of small particles on a collector surface depends on the hydrodynamic conditions in the vicinity of the collector surface and on colloidal interactions between the collector surface and the particles. In a suspension of large and small particles, due to the hydrodynamic action (shear forces) the small particles will collide with the large particles (collectors). In the presence of colloidal attraction forces, some of these collisions will be successful and result in deposition. However, shear forces may detach some of the previously deposited particles if they are strong enough to over come the energy barrier (13), resulting in a detachment (backward) rate. In general, the deposition process actually consists of two elementary processes, deposition of particles onto the surface of the collector and desorption of deposited particles (detachment and escape from the surface). The net deposition rate is the difference between these two rates, analogous to the gas molecular adsorption.

An early attempt at modeling the rate of deposition used Smoluchowski analysis (which is valid for cases of dilute suspension or at initial deposition times, where the surface coverage and the backward rate are negligible). In such cases, the surface of the collector can be considered as a perfect sink for the small particles and thus the deposition rate is given by the following equation (13)

$$\frac{d\bar{N}_{\mathrm{d}}}{\mathrm{d}t} = k_1 N \tag{1}$$

where N is the number of small particles in suspension per unit volume, $\bar{N}_{\mathrm{d}}$ is the number of deposited particles per unit collector surface area, t is the time, and k_1 is the forward deposition coefficient which is given by the following equation (8,12):

$$k_1 = k_{\mathrm{s}} \alpha n_{\mathrm{c}} \tag{2}$$

where k_s is the Smoluchowski collision rate constant, α is the deposition efficiency, and n_c is the number of collectors in suspension per unit volume. Both the collision rate constant (k_s) and the collision efficiency (α) are strongly dependent on the shear rate (or rotational speed in stirred vessels) (8,13) and the size of the colliding particles (17,18).

During the process of deposition and after certain period of time, the surface of the collector will be partially covered with the deposited particles. Thus, of the total colliding small particles, only those that collide with unoccupied sites on the surface of the collector will be bonded to the surface and deposit. Consequently, in the full deposition process, the above analysis has to be modified to account for the fractional coverage of the collector surface. Upon complete coverage, the collector surface can accommodate a certain (maximum) number of small particles ($\bar{N}_{\mathrm{d\,max}}$). For monolayer surface coverage, this maximum value can be estimated geometrically from the surface area of the collector and the projection area of the small particles. The model used by Alince et al. (8) was of such type of modification. In their study of deposition of clay particles on pulp fibers, they anticipated that the deposition was irreversible since the formed clay-fiber bond was strong enough to prevent detachment. Their deposition kinetics equation had the following form:

$$\frac{\mathrm{d}\bar{N}_{\mathrm{d}}}{\mathrm{d}t} = k_1 N \left(1 - \frac{\bar{N}_{\mathrm{d}}}{\bar{N}_{\mathrm{d\,max}}}\right) \tag{3}$$

When the particle–collector bond is not strong enough, the deposited particles are steadily removed away from collector surface by shear forces. For such systems (11,12,19) "Equilibrium" or steady-state concentrations of particles in suspension and on surface were obtained. The final surface coverage was less than the maximum deposition capacity ($\bar{N}_{\mathrm{d\,max}}$) and was dependent on particle concentration in suspension. In such cases, a detachment rate term had to be added to the above analysis since it would not predict such an equilibrium state. This leads to the application of Langmuir analysis to deposition systems. The detachment rate is proportional to the number of deposited particles. Thus, the net deposition rate is given as follows:

$$\frac{\mathrm{d}\bar{N}_{\mathrm{d}}}{\mathrm{d}t} = k_1 N \left(1 - \frac{\bar{N}_{\mathrm{d}}}{\bar{N}_{\mathrm{d\,max}}}\right) - k_2 \bar{N}_{\mathrm{d}} \tag{4}$$

where k_2 is the detachment rate constant, which is dependent on the bond strength between the deposited particle and the surface of the collector (E) and the shear rate (G) as provided by the following equation (19):

$$k_2 = k_2^0(G)\exp(\frac{-E}{RT}) \tag{5}$$

where $k_2^0(G)$ is a shear rate dependent constant (11), T is the temperature, and R is constant. Both k_1 and k_2 are dependent on the shear rate opposing gas molecular adsorption in which k_1 and k_2 depend on the molecular, kinetic, and bonding energies. It should be noted that the interaction forces strongly affect the values of k_1 and k_2. The detachment coefficient, k_2, is largely dependent on the attraction energy between the particles and the collector as can be shown by Eq. (5). Increasing the attraction between the particle and the collector increases k_1 and hence the deposition rate. Langmuir kinetics was shown to provide good fits for deposition rate data for several systems, such as deposition of different types of fillers on the surface of pulp fibers (10,11).

Deposition Model

For a batch system of monodisperse suspension, mass balance requires that the total number of small particles remains constant with time, i.e.,

$$N_0 = N + N_{\mathrm{d}} \tag{6}$$

where N_0 is the initial number of small particles per unit volume of the suspension and N_{d} is the number of deposited particles per unit volume of suspension and is related to $\bar{N}_{\mathrm{d}}$ as follows:

$$N_{\mathrm{d}} = \bar{N}_{\mathrm{d}}\, a_{\mathrm{p}}(1 - \epsilon) \tag{7}$$

where a_{p} is the surface area of plastic particle available for deposition per unit particle volume and ϵ is the volume fraction of liquid in suspension. In dimensionless form Eq. (6) is rewritten as follows:

$$n = 1 - n_{\mathrm{d}} \tag{8}$$

where

$$n = \frac{N}{N_0} \tag{9}$$

and

$$n_{\mathrm{d}} = \frac{N_{\mathrm{d}}}{N_0} \tag{10}$$

Substituting Eqs. (6)–(10) in Eq. (4) yields

$$\frac{\mathrm{d}n_{\mathrm{d}}}{\mathrm{d}t} = k_1^{'}(1 - n_{\mathrm{d}})(1 - \psi n_{\mathrm{d}}) - k_2 n_{\mathrm{d}} \tag{11}$$

where

$$\psi = \frac{N_0}{N_{\mathrm{d\,max}}} \tag{12}$$

which represents the ratio of initially available particles to those required for the full surface coverage and $k_1^{'}$ is the volumetric forward deposition coefficient given by

$$k_1^{'} = k_1 a_{\mathrm{p}}(1 - \epsilon) \tag{13}$$

With initially clean collector surface the required initial condition for the above ODE is $n_d = 0$ at $t = 0$. The solution of Eq. (11) with the above initial condition is

$$n_{\mathrm{d}} = \frac{2(\lambda - 1)}{A(\lambda - 1) + B(\lambda + 1)} \tag{14}$$

$$\lambda = \mathrm{e}^{(k_1^{'} Bt)} \tag{15}$$

$$A = \frac{1}{K} + \psi + 1 \tag{16}$$

$$B = \sqrt{(\psi - 1)^2 + \frac{2(\psi + 1)}{K} + \left(\frac{1}{K}\right)^2} \tag{17}$$

and K is the equilibrium constant, given by the ratio

$$K = \frac{k_1}{k_2} \tag{18}$$

This model has three theoretical parameters; $k_1^{'}$, K (or k_2), and $N_{\mathrm{d\,max}}$ (or ψ). They can be determined experimentally from measured deposition curves fitted to Eq. (14) together with Eq. (8). Alternatively, their approximate values can be determined from the model limiting cases as shown below.

Eq. (14) expresses deposition relative to the initial number of small particles in suspension. This is a useful expression in handling experimental data and fitting it to the model. But, usually it is more convenient to express experimental results in terms of fractional surface coverage (θ, which requires $N_{\mathrm{d\,max}}$ to be known). However, this can only be done after obtaining ψ from the best fit of experimental data to the model expressed by Eq. (14). Then, the fractional coverage for the experimental results can be estimated as follows:

$$\theta = \psi(1 - n) \tag{19}$$

Initial Deposition Kinetics

At the very beginning of the deposition process, the number of deposited particles is very small, i.e., $\bar{N}_d \approx 0$ and hence Eq. (4) becomes similar to Smoluchowski's equation i.e.,

$$\frac{dn}{dt} = -k_1^{'} n \tag{20}$$

The solution of this equation with the initial condition $n = 1$ at $t = 0$ is

$$n = e^{(-k_1^{'} t)} \tag{21}$$

This solution provides that a plot of $\ln(n)$ vs. t at initial times is a straight line, the slope of which represents the forward deposition coefficient ($k_1^{'}$). The estimated value of $k_1^{'}$ from such a plot can be used as an initial guess for fitting the experimental deposition curves to Langmuir kinetics.

Equilibrium

After sufficient deposition time, the number of small particles in suspension reaches a steady state value, providing that no more net deposition takes place. This state is termed "equilibrium" (which means the steady state transport of particles toward and from the surface and not thermodynamic equilibrium as in gas adsorption theory). At equilibrium, the forward deposition rate equals the backward detachment rate and thus the net deposition rate approaches zero. Hence Eq. (4) yields

$$\frac{1}{N_{d,eq}} = \frac{1}{KN_{eq}} + \frac{1}{N_{d\,max}} \tag{22}$$

where $N_{d,eq}$ and N_{eq} are the equilibrium number of deposited small particles and those remain suspended in solution per unit volume of suspension, respectively.

Eq. (22) indicates that a plot of $1/N_{d,eq}$ vs. $1/N_{eq}$ provides a straight line with a slope of $\frac{1}{K}$ and an intercept with vertical axis of $1/N_{d\,max}$. The values of K and $N_{d\,max}$ obtained from such a plot can be used as initial guesses for fitting the experimental deposition curves (n vs. t) to Langmuir model.

EXPERIMENTAL WORK

Sodium stearate solution was prepared according to the procedure followed by Young and Matijevic (20). The concentration of the sodium stearate was equal to the critical micelle concentration (CMC), which is $1.8 \times 10^{-3}\,M$ (21). The pH of the solution was adjusted to a value of 7. To the above solution, a given amount of carbon black particles (BDH Chemicals Ltd, England) was added to have the required initial concentration of carbon particles. Low density polyethylene particles (LDPE) at a concentration of 5 g/L were then added. The carbon and the plastic particles were uniform in size. The average diameter of the carbon particles was 25 μm whereas the plastic particles have an average diameter of 3.29 mm. Calcium chloride, 0.1 g/L was also added. The total volume of suspension was 200 mL. The suspension was then stirred at a constant rotational speed of 300 rpm using a magnetic stirrer.

The rate of deposition of carbon particles on the plastic particles was followed by counting the number of carbon particles remaining in suspension as a function of time. This was done as follows: a sample of 2.5 mL from the suspension excluding plastic particles was taken at certain time intervals using a pipette. This was possible since the plastic particles are large in size. The sample was then transferred to a volumetric flask and diluted to a 100 mL using distilled water (the dilution was made to minimize errors when counting the particles under the microscope). The diluted suspension was then filtered through Whatman #5 filter paper. The average pore diameter of this filter paper is 3 μm, much smaller than the size of the carbon particles. In this case, no carbon particles are lost during filtration. The filter paper was allowed to dry. It was then placed under the microscope (Olympus Optical Co. Ltd, made in Japan) magnified 200 times. The images of the carbon particles were microphotographed at 15 different locations on the paper and then counted. The microphotographs showed that the carbon particles are uniformly distributed over the filter paper. The variation among the different counts is less than 3%. Hence, it can be assumed that the number of the carbon particles obtained by this way, represents the carbon particles that remained in the suspension. Similar procedures were followed in the absence of plastic spheres to determine the initial number of the carbon particles, N_0. The counted number of carbon particles was divided by N_0 to obtain the dimensionless number of carbon particles in the suspension, n.

To confirm the stability of the carbon particles and to assure that the loss of carbon particles is only due to its deposition on the plastic spheres and not due to the coagulation of the carbon particles. An experiment was performed under the same conditions but without adding the plastic particles. The light transmittance of the carbon suspension was measured at different time intervals. The result showed that the intensity of light transmittance remained nearly constant indicating that the carbon particles were stable against shear.

RESULTS AND DISCUSSION

Theoretical Analysis of Deposition Curves

Figure 1 shows comparison between deposition curves obtained from the three different deposition analysis of Smoluchowski, Eq. (1), irreversible deposition, Eq. (3), and reversible deposition, Eq. (14) for the case of $\psi = 0.5$, $k_1' = 0.05\,\text{min}^{-1}$, and $k_2 = 0.01\,\text{min}^{-1}$. In general, Smoluchowski analysis has the fastest deposition rate. However, the three models had the same initial deposition rate at the early stage, where the irreversibility of the process (as well as the site blocking term) are negligible. No steady state condition is predicted by Smoluchowski unless the surface is fully covered (if enough particles are available in suspension, i.e., when $\psi > 1.0$). On the other hand, irreversible deposition approaches steady state conditions after the consumption of all particles from suspension when $\psi < 1.0$ where θ approaches the

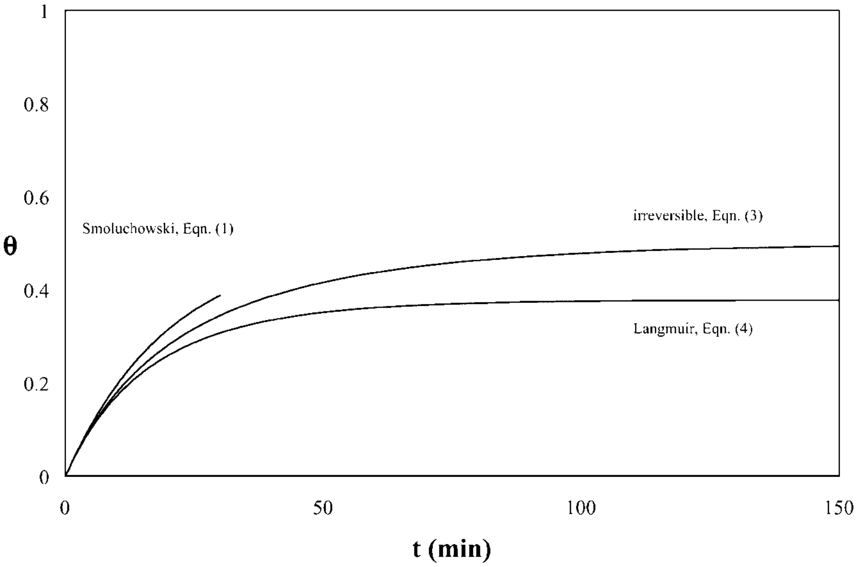

Figure 1. Fractional surface area coverage vs. time using different deposition models for the case where $k_1' = 0.05\,\text{min}^{-1}$ and $\psi = 0.5$.

value of ψ (see Fig. 2) (or after the full coverage of the surface when $\psi > 1.0$ where θ approaches 1.0 (see Fig. 2)). Reversible deposition always yields an equilibrium state where part of the particles remains suspended. The choice of a model type for certain practical system depends on the ratio of hydrodynamic to colloidal forces, the ratio of initial number of particles in suspension to those required for the full coverage of the available surface (ψ) and the time period of interest. For example, with ψ close to 1.0 and for relatively short deposition time period all of the above three analyses yield the same deposition curve. However, when the bond strength is very strong (for example with highly opposite charges for the collector and the particles) the irreversible deposition equation provides a good model for such system (see Ref. (8) for experimental case).

The effects of Langmuir model parameters on deposition curves are shown in Figs. 2–4. The ratio ψ is a very important parameter in determining the deposition behavior. Figure 2 shows that with large values of ψ the deposition curve approaches that of irreversible deposition where a nearly full surface coverage can be obtained (for the case shown in Fig. 2 with $K = 5$, a final surface coverage of 0.98 is obtained when $\psi = 2$). The deposition rate increases

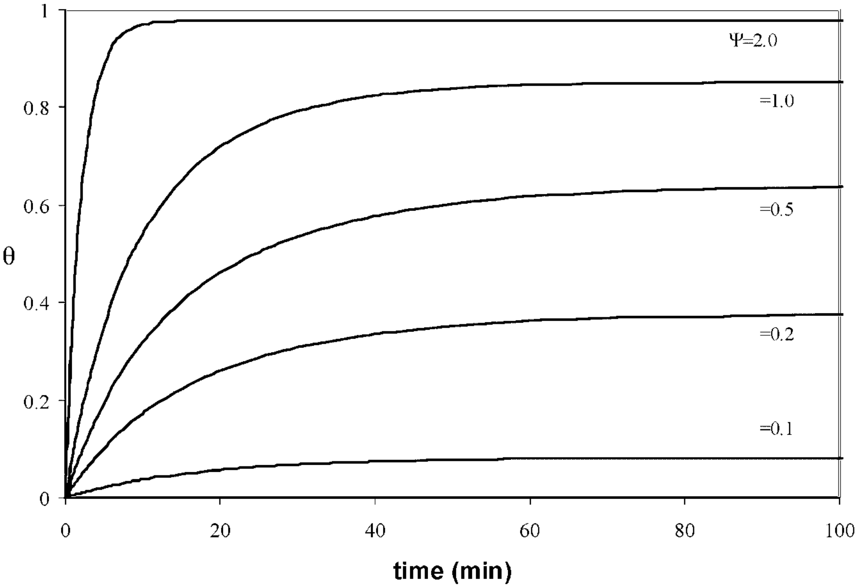

Figure 2. Effect of ψ on Langmuir deposition curves for the case where $k_1' = 0.05\ \text{min}^{-1}$ and $k_2 = 0.01\ \text{min}^{-1}$.

considerably with increasing ψ since the forward deposition rate is directly proportional to ψ.

Figure 3 shows the effect of the forward deposition coefficient ($k_1^{'}$) on deposition curves for the case of $\psi = 0.5$ and $k_2 = 0.01\,\text{min}^{-1}$. Increasing $k_1^{'}$ increases the deposition rate as well as the final surface coverage since the forward deposition rate increases. The value of $k_1^{'}$ can be increased by increasing the deposition efficiency (α), which is dependent on the ratio of hydrodynamic to colloidal forces. In practice, the value of $k_1^{'}$ can be increased by increasing the size or the number of the collectors. The effect of the backward deposition coefficient k_2 is shown in Fig. 4 for the case of $k_1^{'} = 0.05\,\text{min}^{-1}$ and $\psi = 0.5$. Deposition rate and final surface coverage increase with decreasing k_2. To improve deposition by decreasing k_2, the operating conditions should be manipulated (chemically) for strong particle-collector bonding.

However, these deposition curves provide a useful base for rapid understanding of the deposition behavior for certain practical system and they help in planning and choosing experimental conditions for examining new particle deposition systems. For example, for systems of very slow deposition,

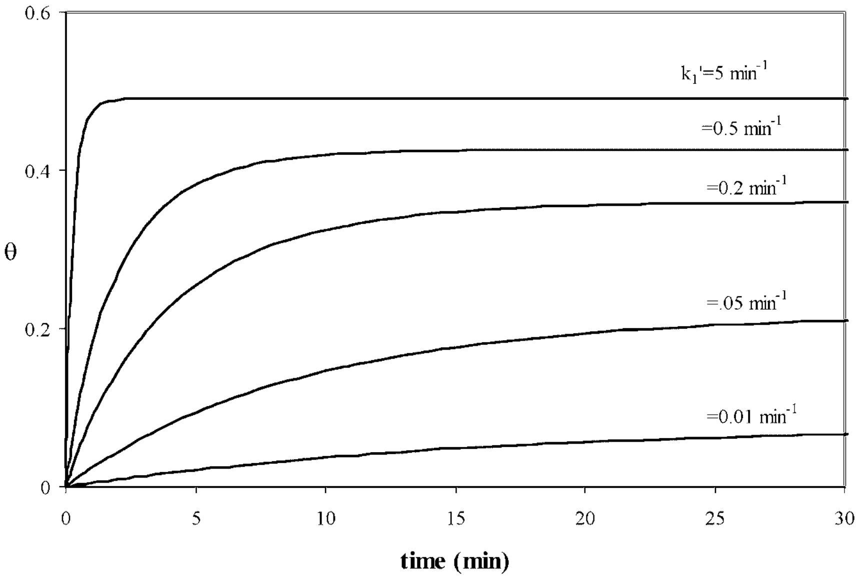

Figure 3. Effect of forward deposition coefficient, $k_1^{'}$ on Langmuir deposition curves for the case where $\psi = 0.5$ and $k_2 = 0.01\,\text{min}^{-1}$.

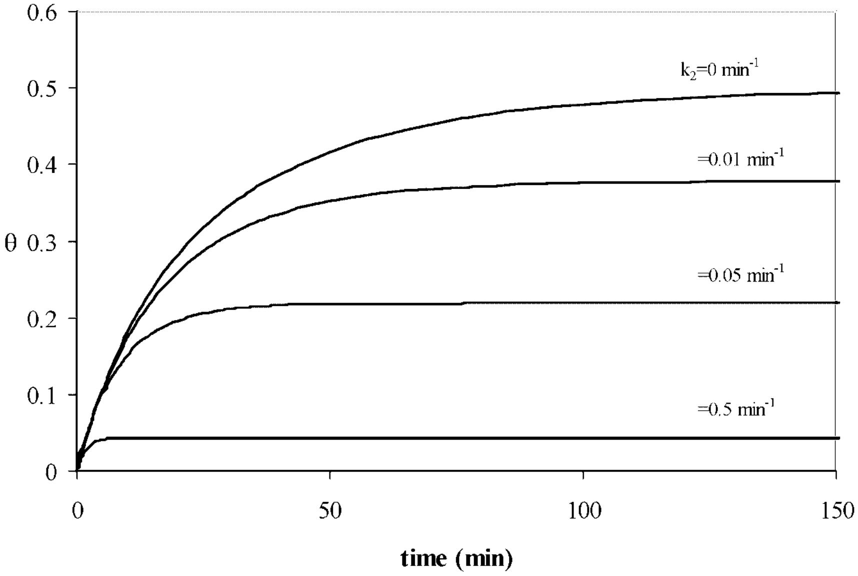

Figure 4. Effect of detachment coefficient k_2 on Langmuir deposition curves for the case where $k_1^{'} = 0.05\,\mathrm{min}^{-1}$ and $\psi = 0.5$.

high initial particle concentration ($\psi > 1$) can be tried in order to shorten the required deposition time.

Mode Comparison with Experimental Results

The kinetics of deposition of carbon particles on plastic particles was investigated experimentally under different initial concentrations of carbon particles for the same plastic particle concentration (i.e., the same vale of $N_{\mathrm{d\,max}}$). Figure 5 shows a typical experimental deposition curve (n vs. t) obtained with initial carbon concentration of 0.3 g/L. The measured dimensionless number of carbon particles in suspension (n) is given as points with error bars indicating the reproducibility of these data (the error bars are smaller than the circles showing the data points, hence they cannot be seen). These experimental data are fitted to Langmuir model using Eq. (14) together with Eq. (8) for the best values of model parameters. The obtained value of ψ from such fit was used to estimate the experimental fractional surface coverage (θ) for each data point using Eq. (19) and plotted on the same figure (curve θ vs. t). This figure portrays that the dimensionless number of carbon particles decreases continuously with time

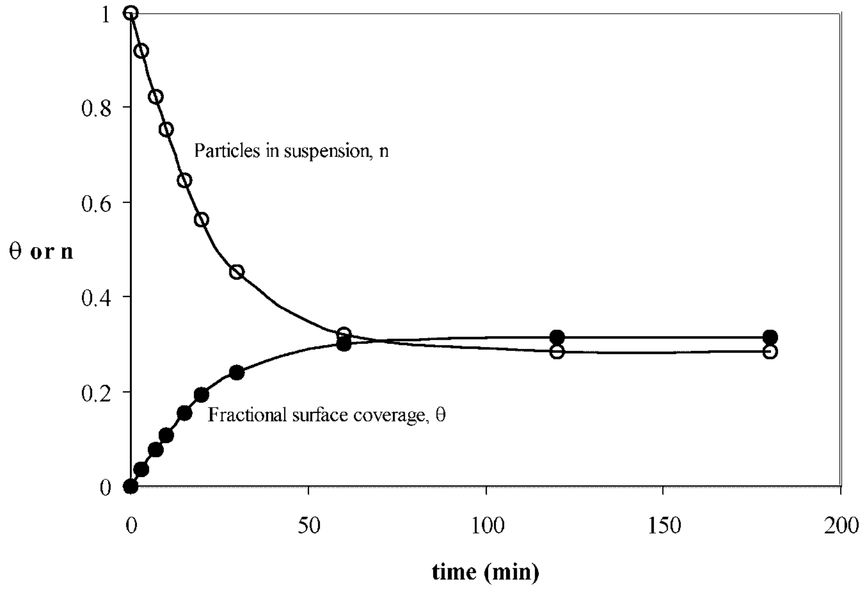

Figure 5. Typical carbon deposition curve showing the measured values of *n* vs. *t* curve (open circles) and the calculated θ vs. *t* (black circles) for the case where the initial carbon concentration = 0.3 g/L.

(while the surface coverage increases) as a result of deposition until a steady state condition (equilibrium) is reached where the net deposition rate approaches zero. This general deposition behavior is similar to other experimental results with reversible deposition obtained by previous investigators for different deposition systems in stirred vessels (6,11). Initially, the deposition rate is high since the

Table 1. The Forward Deposition Coefficient Determined from Smoluchowski's Limiting Case (Initial Deposition Stages)

Initial Carbon Concentration (g/L)	k_1'
0.25	0.032
0.3	0.029
0.4	0.065
0.5	0.032

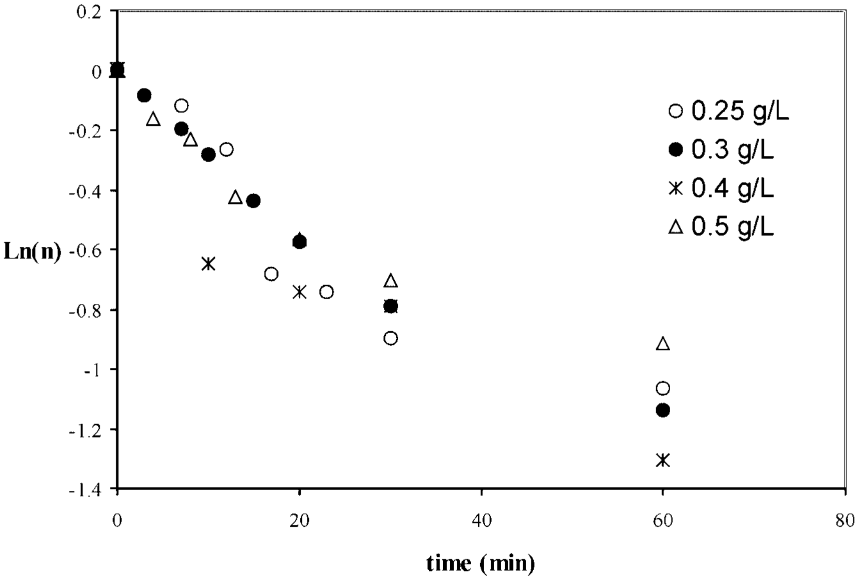

Figure 6. ln(n) vs. t for experiments with different initial carbon concentrations of 0.25 g/L (open circles), 0.3 g/L (black circles), 0.4 g/L (*), and 0.5 g/L (triangles).

whole surface of the plastic particles is available for deposition and according to Smoluchowski, the collision frequency is proportional to the number of suspended carbon particles. As the deposition proceeds, the number of suspended carbon particles and the available deposition area decrease resulting in a decrease in the forward deposition rate as well as an increase in the backward rate, i.e. a net decrease in the deposition rate, until it vanishes. The final surface coverage (θ) is less than ψ (0.441) indicating that reversible deposition is encountered.

A plot of ln(n) vs. time for the initial deposition period is shown in Fig. 6. The slope for each experimental case of initial carbon concentration was determined for the initial linear period which gave k_1'. The determined value of the forward deposition coefficient (k_1') from the slopes in Fig. 6 are tabulated in Table 1. Generally these values do not show dependency on the initial carbon concentration except for the case where the initial carbon concentration is 0.4 g/L. The reason for this is due to the lack of data points at low deposition time.

Figure 7 shows a plot of $1/N_{\mathrm{d,eq}}$ vs. $1/N_{\mathrm{eq}}$. The equilibrium constant (K) and the maximum number of carbon particles ($N_{\mathrm{d\,max}}$) were estimated from the slope and the intercept with the vertical axis, respectively, as provided by Eq. (22). The obtained values of K and $N_{\mathrm{d\,max}}$ are 3.1 and 1.24×10^7, respectively. These estimates of k_1', K, and $N_{\mathrm{d\,max}}$ were given as initial guess for best fitting each of

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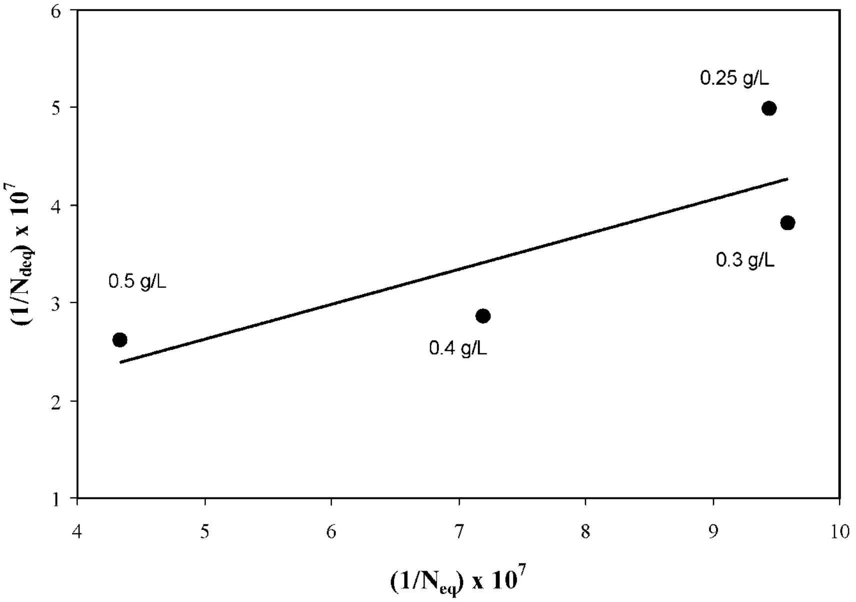

Figure 7. $1/N_{d,eq}$ vs. $1/N_{eq}$ where the slope and the intercept are equal to $1/K$ and $1/N_{d\,max}$, respectively.

deposition curve for the model according to Eq. (14). The estimated fitting parameters are tabulated in Table 2. The obtained value of ψ was used to calculate the fractional surface coverage (θ). The results are shown in Fig. 8 for different initial carbon concentrations. The points represent the experimental surface coverage while the solid curves represent model fit

According to the model, $k_1^{'}$, k_2, and $N_{d\,max}$ are independent of carbon concentration which is obvious in Table 2 for the experimental results within

Table 2. The Model Parameters Determined from the Best Fit of Experimental Deposition Curves to Langmuir Model

Initial Carbon Concentration (g/L)	$k_1^{'}$	k_2	K	ψ	$N_{d\,max} \times 10^6$
0.25	0.036	0.012	3.05	0.43	9.6
0.3	0.036	0.010	3.7	0.44	11.26
0.4	0.088	0.009	9.95	0.99	5.95
0.5	0.041	0.011	3.6	0.86	9.58

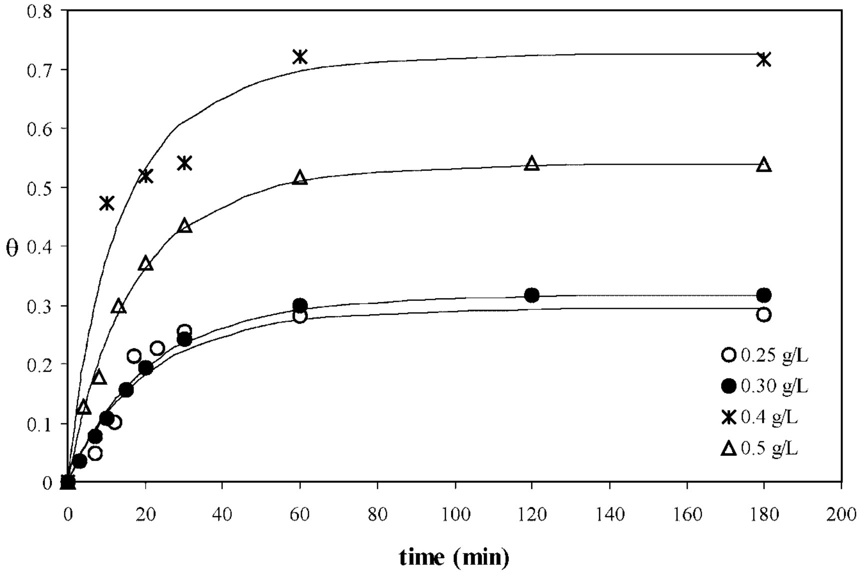

Figure 8. Experimental deposition curve (θ vs. t) for different initial carbon concentrations (data points) fitted to Langmuir model (solid lines).

experimental error. On the other hand, the value ψ is indeed dependent on initial carbon concentration (from its definition in Eq. (12)). The obtained values of ψ increased with increasing initial carbon concentration as expected. It is interesting to note that the experimental trend in Fig. 8 is in agreement with the theoretical trend in Fig. 2 since both are obtained by changing the values of ψ.

It is clear that the estimated model parameters from model limiting cases are very close to the average values in Table 2. This confirms the applicability of the simplified method for parameter estimation. The estimated value of $N_{d\,max}$ from geometrical calculation is 1.8×10^7 particle/unit volume. This is calculated assuming that, the carbon and the plastic particles are perfect spheres. This is in excellent agreement with the values presented in Table 2 or estimated from Fig. 7 (1.2×10^7 particle/unit volume). Note that the geometrical calculations of $N_{d\,max}$ are based on the assumption that voids do not exist between carbon particles on the surface of plastic spheres which is really impossible. Therefore the actual number should be less and hence the agreement is even better.

CONCLUSIONS

As a potential alternative de-inking method, carbon particles can be collected by plastic particles through a deposition process that follows Langmuir kinetics. Langmuir parameters can be estimated easily from the model limiting cases (Smoluchowski analysis and equilibrium line). The estimated model parameters from the experimental curves are in agreement with the expected ones.

NOMENCLATURE

Roman Alphabet

a_p	Surface area of plastic particles available for deposition per unit particle volume
A	Parameter defined by Eq. (16)
B	Parameter defined by Eq. (17)
E	Bond strength between deposited particle and collector surface
G	Shear rate
k_1	Forward deposition rate constant
$k_1^{'}$	Volumetric forward deposition rate constant defined by Eq. (13)
k_2	Detachment rate constant
k_2^0	A constant that is dependent on shear rate
k_s	Smoluchowski's collision rate constant
K	The ratio of the forward deposition rate constant to the detachment rate constant (equilibrium constant)
n	Dimensionless number of small particles in suspension (non-dimensionalized with respect to N_0)
n_c	Number of collectors per unit volume
n_d	Dimensionless number of deposited carbon particles (non-dimensionlized with respect to N_0)
N	Number of suspended small particles per unit volume of suspension
$\bar{N}_d$	Number of deposited small particles per unit surface area of collector
N_d	Number of deposited particles per unit volume of suspension
$\bar{N}_{d\,max}$	The maximum number of particles that can deposit per unit surface area of the collector
$N_{d\,max}$	The maximum number of particles that can deposit per unit volume of suspension
N_0	The initial number of small particles per unit volume
R	Gas constant
t	Time
T	Temperature

Greek Letters

α	Deposition efficiency
ϵ	Volume fraction of liquid in suspension
λ	Parameter defined by Eq. (15)
ψ	Ratio of initial number of small particles in the suspension to the maximum number that can be deposited on the surface as defined by Eq. (11)
θ	Fractional surface coverage (the ratio of deposited small particles to the maximum number of particles that can be deposited, both expressed in the same units)

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