Modelling the effect of shear history on activated sludge flocculation

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Abstract The aim of this paper is to investigate the effect of shear history on activated sludge flocculation dynamics and to model the observed relationships using population balances. Activated sludge flocs are exposed to dramatic changes in the shear rate within the treatment process, as they pass through localised high and low mixing intensities within the aeration basin and are cycled through the different unit operations of the treatment process. We will show that shear history is a key factor in determining floc size, and that the floc size varies irreversibly with changes in shear rate. A population balance model of the flocculation process is also introduced and evaluated.

Keywords Activated sludge flocs; aggregation; breakage; population balances; shear history

Introduction

The activated sludge process is a common and popular aerobic method for biologically treating wastewater. The bacteria exist in the system as aggregates called flocs. Poor or no flocculation may result in the failure of activated sludge to settle, which then leads to excess solids exiting the treatment process with the treated effluent. This is undesirable for two reasons. Firstly, environmental fines may be incurred due to excess solids in the effluent and secondly active biomass, which is used to degrade the wastewater, is lost from the process. Therefore the formation of flocs is crucial to the overall process operation and efficiency.

Despite the importance of this area of research, the mechanisms of flocculation are still largely qualitative and poorly understood. This is largely because of an inability to directly measure flocculation and the existence of no suitable modelling framework.

In the wastewater industry settling and indeed flocculation has been previously studied using indirect methods such as bulk settling characteristics. Biggs and Lant (2000) developed an experimental technique to directly measure the mechanisms of activated sludge flocculation. Even though activated sludge is a heterogeneous biological system, the dynamics of flocculation were found to follow the principles of inorganic shear induced flocculation. Aggregation and breakage were found to be the key mechanisms during the flocculation process with an increase in shear rate resulting in a decrease in floc size.

However, within the treatment process, the flocs may be exposed to dramatic changes in the shear rate. This is possible as the flocs pass through localised high and low mixing intensities within the aeration basin and are cycled through the different unit operations of the treatment process. Spicer *et al*. (1998) found that shear history is significant in determining floc characteristics where periods of cycled shear resulted in larger flocs than tapered or constant shear flocculation. Therefore, it is possible that the history of shear experienced by the activated sludge flocs may have an influence on the overall flocculation dynamics and floc properties.

Activated sludge flocculation has been successfully described using population balances (Biggs and Lant, 2001). A population balance is a statement of continuity that relates the particle size distribution to underlying rate processes and is often used to describe shear induced inorganic flocculation. It provides a tool to express the rate of change of the number of particles of a given size within a given system at a given time and can be used to relate the particle size distribution, system kinetics, vessel properties and material flows.

The specific aims of this paper, therefore, are to determine the effect of shear history on activated sludge flocculation and to describe the response using population balances.

Modelling theory

For activated sludge flocculation it is assumed that aggregation and breakage are the only mechanisms involved. This is a reasonable assumption as no substrate or aeration is supplied during the experiments.

The discretised population balance developed by Hounslow *et al*. (1988) and Spicer and Pratsinis (1996) is used to model the rate of change of the number of particles of a given size during activated sludge flocculation. The basis for the discretisation is a geometric series for the particle volume where $v_{i+1} = 2v_i$

The rate of change of the number of particles in each size class is described by:

$$\frac{dN_i}{dt} = \sum_{j=1}^{i-2} 2^{j-i+1} \alpha\beta_{i-1,j} N_{i-1} N_j + \frac{1}{2}\alpha\beta_{i-1,i-1} N_{i-1} N_{i-1} - N_i \sum_{j=1}^{i-1} 2^{j-1} \alpha\beta_{i,j} N_j - N_i \sum_{j=i}^{\text{imax}} \alpha\beta_{i,j} N_j - S_i N_i + \sum_{j=i}^{\text{imax}} \Gamma_{i,j} S_j N_j \qquad (1)$$

where N_i (#/cm^3) is the number concentration of flocs of size i, α is the collision efficiency and β_{ij} (cm^3/s) is the collision frequency for particles of volume v_i (cm^3) and v_k (cm^3). S_i (s^{-1}) is the fragmentation rate of flocs of size i and $\Gamma_{i,j}$ is the breakage distribution function, which defines the volume fraction of the fragments of size i produced from j sized flocs. In this case it is assumed that binary breakage occurs and therefore $\Gamma_{i,j} = v_i/v_j$ for $j = I+1$ and 0 for all other cases.

For shear induced flocculation, Koh *et al*. (1987), Spicer and Pratsinis (1996) and Ducoste and Clark (1998) described the collision frequency, $\beta_{i,j}$, in terms of the volume of the particles in each size class as well as the average velocity gradient (G) in the system, such that:

$$\beta_{i,j} = 0.31G\left(v_i^{1/3} + v_j^{1/3}\right)^3 \qquad (2)$$

G is determined by:

$$G = \left(\frac{\varepsilon}{\nu}\right)^{\frac{1}{2}} \qquad (3)$$

where ν is the kinematic viscosity (10^{-6} m^2/s) and ε is the average turbulent energy dissipation rate:

$$\varepsilon = \left(\frac{P_0 N^3 D^5}{V}\right) \qquad (4)$$

where P_0 is the impeller power number, N is the impeller speed, D is the impeller diameter (30 mm) and V is the tank volume (1.2 L). P_0 was obtained for individual impeller types using power curves from Holland and Chapman (1966).

The collision efficiency, a, is introduced into the population balance model to incorporate the collision retardation effects of the viscous fluid layer that exists between particles (Flesch *et al.*, 1999). If the primary particle suspension is completely destabilised and every collision is a success then $\alpha = 1$.

The fragmentation rate, S_i is given as a function of the particle volume (Spicer and Pratsinis, 1996; Serra and Casamitjana, 1998):

$$S_i = Av_i^a \quad (5)$$

where $a = 1/3$ and is consistent with the theoretical expectation that the breakage rate is proportional to the floc diameter. A ($cm^{-3}s^{-1}$) is the breakage rate coefficient and is determined by fitting the model to experimental data.

Materials and methods

Wastewater collection

For all experiments, activated sludge was collected from a full-scale continuous biological nutrient removal wastewater treatment plant at Wacol, Brisbane, Australia. Grab samples of effluent were also collected. After collection, the samples were returned to the laboratory (within 1 hour) and stored at 4°C. All samples were kept for a maximum of four days.

Flocculation experiments

The procedure for a standard flocculation experiment is given in detail in Biggs and Lant (2000). The main steps are summarised here.

Step 1: Sonicate activated sludge. For inorganic systems, flocculation is generally measured as an increase in floc size over time from primary particles (Spicer and Pratsinis, 1996). In the case of activated sludge, bacteria could be considered as the primary particles, but flocs collected from a full-scale wastewater treatment plant are already flocculated. So it is necessary to disrupt the flocs and then the "reflocculation" of the disturbed flocs can be investigated in a controlled environment. The disruption of the activated sludge was achieved via sonication using a Branson 450 sonifier. The sonication protocol for the flocculation experiment involved placing 100 mL of activated sludge in an iced water bath and sonicating for 3 minutes at an output level of 50 W. This was found to produce consistently small flocs, but not individual bacteria, without causing significant cell lysis (Biggs and Lant, 2000).

Step 2: Add 60 mL of activated sludge with 1.135 L of filtered effluent (0.45 μm Millipore filters) to a 1.2 L baffled batch vessel and mix with a flat six blade impeller. The ratio of sonicated sludge to effluent was chosen for optimal sizing conditions in the Malvern Mastersizer/E.

Step 3: Recycle the sample through the sample cell of the Malvern Mastersizer/E. This light scattering instrument was used to measure the floc size and operates on the principle of Fraunhofer diffraction theory. The size distribution is based on volume and the average size is quoted as the mass mean (D[4,3]) based on volume equivalent diameter.

Step 4: Measure the floc size online.

Results and discussion

Experiments were conducted to monitor activated sludge flocculation and investigate the effect of shear history on the flocculation dynamics. The suitability of the population balance model to describe the effect of shear history on the flocculation dynamics is also presented and discussed.

To determine the effect of shear history on activated sludge flocculation, step changes in the shear rate were conducted. For each experiment, activated sludge was flocculated at $G = 19.4\ s^{-1}$ until the fast dynamics of aggregation and breakage were complete. For the first experiment (E1), after 85 minutes, the shear rate was increased to $G = 113\ s^{-1}$. This value was maintained for 35 minutes, after which the shear rate was returned to the original value of $G = 19.4\ s^{-1}$. For the second experiment (E2), two consecutive step changes were performed cycling between values of $G = 19.4\ s^{-1}$ to $113\ s^{-1}$. The results of the two experiments can be seen as a change in floc size with time in Figure 1.

The flocculation dynamics are similar to those found by Spicer and Pratsinis (1996) and Serra and Casamitjana (1998) for inorganic systems flocculating under shear. During the initial stages of the experiment, the floc size increases rapidly as aggregation is dominant. It is interesting to note that flocculation occurs even though no flocculating agent has been added to the system. Flocculation occurs due to the presence of polymeric material excreted by the bacteria and cations in the activated sludge.

Changing the average velocity gradient during the flocculation experiment confirms that aggregation and breakage are key mechanisms of activated sludge flocculation as found by Biggs and Lant (2000). From Figure 1, it can be seen that for each experiment, once the average velocity gradient is increased the floc size decreases. At this stage the rate of breakage is greater than the rate of aggregation. The final floc size at $G = 113\ s^{-1}$ is less than the final floc size obtained at $G = 19.4\ s^{-1}$ for both E1 and E2. If breakage was not a key mechanism then the increase in average velocity gradient would not have reduced the floc size.

For each experiment, when the average velocity gradient is decreased from $G = 113\ s^{-1}$ to $G = 19.4\ s^{-1}$, the rate of aggregation exceeds the rate of breakage and the floc size increases. For each experiment, the final floc size, after the average velocity gradient has returned to the original value of $G = 19.4\ s^{-1}$, is less than the final floc size before the average velocity gradient was increased. This suggests that the floc size is dependent on the history of shear as well as the intensity. This change in final floc size after the original average velocity gradient is re-applied is also illustrated in Figure 2, where the volume density distributions at 85, 120 and 180 minutes, for E1 are presented.

Even though the average velocity gradient at 85 and 180 minutes for E1 is the same ($G = 19.4\ s^{-1}$), comparison of the volume distributions illustrates the shift in volume distribution into smaller floc sizes after the original average velocity gradient is re-applied

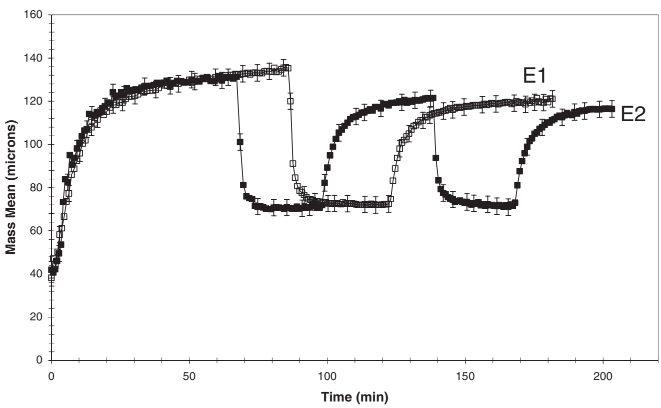

Figure 1 Effect of step change in shear rate on floc size

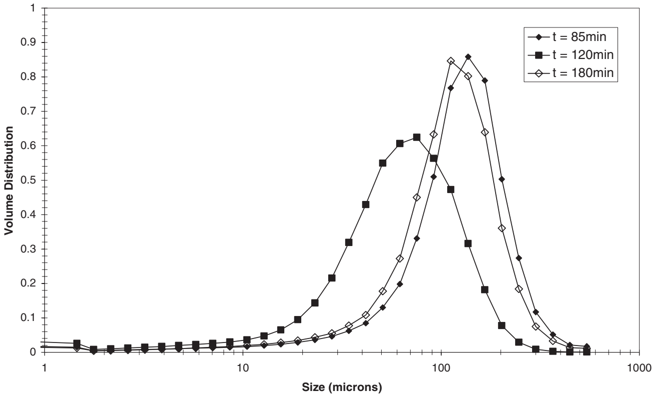

Figure 2 Volume density distributions for step change in average velocity gradient (E1)

(Figure 2). This shift in volume distribution is responsible for the difference in final floc sizes observed in Figure 1.

The observed experimental behaviour of the effect of step changes in shear on flocculation dynamics has been described as either reversible or irreversible (Spicer *et al.*, 1998). If the floc size returns to the same value when the original shear is applied, the flocculation dynamics are thought to be reversible. This is characteristic of systems flocculated by ionic salts as van der Waals forces responsible for flocculation are not affected by the breakage and regrowth mechanisms that occur during the step change (Kusters, 1991; Spicer *et al.*, 1998).

If the final floc size does not return to the same value when the original shear is applied the flocculation dynamics exhibit irreversible behaviour. Irreversible behaviour, as seen in Figure 1, is characteristic of systems flocculated with polymers or precipitated solids (Spicer *et al.*, 1998). At the higher average velocity gradient, particle-flocculant bonds are broken resulting in fragmentation of the flocs and a reduction in floc size.

A similar irreversible behaviour was observed by Leu and Ghosh (1988), for the flocculation of clay particles with a polyelectrolyte. In this case flocs reformed after intense fragmentation but did not return to their original steady state floc size. The smaller floc size was attributed to the detachment of polymer chains from the kaolin particles resulting in a reduction in the collision efficiency. Hence breakage of the bonds during fragmentation reduces the efficiency of subsequent aggregation as the polymer bonds are not able to reform to the same extent (Spicer *et al.*, 1998). This results in the reduction in final floc size once the original shear has been re-applied as illustrated in Figure 1.

Population balances have been used to successfully model the flocculation of inorganic particulate systems. Since the experimental observations of activated sludge flocculation are comparable to inorganic particulate systems it was proposed that population balances would be suitable to describe activated sludge flocculation. The discretised model, Eq. (1) with the algebraic equations Eq. (2)–(5), was solved numerically using the ordinary differential equation solver in MATLAB^{T}. To ensure that the full size range of the experimental data from the Malvern (1–600 μm) was represented in the population balance, 28 size classes were used (ie $i_{max} = 28$). The initial number concentration for the model was obtained by a transformation of the data received from the Malvern Mastersizer/E from a volume distribution to a number distribution.

Biggs and Lant (2001) performed parameter estimation to determine the "best fit" values of α (Eq. (1)) and A (Eq. (5)) for varying values of G by minimising the sum of squared errors between the model and experimental results for the change in mass mean ($D[4,3]$) with time. These values were then used to predict the change in mean size during step

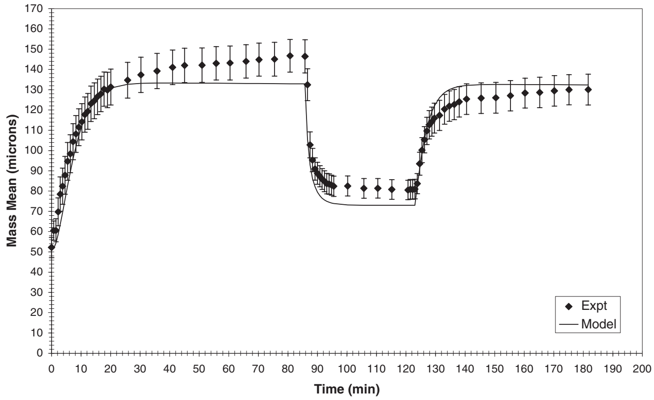

Figure 3 Comparison between experimental and simulated results for step change in shear rate

changes in shear. Preliminary simulations of the change in mass mean with time for experiment E1 as predicted by the population balance model can be seen in Figure 3.

From Figure 3, it can be seen that the model follows the trend in the floc size during the step change in shear rate. The model provides a good approximation of the initial flocculation period and the flocculation period after the shear rate is returned to its original value. However, a discrepancy between the model and experimental results can be seen when predicting the re-growth behaviour after the change in shear rate. The model predicts reversible behaviour, that is, the floc size is the same before and after the increase in average velocity gradient, while the experimental results indicate that activated sludge flocculation is irreversible. This suggests that the population balance model does not accurately describe the mechanisms that are occurring during the regrowth stage after a step change in shear rate. Spicer *et al.* (1998) found that as well as exhibiting irreversible behaviour, the structure of their inorganic particles changed during step changes in the average velocity gradient. Decreasing the average velocity gradient to its original value after an increase in the average velocity gradient resulted in an increase in the fractal dimension (Spicer *et al.*, 1998). This suggests that the aggregates became denser due to the mixing regime.

As structure is not included in the present population balance model this could account for the discrepancy between the model and experimental observations. Recent advances in population balance modelling have accounted for changes in the structure of the aggregates by addition of the fractal dimension in the aggregation rate expression (Flesch *et al.*, 1999). Therefore future work will be focussed towards developing a suitable method to monitor the change in structure on-line during flocculation and to incorporate this into the model.

Conclusions

The aim of this paper was to investigate the effect of shear history on activated sludge flocculation dynamics and to model the observed relationships using population balances.

Using a technique developed to monitor the flocculation dynamics online it was discovered that step changes in the shear rate caused dramatic changes to the floc mean size. Increasing the shear rate resulted in decrease in mean size as rate of breakage exceeded the rate of aggregation. Conversely the mean size increased with a decrease in shear rate as the rate of aggregation exceeded the rate of breakage.

The step change in shear rate also gave insight into the re-growth behaviour of activated sludge flocs. An irreversible re-growth behaviour was observed when the original shear rate was applied. This is characteristic of systems flocculated with polymers.

Population balances were used to describe the change in floc mean size with a step change in shear. Good approximation was found for the initial flocculation period and the flocculation period after the shear rate was returned to its original value. However, the model predicted reversible rather than irreversible re-growth behaviour. This suggests that the kinetics currently used in the population balance model to describe activated sludge flocculation is not entirely suitable and hence this will be the focus of future work.

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