MODELING ASPECTS OF ACTIVATED SLUDGE PROCESSES

PART I: PROCESS MODELING OF ACTIVATED SLUDGE FLOCCULATION AND SEDIMENTATION

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Abstract

Process modeling of activated sludge flocculation and sedimentation reviews consider the activated sludge floc characteristics such as: morphology viable and non-viable cell ratio density and water content, bioflocculation and its kinetics were studied considering the characteristics of bioflocculation and explaining theory of Divalent Cation Bridging which describes the major role of cations in bioflocculation.

Activated sludge flocculation process modeling was studied considering mass transfer limitations from Clifft and Andrew, 1981, Benefild and Molz 1983 passing Henze 1987, until Tyagi 1996 and G. Ibrahim et al. 2002. Models of aggregation and breakage of flocs were studied by Spicer and Pratsinis 1996,and Biggs 2002.

Size distribution of flocs influences mass transfer and biomass separation in the activated sludge process. Therefore, it is of primary importance to establish the role of specific process operation factors, such as sludge loading dynamic sludge age and dissolved oxygen, on this distribution with special emphasis on the formation of primary particles (dispersed bacteria and very small flocs) which flocculate less effectively and may contribute to the level of residual suspended solids (SS) in final effluents.

Settling properties of activated sludge showing the mathematical expressions indicating some properties such as SVI settling velocity and floc size. The secondary clarifier in activated sludge processes has two functions: clarification and thickening of sludge in developing the model for its

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sedimentation dynamics, it was assumed that no significant reactions occur in the settling basin. Sedimentation as amass transfer process was modeled in this study according to the solid flux theory (Marsili Libelli , 1989). Tyagi et al., (1996) showed that the total flux due to gravity and sludge withdrawal from the bottom was expressed

1. Introduction

The activated sludge process is a popular and versatile method of treating wastewater that uses biological reactions to convert the waste into a microbial mass. The biomass is called activated sludge that consists of flocs made up of bacteria and organic and inorganic material. The formation of these flocs is important for the overall performance of the wastewater treatment process. There are many mathematical models used by the designers of biological wastewater treatment systems to investigate the performance of a number of potential systems under variety of conditions.

Quantitative measurements of bacteria growth are essential to quantify the fate of organic compounds in natural (Ducklow and Shiah, 1993) and engineered environments (Grady et al., 1996). In biological wastewater treatment, predicting the ability of the bacterial community to assimilate influent nutrient loads is the basis of the mathematical models that are used to design and operate the process. The growth rate is a kinetic parameter that is a measure of the assimilative capacity. For effective models, the kinetic parameters must accurately mirror the degradation ability of the bacterial population in situ. However, there is no clear consensus on how wastewater growth kinetics should be measured.

Generally, the new developments and innovations in biological reactors have renewed the interest in their modeling. There are at least two reasons for this. One is that models are the basic tools of engineering which facilitate the design process, the other is that models help us to achieve a better understanding the phenomena by guiding our analysis.

A schematic diagram of the activated sludge process with cell recycle is shown in Figure 1. In wastewater treatment engineering, bioflocculation, the process of microbial aggregation, is critical to solid/liquid separation. Poor bioflocculation leads to poor settling and dewatering properties, in other words, poor effluent qualities.

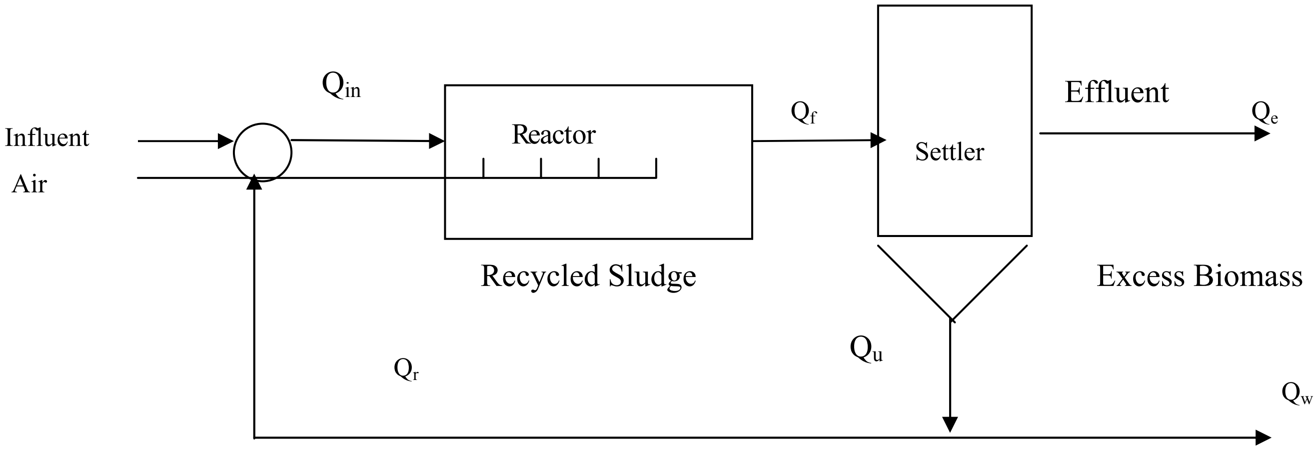

Figure (1): Schematic diagram of the Activated Sludge Process.

Since the conception of the activated sludge process in 1914, researchers have sought to better understand the process of bioflocculation. Yet, compared to other aspect of the process, such as biological reactions and solid-liquid separation, very little is known about the fundamentals (Biggs and Lant, 1999).

A significant amount of research has been performed on the characteristics and mechanisms of bioflocculation and sedimentation process. Since particle size is a critical factor in settling and dewatering of activated sludge suspensions, the process and extent of bioflocculation will ultimately determine the settling and dewatering properties.

2. Activated Sludge Floc Characteristics

The description and characterization of the biological flocs present in a biochemical reactor is as essential in determining the rate of substrate uptake and products formation as knowing the concentration of the limiting nutrient. Unfortunately the deformable nature of biological flocs prevents the establishment of satisfactory measurement procedures.

The effectiveness of the clarification step in the activated sludge process is highly determined by the activated sludge flocs properties. Even if considerable effort has been devoted in order to gain insight in the activated sludge flocculation and to demonstrate the influence of the flocs' structural properties on the sedimentation process, these issues still remain poorly understood. Important properties of flocs include morphology, size range, and number of viable and non-viable cells per unit volume, density, dry weight and water content. Both the macro- and micro- morphology i.e. internal and external morphology, of a floc have to be considered.

2.1 Properties

This section reviews the previous work on: floc morphology, size range, ratio of viable to non- viable cells, and density of the flocs as well as the water content.

Morphology. Stanley and Rose (1967) examined clumps of C. Xeroxes microscopically. Electron micrographs showed the bacteria to be connected by adhesive material, which did not appear to be localized but to be distributed over the bacteria surface. The surface of the bacteria were covered by 'wart- like' lumps. A thin section of a clump showed it to be hollow and to have been formed by a single layer of bacteria collecting around a gas bubble. The ability of the bacteria to remain at least in contact, after preparation of the material for electron microscopy, testified to the mechanical strength of the adhesive material.

The presence of certain microorganisms in a mixed microbial floc adds to its strength. Parker et al., (1971) suggested the presence of filaments within the floc, while McKinney (1956) observed that the dead protozoa liberated solid bodies on which bacteria adhered forming flocs.

Passmore (1973) has presented electron micrographs, of 4-days old colonies of S. cerevisiae. Comparison between glutaraldehyde- fixed and unfixed colonies showed that the cells of the unfixed specimen were coated with a slimy material; glutaraldehyde treatment tended to remove this slime layer and gave a clearer micrograph.

The internal structure of fungal pellets has been shown to vary a great deal. Martin and Waters' (1952) microscopic examination of a Niger pellets have shown that the pellets are dense, spherical with limited lateral hyphae, and with much precipitate enmeshed in the pellet. The individual hyphae are short, greatly thickened, vacuolated and granular with short club-like branches. Particles of precipitate adhering to the hyphae were also observed. Steel et al. (1954) reported similar findings. Pirt and Callow (1959) found that pellet formation of Pencillum chrysogenum was linked with the production of an aberrant form of mycelium. The characteristic of this aberrant form was the presence of short, much branched, swollen and often distorted hyphae. The normal filamentous type was characterized by long, thin hyphae of constant thickness and few branches. They observed the initiation of pellet formation to be aggregation of the hyphae within the individual fragment of mycelium.

Viable/non- viable cell ratio. In the activated sludge process, bacteria, protozoa, inorganic and organic colloids, all contribute to the formation of the flocs. The recycle of activated sludge floc controls the viable/non-viable cell ratio in the floc for any given organic substrate concentration. Low recycle results in a very active floc with a small non-viable fraction (*Atkinson et al)* . The non-viable fraction has a significant absorptive capacity for the organic substrate through rather less than the viable fraction. Thus for a given aeration period and a given waste, flocs of high viability produce an effluent containing less organic matter, but have a higher oxygen demand than flocs of low viability*, McKinney, (1956).*

Clark (1962) has studied the internal structure of A. niger pellets. Under optimum fermentation conditions, each pellet developed as a round mass of mycelium of uniform consistency during the first 24 hours of aeration; subsequently a dense crust of growth formed at the periphery of the pellet and autolysis of cells began at the center. At the end of the fermentation (140 hours), the pellet consisted of a shell of mycelium occupying less than 50% of the pellet volume. Autolysis was thought to result from the resistance to the passage of nutrients and oxygen to cells inside the pellet, by the dense crust grown on the surface.

Density and water content. James and Smith (1975) examined flocs of S. cerevisiae and pellets of A. niger. They found that the average dry density of S. cerevisiae was 1.32 gm/l, while that of A. niger varied significantly during the course of a batch fermentation; 1.24 gm/l was obtained for mature mycelium. After evaluating wet cell density, they suggested a value of about 725 by volume for the liquid content of single cells.

James and Smith (1975) also estimated aggregate densities by measuring the terminal velocities of microbial aggregate that was then computed from knowledge of dry density. For many pellet morphologies the volume fraction of liquid was as high as 99 %. In the case of yeast flocs the corresponding values were in the range of 90-95%. It is of interest to note that Green et al., (1965) reported that the average percentage dry matter in microbial film grown at various temperatures between 5-30 C^o on settled sewage was 3-7%.

Measurements of Floc Density. Obtaining the bulk density of activated sludge floc is difficult due to the hydration water associated with its surface. The principles of sedimentation and centrifugation have been used for floc density determinations, but both methods rely on the assumption of spherical flocs. An indirect method involves the determination of the bound water content of the sludge by the dilatometric technique. Andreas (1993) used a goniometer

$$pd = \frac{2\theta}{360} \qquad (1)$$

analyzer and assisted phase change determinations by use of a half-shade eyepiece. The phase difference (pd) was given by

Where θ is the angle through which the goniometer analyzer is rotated from the position at which matching to the reference area (liquid) is observed to the position at which matching to the floc is observed. The solids concentration of a given floc thickness (d) is

Where a= 0.00185 (Barer and Joseph, 1955).

$$C = \frac{pd}{a * d} \qquad (2)$$

The thickness of the floc was estimated by measuring the optical pat difference (pd1-pd2) produced by the same floc in two immersion media (natural suspension medium and a 2% peptone solution)

With C known (in g cm^{-3}) the bulk density p_f (in g cm^{-3}) of the floc can

$$\rho_f = 1 + \frac{(\rho_s - 1) * C}{\rho_s} \tag{3}$$

be calculated as follows:

Where p_s is the density of dry sludge (in g cm^{-3}). The value of p_s adopted is the density of protein, 1.34 g cm^{-3} , which is very close to the typical density of dried activated sludge

Therefore: Andreas (1993) got a strong correlation between floc density (p_f) and

$$\rho_f = 1 + 0.30 d^{-0.82} \tag{4}$$

size (d). This relationship can be obtained in the form:

This relationship applies to all sludge samples irrespective of sludge age with the exception of the dispersed sludge where for a give floc size (especially for flocs smaller than 30µm) the corresponding density is smaller when compared to the density of a floc of the same size from the other units.

3. Characterization and Kinetics of Bioflocculation

The basic operational unit of activated sludge is the floc. Under the microscope the activated sludge is composed of discrete clumps of microorganisms known as flocs, which vary both in shape and size. Debankur Das et al., (1993) showed that under normal operating conditions activated sludge flocculates naturally. This process, called bioflocculation, is thought to occur as a result of biopolymers secreted by microorganisms present in the mixed liquor. Several different concepts have been advanced explaining this phenomenon. The most commonly acknowledged theory, the polymer bridging model, was extended by Parker et al., (1971 and 1972) who postulated the existence of two levels of structure in activated sludge flocs: the microstructure, and macrostructure, consisting of a filament network which provides for the buildup of primary "backbone" for the building of primary particle "flesh".

3.1 Biofloculation Characterization

Good flocculent growth is important for the successful operation of the process, so that suspended, colloidal, and ionic matter in the wastewater can be removed by adsorption and agglomeration in the aeration tank, and subsequently in the sedimentation tank for the rapid and efficient separation of sludge from the treated effluent. There is a rapid agglomeration of suspended and colloidal matter onto the flocs as soon as the sludge and wastewater are mixed which results in a sharp fall in the residual BOD of the wastewater. The volatile matter content of flocs is generally high, between 60-90 %, although this depends on the nature of the wastewater and the amount of fine suspended and colloidal inert matter present.

Individual flocs are complex biochemical units. Each floc is a cluster of several million heterotrophic bacteria bound together with some inert organic and inorganic material. There is a wide range of particle sizes in the activated sludge process ranging from individual bacteria of between 0.5-5.0 μm up to large flocs which may be greater than 1mm (=1000 μm) in diameter.

In fact, activated sludge is a complex mixture of various constituents and shows a wide variation in its physical, chemical, and biological properties. The biological content is particularly troublesome. The living microorganisms in activated sludge change sludge characteristics continuously, making it almost impossible to carry out controlled experiments in sludge studies. In addition, reproduction of data is difficult.

Urbain V. et al., (1993) showed that the overall floc structure is negatively charged and is the result of physico-chemical interactions between microorganisms (mainly bacteria), inorganic particles (silicates, calcium phosphate and iron oxides), exocellular polymers, and multivalent cations. Exocellular polymers (ECP) have two different origins, (1) from metabolism or lysis of microorganisms (protein, DNA, polysaccharides and lipids) and (2) from the wastewater itself (e.g. cellulose, humic acids…). Divalent cations such as Ca+2 and Mg+2 are known to be involved in the chemical structure of bacterial aggregates and biofilms because of their ability to form negatively charged chemical groups. In spite of the importance of divalent cations in flocculation processes, there is a lack of information about either their accumulation in the exocellular structures of the sludge flocs or their affinity with specific constituents of the ECP.

Urbain et al.(1993) analyzed the settleability, biomass and exocellular composition, surface characteristics and internal hydrophobicity of bioflocs, and indicated that there is not a constant ratio between the constituents of cells and exocellular polymers; the presence of alginate is important in floc formation. High concentration of alginate, however, may deteriorate sludge characteristics, causing and increase in viscosity; Exocellular polymeric substance (EPS) are involved in the formation of a three -dimension matrix or gel where divalent cations act as bridging agents (Urbain et al., 1993).

Bacteria and protozoa are either attached to the surface of the flocs or embedded in some form of material forming a matrix. The exact nature of this flocculating material is still not known although it appears largely bacterial in origin. The material extracted from activated sludge (Brown and Lester 1979) constitutes a significant portion of the dry weight of the sludge, up to 10%. Sobeck and Higgins (2001) demonstrated that microorganisms produce biopolymers that are released to the exocellular environment, either by cell lysis, or by active transport (Sobeck and Higgins, 2001). EPS consists of protein, polysaccharide, humic compounds, nucleic acids, and lipids. Extracellular material has a number of function groups that enable binding through specific protein-polysaccharide interactions, hydrophobic interactions, hydrogen bonding, and ionic interactions (Higgins and Novak, 1997). Since 80% of the masses of bioflocs are made up of EPS, Sobeck and Higgins inferred that the interactions between the EPS will be important to bioflocculation (Sobeck and Higgins, 2001).

All the studies have shown that the material is a polymer, which can be composed of a number of organic compounds such as polysaccharides, amino polysaccharides, and protein (Sato and Ose 1980). Lipids may also be present, but the exact nature of these flocculating polymers will depend on the species of bacteria or protozoa producing it. Each polymer will have varying surface properties and charges which will influence not only the settling characteristics but also the water binding properties of the floc. The polymer is not only giving the floc components cohesion; it is also allowing suspended particles in the waste to bind to the floc by adsorption. So the polymer has a critical role in the operation of the activated sludge process (Forster 1976; Unz and Farrah 1976), these extracellular polymers (ECPs) are not food reserves like ploy β-hydroxybutrates and so are not easily decomposed. The surface charges on the microbial cells and bridge formation by polyvalent cations also contribute to flocculation Atkinson (1971).

The flocculation in activated sludge has been attributed to many factors such as: the surface properties and the energy state of bacteria (McKinney, 1952, 1956), the presence of zoogloea-forming bacteria and protozoa, and above all of biopolymers produced by the bacteria themselves (Busch and Stumm, 1968)

In general, bioflocs have been a net negative charge and provides negative adsorption sites, and the role of cations, such as cobalt, calcium, or copper in bioflocculation, has shown to be important. Three different theories have been proposed, they are: Double Layer Theory or DLVO Theory and Alginate Theory

Divalent Cation Bridging Theory. Sobeck and Higgin proved that DCB Theory best describes the major role of cations in bioflocculation. On the contrary, Liao et al (2001) found that the physicochemical properties of sludge, including hydrophobicity and surface charge, rather than the quantity of EPS, are more important in controlling the flocculating ability of the sludge. They also concluded that hydrophobicity and surface charge of sludge surfaces were affected by the SRT. Sludge surfaces at higher SRTs (16 and 20d) were less negatively charged and more hydrophobic (larger contact angle) than those at lower SRTs (4 and 9d); Moreover, the strong inverse correlation between water contact angles, as well as surface charge, and the level of ESS indicated the importance of physicochemical properties of sludge surfaces in governing bioflocculation (Liao et al., 2001).

3.2 Kinetics of bioflocculation

Flocculation is measured as the increase in floc size with time. This phenomenon is usually described in terms of two key flocculation mechanisms, aggregation and breakage. Rapid increase in floc size is initially due to the dominant rate of aggregation. As breakage becomes more dominant, the rate of increase in floc size decreases until a steady-state floc size is reached (Apiser and Pratsinis, 1996b; Biggs and Lant, 1999). Despite its practical importance, the kinetics of particle collisions that lead to particle coagulation has not been well established.

Coagulation includes two separate and sequential steps, a collision (contact) step followed by an attachment. Three independent collision mechanisms, Brownian motion, fluid shear and differential sedimentation, are important in aquatic systems. Brownian motion, only affecting the movement of small particles (<1 μm), is the random motion of particles caused by the thermal energy of surrounding liquid. Fluid shear, either laminar or turbulent, is caused by velocity gradients that occur in all real flowing fluids. Differential sedimentation is produced at a rate associated with the gravity and buoyancy forces. The kinetics of coagulation was first systematically described by von Smoluchowski (1917) and his research still serves as the foundation for modeling the coagulation process. He proposed collision frequency functions for Brownian motion and fluid shear; subsequently, others defined a collision frequency function for differential sedimentation (Camp and Stein, 1943). These studies were based on a rectilinear collision model, assuming that the particle motion is linear until collisions occur. This conventional model is known to overpredict particle collision frequencies to a great extent since it neglects hydrodynamic interactions and short- range forces between approaching particles (Han and Lawler, 1992; O'Melia and Tiller, 1993; Li and Logan, 1997a).

To overcome the limitations of the rectilinear model, various curvilinear collision models have been developed that account for the hydrodynamics and particle interactions. Curvilinear collision functions, however, are too complicated to be described analytically. Curvilinear models may properly describe collision frequencies between impermeable particles; however, flow through the interior of highly porous aggregates will produce more particle collisions than predicted by the curvilinear model (Li and Ganczarczyk, 1990; Serra and Logan, 1999). Thomas et al (1999) presented a review of flocculation modeling and indicated that surface chemical effects are either ignored or dealt with in a simplistic manner in the flocculation models. However, the fractal dimension is required to make a successful attempt at modeling flocculation because it was important consequences in terms of water and wastewater treatment. Thomas et al (1999) concluded from their review of flocculation modeling that the application of flocculation modeling required renewed effort in experimental work to provide the opportunity to look in detail at both particle structure and flocculation kinetics (Thomas et al., 1999). Recently developed collision models have included the permeability and fractal factor in the calculation of collision frequencies between bioflocs and other particles. This has resulted in estimates of the coagulation rates that lie between those given by the rectilinear model and the curvilinear models (Serra and Logan, 1999; Li and Yuan, 2002).

Experimentally, it has been found that the flocculation of activated sludge is significantly affected by shear and discovered that the biofloc size decreases with increasing shear (Biggs and Lant, 2000). In a sheared fluid, Serra and Logan (1999) proved that bacterial aggregates collided more frequently with small particles than predicted by the curvilinear model (Serra and Logan, 1999). Li and Yuan recently proved that the collision frequencies between the settling biological aggregates and suspended small microspheres were two orders of magnitude lower than calculated by the rectilinear collision model, but one order of magnitude greater than predicted by a curvilinear model.

4. Activated Sludge Flocculation Process Modeling

Substantial amount of research has been conducted on modeling of the activated sludge process with attention focused on modeling the carbonaceous oxidation, the nitrification - denitrification and the dissolved oxygen dynamics (*Clifft and Andrews, 1981; Henze et al., 1987; Lessard and Beck, 1991; Ibrahim and Aba Saeed, 1995*).

All of these studies assumed homogenous modeling. They assumed that the microbial flocs present in the aeration basin and the liquid phase surrounding the flocs were in a single - phase system. The activated sludge kinetic model proposed by the IAWPRC task group (*Henze et al., 1987*) was also based on this assumption. In reality, the intraparticle diffusion limitations within activated sludge flocs may be of significance in practical situations (*Andrew, 1991;*). Research attention has recently focused on mass transfer within flocs of the activated sludge process. (*Haas, 1981; Benefield and Molz, 1983; Andrew, 1991; Bakti and Dick 1992*). *Benefield and Molz*, (1983, 1984) proposed a distributed parameter model including the material balance equations with Monod-type kinetics for the substrates inside the flocs and assumed an average floc size instead of considering the floc size distribution in the system in order to account for the effect of flocs on the dynamics of the system. *Beccari et al.,* (1992) developed a simple floc model with emphasis on the nitrification process in suspended culture taking into account the resistance related to oxygen diffusion inside the biofloc.

Tyagi et al., (1996**)** developed a simple floc model taking into account two growth processes: carbonaceous oxidation and nitrification that were thus interacting through their competition for dissolved oxygen inside the floc. They did not consider two important notes: the first is that the anoxic decomposition of nitrate by denitrifcation was not incorporated into the floc model. Consequently, they assumed the aerobic portion represents 100 % weight of the total floc. The important role of the anoxic growth of heterotrophs is neglected. The second is that they neglected the external mass transfer resistance due to boundary layer.

G. Ibrahim et al., (2002), based on the IAWPRC kinetic model developed, an appropriate mathematical model for activated sludge flocs to study the biofloc characteristics from the kinetics-mass transfer interaction point of view. The model was taking into account three growth processes: carbon oxidation, nitrification and denitrification in terms of four components: substrate, nitrate, ammonia, and oxygen. The effect of their bulk concentrations, diffusivity and external mass transfer of substrates on the biofloc characteristics in terms of the aerobic portion weight to the total floc was studied. It can be said that the aerobic portion was found to be more sensitive to the change of the bulk concentrations of oxygen, substrate, and ammonia in addition to the power input and substrate diffusivity. It was less sensitive to the change of nitrate bulk concentration. This model describes quantitatively the biofloc activity, as it may be totally active, which is totally aerobic or aerobic-anoxic, or it may be partially active.

Furthermore, Parker *et a*l. (1972) performed an early effort to model the activated sludge flocculation process in order to be able to describe changes in settling characteristics. The proposed model describes the changes in supernatant primary particles (turbidity measurements) after settling and was also validated by Wahlberg *et a*l.(1994). Floc aggregation and break-up appeared to be key processes that occur simultaneously. However, the model does not allow overall modeling of the settler, since it only provides information concerning primary particles in the supernatant, determining effluent suspended solids.

Instead of approaching the biomass as a “lumped biophase”, sludge can be viewed as a segregated population of individual flocs. This individuality approach implies that all floc properties are no longer average values, but are given by number distributions (distributed model). These segregated models, also called Population Balance Models (PBMs), allow the description of dynamical changes in these property distributions when the conversion terms are known. Considering floc size as the floc property, conversion terms can be interpreted as aggregation and break-up of flocs and the number distribution based on floc size (N) becomes:

$$\frac{dN_i}{dt} = aggregation + breakage \qquad (5)$$

PBMs have been successfully applied in a number of different disciplines dealing with particle or droplet populations (Hounslow *et a*l., 1988; Kusters, 1991; White and Ilievski, 1996; Spicer and Pratsinis, 1996; Ramkrishna, 2000). The main difference of a PBM compared to the model proposed by Parker *et a*l. (1972) is that it describes changes in the complete particle size distribution instead of only the fraction of primary particles.

Biggs (2000) showed that a PBM based on the aggregation model introduced by Hounslow *et a*l. (1988) and the breakage model described by White and Ilievsky (1996) could be used to describe the activated sludge flocculation process. Both aggregation and breakage can lead to “birth” and “death” of flocs of a certain size. The evolution of the volume-based number distribution n(v) is a result of these four mechanisms and is given by:

$$\frac{dn(v)}{dt} = B(v)_{agg} - D(v)_{agg} + B(v)_{break} - D(v)_{break} \qquad (6)$$

Volume-based integral expressions of aggregation birth ($B(v)_{agg}$) and aggregation death ($D(v)_{agg}$) can be found in Hounslow *et a*l. (1988), those for breakage birth ($B(v)_{break}$) and breakage death ($D(v)_{break}$) in White and Ilievsky (1996). Solving this “integro-partial differential equation” is, however, no trivial task. Since an analytical solution is not possible, a discretisation allowing numerical integration is needed. This discretisation divides the particle size range in a number of classes, each represented by a floc size and volume. The discretised PBM and the expressions used to describe the different processes were obtained by Hounslow et al. (1988) and are summarized in the following equation.

In this model Ni (#.l -1) is the number concentration of flocs of size i, α(-) is the collision efficiency, and β_{ij} (m ^{3} .s $^{-1}$) is the collision frequency for particles of volume v_i (m ^{3}) and v^j (m ^{3}). S_i (s $^{-1}$) is the breakage rate of flocs of size i and βi,j(-) is the breakage distribution function which defines the volume fraction of the fragments of size i produced from j sized flocs. The parameter α (collision efficiency) was introduced in the discretised model in the aggregation expressions. This parameter (value between 0 and 1) represents the number of successful collisions since not every collision will result in aggregation. It can be interpreted as a correction factor that is introduced to correct the number of collisions (β which is obtained only on the basis of the floc size as floc property. Details on the discretisation-grid and the mass conservation can be found in Hounslow *et al.* (1988). Discretisation resulted in 28 floc size classes and therefore in 28 differential equations that need to be solved simultaneously.

In order to make the described model operational, functional relationships of the collision frequency βi,j, the breakage rate Si and the breakage distribution function $\Gamma_{i,j}$ must be available. Spicer and Pratsinis (1996) described the

$$\beta_{i,j} = 0.31G\left[v_i^{1/3} + v_j^{1/3}\right]^3 \quad (7)$$

collision frequency, βi,j, in terms of the volume of the particles (v_i, v_j) that collide and the average velocity gradient, G:

In which:

$$G = \left(\frac{\varepsilon}{\upsilon}\right)^{\frac{1}{2}}$$

With:. ν = the kinematic viscosity (m ^{2} .s $^{-1}$)

ε = the average turbulent energy dissipation rate (m ^{2} .s $^{-3}$)

Through above both equations, the PBM becomes directly linked to the Computational Fluid Dynamics (CFD) results, since the value of ε is produced by the CFD-model. The breakage rate (Si) can be described as function of the particle volume (Spicer and Pratsinis, 1996; Serra and Casamitjana, 1998):

$$S_I = Av_i^a \tag{8}$$

With: a = constant (=1/3)

A = the breakage rate coefficient ($cm^{-3a} s^{-1}$)

It is assumed that only binary breakage occurs. This means that flocs break into 2 smaller flocs with equal volume.

Despite the complexity of the above model, only 2 parameters need to be estimated from the floc size distribution (FSD) data: α, the collision efficiency, and A, the breakage rate coefficient. More important, however, in view of the future use of such a model for better understanding and prediction of flocculation (and thus settling) is that one may try to derive relationships between these two key model parameters and (1) applied environmental conditions such as shear rate, ionic strength, temperature, and (2) floc properties (structure, strength, density, settling velocity and SVI). These relationships should then be built into the PBM. Indeed, it can be expected that both α and A will not be constant throughout the complete flocculation process and that they could be time varying (through a changing environmental factor or floc property). To model this time-dependency, however, more detailed knowledge about the flocculation process is needed with regard to relationships between floc growth and floc density on the one hand and the rate of both aggregation (α) and breakage (A) on the other hand. Some work on the functionality of α has already been reported in literature (Han and Lawler, 1992; Thomas *et a*l., 1998).

5. Factors Affecting Dispersion of Activated Sludge Flocs

Size distribution of flocs influences mass transfer and biomass separation in the activated sludge process. Therefore, it is of primary importance establish the role of specific process operation factors on this distribution with special emphasis on the formation of primary particles (dispersed bacteria and very small flocs) which flocculate less effectively and may contribute to the level of residual suspended solids (SS) in final effluents.

Li and Ganczarczyk (1993) applied statistical tests to evaluate the concurrent effects of the major process operation factors on the probability functions of the size distribution of the activated sludge flocs. They used models of power-law and long-normal to identify the significance of influencing factors on the size distribution of activated sludge flocs through a determination of correlations between influencing factors and the distribution models' parameters.

Most of previous works on the relationships between process operation pattern and size distributions of activated sludge flocs were focused mostly on one or two operation factors and often measured the resulting dispersion in a simplified way. (for example , as mean floc size) or indirectly as an amount of SS in the plant final effluent. Ganczarczyk (1968), in laboratory tests on different samples of activated sludge, demonstrated that the dispersion of flocs measured as mean floc sizes was a function of mixing intensity and time of mixing. However, he noticed that the origin of activated sludge also strongly affected this relationship. Bisongi and Lawrence (1971), in laboratory experiments performed with the use of a soluble substrate, correlated the biological solids retention times (SRT), with settling characteristics of the sludge measured as sludge volume index, zone settling velocity, and present dispersions. The latter indicator was based on measurements of the remaining solids after 1 hour settling of the mixed liquor samples. Chao and Keinnath (1979) studied the influence of process loading intensity on sludge clarification and thickening characteristics. Palm et al (1980) investigated the relationship between organic loading, dissolved oxygen concentration, and sludge settlabilty. Das et al (1991) studied floc breakup in24 dull scale activated sludge plants for the purpose of minimizing SS in the final effluents, but only the mixing intensity in aeration tanks and the presence of elbows and free fall from mixed liquor conduits were taken into consideration.

Li and Ganczarczyk (1991) demonstrated that size distribution of activated sludge flocs in an aeration tank, including dispersed microorganisms

$$f(x) = \alpha x^{-\beta} \tag{9}$$

and very small flocs, can be best fitted by the power-law model

Where f (x) equals the power-law probability density function x equals floc size, and α and β are the distribution parameters. As the power law floc size distribution is completely determined by these two parameters, the effect of any factors on the parameters will be equivalent to that on the size distribution itself.

The distribution parameters have specific technical meanings for size distribution. According to Li and Ganczarczyk (1991) the parameter α can be interpreted as the scale factor that is related to the total number of flocs in a given volume of the mixed liquor. The parameter β is related to the number of flocs in each size class. Li and Ganczarczyk (1991) showed that an increase in β would result in a shift in the floc size sidtribution from small to large. In other words, the number of flocs in small size classes wii decrease with increasing β. In addition, the distribution parameters are directly related to the most common measure of floc, size, the mean μ_x , which can be expressed as

$$\mu_x = \int x(\alpha / N)x^{-\beta} dx = (\alpha / N)[1/(2-\beta)](x_{\max} - x_{\min}) \tag{10}$$

Where N equals the total number of flocs across the whole size spectrum and x, α and β are the same in the above both equations.

Flocs larger than 10 μm are major contributors to the total biomass surface area, volume, and mass, and their size distribution is best fitted by the

$$f(x) = \frac{1}{\sigma_{\ln x}\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2_{\ln x}}(\ln x - \mu_{\ln x})^2\right] \tag{11}$$

log normal density function (Li and Ganczarczyk (1991))

Where $\mu_{\ln x}$ equals the logarithmic mean of x, and $\sigma_{\ln x}$ the logarithmic standard deviation. Parameter $\mu_{\ln x}$ and $\sigma_{\ln x}$ represent the central tendency and the dispersion of the logarithm of the floc size, respectively. The parameter $\mu_{\ln x}$ is directly proportional to the geometric mean of the floc size. Arithmetic mean floc size can be calculated from these parameters as follows:

$$\mu_x = \exp\left(\mu_{\ln x} + 0.5\sigma_{\ln x}\right) \tag{12}$$

The effects of the particular process operation factors on dispersion of the activated sludge flocs are summarized below.

Sludge loading. Li and Ganczarczyk (1993) showed the relation between the parameter α and F:M ratio . They showed the parameter α decreased rapidly with the increasing F: M ratio to approximately 0.5 kg/ kg. d Further increase in F:M ratio seemed to have little effect on α as the decreasing tendency in α leveled off at higher F:M ratio. However, regression using common variable transformations did not generate any statistically acceptable correlation for these data. For the parameter β , increasing organic loading resulted in a steady increase in this parameter, and a regression analysis indicated a correlation between β and F:M ratio (Correlation coefficient = 0.72).

This relationship clearly showed that high organic loadings the number of large activated sludge flocs would decrease, and that the number of small flocs would increase. This observation may be related to the presence of exocellular polymers in the system. According to the findings of Pavoni et al. (1972), exocellular polymer production is lower at higher organic loadings of the activated sludge. As exocllular polymers are one of the main factors that facilitate bioflocculation and keep flocs intact, the reduced production in the polymers may be responsible for the shift in activated sludge size distribution. The floc size distribution changes in response to variations in organic loading were consistent with several previous studies. For example, Chao and Keinath (1979) reported that increasing in effluent SS, which consisted mainly of small flocs and dispersed microorganisms, were observed as a result of increases in organic loading.

No clear correlation with the sludge loading could be ascertained for the parameter $\mu_{\ln x}$ which is a measure of central tendency for flocs larger than 10 μm. Given the fact that β increased with the increasing organic loading, this observation implied that organic loading might mainly affect the number of small flocs. The standard deviation of in lnx was increased with the increasing organic loading for flocs larger than 10 μm this was shown by significant correlation between the parameter $\mu_{\ln x}$ and the F:M ratio.

Table 2 correlation coefficients of the process operation factors and the parameters of the distributed model

	Power-law model		Log-normal model	
	α	B	$\mu_{\ln x}$	$\sigma_{\ln x}$
F:M	-	0.72	-	0.66
Dynamic sludge age	-	-0.53	-	-
MLSS	0.61	-0.37	-	-
Mean velocity gradient	0.48	-	-0.45	-
Hydraulic retention time	-	-	-	-
Dissolved oxygen	-0.62	-	-	-
Mixed liquor temperature	-	-	-	-

Dynamic sludge age. Li and Ganczarczyk showed that a linear correlation existed between dynamic sludge age (DSA) and the β parameter, although the correlation coefficient was only r = - 0.53 the fact that the number of larger flocs increased in relation to that of small ones (corresponding to the decreased β) might be explained by the fact that floc formation was enhanced at higher sludge age (McKinny, 1956 and Pavoni et al., 1972) . The variation in β with the changes in sludge observed in this study are generally in agreement with observations by other investigators, such as Bisogni Lawrence (1971) and Chao and Keinath (1979) who reported decreases in the percentage of dispersed particles due to the increases in sludge age. The mechanism behind this phenomenon was the plausible polymer-bridging hypothesis of biofloccuation. As indicated in Table 2, there was no statically acceptable relationship between DSA and the parameter α and between DSA and the two parameters of the log-normal distribution. This implies that the size distribution of flocs larger than 10 μm was not affected by DSA over the range studied. Therefore, it can be reasonably assumed that biopolymers produced at higher sludge ages effectively reduced the number of small flocs.

Dissolved oxygen. DO was found by Li and Ganczarczyk to directly affect only the scale of the floc size distribution as shown by a significant correlation between DO and the parameter α with a correlation coefficient of –0.62 (Table 2) . Although the parameter β changed in response to individual values of DO, there was no consistent trend in the change of the parameter β over the range of the DO levels studied. Several previous studies have shown that DO is a factor that could have significant influence on the relative number of flocs in different size ranges. However these findings have not been consistent, Sezgin et al. (1978) reported that for a given level of organic loading, activated sludge floc size tended to increase as DO level decreased. It was concluded that this was due to the growth of filamentous microorganisms, which survive better than floc, forming bacteria in an oxygen deficient environment. A different mechanism, namely the inhibition of exocellular polymer production and the inhibition of eukaryote population was considered by Starkey Karr (1984) as a reason for an increase in effluent turbidity (formation of small flocs) with decreasing DO level. On the other hand, Knudson et al. (1982) did not observe any apparent changes in floc size distribution when comparing flocs from activated sludge systems operated at sharply different DO levels. The latter findings are more in agreement with the findings of this study. It seems that the effect of the DO levels on floc size or floc size distribution varies, depending on other operating conditions of the activated sludge process, especially the organic loading of the system. Palm et al. (1980) showed that the sufficiency of the DO level in an activated sludge system was not a single value. Instead, it varies depending on the system's organic loading. Moreover, there are other factors that influence floc size and size distribution, which could offset of DO on floc size. Therefore, the effect of the DO levels may become unclear when other process operation factors vary.

No recognizable correlation between DO and the two parameter of the log-normal distribution was found in this study, suggesting that size distribution of the larger flocs was not affected by this factor in a consistent way, once again, the lack of clear correlation between the DO levels and the log-normal distribution might be due to the effects of other variable process operation factors.

Turbulence intensity. Expressed as mean velocity gradient G, turbulence intensity in the aeration tanks was found to have a significant influence on the parameter α, the scale of the power law size distribution, although the correlation coefficient was only 0.48 (Table 2). Although data were scattered, α increased with increasing G. However, the lack of a clear trend in the change of the parameter β over the range of G values implied that their relative contribution to the number of flocs in each size class did not always change in the same fashion. Several investigators (for example, Parker et al, 1971) have observed decreasing floc size with increasing G or turbulence intensity in the aeration tank. However, most studies that reached this conclusion were based on experiments where all other factors were relatively stable while applying a much broader range of G. When G is the sole variable, the effect of G on floc size is undisputed. But in the case of full-scale aeration tanks, the effect of G may not be pronounced which could offset, to a certain extent, the effect of turbulence intensity. A correlation between G and the parameter $\mu_{;nx}$ was established with the correlation coefficient of – 0.45 (Table 2), while no correlation existed between G and $\sigma_{\ln x}$. As expected, $\mu_{;nx}$ tended to decrease with increasing G, suggesting that within the floe size range larger than 10 μm, the relative number of larger flocs would decrease and that of the smaller ones would increase with greater turbulence intensity in the aeration tanks. Because no clear correlation between G and the distribution parameters was found for the floes across the whole size spectrum, the correlation between G and $\mu_{;nx}$ implies that the effect of G was mainly on relatively large floes.

Hydraulic retention time. No correlation could be established between any of the four distribution parameters of the distribution models studied and the mixed liquor HRT in the aeration tanks. This observation was generally consistent with the research by Magara et al. (1976), which showed no appreciable effects of HRT on floe size.

Mixed liquor suspended solids. Linear correlations were found between α and β parameters and MLSS. While both correlations were significant, the former had a correlation coefficient of 0.61, and the latter one of only -0.37. This correlation indicated that the MLSS level affected the number of floes in a unit volume of mixed liquor represented by the α parameter (the scale factor). The two parameters of log-normal distribution appeared to decrease with increasing MLSS, although a regression analysis using common variable transformation for correlations between the parameters and MLSS indicated only insignificant correlation.

Temperature. No correlation could be established between the mixed liquor temperature and the parameters of both power-law and log-normal distributions. Since the samples of activated sludge flocs were taken in different seasons of the year, this finding indicated that the temperature over the range studied did not have significant effects on the floc size distributions.

The combined effect of operating factors on floe size distribution. Stepwise regression was used to investigate the combined effects of the process operating conditions as factors potentially influencing power-law and log-normal floe size distributions. Because some factors correlated best with the distribution parameters in nonlinear forms, a function of the factor instead of the factor directly, was often employed in the stepwise regression procedure.

The interaction of selected operating factors was also studied in the stepwise regression. The dimensionless product of G and HRT (Gt—the mean velocity gradient multiplied by the hydraulic retention time) represented the duration of the exposure of the activated sludge flocs to the turbulent forces. As discussed previously, the requirement for DO in the activated sludge process depends to a large extent on the organic loading of the system. A level of DO that is sufficient for a given organic loading could be deficient at higher organic loadings, as demonstrated by Palm et aI. (1980). Therefore, there clearly is an interaction between DO and organic loading.

The results of the stepwise regression analysis are presented in Table 3. It can be seen that the product Gt and $DO^{-0.64}$ had significant influence on the parameter α of the power-law model. For the parameter β of the model, the significant factors were the F:M ratio raised to the power of 0.065 and DO/(F:M). The significance levels for these estimates were lower than 0.01, and indicated that the null hypothesis could be rejected with little risk of committing a mistake. The other factors analyzed were rejected because their significance levels exceeded 0.05, and therefore were considered insignificant for the power law distribution. The results of the step wise regression clearly showed that the organic loading and the availability of DO per unit of organic loading were the two most significant factors that would affect the size distribution of the flocs in a activated sludge system. The effect the strong influence of these two significant factors may be much less noticeable.

For floes larger than 10 µm, the factor Gt had significant effect on both parameter of the log-normal distribution (Table3). Moreover, the significance levels for Gt on both parameter of log-normal distribution were much smaller than the other significant factors identified. Therefore, the log-normal distribution of the flocs was to a considerable extent controlled by factor Gt which accounted for the combined effects of aeration intensity and duration. In addition to the factor Gt, the dynamic sludge age had a significant influence on the $\mu_{\ln x}$ parameter, while MLSS had a significant effect on the $\sigma_{\ln x}$ parameter.

The effect of operation factors on the presence of dispersed microorganisms. In the studies of the size distribution of the flocs across the whole spectrum, it was found that the mode of the distribution was always in the first two size intervals (from 0.5 to 2 µm) (Li and Ganczarcyk, 1991). To a large extent variations of the occurrence frequency in this range significantly affected the scale and the shape of power-law distribution.

Moreover, because of overwhelming presence of the number of particles in this range relative to that in others, the frequency of occurrence of dispersed particles played a decisive role in determination of mean floc size.

Table 3- Step-wise regression analysis of the distribution model parameters and the process significant factors

Model	Parameters	Significant factors	Significance level
Power- Law	α	Gt	<0.0001
		$DO^{-0.64}$	0.0005
	β	$(F:m)^{0.065}$	0.0012
		DO/(F:M)	0.0019
Log-normal	$\mu_{\ln x}$	Gt	0.0004
		DSA	0.0137
	$\sigma_{\ln x}$	Gt	0.0099
		MLSS	0.0171

The particles smaller that 2 µm were mostly individual microbial cells which were the primary particles canticles constituting the flocs. They were not only the largest group in terms of their number but also were substantial contributors to the total biomass (Li and Ganczarcyk, 1991). In secondary clarification, these cells could not be separated from the treated effluents unless they flocculated or become associated with large flocs during the course of setting. These particles contributed to the effluent SS and caused problems in an effluent disinfection process. Excessive quantities of such particles could indicate the formation of pin-point floc sludge and in a turbid final effluent.

For all these reasons, it was of interest to find out how the operation factors the proportion of these primary particles in relation to the lager ones, as determined by the logistic regression described earlier. Identification of factors influencing the occurrence of primary particles provides information that may be used in treatment plant operation to and improve the quality of the final effluent.

6. Settling Properties of Activated Sludge

The quality of the effluent of a wastewater treatment plant mainly depends on the efficiency of the secondary clarifier where the separation of the sludge and the effluent due to sedimentation takes place. The sludge settling properties have a crucial impact of treated water quality. High quality can hardly be achieved with sludge with poor settling properties.

L. Akca et al (1993) showed that The settling properties in secondary clarifiers depend on the type of dominant microorganisms in biomass and the amount and characteristics of the exocellular enzymes produced by microorganisms. These factors are closely related to the operational conditions of aeration basins.

Several researchers show that sludge age is one of the most important parameters affecting the settling properties of biomass (Diagger and Roper,1985:Knocke,1986; Li et al., 1986). L. Akca et al (1993) evaluated the data of these researches and established a relationship between sludge volume

$$SVI = 246.9\exp(-0.0742\theta_x) \qquad (13)$$

index (SVI) and sludge age. The mathematical expressions of these relation was determined as:

Where θ_x = sludge age, day

The settling velocity equation, which proposed, by Veslined (1968) was adopted as

$$V = V_0 \exp(-nX) \quad (14)$$

Where V_0 and n are constants. There are also consistent correlations between sludge volume index and the two constants (V_0, n) of the settling equation.

$$V_0 = 28.1(SVI)^{-0.2667} \quad (15)$$

$$n = 0.177 + 0.0014(SVI) \quad (16)$$

Having evaluated the published data (Diagger and Roper,1985: Knocke,1986), the relationships of V_0 – SVI and n-SVI were developed considering the values of sludge volume index (SVI) and sludge age . the relationships between sludge volume index and coefficients of solid flux model , V_0 and n, are as follows

In order to compare the V_0 and n values obtained from the previous both equations, Table 4 was constructed for three different values of SVI. L. Akca et al (1993). From the previous four equations V_0 and n can be expressed in terms of sludge age (θ_x) as follows

$$V_0 = 6.466 \exp(0.0198\ \theta_x) \quad (17)$$

$$n= 0.177+0.346 \exp(-0.0742\theta_x) \quad (18)$$

Secondary clarifier design can be achieved by using these relationships. it could be possible to make correlations between the settling velocity equation constants and the sludge volume index in order to be easily applied to plant design and control.

Table 4. Comparison of V_0 and n values calculated from different values

V_0 (m/h)				n(1/g)		
SVI	50	100	150	50	100	150
Diagger and Roper (1985)	7.8	7.8	7.8	0.253	.358	0.46

						3
Wahlberg and Keinath (1988)	12.2	9.2	6.1	0.370	0.585	1.07 0
L Akca et al 1993	9.9	8.2	7.4	0.247	0.317	0.38 7

The sludge settling properties are affected by many factors but can be characterized by two main parameters: the specific settling velocity and resistance velocity (Renko et al., 1992) these parameters are time-varying in general and constant in diminished time scale (1-5 h).

R. Tenno et al., (1995) showed that a typical settling curve as a function

$$\frac{dh}{dt} = c - \alpha \int(x) h_t, \quad h_0 = H, \int(x) = \frac{x}{x^2 + \beta} \tag{19}$$

of time and concentration can be described with the following model

Where h =sludge blanket interface height, H= initial height, X= activated sludge concentration, α= specific settling velocity, c= resistance velocity caused by non-absolute (lim h1 ≠0) thickening, β= small parameter for description of the special situation in low concentration case when the settling velocity cannot be improved reduction of the sludge concentration, only. Typical values of these parameters are α=2-10 kg SS/m^3 h, c-0.2-1m/h, β=0.02-0.1kgSS^2 /m^6 . The sludge zone interface height for infinite settling period

lim h_t = c/αf(x) and the zone settling velocity ZSV ≅ α f(x)h_0 –c can be used as well known characteristics for interpretation of these parameters.

The effectiveness of activated sludge process is subject to a good solid liquid separation, which is strongly determined by the activated sludge settling properties .In turn, the settling properties depend mainly on the flocs' structural properties and on activated sludge microbial population.

Monitoring of the activated sludge settling properties as well as the structural properties and the dynamics of microbial populations can provide insights into the relation between the microbial community changes the process performance. Several attempts have already been made to evaluate the settling and floc structural properties of activated sludge (Andreadakis, 1993; Wilen and Balmer, 1999 Dagot et al., 2000) or to monitor the population dynamics under stable environmental conditions (Kaewpppat and Grady, 2002). However, due to the high sensitivity of the microorganisms to environmental conditions, many characteristics of the biological treatment system remain poorly understood and therefore, difficult to control.

R. Govoreanu et al., (2003) tried to investigate possible links between activated sludge settling properties where the changes in (SVI), structural Properties floc size distribution (FSD) and bacterial community composition (DGGE) were monitored in an SBR during a period of 227 days.

The microbial flocs in the aeration basin of an activated sludge plant are not uniform in size but are associated with certain type of size distribution, which could span three to four order of magnitude in size (Li and Ganczarczyk, 1991). The effect of particle size distribution in activated sludge system on such basis physical and chemical phenomena as flocculation, substrate transfer and utilization was highlighted by Li and Ganczarczyk, (1991. To achieve a better understanding of the activated sludge dynamics so as to be able to develop a more effective control strategy for this process, it is important to take into account the floc size distribution.

Evaluating the structural properties, floc size and size distribution measurements open opportunities for detecting changes in the floc properties during various treatment steps and provide valuable information about how well the separation process work.

R. Govoreanu et al., (2003) used the laser light scattering technique to obtain floc size measurements. This technique allowed online determination of the changes in floc structure such as fractal dimension or direct size distribution. Settling properties (sludge volume index (SVI)) of the activated sludge were compared with on-line measurements of floc size and size distribution obtained by using a laser light scattering technique. Three distinct stages in SBR evolution were observed. In the first stage, the structure floc properties showed predominant presence of floc forming bacteria in the activated sludge. A good correlation between floc size settling properties and microbial community evolution was observed by R. Govoreanu et al.,. The second stage showed a good balance between floc forming and filamentous bacteria, with good settling properties and a highly dynamic community in the SBR. In the third stage, an increase in the filamentous bacteria was observed. R. Govoreanu added that a correlation between the floc size and settling properties is highly dependent on the type of microorganisms preset in the floc structure.

Sludge Volume Index. This is a measure of the settleability and compactability of sludge. It is measured by a standard lab test in which mixed liquor is placed in a 1-or 2-l cylinder and allowed to settle for 30min (usually). At the end of the settling period, the volume of sludge solids on the bottom of

$$SVI = \frac{y}{X_T V_C}(1000mg/g) \qquad (20)$$

the cylinder is measured. The calculation relies on knowing the original density of the total suspended solids and the volume. e.g.

Where: SVI= sludge volume index (ml/g), Y= volume of sludge after settling (ml), X_T=TSS content of mixed liquor (mg/l_, V_C= Volume of cylinder (L),

A low SVI indicates that the sludge settles well. This can be used to estimate the concentrations of the VSS and TSS in the recycle line if the ratio of VSS to TSS IS KNOWN (X_V/X_T typical 0.75-0.8). Sezgin (1982) demonstrated that SVI is influenced by sludge characteristics such as floc size, sludge concentration and the filamentous organisms abundance and found that for a very low content of filaments compact, high density “floc-to-floc” aggregates were formed, which had no significance changing effect on the SVI.

Correlation between Settling Velocity and Floc Size. In order to investigate the settling behavior of activated sludge in secondary clarifiers of wastewater treatment plants and to find a substitute for this sludge for laboratory experiments, K Hoffmann et al (2000) used the Digital Particle Image Velocimetry (DPIV) to detect the settling velocity of the suspended particles. A suspension of olive stone flour was tested as a possible substitute. The used experimental setup consists of a column with a measurement section where the particles are illuminated by a laser light. A conventional CCD-camera and an overlay frame grabber was used to digitize the frames. The velocity is calculated by a cross-correlation method. In addition the size of the particles and the concentration is measured to find the correlation between these parameters. It was found that DPIV is a suitable method for detecting settling velocities even if the particles are relative large and their shape is irregular as it is in activated sludge suspensions. The advantage of this method is that even small velocities are detectable directly.

K Hoffmann et al (2000) got a correlation between settling velocity and floc size

$$v_s = p_1.D^{p_2} \tag{21}$$

can be described by:

Where Vs = settling velocity, D = diameter, P1 = empirical parameter, P2= empirical parameter

Hoffmann et al showed that the values for P1 respectively P1 lay between 0.01 and 0.04 respectively 1.45 and 1.65. A comparison of these test results with literature data shows correspondence concerning the functional correlation. LEE et al. also found a power function to describe the correlation between the sedimentation velocity Vs and the diameter D of activated sludge flocs. However, their value of the exponent p2 only lies between 0.7 and 0.8.

LEE et al. used a system where the settling column was filled with a well-mixed sample suspension where as in Hoffmann 's investigation the sample entered the water filled column. Additionally the floc size spectra which LEE et al. evaluated does not exceed 1 mm while Hoffmann detected floc sizes lay between 0.3 and 3 mm.

Floc Size Measurements

The measurement of size and size distribution is an efficient way of detecting changes in the floc properties at the various treatment steps, or shifts in growth conditions in the wastewater treatment plant, as well as how well the different separation processes work. The size range can be as wide as from a few microns up to 1000 m (Parker et al, 1971; Li and Ganczarczyk, 1991.)

Various methods have been used to measure the size of activated sludge floc such as direct microscopic observation (Barbusinski and Koscielniak, 1995; Li and Ganczarczyk, 1987); image analysis (Li and Ganczarczyk, 1991; Grijspeerdt and Verstraete, 1997), Coulter Counter (Andreadakis, 1993) and laser light scattering (Biggs, 2000). Flocculation is a reversible process. When the activated sludge flocs are exposed to different environmental conditions (i.e. shear stress, anaerobic condition) small particles are disrupted from larger flocs, which is known as deflocculation.

R. Govoreanu et al., (2002) used the microscopy technique as approach for structural characterization of the activated sludge flocs. It is an excellent technique as it allows to directly examine the flocs. Consequently, the shape of the flocs can be observed and this is important for understanding the real structure of the flocs. However, for manual microscopy elaborate sample preparation is necessary and only few particles can be examined. Recently, by connecting the microscope to automated image analysis software it became possible to faster evaluate the activated sludge properties (Li and Ganczarczyk, 1991; Grijspeerdt and Verstraete, 1997; Alves et al., 2000). By using the image analysis, R. Govoreanu et al., (2002) separated the selected particle analysis parameters in two groups. The first group covers measures of size while the second deals with various aspects of the particles' shape. Within each of these categories, there are a variety of individual parameters that can be measured or calculated from others that are measured directly.

R. Govoreanu et al., (2002) showed that the size measurement results were first evaluated starting from the assumption of a spherical shape of the flocs and, second from the real size parameters of the flocs (area, perimeter, length, width). It is showed as following:

Biggs and Lant (2000) customized an on-line technique developed by Spicer et al. (1998) to follow dynamic changes in the floc size distribution (FSD) of activated sludge using on-line laser light diffraction. This technique allows the dynamics of the activated sludge flocculation process to be followed in a quantitative way.

To improve the understanding of several biological and physico-chemical processes and to be able to control them, mathematical modeling has already been shown to be a valuable tool. In the area of wastewater treatment this has resulted in Activated Sludge Models 1-3 (ASM), in which the biological processes taking place in the treatment process (e.g. COD-removal, (de)nitrification and phosphorous removal) are described. However, in the complete treatment plant models built around these ASM's, the model of the final clarification step tends to be the weakest part.

A linear measure of the size is often more useful than the area and it is common to convert the measured area to the equivalent sphere diameter. The data analysis is performed by using a program developed in Matlab, which is running within Lab-VIEW. Particle size distributions are further obtained as function of number, area and volume. The distributions are generated as histograms on a semi-logarithmic scale.

Size measurements based on size parameters. The most important size parameters are the particles area and number. By using these two parameters the area number frequency distribution is determined. A particularly useful size parameter is also the particle length (maximum Feret's diameter) defined as the length of the longest segment in the convex hull of a particle in all possible directions of projection**.**

Current research aims at evaluating the possibility to measure on-line particle size distributions (PSD) under different experimental conditions, such as sludge concentration, sonication, mixing and at analyzing the influence of some setup components. (i.e. tubes length, T-part).

R. Govoreanu et al., (2003) showed that to describe the mean particle size, the volume - weighted average diameter or the mass mean diameter, D[4,3]. Should be used. This parameter is calculated as:

$$D[4,3] = \frac{\sum_{i=1}^{n} \Delta F_N(x)_i \, x_i^4}{\sum_{i=1}^{n} \Delta F_N(x)_i \, x^3} \tag{22}$$

Where x_i is the diameter of size class i and $\Delta F_N(x)_i = N_i / \sum N_i$ is the number fraction in size class i.

7. The Sedimentation Model

The secondary clarifier in activated sludge processes has two functions: clarification and thickening of sludge in developing the model for its sedimentation dynamics, it was assumed that no significant reactions occur in the settling basin. Sedimentation as amass transfer process was modeled in this study according to the solid flux theory (Marsili Libelli , 1989). Tyagi et al.,

$$F(X,U) = X\upsilon + Xu \tag{23}$$

(1996) showed that the total flux due to gravity and sludge withdrawal from the bottom was expressed as

Where ν and u are, respectively, the settling and bulk velocity of biomss.

$$\upsilon = nX^{a-1} \tag{24}$$

The power law approximation was used in this study to describe the settling velocity.

Where n and a are the settling parameters (Shin and Dixk 1980):

$$F(X,U) = nX^{a} + Xu \tag{25}$$

lauria et al., 1977). The total flux is then expressed as :

Also tyagi et al showed the limiting quantities X^* and F^* were determined by letting

As function of the underflow velocity u

$$X^* = \exp(1/(a-1)\ln(-u/na)) \qquad (26)$$

$$F^* = n(X^*)^a + X^*u \qquad (27)$$

Efforts have been performed to model clarifiers by using Computational Fluid Dynamics (CFD) (Stamou and Rodi, 1989; Krebs, 1991; Zhou and McCorquodale, 1992; Lyn et al., 1992; Armbruster et al., 2000). CFD primarily aims at modeling the fluid dynamics of the clarifier by using continuity, momentum and turbulence equations. This allows to predict a velocity and sludge concentration pattern for the complete clarifier both in space and time. In such models the transport of water can be included quite easily. To be able to predict the sludge concentration profile in the settler, however, more detailed information about the activated sludge settling process is needed. This sludge settling depends on floc settling properties like floc size and floc structure. These are influenced by local flocculation conditions including shear forces (induced by the flow regime), dissolved oxygen concentration, loading rate, sludge concentration, ionic strength, etc., which vary throughout the settler. Detailed information about the activated sludge flocculation process and the interactions between the fluid and solid phase should, therefore, be included in the model.

To model the flocculation process to a reasonable degree of detail for inclusion in a CFD model, a more sophisticated “segregated” model, often referred to as Population Balance Model (PBM), is needed (Ramkrishna, 1979; Frederickson, 1991). In this contribution a PBM and the laser light diffraction technique will be combined to collect flocculation-relevant experimental data to support these models and show how this combination of new approaches can further improve our knowledge about the activated sludge flocculation process and the influences it is subject to size measurements based on spherical assumption of the flocs

A real plant often has a principal outline according to Figure 1, with one flow into the settler (Q_f) and two flows leaving the settler (Q_e and Q_u). At the plant where we have gathered the data, the biological part (including sedimentation) is not the only one, instead it is followed by a polishing step with chemical precipitation, flocculation and flotation. Consequently, the volume (and area) of the settler is not dimensioned to remove all suspended solids (SS) and therefore you may sense that the effluent suspended solids concentration is rather high. However, this is a common configuration and may often be an efficient solution, which reduces the total volume requirement.

A fairly simple and well functioning model of the settling process is the multi-layer model. In this *one-dimensional* model (only dynamics in one dimension is modeled) the settler is divided into a number of layers, usually between 10 and 50. The transport of sludge between each layer depends on bulk flow, which is related to the water flow (upwards or downwards), and gravitational flow, which depends on the influence of gravity on the sludge flocs and is always, directed downwards. Above the layer which receives the influent flow (Q_f) of sludge (i.e. the feed layer), the bulk flow is always directed upwards and below the feed layer the bulk flow is directed downwards. This means that the flow upwards (Qe) is equal to the effluent flow, while the flow downwards (Q_u) is equal to the sum of the recycled flow (Q_r) and the excess sludge flow (Q_w) (see Figure 3).

$$\frac{dX_i}{dt} = \frac{J_{up,i+1} + J_{s,i-1} - J_{up,i} - J_{s,i}}{z_i} \qquad (28)$$

The changes in concentration within each layer above layer *m* can be expressed as:

Where z_i is the height of layer i. Equivalently, the changes in concentration within all other layers are described (simple mass balances according to Figure 3). The relations between the different flows are, in accordance with Figure 1, given as:

$$Q_f = Q_{in} + Q_r$$
$$Q_e = Q_{in} - Q_w$$
$$Q_u = Q_r + Q_w$$

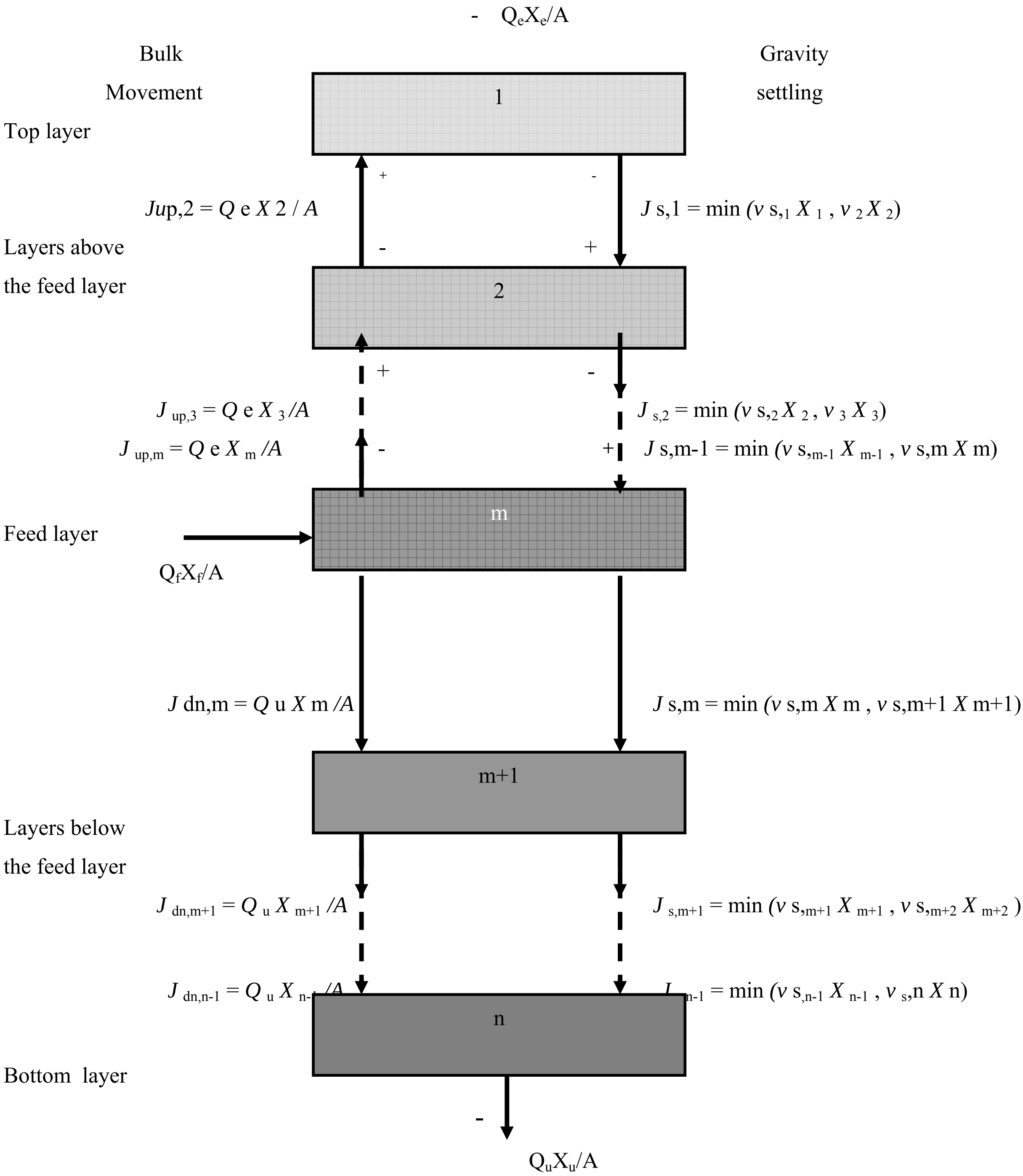

Figure 3. The principle for the multi-layer model describing the settling process.

Different alternatives exist to describe the particulate material (X): either let X denote a composite variable of all different particulate components in the biological model or use a separate state variable, X i , to describe each particulate fraction. The first alternative gives a small error of how the proportions between the different fractions propagate through the settler during dynamic conditions but requires significantly fewer state variables (in a 10-layer model 10 state variables are needed for alternative 1 and 40 state variables for alternative 2). In steady state both alternatives will produce identical results. Furthermore, in our settler model the suspended solids are given in the unit mg SS/l and not, as in the biological model, in mg COD/l and consequently the units must be transformed. In this exercise, alternative 1 will be used and the different particulate fractions will be added together and transformed according to:

$X_f = 0.75 (X_S + X_{IP}) + 0.9 (X_{BA} + X_{BH})$

Where X_f is the SS-concentration entering the settler and the other variables describe the concentrations in the last biological reactor. X_{ND} is treated in a special way. The reason for this is that X_{ND} is actually a part of X_{BA} and X_{BH}, but is described as a separate variable in the biological model for special technical reasons. When the sludge is returned to the reactor, X_u (the SS-concentration in the sludge recirculation stream) must again be divided into the

$$X_{S,r} = \frac{X_U}{X_F} X_{S,f} \qquad (29)$$

different fraction using the same principle as above. This means that for example X_S in the sludge recycle flow is calculated as ($X_{s,r}$ is the concentration of the Xs which is reintroduced into the reactor and $X_{s,f}$ is the concentration of Xs which enters the settler with the flow Q_f):

Using the same method the concentrations for each particulate fraction is calculated, including X_{ND} although it is not a part of X_f. However, it is reasonable to assume that also this fraction is concentrated in the settler in the same proportion as the other fractions. An important parameter for the sedimentation is the settling velocity, vs. It is not constant instead it depends on the SS-concentration. In the literature many different functions can be found, which are considered to describe the settling velocity as a function of the SS-concentration.

$$v_s = \max(0, \min(v_0^{/}, v_0(e^{-r_h(X - X_{\min})} - e^{-r_p(X - X_{\min})}))) \qquad (30)$$

One commonly used function is the double-exponential function:

This function takes into account that the settling velocity does not increase exponentially when the concentration is lower than a limit value,

$$v_s = \max(0, v_0(e^{-r_h X} - e^{-r_h X})) \qquad (31)$$

instead it decreases. In this exercise we will use a simplified version of the double-exponential function, i.e.:

This simplification implies that the settling velocity is zero when the concentration is equal to zero and immediately increases when the concentration increases and it does not have the flat top given by v_0'.

Suggested parameter values for v_0, rh and rp are:

V_0 = 150 m/d, r_h = 0.00042 m3/g. r_p = 0.005 m3/g.

To simplify the model we assume that the dissolved fractions are not affected by the sedimentation, i.e. all soluble concentrations in the effluent water (Q e) and in Q u are identical to the concentrations in the settler feed flow (Q_f).

Conclusion

A review of flocculation modeling indicated that characteristics of activated sludge flocs such as floc size distribution, viable/ non-viable cell ratio, density and water content, and kinetics of bioflocculation affect the flocculation models. It was of interest to find out how the operation factors such as sludge loading , dynamic sludge age, dissolved oxygen DO, turbulence turbidity hydraulic retention time, and mixed liquor suspended solids affect the floc size distribution and the bioflocuulation and finally on the plant performance

The review of settling properties of activated sludge indicated that sludge age is one of the most important parameters affecting the settling properties of biomass; therefore, the mathematical expressions between SVI, sludge age, and the settling velocity should be used in reactor and sedimentation modeling.

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