SECONDARY CLARIFIER OPTIMIZATION: TOOLS AND TECHNIQUES

David J. Kinnear, Bob De Clercq, and Peter A. Vanrolleghem
BIOMATH, Ghent University, Belgium

ABSTRACT
This paper reviews available tools and techniques required to optimize activated sludge secondary clarifier performance and capacity. The paper also discusses the benefits and detriments of each method and suggests directions for research to improve their usefulness.

KEYWORDS
activated sludge, secondary clarifiers, performance testing, state point analysis, computational fluid dynamics

INTRODUCTION

The secondary clarifier plays several critical roles in the activated sludge process, including most importantly:

1. Secondary clarifiers frequently serve as the final unit process in a treatment facility; therefore their performance in terms of minimizing effluent pollutants often determines the overall facility effluent quality.
2. The solids flux through the secondary clarifier typically limits the overall capacity of an activated sludge process and therefore the overall capacity of a treatment facility.

Performance and *capacity* define these related, but separate roles and effective secondary clarifier optimization requires treating these issues separately (Kinnear, 2000).

Reducing the cost to treat wastewater requires an improved understanding and optimization of secondary clarifiers and therefore an improved understanding of the complex transport phenomena that occur in secondary clarifiers. Accomplishing this requires application of many specialized tools and techniques developed specifically for wastewater treatment or transferred from other fields. This paper summarizes the tools and techniques applied to the optimization of secondary clarifiers and provides some critical evaluation of their value.

Factors Influencing Performance and Capacity

Successful secondary clarifier evaluations begin by considering factors contributing to performance and capacity. Table 1 summarizes these factors, categorizing them as physical, process/operations, biological solids characteristics, or environmental. The table includes a brief explanation as to how each factor affects performance or capacity. Each of the tools and techniques described below attempts to determine the magnitude of the influence of these factors on the secondary clarifier.

Empirical and Traditional Design Techniques

Prior to the development of mechanistic models, engineers applied empirical techniques to the design of secondary clarifiers. These techniques do not account for all the transport phenomena occurring in a secondary clarifier, but typically provide a conservative design based on pilot experimentation and operational experience.

Table 1. Factors Affecting Secondary Clarifier Performance and Capacity

Category/Factor	Performance	Capacity
Physical		
Clarifier Area	affects hydraulics	determines total settling flux and storage of excess solids
Clarifier Depth	affects hydraulics	storage of excess solids
Clarifier Volume	inlet kinetic energy dissipation	efficient storage of excess solids
Aeration Basin Volume	probably no affect	determines system mass
Inlet Configurations	affects hydraulics	?
Outlet Configurations	affects hydraulics	?
Solids Removal Device	may disturb settled solids	?
Process/Operations		
Influent Flow	affects hydraulics	Influent solids flux
Recycle Flow	affects hydraulics	influent/underflow solids flux
Operations Experience	improves performance	increases capacity
Control System	provides required data	provides required data
Inlet Solids Concentration	density current	influent flux
Solids Temperature	X	hindered/compressive settling
Biological Solids Characteristics		
Flocculation Properties	ability to flocculate	affects settling velocity?
Flocculation State	proper flocculation	probably no affect
Floc Permeability	sludge blanket height?	hindered/compression settling velocity
Compressive Resistance	sludge blanket height?	compression settling velocity/sludge blanket height
Environmental		
Air Temperature	convection currents	?
Inlet Water Temperature	density currents	?
Wind	disrupts hydraulics	probably no affect

These empirical parameters do not consider performance or capacity separately and include parameters such as surface overflow rate, solids loading rate, and weir loading rate. Many engineers still apply these design techniques, while the use of more precise techniques incorporating fundamental processes begins to show promise of improved process optimization.

PERFORMANCE

Flocculation Effects

The ability of biological solids to flocculate due to the natural presence of exocellular enzymes and polymers creates flocs that settle rapidly enough allowing an economically sized clarifier to produce acceptable effluent quality. Parker (1983) reports smaller flocs that remain isolated and do not become incorporated into a larger floc mass report to the effluent instead of reporting to the underflow. These solids comprise a high percentage of the effluent suspended solids (ESS) and thus effluent particulate pollutant concentration.

Flocculation may occur via three mechanisms in secondary clarifiers, although the extent to which each occurs requires further investigation:

1. Orthokinetic (OK) – Floc collisions resulting from fluid velocity gradients within the carrier fluid.
2. Perikinetic (PK) – Floc collisions resulting from Brownian motion of the flocs.
3. Differential Settling (DS) – Floc collisions resulting from rapidly settling flocs overcoming less rapidly settling flocs.

Bioflocculation Modeling

Incorporating the three flocculation mechanisms into mechanistic models of the bioflocculation process that can be utilized for either design or process optimization proves difficult. Thomas, *et al*. (1999) and Lawler (1993) describe some of these challenges which include:

1. Determining the floc collision efficiency (α) remains difficult. The influence of short-range forces and particularly hydrodynamic effects (rectilinear vs. curvilinear models) significantly changes the results of previous studies and indicate that OK flocculation may not play a significant role.
2. If OK flocculation does not play a significant role then models and techniques based on the root mean square velocity gradient (**G**) may not be appropriate. A majority of research and modeling efforts utilize **G** to represent flocculation mixing energy.
3. If OK flocculation does play a role in the flocculation reaction, Kramer and Clark (1997) describe how **G** would not be an appropriate independent variable for modeling collision frequency and discuss how the maximum magnitude of the elements of the diagonalized strain rate tensor (a_{max}) defines OK flocclulation for laminar flow. Very few models presently incorporate a_{max}, however and turbulent conditions under field conditions for which limited understanding exists.
4. Models assume monodispersed spherical particles before and after collisions complicating development of accurate bioflocculation models. Population balance techniques described by Nopens *et al*. (2001) might compensate for these assumptions.
5. Frølund, *et al*. (1996) describe how up to 80% of the biological solids matrix consists not of either spherical or even filamentous bacterial cells, but of exocellular polymeric substances (EPS). No bioflocculation models presently address EPS.
6. Defining floc breakage and developing techniques to independently measure aggregation and breakage remains challenging.
7. Measuring in-situ particulate characteristics of mixed liquor indicating the degree of flocculation in a full-scale system remains difficult. De Clercq, et al. (2002) discuss an initial attempt to measure in-situ particle size distributions using a Lasentec FBRM M500 particle sizer. However, confidence cannot be placed in the results before completing further research.

In addition to the above difficulties, Novak (2003) describes physical characteristics of the activated sludge matrix and various physical environmental factors, such as monovalent to divalent cation ratio and the effects of electophilic chemicals known to influence flocculation, but not yet considered in models.

Dispersed Suspended Solids/Flocculated Suspended Solids Testing

The difficulties expressed above limit the usefulness of bioflocculation models in practical design applications. To overcome these limitations, practical testing techniques utilize full-scale clarifiers to diagnose performance problems. Wahlberg (2002) and Ekama *et al*. (1997) describe these tests in detail. This section describes one such test, the dispersed suspended solids/flocculated suspended solids (DSS/FSS) test, which determines specific causes of inadequate performance.

Conducting the DSS/FSS test requires the collection of three samples, two of which must be collected in a special manner. The FSS sample consists of supernatant from a settled mixed liquor sample following flocculation in a standard 2.0-liter rectangular beaker flocculation apparatus. The FSS sample represents the best performance (lowest effluent suspended solids (ESS)) expected from the secondary clarifier because theoretically ideal flocculation and settling occurred prior to sampling the supernatant.

The DSS sample consists of secondary clarifier effluent collected using a modified Kemmerer sampler at the clarifier effluent weir. Ekama *et al*. (1997) provides details of the modified Kemmerer sampler. Immediately following sample collection, a portion of the initial Kemmerer sampler contents becomes the ESS sample. Following 30 minutes settling in the Kemmerer sampler, of solids that did not settle in the clarifier, the supernatant becomes the DSS sample.

Analyzing these samples for total suspended solids (TSS) permits the ESS to be categorized as follows:

1. Biological Flocculation Problems: (FSS – FSS goal) – Unflocculated solids in the effluent due to biological conditions in the activated sludge system. These solids theoretically lack the surface characteristics to flocculate properly. The FSS goal should be set by conducting many FSS tests to determine some achievable value, but typically greater than 10 mg l^{-1}.
2. Physical Flocculation Problems: (DSS – FSS) – Unflocculated solids in the effluent due to improper flocculation "energy" from either insufficient floc aggregation or excessive floc breakage. Conducting the DSS/FSS test at several locations (besides the effluent weir) permits determination of flocculation/deflocculation locations.
3. Hydraulics Problems: (ESS – DSS) – Flocculated solids in the effluent due to the flow pattern in the clarifier resulting from poor internal design or convection phenomena.

Repeating DSS/FSS tests several times provides improved confidence in the results due to the high variability in clarifier ESS. Analyzing hourly discrete effluent ESS samples improves test results by indicating diurnal patterns and therefore the most appropriate time to conduct the DSS/FSS test. The DSS/FSS test presently offers the most practical method to analyze secondary clarifier performance.

Hydraulic Testing

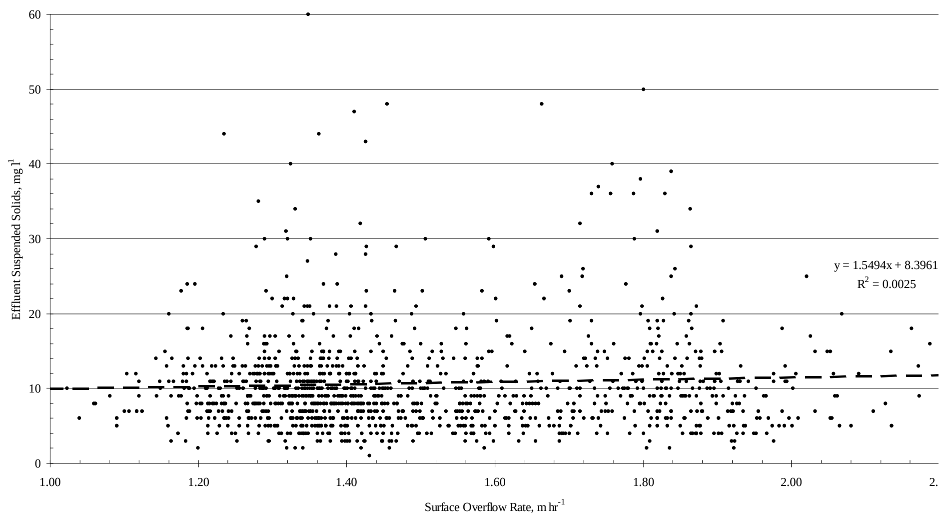
Early research by Anderson (1945) into secondary clarifier performance revealed that hydraulic characteristics of the clarifier basin, as would be expected, impacts clarifier performance. The DSS/FSS test discussed above determines the extent to which hydraulics impact effluent quality. Engineers should only perform hydraulic testing when DSS/FSS testing indicates hydraulic performance problems.

Figure 1 plots ESS against surface overflow rate, a measure of the hydraulic loading on a secondary clarifier, for a medium sized wastewater treatment facility located in the Midwestern United States. The figure demonstrates that hydraulics alone do not determine effluent quality in agreement with the concepts of the DSS/FSS testing described above.

Hydraulic testing includes flow through curve determination via dye testing, velocity profile determinations using drogues, and vertical solids profiles using modified sludge profile samplers. Hydraulic testing provides insight into clarifier performance, but data interpretation often requires subjective interpretation.

Recent developments in hydraulic testing techniques might provide additional insight into secondary clarifier hydraulics. Kinnear and Deines (2001) describe the use of an acoustic Doppler current profiler (ADCP) capable of measuring three-dimensional velocity profiles with a 5 cm spatial resolution, a 1.0 Hz sampling frequency, and an accuracy of 1.0 mm s^{-1}. ADCP techniques permit collection of not only accurate velocity measurements, but also the measurement of turbulence due to the high sampling frequency. Figure 2 presents an ADCP profile for a Western United States secondary clarifier collected during a period of typical hydraulic loading and a low return activated sludge flow rate with the basin scraper mechanisms turned off. The figure presents radial (u), tangential (v) and two measures of vertical velocity (w).

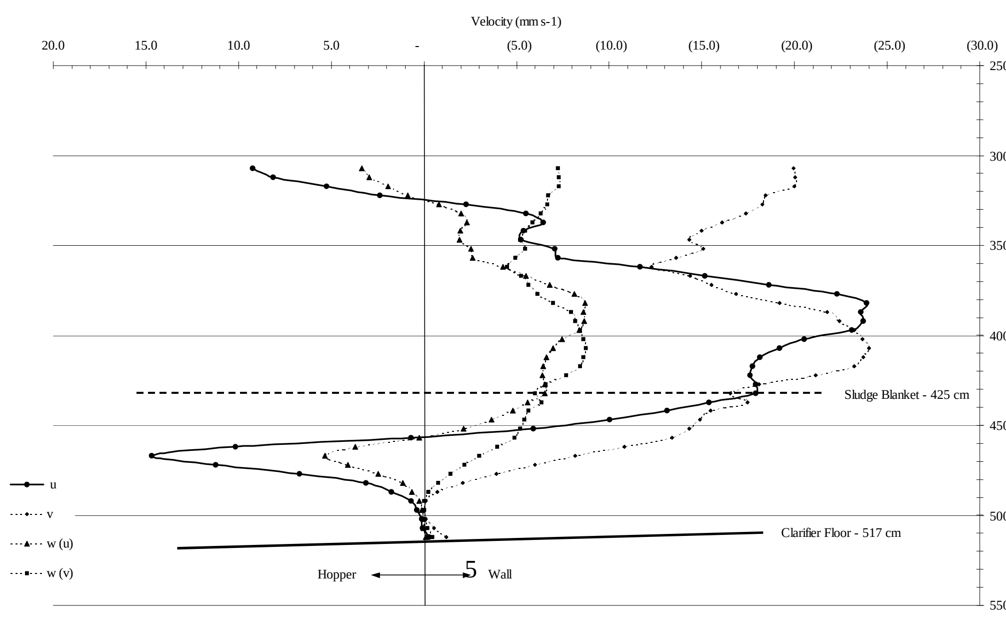
Figure 1
Secondary Clarifier Performance Data
Impact of Surface Overflow Rate on Effluent Suspended Solids



Secondary clarifier ADCP studies revealed several new insights including:

1. The sludge blanket moves hydraulically toward a centrally located hopper under the force of gravity in a conical clarifier (sloped floor), with a parabolic velocity distribution contradicting previous belief that non-Newtonian characteristics prevent hydraulic transport.
2. The no-slip condition at the clarifier floor creates a region of very low velocity. The clarifier mechanism likely serves to mix this low flow region into the overlying higher flow region.
3. Anderson (1945) first determined that the secondary clarifier flow field includes a radial density current located directly above the sludge blanket resulting from buoyancy effects due to the greater influent solids density compared to the tank contents. ADCP studies determined that the density current penetrates into the

Figure 2
ADCP Velocity Profile



sludge blanket, causing the upper regions of the sludge blanket to flow toward the wall rather than the center, negatively affecting the overall solids residence time distribution.

ADCP techniques promise not only to improve field measurements of secondary clarifier velocities but also to improve the calibration of the computational fluid dynamic models discussed below. ADCP's do suffer from limitations which requires opposing beams to sample from similar flow field for accuracy to be maintained. This may not occur in secondary clarifiers to the degree required, particularly near boundaries.

CAPACITY

Flux Theory/State Point Analysis

Coe and Clevenger (1916) produced a seminal paper regarding the gravitational separation of solids from a liquid/solids slurry. Metcalf & Eddy (1991) separate settling phenomena into four types, each of which occurs in a secondary clarifier:

1. Type I: Discrete – flocs settle individually according to Stokes Law without interfloc interactions.
2. Type II: Flocculent – flocs settle individually according to Stokes Law, however floc agglomeration, via DS flocculation, changes the settling velocity.
3. Type III: Hindered – hydrodynamic floc interaction occurs during settling because the boundary layers of individual flocs interact with one another, not permitting relative floc motion. This *hinders* the settling velocity relative to the Stokian velocity.
4. Type IV: Compressive – both structural and hydrodynamic floc interactions occur during settling, which also does not permit relative floc motion.

These definitions suggest discrete settling represents a specific category of flocculent settling in which DS flocculation does not occur due to either low floc concentration or the lack of relative floc settling velocity. They also suggest hindered settling represents a specific category of compressive settling in which only hydrodynamic interactions occur between the flocs.

Ekama *et al*. (1997) also describe presently accepted theories of how capacity limitations occur in the sludge blankets of secondary clarifiers. Kynch (1952) developed an analysis of hindered settling assuming the settling velocity depended solely on the concentration. This assumption amounts to ignoring the conservation of momentum equations in the governing equations and solving only the continuity equations. Although this approach provides insight into hindered settling phenomena it does not permit a complete solution.

To evaluate clarifier capacity, many engineers apply State Point Analysis (SPA) to determine if a clarifier operates in underloaded or overloaded conditions with respect to thickening. Using operating data including flowrate, underflow rate, clarifier area, mixed liquor concentration, and settling properties, the SPA technique conducts a mass balance around the clarifier to determine if hindered blanket formation occurs. SPA typically uses the Vesilind equation to represent the settling flux of a particular biological solid using data collected from a series of hindered settling tests. The Vesilind equation assumes biological solids settling velocity varies solely as a function of concentration – equivalent to the Kynchian assumption discussed above. The technique allows designers and operators to determine under which conditions hindered blanket formation occurs, called thickening failure, and avoid or minimize this condition in system operations. Kinnear *et al*. (2001) and Ekama *et al*. (1997) describe SPA in detail as well as field verification of the technique.

Compression Modeling

Although becoming widely applied, SPA suffers from both theoretical and practical problems in application. These problems include ignoring the conservation of momentum equations and the inability to calculate the sludge blanket elevation or the biological solids mass resident in the clarifier as well as insufficient accuracy during the field verifications described in Ekama *et al*. (1997).

Kos (1978), Cacossa and Vaccarri (1995), and Kinnear (2002) provides an alternative to SPA by taking a multiphase CFD approach and including both the liquid and floc phase continuity and momentum equation's. This work derives an alternative equation to the Vesilind equation, presented in Equation (1).

$$V_f = \left((1-\varepsilon)(\rho_l - \rho_f)g + P_y \frac{\partial \varepsilon}{\partial z} \right) \frac{k}{\mu} \tag{1}$$

where:

V_f = floc velocity [L T^{-1}]
ε = porosity [L^3 (liquid)/ L^3 (total)]
ρ_l = liquid density [M L^{-3}]
ρ_f = floc density [M L^{-3}]
g = acceleration due to gravity [M T^{-2}]
P_y = $P_y(\varepsilon)$ = biological solids matrix compression yield stress [M L^{-1} T^{-2}]
z = distance from the base of the settling vessel [L]
k = k(ε) = biological solids intrinsic permeability [L^2]
μ = dynamic viscosity of water[M L^{-1} T^{-1}]

Solving this equation numerically coupled with an aeration basin resulted in realistic clarifier sludge blanket concentration profiles. Compared to the Vesilind equation, Equation (1) contains more fundamental-parameters concerning the physical properties of biological solids as well as meaningful physical constants rather than lumped parameters. Research continues into the application of clarifier models and the integration of the compressive model with International Water Association Activated Sludge Models to improve the accuracy of complete activated sludge models and design tools.

COMPUTATIONAL FLUID DYNAMIC MODELING

As computational power continues to become more affordable, the ability to simultaneously simulate the complex transport phenomena described above along with the flow field promises improved insight and design optimization. Ekama *et al*. (1997) provide a review of progress in secondary clarifier computational fluid dynamic (CFD) models.

Existing models require improvement, however, before achieving confident prediction of clarifier performance. Challenges to overcome include:

1. Accurate ESS prediction requires incorporation of accurate bioflocculation submodels. Since existing CFD models do not incorporate these submodels, they should not be considered capable of predicting ESS.
2. Accurate prediction of the solids distribution between the aeration basin and the clarifier or sludge blanket solids profile requires incorporation of compressive submodels.

3. Most models rely on the sludge volume index (SVI) to define settling parameters and numerous studies determined the SVI to be of limited use in defining settling properties. CFD models must incorporate improved measurements of the physical properties of biological solids
4. Rheological properties of biological solids require further study to properly define the sludge blanket flow field.
5. Calibration remains difficult due to difficulties in working with both pilot and full-scale secondary clarifiers.

Due to the concerns stated above, researchers and particularly model users must be careful not to overstate the predictive capacity of current CFD models. For example, models typically predict increased ESS as hydraulic loading increases, inconsistent with field data similar to that presented in Figure 1. This does not imply that CFD models do not represent significant contributions or CFD techniques should not be applied. Combining several techniques such as hydraulic testing and CFD modeling presently offers the best approach.

CONCLUSIONS

Research continues into the optimization of secondary clarifiers in the activated sludge process. Many tools and techniques under development offer the promise of achieving this goal although considerable research challenges remain.

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