SLUDGE (DE)FLOCCULATION DYNAMICS IN SECONDARY CLARIFIERS

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INTRODUCTION

During the biological treatment of wastewater the waste is biodegraded by micro-organisms. This is one of the principal goals. A probably even more crucial unit process is the clarification. Indeed, clarifying the “purified” water is necessary to remove the particulate fraction in which the micro-organisms reside. According to Wanner (1994) the washout of sludge contributes to 50 to 80% of the effluent BOD. This stresses the importance of the clarifier.
The efficiency of sludge sedimentation depends on several factors. Of course, the hydrodynamics are essential, but also the biology plays a considerable role. Settling of sludge flocs is dependent on the combination of porosity and size of the flocs. Depending on the operational circumstances in the clarifier the floc size distribution changes along the length of the unit because of flocculation and deflocculation processes. In that way, shear rate, pH, ion strength and zeta potential are very important variables, but one should not underestimate the relevance of biological factors. Hence, not considering effects of oxygen concentration, load and residence time in (de)flocculation studies would be a huge mistake.

From a literature review it is clear that (de)flocculation is a problematic issue due to many interacting influences. Past studies have typically only focussed at a specific variable without taking into account the others. As far as known, no holistic study has ever been done about the interrelation between the different variables. Nevertheless, this is essential since the clarifier imposes changing environmental conditions on the floc’s trajectory.

The goal of this FWO-V (Fund for Scientific Research - Flanders) project is an as accurate as possible modelling of the secondary clarifier behaviour. This demands for a combination of different modelling techniques:

- Population Balance Modelling (PBM), to simulate the (de)flocculation dynamics,
- Computational Fluid Dynamics (CFD), to simulate the hydrodynamics.

In order to model (de)flocculation in an appropriate manner, experiments are set up to study the influence of different environmental conditions imposed to the sludge. From these, several PBM parameters are to be estimated.

EXPERIMENTAL SETUP

As mentioned previously, experiments have to be carried out to obtain the parameters in the PBM. Also, some characteristics of the sludge mixture have to be known to model the hydrodynamics, e.g. the sludge settling velocity and viscosity.
In order to relate the data of the different experiments it is necessary to eliminate as much as possible the variance originating from the biological changes in the microbial population. Hence, a kind of standardized sludge is pursued. A Sequential Batch Reactor (SBR) will be set up to breed sludge. After each process cycle of 3 hours the sludge is allowed to settle. Part of this excess sludge can be drained and used in (de)flocculation experiments.
The thickened sludge is brought into a second reactor, the test vessel. The latter has a volume of 5L, is double-walled and heated/cooled to the desired temperature. The sludge will be diluted on-line with filtered effluent to obtain the appropriate sludge concentration. The vessel is especially equipped to impose different environmental conditions. To introduce shear stresses a mixer with torquemeter is present. The mixing blade is a grid-like blade to obtain a homogeneous turbulence in the vessel. To avoid any momentum introduced by air bubbles, a perfusion-based oxygenation system is preferred. Since substrate is used by the micro-

organisms during the experiment, it has to be added to maintain a constant operational load. This becomes complicated due to the continuous sludge removal at the bottom. Indeed, the aim is to study the (de)flocculation dynamics. Consequently, sludge is discharged from the test vessel to measure the floc size distribution with a Malvern Mastersizer (Malvern Instruments Ltd., distributed by Meyvis, Bergen-op-Zoom). The measuring principle of this advanced particle sizer is based on light scattering. Remaining sludge is used off-line to determine the zeta potential, viscosity and settling velocity. Figure 1 gives a general view on the experimental setup.

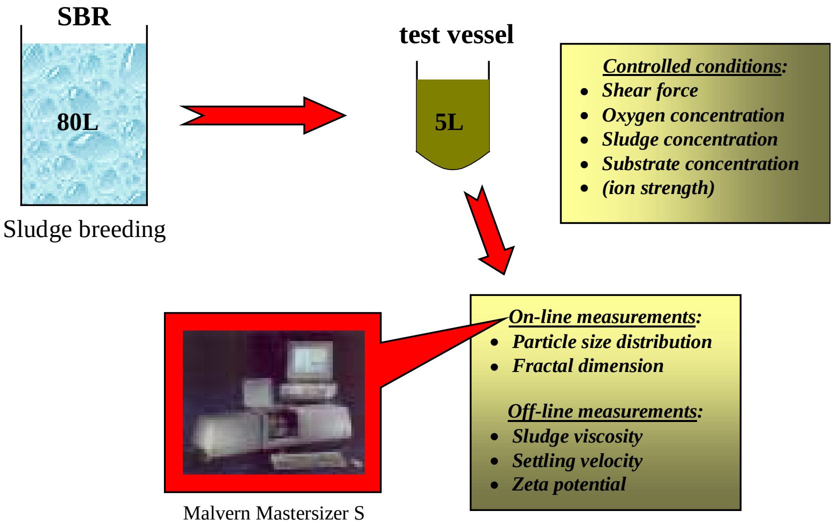


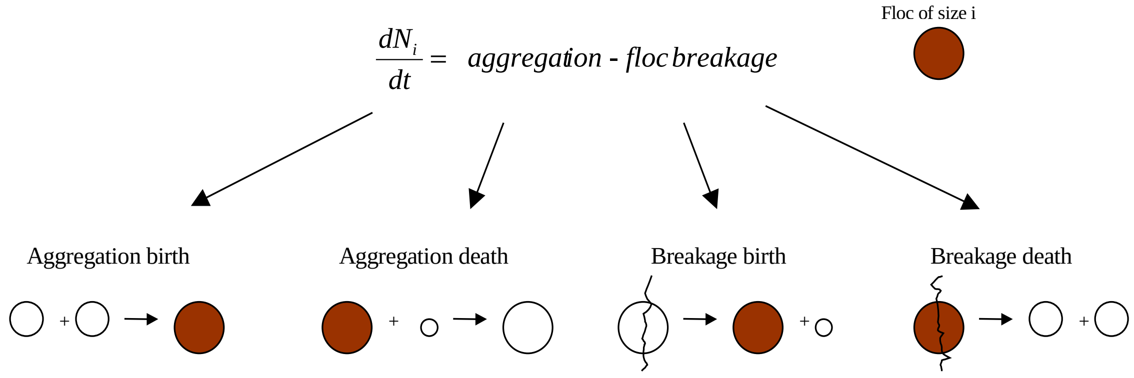
Figure 1. Experimental layout

MODELLING ASPECTS

As mentioned before, two modelling approaches are combined to come to a complete description of the secondary clarifier. The first, the population balance model, is extremely appropriate to describe the (de)flocculation dynamics. The second, the computational fluid dynamics model, is complementary to the first. Both are related to and depend on each other. The two models are described more in detail in the following paragraphs.

POPULATION BALANCE MODELLING

The art of PBM has its origin in demographics and can lean on several successful applications in chemical and bio-engineering. As already mentioned, PBM is a methodology to describe the numbers of objects in a certain system. Here, flocs of different size are considered as the objects. A PB takes not only into account transport processes but also internal processes like (de)flocculation are included. It is clear that the latter influences the PB and refers to floc aggregation, breakage and floc growth. These subprocesses are function of floc characteristics (e.g. size and fractal dimension) and environmental conditions (e.g. shear rate, temperature, oxygen concentration, load,…). A lot of research has already been done on this topic (see e.g. Serra and Casamitjana, 1998; Biggs, 2000;…).
The resulting equations are integro-partial differential equations. These equations are extremely difficult to solve. In practice, the solution of a PBM is tackled by discretisation of the distribution into size classes. Figure 2 shows the discretised PBM without any transport terms. In the population balance equation N_i is the number concentration of flocs of size i, α is the collision efficiency and $\beta_{i,j}$ is the collision frequency for particles of volume v_i and v_j. S_i 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.



Birth of floc size i by collision with smaller flocs

$$\frac{dN_i}{dt} = \sum_{i=1}^{i-2} 2^{j-i+1} \alpha\beta_{i-1,j} N_{i-1} N_j + \frac{1}{2}\alpha\beta_{i-1,j-1} N_{i-1}^2$$

Death of floc of size i by collision with any other flocs

$$- N_i \sum_{j=1}^{i-1} 2^{j-1} \alpha\beta_{i,j} N_j - N_i \sum_{j=1}^{i\max} \alpha\beta_{i,j} N_j$$

Birth of floc of size i by breakage of larger flocs

$$+ \sum_{j=1}^{i\max} \Gamma_{i,j} S_j N_j$$

Death of floc size i by breakage of floc of size i

$$- S_i N_i$$

Figure 2. Population balance modelling (from Biggs, 2000)

COMPUTATIONAL FLUID DYNAMICS

Besides the PBM, computational fluid dynamics are essential to model floc transport in the secondary clarifier. To calculate the flow field, the equations for mass (continuity) and momentum conservation have to be solved:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \qquad \mathrm{U, V = velocity\ in\ x, y\ direction}$$

$$\frac{\partial U}{\partial t} + \frac{\partial U^2}{\partial x} + \frac{\partial UV}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\nu_{eff}\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{eff}\frac{\partial U}{\partial y}\right)$$

$$\frac{\partial V}{\partial t} + \frac{\partial UV}{\partial x} + \frac{\partial V^2}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\nu_{eff}\frac{\partial V}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{eff}\frac{\partial V}{\partial y}\right) + g\frac{\rho - \rho_w}{\rho_w}$$

$$\text{mixture density}:\ \rho = \rho_w + \sum_i X_i\left(1 - \frac{\rho_w}{\rho_s}\right)$$

where g is the gravitational acceleration and ν_{eff} is the effective viscosity. X_i is the sludge concentration corresponding to the different size classes i. ρ_w and ρ_s are the densities of water and sludge. The effective viscosity consists of the dynamic viscosity ν and the turbulent viscosity ν_t as can be seen below. The turbulent kinetic energy k and the energy dissipation ε are essential to calculate this turbulent viscosity (c_μ is an empirical constant). They can be modelled in several ways (Rodi, 1984). Here, transport equations for these variables are set up and have to be solved together with the continuity and momentum equations. σ_k, σ_ε, c_1 and c_2 are constants. P_r denotes the energy production by shear and P_g the buoyant production/destruction.

$$\nu_{eff} = \nu + \nu_t \qquad \nu_t = c_\mu \frac{k^2}{\varepsilon}$$

$$\frac{\partial k}{\partial t} + \frac{\partial Uk}{\partial x} + \frac{\partial Vk}{\partial y} = \frac{\partial}{\partial x}\left(\frac{\nu_{eff}}{\sigma_k}\frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_k}\frac{\partial k}{\partial y}\right) + P_r + P_g - \varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial U\varepsilon}{\partial x} + \frac{\partial V\varepsilon}{\partial y} = \frac{\partial}{\partial x}\left(\frac{\nu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right) + c_1\frac{\varepsilon}{k}P_r - c_2\frac{\varepsilon^2}{k}$$

$$P_r = \nu_{eff}\left[2\left(\frac{\partial U}{\partial x}\right)^2 + 2\left(\frac{\partial V}{\partial y}\right)^2 + \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)^2\right]$$

$$P_g = \frac{g}{\rho_w}\frac{\nu_{eff}}{\sigma_c}\frac{\partial(\rho - \rho_w)}{\partial y}$$

In the equations above, only one phase has been considered. The proposed approach here is that wastewater and sludge are modelled as a mixture with the same velocity for all mixture components. To take into account specific transport processes for the sludge, e.g. settling, one can set up so-called scalar transport equations. This equation describes the transport of each floc size class i with the velocity of the mixture (bulk flow), but including floc settling and conversion, i.e. (de)flocculation kinetics.

$$\frac{\partial X_i}{\partial t}+\frac{\partial UX_i}{\partial x}+\frac{\partial\left(V-V_{s,i}\right)X_i}{\partial y}=\frac{\partial}{\partial x}\left(\frac{\nu_{eff}}{\sigma_c}\frac{\partial X_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_c}\frac{\partial X_i}{\partial y}\right)+m_{p,i}r_i$$

where σ_c is the Schmidt number describing turbulent mass transport. $V_{s,i}$ is the settling velocity corresponding to size class i. r_i equals the right-hand side of the PB (Fig. 2) and $m_{p,i}$ is added to convert number concentrations to mass concentrations.

PERSPECTIVES

To demonstrate the possibilities of such a deterministic model a simulation example is shown in Figure 3. The sludge concentration profile in a circular clarifier is calculated. One clearly notices the sludge blanket structure. It should be stressed that this result is obtained without the inclusion of the PBM. The combination of the two modelling techniques should make it possible to model in a more accurate way

- the (de)flocculation dynamics in the clarifier,
- the effluent suspended solids concentration,
- the sludge settling in the clarifier.

This is possible due to the fundamental experiments, resulting in in-depth knowledge about the sludge behaviour under different environmental conditions.

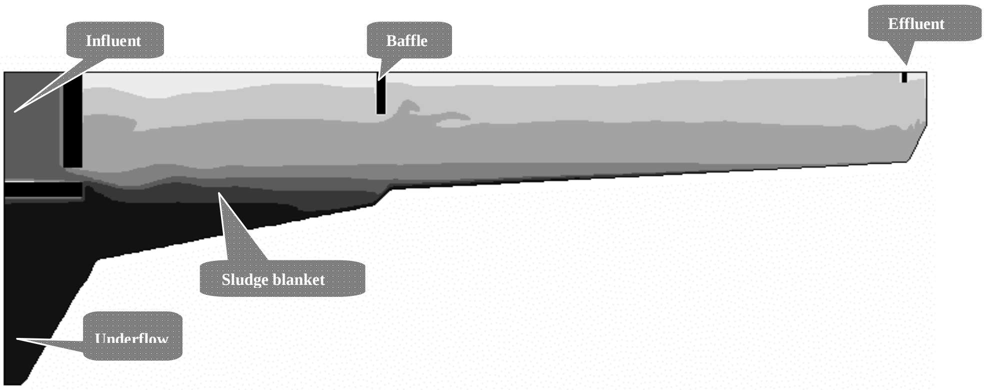


Figure 3. Example of CFD-calculated sludge concentration profile in a circular clarifier (Armbruster et al., 2000)

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