WATER RESEARCH 50 (2014) 160–170

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Dynamic one-dimensional modeling of secondary settling tanks and design impacts of sizing decisions

Ben Li, Michael K. Stenstrom*

Civil and Environmental Engineering Department, University of California, 5732 Boelter Hall, Los Angeles 90095-1593, USA

ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form
10 October 2013
Accepted 24 November 2013
Available online 10 December 2013

Keywords:
Clarification
Activated sludge
Control
Wastewater treatment

ABSTRACT

As one of the most significant components in the activated sludge process (ASP), secondary settling tanks (SSTs) can be investigated with mathematical models to optimize design and operation. This paper takes a new look at the one-dimensional (1-D) SST model by analyzing and considering the impacts of numerical problems, especially the process robustness. An improved SST model with Yee–Roe–Davis technique as the PDE solver is proposed and compared with the widely used Takács model to show its improvement in numerical solution quality. The improved and Takács models are coupled with a bioreactor model to reevaluate ASP design basis and several popular control strategies for economic plausibility, contaminant removal efficiency and system robustness. The time-to-failure due to rising sludge blanket during overloading, as a key robustness indicator, is analyzed to demonstrate the differences caused by numerical issues in SST models. The calculated results indicate that the Takács model significantly underestimates time to failure, thus leading to a conservative design.

1. Introduction

Biological secondary treatment processes are widely used in wastewater treatment plants to remove organic matter and reduce nutrients such as nitrogen and phosphorus. In all cases, efficient operation requires the sludge to be removed from the wastewater by sedimentation, filtration or other solids–liquid separation processes.

For sedimentation to be successful, the biomass must be composed of large particles or flocs, which have sufficient settling velocity to be removed in a settling tank of manageable size. To achieve this goal, it is necessary to grow the biomass to select floc-forming organisms as well as understanding solids–liquid separation processes (Parker et al., 2004).

Several types of treatment processes can achieve the solids–liquid separation, but secondary settling tanks (SSTs) are most commonly used. SSTs, also known as sedimentation basins or solids–liquid separators, use gravity to separate the biomass from the fluid, and have two similar but distinct functions: clarification and thickening. Clarification is the removal of finely dispersed solids from the liquid to produce a low turbidity effluent; Thickening is the process of increasing the sludge concentration in order for it to be recycled or disposed in less volume. In SSTs, the clarification process occurs in the upper zone while thickening occurs near the bottom. The result is an effluent from the top, low in suspended

* *Corresponding author.*
E-mail address: stenstro@seas.ucla.edu (M.K. Stenstrom).
0043-1354/$ – see front matter
http://dx.doi.org/10.1016/j.watres.2013.11.037

Nomenclature

A	cross-sectional area of SST [m^2]
C	sludge concentration [g/m^3]
C_{min}	non-settleable solids concentration [g/m^3]
C_T	total ASP cost [dollar]
G	flux [$g/(m^2h)$]
G_s	gravity settling flux [$g/(m^2h)$]
h	SST inlet depth [m]
H	SST depth [m]
H_s	Sludge blanket level [m]
n	Veslind settling parameter [m^3/g]
Q	flow rate [m^3/h]
r_h	Takács settling parameter [m^3/g]
r_p	Takács settling parameter [m^3/g]
R_c	relative cost coefficient
S	biodegradable substrate concentration [g/m^3]
v	settling velocity [m/h]
v_0	Veslind settling parameter [m/h]
V	bioreactor volume [m^3]
$v_{0,\max}$	Takács settling parameter [m/h]
v_s	hindered settling velocity [m/h]
t	time [h]
z	height above SST bottom [m]

Greek letters

Φ	flux [$g/(m^2h)$]
Φ_l	limiting flux [$g/(m^2h)$]
μ/Y	F/M ratio ((kg BOD_5/kg MLSS) d^{-1})

Subscripts

e	effluent
f	feed
i	index of model layer
in	incoming
u	underflow
w	waste

Superscripts

n	index of time

solids, and a second stream of settled, concentrated solids from the bottom, suitable for recycling or disposal.

As one of the most important units in wastewater treatment process, the SST is often a "bottle neck," limiting the capacity of the wastewater treatment process (Ekama et al., 1997; Ekama and Marais, 2002). The SST sizing must be combined with the bioreactor sizing to guarantee the minimum necessary performance to meet the design basis, as well as maintaining required efficiency for contaminant removal. If the SST does not remove solids from the effluent, or fails to produce a recycle stream, process failure occurs with effluent permit violations and loss of biomass from the reactor. Therefore, two commonly used parameters: overflow rate and solids flux, have been developed for SST design and evaluation.

Nevertheless, given the fact that the wastewater characteristics vary, such as flow rate and contaminant concentrations, traditional design procedures for SSTs tend to be more empirical and conservative by introducing averaged parameters with safety factors (Coe and Clevenger, 1916). Therefore SST performance can suffer unanticipated fluctuations, which may cause process control problems and increase the risks of failure. Stringent standards for effluent quality and the need for optimization of WWTP performance have made such variations in effluent quality undesirable, and have encouraged the use of dynamic controls for wastewater treatment process. For the purpose of developing such an automatic control system to provide consistent effluent water quality, great effort has been made to create accurate mathematic descriptions of wastewater treatment process (mathematical models), and the one-dimension (1-D) SST model for predicting the time dependent responses to transient process inputs of SSTs is a good example.

1-D SST models, based on solids-flux theory (Kynch, 1952), describe sludge transport by a scalar conservation partial differential equation (PDE). Although many 1-D SST models are available and some of them, especially Takács model (Takács et al., 1991), have been widely utilized in engineering practice, the predication of the sludge settling characteristics and concentration profiles in and out of a SST is still far from satisfactory.

The presently available 1-D models are highly dependent upon empirical equations to express clarification, thickening and compaction process and these equations or functions can be an error source that can profoundly affect simulation results. A second challenge is the difficulty of making full-scale measurements in working SSTs that has caused a lack of data sets for model calibration and verification. As a consequence, further research is still needed to improve the performance of the 1-D model.

The first goal of this paper is to review the previous, major developments in SST design and analysis to show how they have been used to develop 1-D models. The second goal is to review the 1-D models especially with regard to the numerical methods used to solve the resulting PDE, and to provide an improved method for solving the PDE. The final goal is to show how the 1-D model can be used in the design process to better understand the interaction between bioreactor and SST, particularly with regard to dynamic inputs, such as the time-to-failure after a shock load or appearance of filamentous bulking organisms.

2. Background

2.1. *Flux theory and state point analysis*

As theoretical foundations of solids–liquid separation, flux theory and state point analysis are widely used in SST studies, such as SST design, capacity analysis, and optimizing daily operations. For the purposes of quantifying biosolids settling characteristics, the starting point of both flux theory and state point analysis is usually the batch settling test. Table 1 lists the major contributors to solids flux theory and shows that Coe and Clevenger (1916) performed one of the earliest batch settling studies. Their major contribution was a comprehensive method to understand and utilize batch settling test