Desalination and Water Treatment
www.deswater.com

51 (2013) 1571–1576
February

doi: 10.1080/19443994.2012.715073

Taylor & Francis
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A simple model for secondary clarifier: application to wastewater treatment plant

Zahir Bakiri*, Saci Nacef

Laboratory of Chemical Process Engineering (LGPC), Department of Chemical Engineering, Ferhat Abbas University of Setif, Setif, Algeria
Tel. +213 773 22 76 18; Fax: +213 36 92 84 18; email: zahir.bakiri@gmail.com

Received 29 February 2012; Accepted 18 July 2012

ABSTRACT

Wastewater treatment by low-rate activated sludge in aerobic stabilization ponds is a treatment process that has been, for most Algerian towns, the preferred tool for treating their wastewater because it has proven most reliable and easier to operate. The wastewater treatment plant of the City of Setif (Algeria) is a good example for this type of process. It has a capacity of 330,000 pop-equivalents and has been designed to accommodate 66,000 m^3/d in dry weather. The work is based on the technical analysis from 2007. The mathematical model for the secondary clarifier was developed, including, propose a modified expression of the settling velocity. The treatment of the pollution parameters has been estimated. The test results have been updated, so that the results correspond to the present Algerian normalization.

Keywords: Wastewater; Activated sludge; Mathematical modeling; Settling velocity; Secondary settler; Sedimentation

1. Introduction

The performance of wastewater treatment plants (WWTPs) based on the activated sludge process depends essentially on the behavior of the secondary sedimentation tanks [1]. The characterization of the sedimentation tank is less developed compared to the aeration tank [2]. This is partly due to the diversity and complexity of the mechanisms involved in the separation of liquid and solid phases [3,4].

The design and operation of secondary settlers is commonly based on the solid flux theory using the state point analysis [5–7]. Regardless of the model chosen, measurements of settling velocities determined using zone settling tests are commonly used for calibration [8].

Batch settling curves have also been applied in order to include compression settling, using the Vesilind Model [5], and also for the different regimes separation following the Vesilind form [8,9].

Therefore, this study focused on the characterization of the movement of the sludge blanket in the secondary settler using the solid flux theory and the velocity settling. This allowed us develop a model with dispersion based on a thorough experimental study carried out *in situ* and the application of online data which are the mass load flow, transfer concentration, and influent characteristic. On the other hand, introducing corrections values of the sludge volume index (SVI)

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*Corresponding author.

Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain

allowed the model to reduce sludge height variations and thus, increase the solid/liquid separation.

2. Materials and methods

2.1. Description of the WWTP

The WWTP in this study is located in the city of Sétif-Algeria. The plant is operated by the National Algerian Wastewater Board. It is a 330,000 P.E. (influent 66,000 $m^3 day^{-1}$). The plant consists of gridirons, primary/secondary clarifiers, and oxidation reactors.

Wastewater is first introduced and mixed in the aeration reactor by a turbine. Then, the mixed liquor is allowed to settle in the settling period. The activated sludge is settled in secondary settlers. At the end of each cycle, the excess mixed liquor is discharged from the reactor. After settling, the effluent is discharged into a nearby river.

Municipal wastewater plant characteristics, expressed in terms of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS), are typical of those of low-to-medium load. Treatment efficiencies in terms of BOD_5, DCO, TSS, and ammonia (NH_3–N) exceeded 97, 95, 99.5, and 78%, respectively.

2.2. Experimental procedure

A secondary clarifier helps to separate the solids from the liquid phase of the mixed liquor and remove settled solids from the bottom of the settler. In a WWTP, the secondary settler is the fundamental work that ensures the gravity separation of sludge and treated water discharged into the receiving environment. The good knowledge of the process is a prerequisite for any attempt to develop a mathematical model. The proper functioning of this settler implies a good design and a rational management of sludge production and control of its settleability.

Fig. 1 is a scale representation of the settling tank of the WWTP in Setif. It is a cylindrical–conical clarifier with a diameter of 46 m and is 7.20 m deep. This develops an area of 1,661 m^2. The height of the cylinder is 4 m and that of the conical part is 3 m with a bridge and a scraper or a large Clifford (skirt distribution). The figure shows the position from where the samples were taken.

2.3. Verification of the horizontality of the sludge blanket

A manual exploration of the surface of the sludge blanket was carried out using a white disk having a diameter of 20 cm attached in its center by means of a cable 5 m long and 0.1 m graduated.

Measurements were made on four perpendicular radials (Fig. 2) within a regular interval of time of half an hour. The sludge blanket is located at a depth below the base of Clifford.

Apart from a turbulent area near the Clifford (skirt distribution), the measurements show a good horizontality (a precision of ±50 cm) of the sludge blanket throughout the entire surface of the decanter.

From this figure one can note the following:

- The feeder layer of the decanter is located at the Clifford.
- The horizontality of the sludge blanket was also observed visually when it approaches the surface of the decanter.
- A one-dimensional model is possible.

These results have also been reported in the literature [10,11].

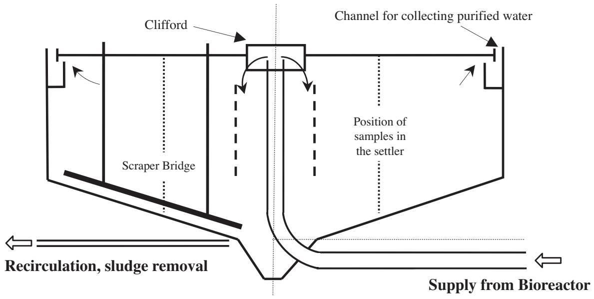

Fig. 1. Geometry of the secondary settler of the WWTP in Setif.

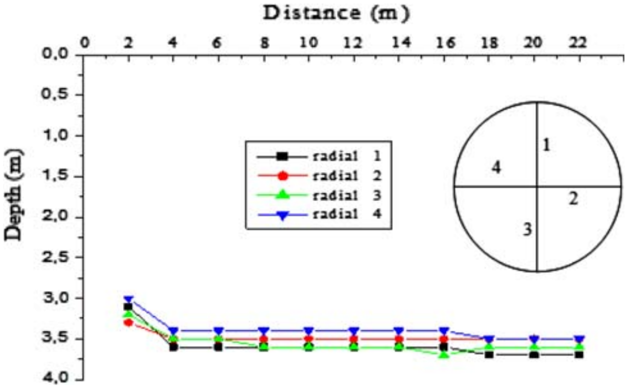

Fig. 2. Manual measurement of the depth of sludge blanket.

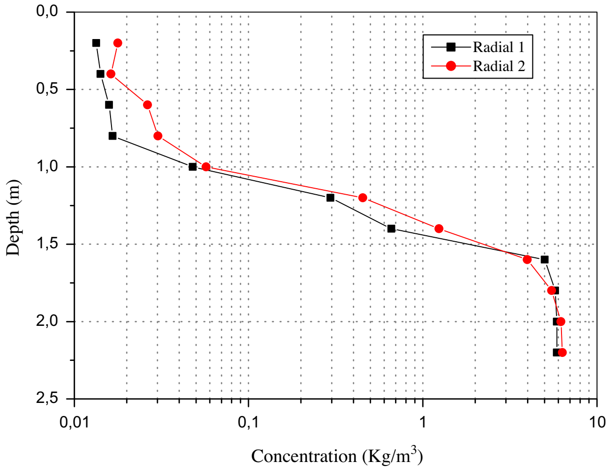

Fig. 3. Measured concentration (TSS) as a function of the depth in the secondary settler.

2.4. Concentration profiles of the sludge

The measurements consist of taking samples from the secondary settler and parallel to the Clifford (see Fig. 3). The samples are taken for two radials.

The sludge concentration is expressed as TSS and averaged for each depth. All measurements were taken in dry time (no rainy periods) and without interruption or sludge blanket overflow. The sludge blanket is located at a depth of 3 m.

The transfer concentration from the aerator to the settler is 5.5 kg/m^3. On the average, the concentration at the Clifford feeding the decanter sludge is only 2.5 kg/m^3. This concentration is low upon leaving the Clifford. The water in the clarification zone quickly dilutes the sludge [10].

Finally, it is to be noted that the variations in the height of the sludge blanket were taken based on the real operating parameters of the sewage treatment plant of Setif. This is to get an operational model that would be validated through experience.

3. Dynamic modeling of the secondary settler

The proposed model with dispersion has enabled us to attain a better knowledge of the decantation process on the settling of activated sludge in the secondary settler. In a secondary settler, the existence of an area where settling occurs in mass is a priori not obvious in a conventional operation. Lee [4] clearly distinguishes his work compared to that of Bürger [12] who rather introduce a critical area. According to the classical theory of Marsilli-label [3] and Chancellor [13,14] (originally from the theory of flow), the boundary layer to a separator system is formed in the settling mass. However, Bürger [15] and Sin [16] showed that the critical area could also form in the compression zone, but Lee [4] states that this area appears only in the compression zone. Nevertheless, the continuous flow of the solid sludge in the feeder layer zone causes a perturbation of the sludge blanket leading to an increase of its height.

3.1. Model overview

Our model is a one-dimension model based on the flow theory and with integrating the dispersion.

The assumptions made for this model are the following:

- This model deliberately neglects sludge growth and assumes a constant mass in the system.
- The sedimentation velocity depends only on the concentration.
- There is a conservation of mass, and biological reactions are neglected.
- The two settler compartments (clarification and thickening) are assumed to be homogeneous.

3.2. Numerical resolution

Sedimentation of solid compounds in the secondary clarifier produces an accumulation of the sludge and becomes more compact at the bottom of the unit. This variation in concentration permits to distinguish two different compartments; the clarification compartment and the thickening compartment (Fig. 4).

The mass balance equation (Fig. 4) is given as follows:

$$\frac{\partial(X.A.\Delta z)}{\partial t} = F_{\mathrm{h}}(z) - F_{\mathrm{h}}(z+\Delta z) + J(z) - J(z+\Delta z) + F_{\mathrm{S}}(z) - F_{\mathrm{s}}(z+\Delta z) \qquad (1)$$

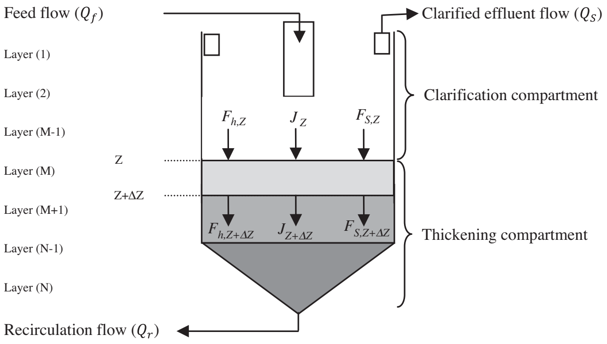

Fig. 4. Mass balance at the thickening compartment.

The downward bulk flux, dispersive flux, and gravity settling flux are defined as

$$F_h = \frac{Q_r}{A} X, \; J = -D_S \frac{\partial X}{\partial Z} \quad \text{and} \quad F_S = V_S X \tag{2}$$

Eq. (1) takes the following form

$$\frac{\partial X}{\partial t} = -\frac{\partial F_h}{\partial Z} - \frac{\partial F_S}{\partial Z} + \frac{\partial}{\partial Z}\left(D_S \frac{\partial X}{\partial Z}\right) \tag{3}$$

where D_S is the dispersion coefficient of solids.

After differentiation of Eq. (3), we have

$$\frac{\partial X}{\partial t} = -\frac{Q_r}{A}\frac{\partial X}{\partial Z} - \frac{\partial (V_S X)}{\partial Z} + D_S \frac{\partial^2 X}{\partial Z^2} \tag{4}$$

We can simulate Eq. (4) for the clarification zone (see Fig. 4), we have

$$\frac{\partial X}{\partial t} = -\frac{Q_S}{A}\frac{\partial X}{\partial Z} + \frac{\partial (V_S X)}{\partial Z} + D_S \frac{\partial^2 X}{\partial Z^2} \tag{5}$$

For layer ($i = 1$),

$$\frac{dX_1}{dt} = \frac{Q_S(X_2 - X_1) - V_{S,1} X_1 A + D_S\left(\frac{X_2 - X_1}{\Delta Z}\right) A}{A \cdot \Delta Z} \tag{6}$$

For layers above the feeder layer,

$$\frac{dX_i}{dt} = \frac{Q_S(X_{i+1} - X_i) - V_{S,i-1} X_{i-1} A - V_{s,i} X_i A + D_S\left(\frac{X_{i+1} - 2X_i + X_{i-1}}{\Delta Z}\right) A}{A \cdot \Delta Z} \tag{7}$$

For feed layer,

$$\frac{dX_M}{dt} = \frac{Q_A(X_f - X_M) + V_{S,M-1} X_{M-1} A - V_{S,M} X_M A + D_S\left(\frac{X_{M+1} - X_M}{\Delta Z}\right) A - D_S\left(\frac{X_M - X_{M-1}}{\Delta Z}\right) A}{A \cdot \Delta Z} \tag{8}$$

For layers under layer fee,

$$\frac{dX_i}{dt} = \frac{Q_r(X_{i-1} - X_i) + V_{S,i-1} X_{i-1} A - V_{S,i} X_i A + D_S\left(\frac{X_{i+1} - 2X_i + X_{i-1}}{\Delta Z}\right) A}{A \cdot \Delta Z} \tag{9}$$

For bottom layer ($i = n$),

$$\frac{dX_N}{dt} = \frac{Q_r(X_{N-1} - X_N) + V_{S,N-1} A - D_S\left(\frac{X_N - X_{N-1}}{\Delta Z}\right) A}{A \cdot \Delta Z} \tag{10}$$

Table 1
Experimental data for sludge settling at low load

Parameters	Settleability (ml/l)	TSS (kg/m^3)	SVI (m^3/kg)	V_S (m/h)
Undiluted	250	0.90	0.2772	3.75
First dilution	165	0.56	0.2913	5.85
Second dilution	98	0.39	0.2483	6.75
Third dilution	68	0.20	0.3365	9.19

The Eq. (10) gives the settling dynamic model with a term of dispersion, where (X) is the concentration, (N) is the number of layers, and (Z) is the height.

The nonlinear differential equations are solved by the iterative method.

4. Results and discussion

The mathematical equation that describes sedimentation is given by Eq. (11) which expresses the relationship between sedimentation rate and concentration. Some examples of speed functions are summarized in Table (1). These data were obtained from the WWTP of Setif.

In the classical theory, the settling velocity is estimated from tests on batch settling. In this study, the settling velocity was obtained from the variation of the liquid/solid interface with time.

In the proposed model, the new velocity law (double-exponential function) used (Eq. (11)) is based on the Vesilind [17] function which is expressed as follows:

Table 2
Characteristics of the secondary settler at Setif WWTP

Parameters	Values
A	1,661 m^2
Q	100–1,320 m^3/h
X_f	1.5–7.0 kg/m^3
D_s*	11.7263 m^2/s

*Used by Hamilton et al. [18].

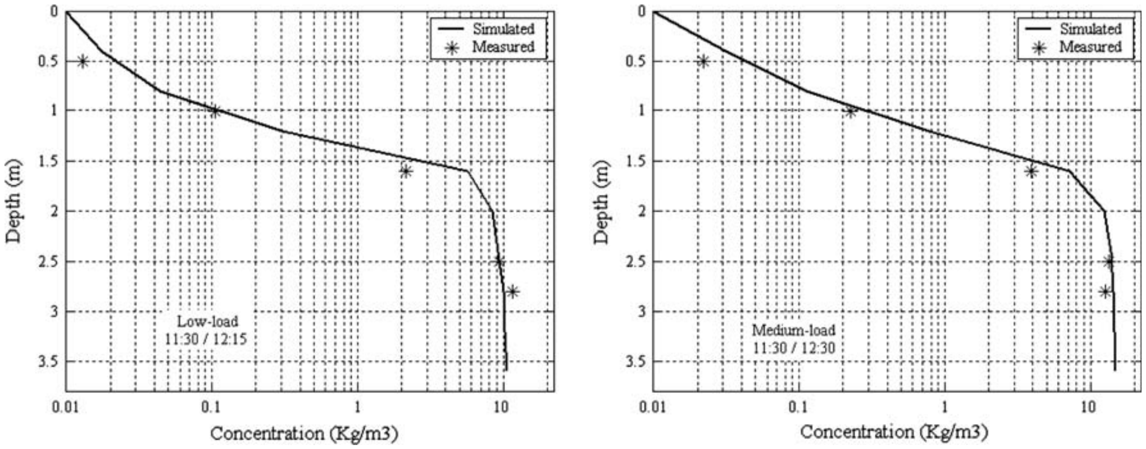

Fig. 5. Sludge concentrations measured and simulated as a function of depth in the secondary settler.

$$V_s = \begin{cases} V_o e^{-(0.155+0.0025.\mathrm{SVI})X} & 0 \leq X < X_T \quad \text{Clarification Compartment} \\ V'_o e^{-(0.120+0.0021.\mathrm{SVI})X} & X \geq X_T \quad \text{Thickening Compartment} \end{cases} \tag{11}$$

where X_T is the sludge concentration at the onset of the thickening compartment. The parameters V_o, V'_o and SVI are regarded as constants that require estimation for the low load case and medium load case, respectively, and can be obtained by batch settling tests.

4.1. Application of the model to the WWTP of Setif

In this part, the measured experimental results will be compared to those predicted by the proposed model taking into account the real operating conditions of the WWTP of Setif, which are listed in Table 2.

As shown in Fig. 5 (for both low and medium loads), the experimental results are in accordance with those predicted by the proposed model at low values of the depth (0.0–2.0 m). However, at higher values of depth (2.0–3.8 m), the curve of the variation of concentration with depth for the experimental results is slightly above that of the model. It is interesting to note that the largest differences are found at the thickening zone. These differences could be attributed to the difficulty in taking samples at a depth of more than 2.0 m.

5. Conclusion

The aim of this study was to develop a mathematical model for the secondary settler of wastewater treatment. The requirement for a successful application of this model is the running of an extensive calibration and validation procedure (V_o, V'_o maximum theoretical settling velocity and SVI for velocity function), as demonstrated in this study.

In this study, the movement of the sludge blanket was characterized using the solid flux theory and the new velocity settling function.

The model included also the real operating conditions of the WWTP of Setif—Algeria. It was found that the experimental results in terms of variations of the sludge concentration with depth were in accordance with that predicted by the model for a depth range of 0.0–2.0 m.

For a more realistic model, it would be necessary to involve the secondary settler design and understand better the characterization of the sludge settling.

Nomenclature

A	—	clarifier surface area, m^2
BOD_5	—	biochemical oxygen demand in five days, kg/m^3
COD	—	chemical oxygen demand, kg/m^3
D_S	—	dispersion coefficient, m^2/s
F_h	—	downward bulk flux, kg/m^2 h
F_s	—	gravity settling flux, kg/m^2 h
NH_3–N	—	ammonia, kg/m^3
Q_r	—	recirculation flow rate, m^3/h
Q_f	—	feed volumetric flow rate, m^3/h
Q_s	—	outward volumetric flow rate, m^3/h
SVI	—	sludge volume index, m^3/kg
TSS	—	total suspended solids, kg/m^3
V_o, V'_o	—	maximum theoretical settling velocity, m/h
V_S	—	gravity settling velocity, m/h
X	—	total suspended solids concentration, kg/m^3
z	—	sludge blanket height, m

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